Undrained peatland areas disturbed by surrounding drainage: a large scale GIS analysis in Finland with a special focus on aapa mires

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SUMMARY

Half of the Finnish peatland area is drained for forestry. The remaining undrained peatlands are not all pristine, because surrounding drainage may disturb their hydrology. This concerns especially aapa mires, which are dependent on hydrological connections to their upper catchments. We investigated the amount and sizes of Finnish undrained peatlands, the drainage state of their margins, and the naturalness of aapa mires in large (> 50 ha) undrained peatland areas, using a GIS analysis based on digital map data, aerial images and an elevation model. The results show that a majority (66.7 % of count, 84.7 % of area) of undrained peatland areas have at least partly drained margins. Drainage activities commonly disturb minerotrophic water discharge to aapa mires. In the middle boreal zone, on average 41.6 % (median 42.8 %) of the catchment area of aapa mires is such that hydrological connection with the mire is disturbed by intervening drainage. In the southern boreal zone, the figure is 25.1 % (median 16.1 %), and in the southern part of the northern boreal zone 24.2 % (median 9.9 %). Possible implications of the disturbances include tree encroachment, hummock formation and fen–bog transition, which is likely to cause a loss of biodiversity but could potentially increase peat growth and carbon sequestration.

KEY WORDS: anthropogenic disturbance, bog, catchment, fen, peatland hydrology

INTRODUCTION

A cool and moist climate and a level topography have favoured peat formation in Finland, where almost one third of the land area is covered by different types of peatland (Ilvessalo 1956, LUKE 2017, Wu *et al.* 2017). However, according to an official figure given by the Natural Resources Institute Finland, 53 % of the total peatland area of 8,644,000 ha has been drained in order to promote timber growth (LUKE 2017). In southern Finland, the drainage percentage is 75 %. Peatland refers here to all environments with a surface peat layer, such as open mires and peatland forests (Figure 1).

Forestry ditching began in Finland in the early 1900s, and the most active phase was in the 1960s and 1970s (Lindholm & Heikkilä 2006a). Peatlands that were originally tree-covered were the most likely to be drained (e.g. Päivänen & Hånell 2012). Currently, all wooded peatland habitat types except the poorest from a silvicultural standpoint are endangered in southern Finland (Raunio *et al.* 2008, Kontula & Raunio 2009, 2018). Draining of open mires has not been so common, and ombrotrophic bogs and the wettest fens were most often left aside from drainage, although their margins were frequently drained (Eurola *et al.* 1991). It is assumed that today much of the remaining undrained peatlands are remnant patches of larger mires (Kaakinen *et al*. 2008), but exact statistics of the situation are unavailable.

Fragmentation of mire landscapes and drainage of peatland margins may have multiple consequences, including changes in biodiversity and the carbon cycle. Drainage has changed mire-forest ecotones, and the undrained inner areas may have also been affected if their hydrology has been altered by the disturbance at the margin (Tahvanainen 2011). This kind of remote disturbance may concern especially mire types that are dependent on the water flowing from their surroundings; in boreal environments especially aapa mires and related minerotrophic peatlands (see section **THE AAPA MIRE CONCEPT** below).

An example of remote hydrological disturbance is given by Tahvanainen's (2011) study of a boreal aapa mire in Eastern Finland. Historical aerial photographs, peat stratigraphy and vegetation data demonstrated that when water supply to the mire was disrupted by surrounding ditches, acidification was

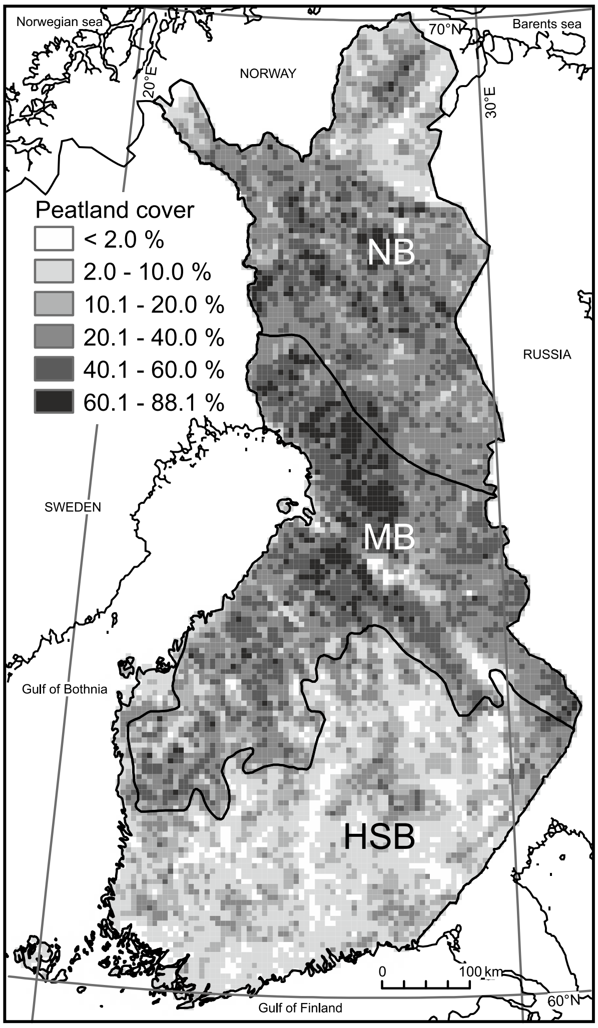

Figure 1. Peatland cover in Finland. Peatland refers here to all environments with a surface peat layer. Percentage cover is shown for 6 × 6 km squares (TM35 1:10,000 map sheets). HSB = hemiboreal and southern boreal zone, MB = middle boreal zone, NB = northern-boreal zone (peatland data: National Land Survey of Finland and SYKE; climatic-phytogeographical zones: SYKE; base map: HELCOM).

initiated, and *Sphagnum* mosses covered the mire's formerly open wet surfaces within just a few decades. The vegetation change could be characterised as a fen to bog transition, and the change was accompanied by accelerated peat growth. In a more extensive study, Rehell (2017) inspected 71 seemingly undrained aapa mires located in the middle boreal zone of Finland by visual interpretation of aerial images and maps. He suggested that 36 % of the upper catchment area of the mires was, due to margin drainage, no longer discharging water to the mires.

In the Finnish assessment of habitat types, the status class of various aapa mire complex types varies between 'least concern' (LC) and 'endangered' (EN) (Raunio *et al.* 2008, Kontula & Raunio 2009, 2018). The European Red List of Habitats (Janssen *et al.* 2016) classifies the 'aapa mire habitat' (referring to wet central fens of aapa complexes) as LC. Problems with both these assessments include insufficient knowledge of the changes that have occurred in the undrained mires and the inability to predict the future changes. Catchment disturbances are recognised as a threat to aapa mires with potentially significant implications for ecosystem services and biodiversity, but the risk cannot be reliably estimated because of the lack of quantitative data (Janssen *et al.* 2016, Tahvanainen 2016).

For studying the hydrological disturbances of undrained mires, Finland is a well suited area, owing to its abundance of peatlands, their relatively intensive utilisation, and a climatic and vegetation gradient across the country (Lindholm & Heikkilä 2006b). The research motivation is, however, not confined only to Finland, as the situation of catchment modification by surrounding land use is common everywhere where peatlands are located in inhabited and managed areas. The role of peatlands in global climate regulation and biodiversity and the prevalence of minerotrophic peatland types in northern latitudes worldwide emphasise the international importance of the topic (e.g. Frolking & Roulet 2007, Yu 2012, Janssen *et al.* 2016).

In the present study, we develop GIS-based methods for investigating the naturalness of undrained peatlands and the hydrological disturbances caused by surrounding land use. At the same time, we gain large scale knowledge of the state of Finnish undrained peatlands and the remaining aapa mires. First, we determine the amount of undrained peatland areas and drainage status of their margins in different parts of Finland. Then, we study the remaining aapa mires, in particular the extent to which land use disturbs the potential inflow of water from their upper catchments. In connection with this, we also explore the relationship between nature conservation and naturalness of mires.

THE AAPA MIRE CONCEPT

Traditionally, aapa mires are regarded as boreal mire complexes with wide central fen areas but also include the surrounding drier peatlands (Ruuhijärvi 1960, Laitinen *et al.* 2005, 2007). In another approach, aapa mire can be regarded as synonymous with a patterned (ribbed) fen, a minerotrophic mire area where wet, sparsely-vegetated depressions (flarks) alternate with drier and narrower strings

(Figure 2). The strings are typically covered by fen vegetation with *Sphagnum* mosses and they are oriented perpendicular to water flow, acting as dams to store water in the flarks. Trees are absent or sparse on hummock strings and in mire margins. This second characterisation conforms to the definition of 'aapa mire habitat' in the European Red List of Habitats (Janssen *et al.* 2016, Tahvanainen 2016).

Patterned fens are fairly common in the boreal zone (Ruuhijärvi 1983, NWWG 1988, Masing *et al*. 2010, Gunnarsson & Löfroth 2014). They function as water conveyers in peatlands and are found in locations collecting sufficiently large amounts of water from the upper catchment areas (Laitinen *et al.* 2007, McCarter & Price 2017). It is easy to detect them in aerial photographs, but occurrence of patterning is not an on/off phenomenon. On the contrary, there is a range of variation from a strong patterning to a faint, scarcely recognisable one. To include all this variation, the aapa mire concept can be used in a wide sense, referring to any larger boreal open minerotrophic mire in which the minerotrophy is based on near-surface runoff from the upper catchment, and which have some gradient to allow directional mire water flow. String-flark patterning is usually found in this kind of mire, but the patterning is not a necessary characteristic of this wider aapa concept (Laitinen *et al*. 2005, 2007, Lindholm 2015).

The relatively short and cool summer of the boreal region, enhancing mire wetness and suppressing biological productivity, is an important contributor to aapa mire occurrence (Ruuhijärvi 1960, Tahvanainen 2016). Another is seasonal flooding caused by snow melting, as the meltwater flushes away the accumulated humic acids from surface peat, thus preventing acidification and restricting the growth of *Sphagnum* mosses (Tahvanainen *et al*. 2003, Sallantaus 2006).

In practice, there is a gradual variation in all of the typical aapa characteristics, not only in the extent and clarity of patterns, but also in wetness and abundance of flarks, density of tree cover, strength of minerotrophy, characteristics of water flow etc. This ensures that, regardless of chosen definition for aapa mire, there are borderline-cases for which it is difficult to say whether or not they are aapa mires. This kind of delineation problem, however, is not unique to aapa mires, since it concerns all such concepts that draw borderlines to continuums, which is often the case in ecology (Joosten *et al*. 2017).

Another kind of delineation problem arises in landscapes where peatlands form wide interconnected networks lacking confining basins: where to assign the outer boundary of an individual aapa mire complex? In this study, we take a hydrological solution to this problem: surrounding peatlands belong to the aapa complex when they belong to the upper topographic catchment of the wet central area; i.e., if they discharge water to the aapa mire's wet fen areas.

STUDY AREA

Finland is located in north-western Europe, where Atlantic oceanic and Eurasian continental influences meet (Figure 1). The mean annual temperature is +5 °C on the south-western coast and below -2 °C in

Figure 2. Patterned fens and flark fens belonging to an aapa mire landscape. Palosuo mire, Kuusamo, Finland, northern boreal zone (digital orthophoto: National Land Survey of Finland).

the north-western areas. The annual precipitation is 400–750 mm, 30–50 % of which falls as snow, and the duration of snow cover ranges from 85 to 225 days (Tikkanen 2006a, FMI 2018). The terrain is generally rather flat and low. Altitudes range from sea level to 1,328 m, but 80 % of the area is less than 200 m above sea level (Seppälä 1986). The most common surficial deposit is glacial till, which is relatively impermeable material, and an additional factor that explains the prevalence of peatlands in Finland (Tikkanen 2006b).

Finland covers much of the climatic-phytogeographical variation of the circumboreal-Arctic area: hemiboreal, southern boreal, middle boreal, northern boreal, alpine, and arctic zones (Ahti *et al.* 1968, Tuhkanen 1984), although the last two comprise only small areas in the highest hills in the north. Moreover, since the hemiboreal zone is in Finland a relatively narrow coastal area with a low coverage of peatlands, it is joined in the present study with the southern boreal zone (Figure 1). Delimitation of the zones is based on vegetation differences induced by the macroclimate. For example the length of the growing season and the effective temperature sum differ between the zones (Solantie 2006).

The wetness of peatlands generally increases northwards in accordance with the humidity of the climate. Open pools of water are most abundant in the peatlands of the northern boreal zone (NB hereafter), which is the centre of the aapa mire distribution. Aapa mires are common also in the middle boreal zone (MB), but they are generally drier. In the hemiboreal and southern boreal zone (HSB), aapa mires are confined to places where local hydrological conditions inhibit the development of ombrotrophic bogs, which are the climatic climax type in this southerly zone. The outlined picture of climate-geographical variation in Finnish peatlands follows Ruuhijärvi (1960) and Eurola (1962; see Ruuhijärvi 1983).

Peatland drainage has roughly doubled the annual growth of wood on peat substrates in Finland, and today approximately 20 % of timber growth in Finland takes place in peatland forests (Tomppo 1999). However, some 0.5 to 1 million ha of peatland drainage has not been successful in forestry terms (Laiho *et al.* 2016). Peatland agriculture, peat-mining, water reservoirs and various construction activities have further reduced the undrained peatland area (Kaakinen *et al.* 2008). The extent of agricultural peatland fields in Finland is currently about 310,000 ha (Myllys & Soini 2008), but agriculture has probably reduced the peatland area by up to one million hectares (Lindholm & Heikkilä 2006a). Minerotrophic mires have been preferred in both forestry and agriculture. At present they are among the threatened peatland types in southern Finland where they are naturally less common and where land use is more intensive (Raunio *et al.* 2008).

METHODS

Overview

To satisfy the aims of the study, we utilised two peatland GIS data sets, 1) the peatland drainage status raster and 2) the data base of undrained peatland patches, both developed in the Finnish Environment Institute SYKE. In the following sections, we describe the data sets, and how we further developed and analysed them. We performed spatial data processing and analysis in ArcGIS. Table calculations were done in Excel and statistical analysis in R (package: dplyr).

Peatland drainage status data

The peatland drainage status raster (SOJT_09b1 2009) of the Finnish Environment Institute SYKE covers the whole of Finland, and it is based on the Finnish National Land Survey's digital map data 'Topographic Database' from the year 2008 (see NLS 2018). Peatlands of the Topographic Database are rasterised into a 25 m resolution grid, and roads, fields, and narrow (< 5 m) streams are enlarged by 50 m wide buffers and embedded in the raster. Peatland cells that are located under the buffers are defined as drained peatlands (Figure 3a). In southern Finland, narrow streams are almost invariably artificial ditches, but in northern Finland natural brooks are more common. Natural brooks are identified sub-automatically based on their irregular shape and deleted. Peat mining areas are added from the Corine Land Cover 2006 classification background data (CLC2006 2009).

There is variation in how far the influence of a ditch extends into a peatland, but an approximate width of 50 m is used in the drainage status raster, because it is a common distance between ditches in forestry drained peatlands, and using it helped to prevent formation of small undrained strips between ditches. It was also customary to choose a multiple of 25 m, which is the cell size of the data.

Previous uses of the drainage status raster include those by Kaakinen *et al.* (2008) and Kareksela *et al.* (2013). In the present study, we used it to determine the extent of peatlands and their drainage status in various areal divisions. We calculated the areas with ArcGIS's *Tabulate areas* function. Forest-covered peatlands (canopy cover > 10 %) were distinguished from open mires by combining the Corine Land Cover 2012 (CLC2012 2015) classification's information with the peatland raster data.

Undrained peatland patches

A polygon data set of the remaining patches of undrained peatland was constructed by vectorising the raster cells denoting undrained peatland in the drainage status raster. With the resulting data set, it was easy to locate the undrained peatlands and measure their areas. The drainage status of margins of the undrained patches was determined with ArcGIS's *Polygon neighbors* tool by calculating the length of coincident edges of undrained patches and

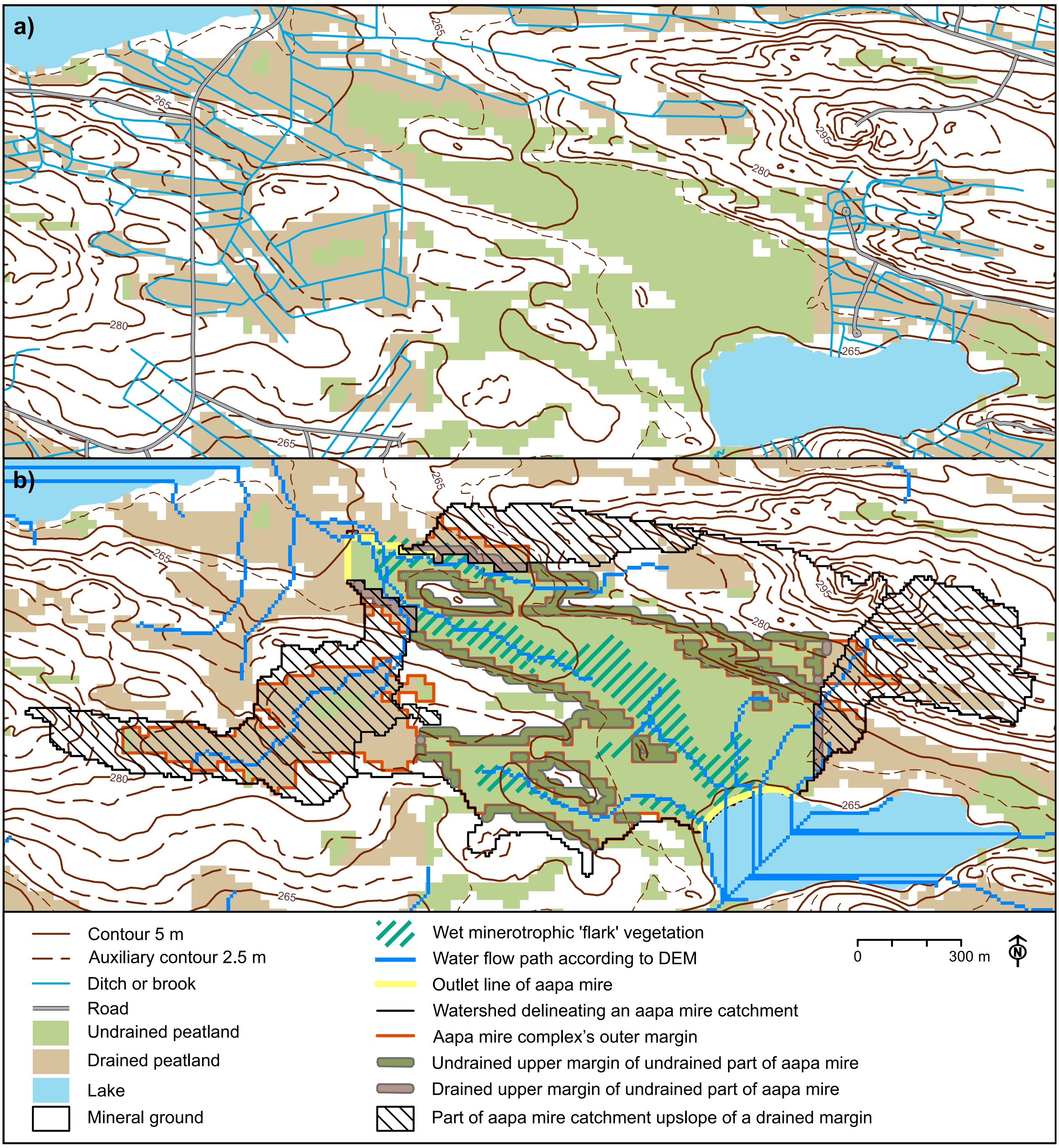

Figure 3. a) The principles of the peatland drainage status raster. Peatlands within a 50 m proximity to ditches, roads or fields are defined as drained peatland. b) GIS-analysis of aapa mire naturalness. The aerial image in Figure 2 shows the same location. (Peatland data: SYKE; contours and waters: National Land Survey of Finland; roads: Finnish Transport Agency; flark area digitised on aerial photograph).

their neighbouring drained patches and summing up the lengths patch by patch. Because the peatland patches are produced from raster data, there are also cornerwise connections between the undrained and drained patches. These do not add to drained margin, although it is likely that in reality some length of margin is drained also in these instances. To take this fact into account, while not overestimating it, we counted 5 m of drained margin for every cornerwise connection of this kind.

The Finnish environment institute SYKE has conducted a data collection project in which large undrained peatland patches have been investigated visually from colour and IR aerial images at a resolution of 0.5 m (hereafter 'SYKE air photo investigation'). The collected information includes mire types and degrees of hydrological disturbance, estimated mainly by one experienced interpreter (Phil. lic. Hanna Kondelin). Previous uses of the SYKE air photo investigation data include Finnish national plans for peatland use and conservation (MAF 2011, Alanen & Aapala 2015). We will briefly explain the data below, since it was used in the present study to identify peatland patches with aapa features.

The SYKE air photo investigation data contains information on 4,701 undrained peatland patches, the minimum area of which is 20 ha for the HSB zone, 50 ha for the MB zone and the south-eastern part of the NB zone, and 100 ha for the rest of the NB zone, although the northernmost part is excluded. There are 3,884 patches that are larger than 50 ha, 18.5 % of which are classified into the best hydrological condition class 'good' (i.e. 'in a natural state, or at most with some small insignificant ditching'). Other classes are 'sustainable' (36.1 %, 'there are drained areas bordering the undrained patch, but these do not threaten the hydrology of the undrained area'), 'weakened' (32.0 %, 'land use around the undrained peatland patch has weakened the unity of the peatland, but it is still regarded as a functioning ecosystem'), 'weak' (2.8 %, 'land use has altered the peatland complex so that it is not anymore a properly functioning ecosystem'), 'destroyed' (0.7 %, 'the peatland has ceased to exist as an ecosystem') and 'not evaluated' (9.9 %, mainly large disorganised networks of peatland, postponed for later evaluation, in the NB zone) (Table 1).

Determining aapa mire naturalness

Sampling protocol

The SYKE air photo investigation data allows for a random sample of aapa mires to be drawn, since it includes information on mire complex types. Unfortunately, the smallest peatland patches are not included and the minimum size varies. We set the minimum at 50 ha for the present study. Another feature of the data worth a mention is the wide aapa concept. Patterned fens, wet soaks, and wide minerotrophic treeless mire areas are regarded as aapa features, and all peatland patches with some of these features are marked as aapa mire patches. These include showpiece examples of large aapa mires

Table 1. Hydrological condition of undrained peatland patches (> 50 ha) according to the Finnish Environment Institute's air photo investigation.

Hydrological condition class	Areal division						Total	
	HSB		MB		NBS			
	Count	%	Count	%	Count	%	Count	%
Good	58	18.1	323	13.8	339	27.6	720	18.5
Sustainable	163	50.8	940	40.3	300	24.4	1403	36.1
Weakened	87	27.1	964	41.3	192	15.6	1243	32.0
Weak	11	3.4	87	3.7	10	0.8	108	2.8
Destroyed	2	0.6	20	0.9	4	0.3	26	0.7
Not evaluated	0	0.0	0	0.0	384	31.2	384	9.9
Total	321	100.0	2334	100.0	1229	100.0	3884	100.0

Note. HSB = hemiboreal and southern boreal zone, MB = middle boreal zone, NBS = southern part of northern boreal zone.

dominated by distinctly patterned fens as well as many kinds of borderline cases, in which the aapa features are subordinate and sometimes difficult to judge.

Altogether, 2,684 peatland patches exceeding the size limit of 50 ha contain aapa features: 93 in the HSB zone, 1794 in the MB zone and 797 in the southern part of NB zone. Because of the differences in the prevalence of aapa features between the climatic zones, southern Finland would be underrepresented if a simple random sampling was applied to the whole study area. Thus, we grouped the peatland patches with aapa features into three lists according to climatic zones (HSB, MB and NB). Then, we excluded the mires outside the range of the digital elevation model, randomised the order of peatland patches in the lists and selected the first 40 appearing on each list for a total of 120 aapa mire patches (Figure 4).

Water flow model and delineation of aapa mire complexes

We delineated the aapa mire complexes and their catchments with the help of a digital water flow model. The basic idea is that the wettest mire vegetation through which minerogenic water flows is the centre of an aapa complex and the peatlands surrounding it are regarded as belonging to the complex if they are upslope of the wet central area and constitute a continuous peatland with it. Some of the peatland patches did not contain proper wet 'flark' vegetation, but the minerogenic flow paths were anyway located.

Water movements in peatlands are three-dimensional, but according to the acrotelm-catotelm model of peatlands (Ingram 1978, 1983), the vertical water movements are small in comparison to the horizontal movements. Most of the water flow occurs in the upper peat layer, which is less humified than the deeper, non-aerated layers. This model holds true in the majority of Finnish mires (Rehell *et al.* 2014). Rare exceptions are peatlands with considerable vertical groundwater flows and so-called percolation mires, where water is flowing horizontally through thick layers of permeable peat (Joosten & Clarke 2002, Laitinen *et al.* 2007). Accordingly, we ignored the vertical movements and modelled the water flows two-dimensionally based on surface elevation.

We used a LIDAR-based, 2 m resolution digital elevation model (DEM), produced by the National Land Survey of Finland. We aimed at showing what the natural water flow paths would be in the landscape in the absence of drainage, and after that we could assess how drainage interrupts the water flow. For minimising the effects of ditches, roads and

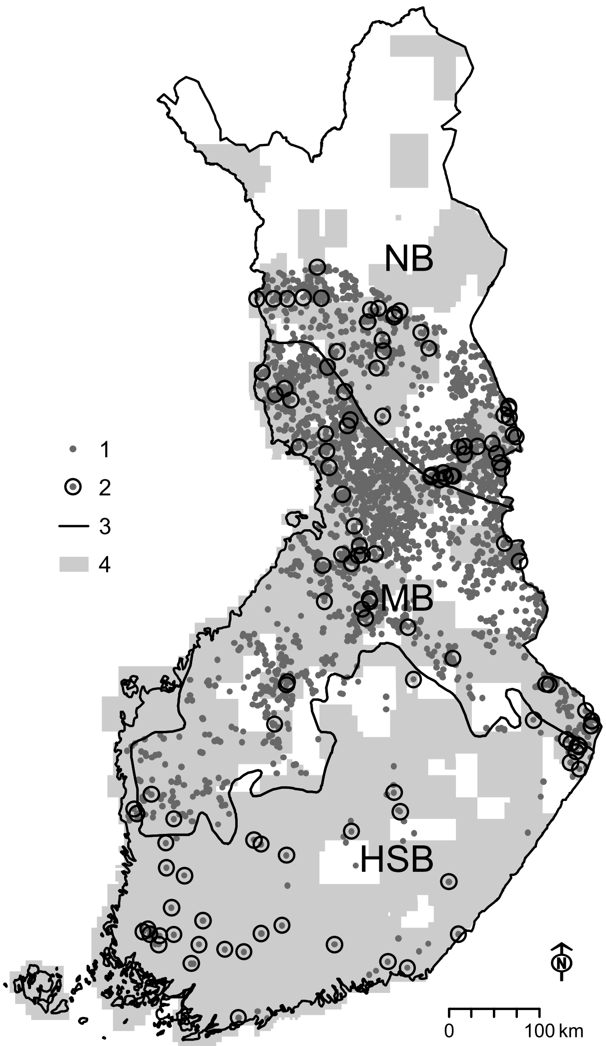

Figure 4. Aapa mire samples and their source population. Legend: (1) undrained peatland patch with aapa features and more than 50 ha in size; data for northernmost Finland unavailable; (2) sampled aapa mire; 40 for each climate zone, giving a total of 120; (3) climatic-phytogeographic zone border; HSB = hemiboreal and southern boreal zone, MB = middle boreal zone, NB = northern boreal zone; (4) extent of digital elevation model (base map: SYKE).

other artificial features in the natural flow paths, we generalised the DEM into a 10 m resolution by aggregating 25 nearby cells and defining their median elevation as the elevation of the aggregated cell. The median was chosen instead of mean because it is more resistant to extreme values. The treatment smoothed away most of the ditches. However, the deepest ones and severely subsided areas around the ditches persisted, which must be accepted as a potential source of error in the results.

In delineating the aapa mires and their

catchments, we mainly followed the basic eight-neighbour (D8) approach for DEM-based watershed delineation (O'Callaghan & Mark 1984, Jenson & Domingue 1988). However, instead of the precise outlet points often used for indicating the locations of water outflow, we drew 'outlet lines' at the zone through which water flows out of an undrained peatland patch (see Figure 3b). Table 2 presents the workflow. Positioning of an outlet line was straightforward if there were no deep ditches or severe ground subsidence near the target fen area. But if these were present, we had to judge, on the basis of aerial photographs, contours and water flow lines, which of the flow lines presently passing by the fen had originally flowed in it. Then, we extended the outlet line beyond the undrained patch to reach these flow lines. This more complicated procedure was done for 25 outlet lines, and their mean extension outside the undrained patch was 61.6 m (SD 67.3 m).

Measures of disturbances

We evaluated the hydrological connectivity between the undrained parts of aapa mires and their upper catchments. In short, the workflow was that we first delineated the parts of aapa mire catchments that have undisturbed connections with the undrained mire parts. These were subtracted from the aapa mire catchments, resulting in the parts of the catchments that have only disturbed or disrupted connections with the undrained parts of the mire (Table 3). Another possibility could be to delineate directly the catchments of disturbed upper margins, but this was not chosen because of the uncertainty caused by the complexity of mire margins. Namely, there are instances where a water flow path in our model enters, exits and re-enters the undrained mire. It is possible that if a flow path originally enters an aapa mire through an undisturbed margin, it may on a second time enter through a drained margin or vice versa. As only one type of entry can be registered in our method, we chose the undisturbed entries so as not to overestimate the disturbances.

Another kind of uncertainty is caused by mineral islets. They contribute to the complexity of mire margins as well, but because the mire margins against mineral islets tend to be less drained than other types of mire margin, the occurrence of mineral islets may cancel out the influence of a drained upper margin in our model. Although mineral islets can be important sources of minerogenic influence, their occurrence would unduly raise the proportion of undrained margin. To moderate this effect, we restricted the influence of mineral islets to the islet area and not the whole catchment.

Table 2. Delineation of aapa mire complexes and their catchments in ArcGIS environment.

Step	Procedure
1	Fill the sinks in DEM to obtain a DEM in which every cell is a part of a decreasing path of cells leading to the edge of the data set, after which compute a raster of flow directions from each cell to their steepest downslope neighbour and a raster of accumulated flow into each cell.
2	From the flow accumulation raster, select the cells that receive water from at least 500 cells (50,000 m^2) to make the important surface water flow paths visible.
3	Identify the water flow paths that coincide, according to air photos, with wet minerotrophic vegetation. Digitise outlet lines to locations where these water flow paths exit undrained peatland. If a wet minerotrophic area has several discharge directions, digitise outlet lines for all of them.
4	Run 'Snap pour point' tool for outlet lines to ensure the selection of the right cells for a mire outlet, after which determine the contributing areas above the outlets with Watershed tool and the flow direction raster. Vectorise the resulting catchment raster in order to create catchment polygons.
5	Clip peatland polygons with the catchment polygons for delineating the aapa complexes.
6	Clip undrained peatland polygons with the catchment polygons for delineating the undrained parts of aapa complexes.

The resulting data sets were used to calculate three variables:

(1) *Drained proportion of an aapa mire complex (%)*

(2) *The proportion of an aapa mire's catchment that is upslope of a drained margin (%)*

(3) *The proportion of the total mineral ground area within an aapa mire's catchment that is upslope of a drained margin (%)*

The first variable is a measure of how pristine the mire ecosystem is. The second variable roughly indicates how much the catchment has decreased due to drainage, as the areas upslope of drained margins have a weakened or disturbed hydrological connection with the undrained part of the mire. Since the mineral ground areas of catchments are the sources of minerogenic water, the third variable is indicative of the magnitude of reduction of minerogenic influence in aapa mires.

RESULTS

Amount of undrained peatlands in Finland

According to our raster data, the peatland area of Finland is 8,319,800 ha, 57.7 % of which is drained. The proportion of forest-covered peatlands is 68.9 % (canopy cover > 10 %). Among drained peatlands, 88.7 % are covered by forest, while 41.8 % of undrained peatlands are covered by forest. The extent of undrained non-forested peatlands (= open mires) is 2,049,200 ha, which accounts for 24.6 % of total peatland area. Active and abandoned peat mining areas, 112,800 ha, are included in the drained peatlands category (1.4 % of total peatland area).

The MB zone is the most peatland-rich area in Finland, but the amount of undrained peatlands is bigger in the NB zone. The HSB zone is the most drained zone and it has the smallest peatland area (Figure 5). The extent of undrained non-forested peatlands is 73,900 ha in the HSB zone (5.4 % of the peatland area in the zone), 516,300 ha in the MB zone (13.0 %) and 1,459,000 ha in the NB zone (49.2 %).

The undrained peatland area is divided into 1,772,778 separate patches in our data. This figure should not be taken as the exact number of undrained peatlands in Finland for two reasons: 1) the smallest peatlands are not included in the data because of the relatively coarse cell size and 2) many of the small patches in the data may in reality belong to narrow continuous strips of peatland, but the raster format cannot represent them as continuous unless they happen to be parallel to the raster grid.

Most of the undrained patches are small: 87.3 % (n = 1,553,625) of them are smaller than one hectare.

Table 3. Creating data sets for analysing the hydrological naturalness of aapa mires (steps taken after the steps listed in Table 2).

Step	Procedure
7	Enlarge (buffer) the undrained aapa mire polygons outwards by 25 m, and clip the resulting buffers with the catchment polygons. Only the buffers on the catchments of the aapa mires are left.
8	Separate the drained and undrained parts of the buffers on the grounds of the peatland drainage raster. For removing the small fragments formed as a by-product of the clipping operations, shrink the buffers by 12 m inwards, after which enlarge them back to the original width.
9	Convert the undrained buffer polygons to line features and delineate their catchments using the Watershed tool. Do this separately for the buffers in mineral islets and for the other undrained buffers. Latter results in polygons denoting the parts of upper catchments that have undisturbed connections with undrained parts of aapa mires. Former is processed further by clipping them with mineral islet polygons.
10	From the aapa catchment polygons, erase the polygons denoting undisturbed upper catchments, undisturbed mineral islets, and undrained parts of aapa mires. Resulting polygons represent the parts of the aapa catchments that are upslope of drained margins. There may also be some small fragments caused by imperfect fit between the different GIS data. For removing these, select only the polygons that intersect drained upper margins.

These small patches contain only 9.2 % of the undrained peatland area of Finland. Thus, in area terms, the larger patches are more important. There are 219,201 undrained peatland patches that are larger than one hectare, and they contain 90.8 % of the total undrained peatland area. See Table 4 for other size classes and geographical variations.

Margin drainage of peatland patches

In total, 18.6 % of margins of undrained peatland areas in Finland are drained. In the HSB zone, this proportion is 20.6 %, in the MB zone 33.1 %, and in the NB zone 10.1 %. The patch-wise mean of margin drainage proportion is 21.6 % (SD 28.9 %) in Finland. Excluding patches smaller than 1 ha, the respective mean proportion is 25.8 % (SD 31.0 %). This figure excludes most small artefacts created by the raster format but still covers 90.8 % of the undrained peatland area. Thus, it can be summarised that about one-fourth of the margin length of an average undrained peatland area is drained in Finland. Geographical differences are considerable, however, and margins of large peatland patches are more intensively drained than those of small patches (Figure 6).

Among undrained peatland patches of at least one hectare in size, a vast majority (66.7 % of the count, 84.7 % of the area) has some portion of their margin

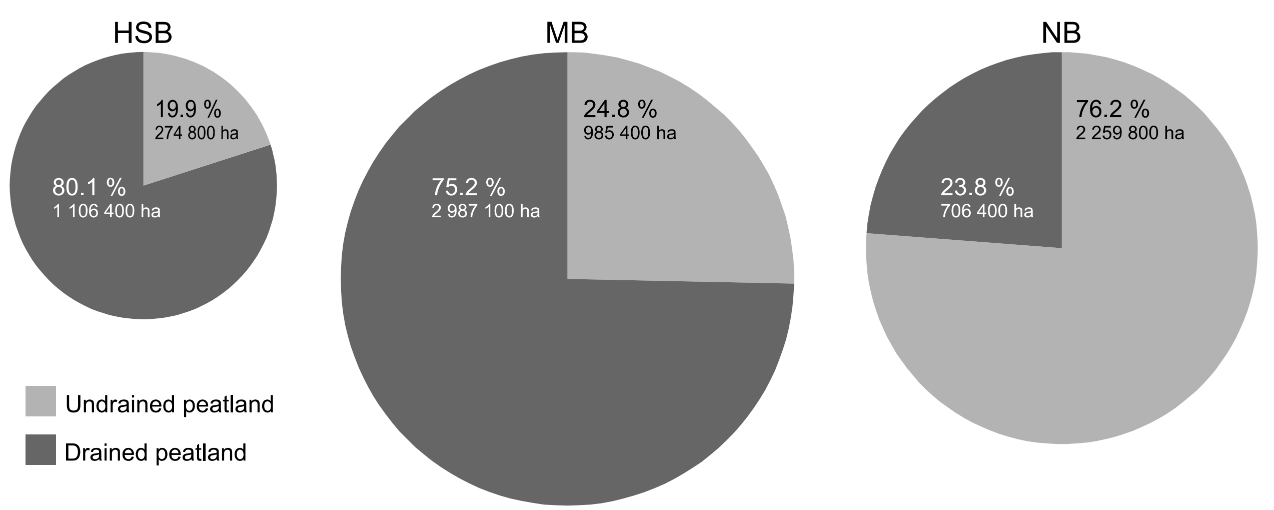

Figure 5. Areas of drained and undrained peatlands in Finland according to the drainage status raster. Peatland refers to all peat-covered areas, including forested environments and areas with thin layers of peat less than 30 cm thick. HSB = hemiboreal and southern boreal zone, MB = middle boreal zone, NB = northern boreal zone.

Table 4. Number and area of undrained peatland patches of different size classes in Finland.

Areal division	Size class							
	> 1 ha		> 10 ha		> 100 ha		> 1000 ha	
	Count	Area (ha)	Count	Area (ha)	Count	Area (ha)	Count	Area (ha)
HSB	39,940	166,600	2,098	83,400	142	35,300	2	3,100
MB	78,750	881,300	11,529	694,600	1,055	415,800	66	182,600
NB	100,511	2,148,800	16,873	1,908,200	2,357	1,508,200	253	955,700
Total	219,201	3,196,700	30,500	2,686,100	3,554	1,959,300	321	1,141,400

Notes. The areas do not include the mineral islets and water bodies inside the peatlands. HSB = hemiboreal and southern boreal zone, MB = middle boreal zone, NB = northern boreal zone.

drained. These patches have formerly been larger peatlands. Some of the patches are completely surrounded by drained margins. There are 5,784 such cases, and they comprise 2.63 % of the count of undrained peatland patches (0.5 % of the area) in the size class > 1 ha. In contrast, 73,054 peatland patches in this size class have no margins drained. These can be considered pristine peatlands. They comprise 33.3 % of the count of undrained peatland patches (15.3 % of the area) in this size class. Geographical differences are shown in Figure 7.

Based on SYKE air photo investigation data, it is possible to compare the margin drainage percentages of large (> 50 ha) undrained peatland patches with aapa features and without them. It appears that in the HSB and MB zones, peatland patches with aapa features have slightly less intensively drained margins than the non-aapa patches (Table 5).

Naturalness of remaining aapa mires

We sampled 120 large (> 50 ha) undrained peatland patches with aapa features, 40 for each zone: HSB, MB and NBS (NBS refers to southern part of the northern boreal zone, because data is unavailable from the northern part). For testing the representativeness of the samples, we conducted a Chi-square goodness of fit test using the hydrological state class from SYKE air photo investigation as a categorical test variable. The results suggest that the samples are representative, as there were no significant differences between the hydrological state classifications of our samples and their source data (p = 0.142, 0.411 and 0.580 for HSB, MB and NBS, respectively).

Patterned fens covered variable areas of the sampled peatland patches. However, three peatland patches, one in each climatic zone, were lacking patterned fens, but they nonetheless contained wet fen vegetation through which minerogenic water flows. On the other hand, four peatland patches (in the HSB and MB zones) were lacking wet fen vegetation, but they had patterned micro-topography resembling aapa mires. In addition, one peatland patch in the HSB zone was lacking both the patterns and wet fen vegetation, but also in this case upper catchment could be delineated, indicating at least a potential source of minerogenic water.

The sizes of the aapa complexes in our samples varied between 7.7 ha and 885.3 ha, and the mean was 115.3 ha (SD 164.8 ha) in the HSB zone, 146.9 ha (SD 132.7 ha) in the MB zone, and 119.4 ha (SD 98.1 ha) in the NBS zone. The sizes of the mire catchments (including the aapa mires) ranged from 17.3 ha to 1,230.9 ha, and the mean was 197.3 ha (SD 257.8 ha) in the HSB zone, 253.5 ha (SD 208.2 ha) in the MB zone, and 240.8 ha (SD 194.8 ha) in the NBS zone.

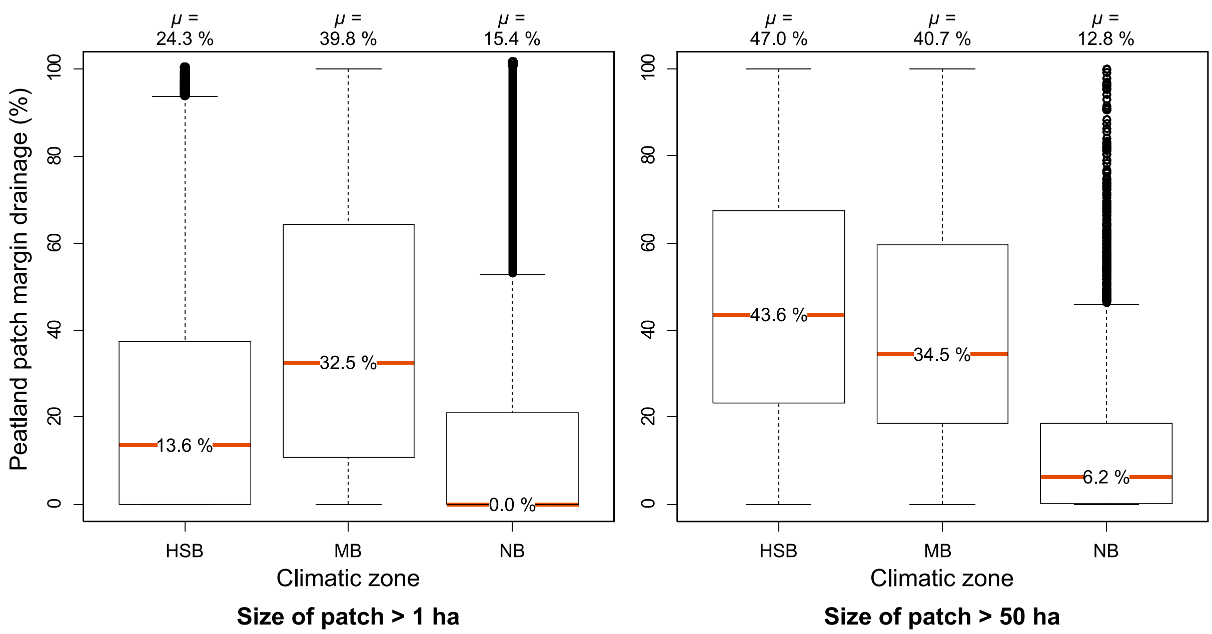

Figure 6. Drained proportion (%) of the margin length of undrained peatland patches in Finland. Left: minimum area 1 ha (N = 219,201); right: minimum area 50 ha (N = 7,002). Medians are shown on the median lines and means are above the diagram. HSB = hemiboreal and southern boreal zone, MB = middle boreal zone, NB = northern boreal zone.

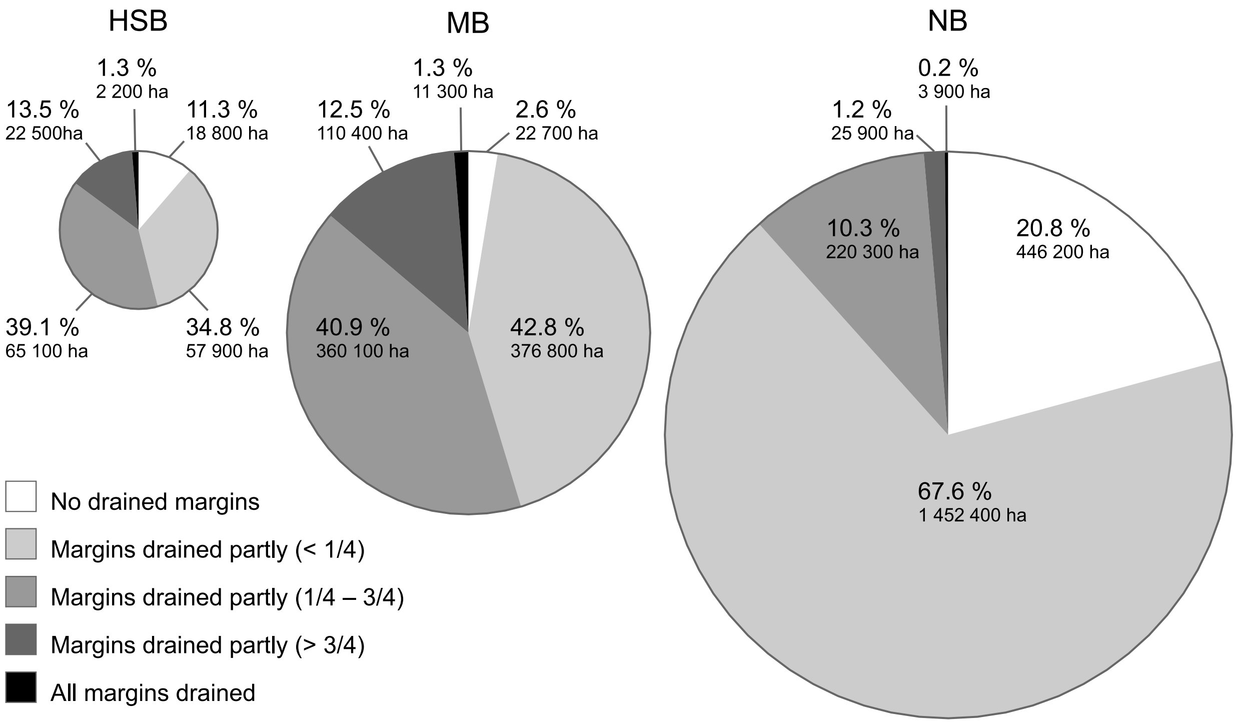

Figure 7. Undrained peatland area of Finland classified according to margin drainage. Peatland patches less than 1 ha in size are excluded, which explains the difference between the totals in this figure and those in Figure 5. HSB = hemiboreal and southern boreal zone, MB = middle boreal zone, NB = northern boreal zone.

Table 5. Average margin drainage status (%) of large (> 50 ha) undrained peatland patches with aapa features and without them.

Areal division	Type of patch	Count	Margin drainage percentage		
			Mean (%)	SD (%)	Median (%)
HSB	With aapa features	93	41.4	25.1	36.6
	No aapa features	228	49.2	28.6	47.4
MB	With aapa features	1,794	39.3	26.6	32.6
	No aapa features	540	45.2	28.5	40.7
NBS	With aapa features	797	18.0	16.3	13.2
	No aapa features	432	16.4	14.9	11.9
Total	With aapa features	2,684	33.0	25.9	25.6
	No aapa features	1,200	35.6	28.4	27.7

Notes. Aapa features include patterned fens, wet soaks and large minerotrophic treeless mire areas. Margin drainage status refers to the drained proportion (%) of margin length of individual undrained peatland patches. HSB = hemiboreal and southern boreal zone, MB = middle boreal zone, NBS = southern part of northern boreal zone.

One of the measures of aapa mire naturalness was 1) *the drained proportion of an aapa complex* (Table 6). As noted above, we considered aapa complexes that have their undrained parts in large (> 50 ha) undrained peatland patches. These complexes are most intensively drained in the MB zone, where, on average, one-third of an aapa complex's total extent is drained (Table 6). For the HSB and NBS zones, the averages are closer to one-fifth. Notice in Table 6 that the medians differ markedly from the means. An estimated mean for the whole study area, based on regional means and regional statistical population sizes, is 30.4 %.

The second measure of aapa mire naturalness was 2) *The proportion of an aapa mire's catchment that is upslope of a drained margin* (Table 7). The drained margin diminishes or prevents the flow of minerogenic water entering an aapa mire. This variable shows clear differences between the climatic zones, and the MB zone is again the most disturbed zone. An estimated mean for the whole study area, based on the regional means and regional statistical population sizes, is 35.9 %.

The third measure of aapa mire naturalness, 3) *The proportion of the total mineral ground area within an aapa mire's catchment that is upslope of a drained margin*, shows larger values than the previous variable (Table 8). In the MB zone, on average half of aapa mire catchment's mineral ground areas are behind disturbed hydrological connections. An estimated mean for the whole study area, based on the regional means and regional population sizes, is 45.4 %.

Nature conservation and naturalness

Among the studied 120 aapa complexes, 44 are at least partly located in nature conservation areas (European Union's Natura 2000 network): 25 in HSB, 15 in MB, and 4 in NBS zone. Among these, 37 are such that more than 90 % of the undrained aapa area is conserved (24 in HSB, 10 in MB, and 3 in NBS). On the other hand, in 78 aapa complexes, the undrained area is entirely outside a conservation designation (15 in HSB, 27 in MB and 36 in NBS).

We conducted independent-samples *t*-tests to compare the naturalness of aapa mires in conservation

Table 6. Drained proportion of an aapa mire complex (%).

Areal division	N	Min	Max	Median	Mean	SD	95 % confidence interval for mean	
							Lower	Upper
HSB	40	0.0	63.0	10.4	18.1	18.5	12.2	24.0
MB	40	0.5	84.7	28.8	34.4	25.4	26.2	42.5
NBS	40	0.0	75.1	12.8	22.8	21.5	16.0	29.7

Notes. The results concern aapa mire complexes in large (> 50 ha) undrained peatland patches. HSB = hemiboreal and southern boreal zone, MB = middle boreal zone, NBS = southern part of northern boreal zone.

Table 7. The proportion of an aapa mire's catchment that is upslope of a drained margin (%).

Areal division	N	Min	Max	Median	Mean	SD	95 % confidence interval for mean	
							Lower	Upper
HSB	40	0.0	78.6	16.1	25.1	24.6	17.3	33.0
MB	40	0.0	89.0	42.8	41.6	29.1	32.3	50.9
NBS	40	0.0	78.5	9.9	24.2	26.4	15.8	32.7

Notes. Aapa mire's catchment includes also the aapa mire. Results concern aapa mires in large (> 50 ha) undrained peatland patches. HSB = hemiboreal and southern boreal zone, MB = middle boreal zone, NBS = southern part of northern boreal zone.

areas (> 90 % of undrained area conserved, Group 1) and outside them (0 % conserved, Group 2). When comparing the groups on the grounds of the drained proportion of aapa mire complexes (means 20.6 % and 26.5 % for Groups 1 and 2, respectively), the *p*-value was 0.1968 (t = -1.2983, df = 113). A comparison on the grounds of the proportion of an aapa mire's catchment that is upslope of a drained margin (means 28.8 % and 30.6 % for Groups 1 and 2) yielded a *p*-value 0.7507 (t = -0.31843, df = 113), and the proportion of the total mineral ground area within an aapa mire's catchment that is upslope of a drained margin (means 39.7 % and 39.6 % for Groups 1 and 2) gave a *p*-value 0.9895 (t = 0.013202, df = 113).

To conclude, there were no significant differences between the groups in any of the comparisons. Thus, the tests indicate no dependency between conservation status and naturalness of aapa mires in large (> 50 ha) undrained peatland patches. Comparisons within the climatic zones gave similar results (not shown).

DISCUSSION

Drainage status of Finnish peatlands

The area of Finnish peatlands is 8,644,000 ha according to the Natural Resources Institute Finland (LUKE 2017) and 8,319,800 ha according to our results. The proportion of drained peatlands is 57.7 % in our results, while LUKE's estimate is 53.2 %. It can be concluded that our method gives roughly similar results as LUKE's completely different method that is based on field observations from a statistical sample of sites of the National Forest Inventory. The strength of our method is that it makes it possible to calculate the peatland area and drainage status for any location or areal division. Moreover, it is free from any potential bias of sampling representativeness and it allows for localisation of every single peatland patch.

In the HSB and MB zones, more than three-quarters of the peatland area is drained. The drained area is over four million ha, and as a relatively recently forestry-drained area it is globally exceptional (Lindholm & Heikkilä 2006a). However, in a general comparison of peatland exploitation among European countries, the Finnish figures are not extraordinarily high (e.g. Janssen *et al.* 2016). Drainage has been a threat to peatlands wherever there has been permanent human settlement, but a shortage of data on the original extent of peatlands often hides this fact (Kaakinen *et al.* 2008, Janssen *et al.* 2016). In Finland, this applies especially to southern areas, where peatlands have been utilised in agriculture for centuries and entire peat layers of cultivated mires have been gradually lost by mineralisation. Anyway, agricultural land on peat substrate was not included in our raster data, which inevitably resulted in underestimation of the drained area.

Our results show that majority of the Finnish peatland area is covered by forest. This is partly a consequence of drainage, as it has increased tree growth, shifting some of the open mires to the category of forested peatlands. However, afforestation has not always been successful, since only 88.7 % of the drained area fulfils the modest forest definition of 10 % canopy cover. In any case, much of the forestry drainage activities have been directed to originally forested or treed peatlands (e.g. Päivänen & Hånell 2012). When successful, drainage has changed the peatland ecosystems to managed forests. These are still regarded as peatlands in the Finnish classification system if the peat layer is remaining, but they no longer represent the original forest-covered peatland habitat types, nearly all of

Table 8. The proportion of the total mineral ground area within an aapa mire's catchment that is upslope of a drained margin (%).

Areal division	N	Min	Max	Median	Mean	SD	95 % confidence interval for mean	
							Lower	Upper
HSB	40	0.0	100.0	23.7	39.4	37.6	27.3	51.4
MB	40	0.0	100.0	57.5	53.1	37.5	41.1	65.1
NBS	40	0.0	85.1	13.0	28.8	31.4	18.7	38.8

Notes. Results concern aapa mires in large (> 50 ha) undrained peatland patches. HSB = hemiboreal and southern boreal zone, MB = middle boreal zone, NBS = southern part of northern boreal zone.

which are endangered in southern Finland (Raunio *et al.* 2008, Kontula & Raunio 2009, 2018).

Finnish peatlands are mostly forests also in many important typologies, such as the EUNIS habitat classification (Tahvanainen 2017, EEA 2018). On the other hand, *mires* are defined as 'open, treeless wetlands with vegetation on accumulating peat' in the European Red List of Habitats (Janssen *et al.* 2016). Those parts of Finnish peatlands that fit under this mire concept are mainly the non-forested undrained peatlands. Their area is according to our results 2,049,200 ha, which is 24.6 % of peatlands and 6.7 % of the land area in Finland.

The remaining undrained peatland patches

According to our data, undrained peatland areas in Finland are smaller in the HSB zone than in the MB zone, and they are smaller in the MB zone than in the NB zone. This situation can be explained by differences in climate and terrain, but also land use has an influence on it, as southern parts of the country are more densely populated, have a longer history of peatland agriculture and more intensive peatland forestry (e.g. Kaakinen *et al.* 2008).

If an undrained peatland patch shares a coincident edge with a drained peatland, they have together formed a larger peatland unit in the past. The results show that a vast majority of undrained peatland areas in Finland are this kind of remnant patch. Nonetheless, peatlands that have all their margins drained are not so common and their combined area is rather small. With the criteria used in this study, however, margins of mineral soil islets or water bodies within a peatland patch should also be drained before all margins were assessed as drained. As a consequence, small peatland patches without any mineral islets or bodies of water are more likely to have all margins drained than large patches with many such features.

We found that the margins of large peatland patches are more frequently drained than those of smaller patches. One explanation for this finding is that in cases of large peatlands, it is more likely that disturbing land use extends to their margins than in cases of small peatlands. On the other hand, when a peatland is exposed to human activity, it is more likely for a small peatland to be completely drained, while some part of a large peatland is more likely to be left outside management to form a remnant patch. Land ownership may have a similar influence, as it is likely that a large peatland has many owners, possibly making different land use decisions, whereas a small peatland is more likely to have only one owner who may decide to alter or protect the peatland as a whole.

Partly similar reasoning can explain the geographical differences. In northern Finland, peatlands are large and form connected systems not confined to separate basins. If there is forestry, agriculture or construction activity in the vicinity, it is probable that some peatland is disturbed. This is why intact peatlands are uncommon also in the less intensively utilised NB zone. However, the proportion of intact peatlands is especially small in the MB zone, where large peatlands are plentiful and land use is more intensive than in NB zone. In the HSB zone, on the other hand, peatlands are often small and confined to separate basins, which are not so easily exposed to disturbances. This may explain why the margins of remaining undrained peatlands are less drained in the HSB zone than in the MB zone, even though drainage in general has been most intensive in the HSB zone. But among the largest patches (> 50 ha), the HSB zone has the highest margin drainage proportions. However, most of the largest peatlands in this southern area are raised bogs, which are likely to be less dependent on natural hydrological connections to their catchments.

The state of aapa mires

The aapa complexes in large (> 50 ha) undrained peatland areas are often partly drained; these have originally extended beyond the margins of the remaining undrained areas. The drained part comprises on average one-third of an aapa complex's area in the MB zone, and clearly less in the HSB and NB zones. Why are the remaining aapa complexes in the Finnish HSB zone relatively well preserved? One reason could be that because these are located outside of their climatically determined distribution area (Ruuhijärvi 1960, 1983), they are easily disturbed, and, therefore, only relatively undisturbed peatlands have remained as aapa mires until today. Differences in compactness of mires may also contribute: smaller parts of the upper catchments are likely to be drained in HSB, where peatlands are generally more distinctly separate units in the landscape than in the more northern zones, where vast peatland areas are often interconnected.

An additional explanation could be that because the large undrained peatlands with aapa features are rare in the HSB zone, many of them are located in nature conservation areas, and might therefore be well preserved. However, our results did not support this hypothesis, as conservation status was not statistically connected with the naturalness of aapa mires. The majority of the Finnish mire conservation areas have been established since the early 1980s, when the National Program for Mire Conservation was launched (Kaakinen & Salminen 2006). At that time, most of the forestry drainage had already been carried out. Usually only the undrained parts of mire complexes were accepted for conservation, while the surrounding land use would continue with no restrictions from conservation (Kaakinen & Salminen 2006, Lindholm & Heikkilä 2006a).

Hydrological changes largely determine how the surrounding land use affects a peatland. The central fen areas of aapa complexes depend heavily on minerogenic water, and catchment disturbances like margin drainage may change their ecology. According to our results, the hydrology of aapa mires in large undrained peatland patches are the most disturbed in the MB zone, where, on average, well over one-third of an aapa mire's catchment is upslope of a drained margin, leaving more than half of the catchment's mineral ground areas behind disturbed hydrological connections. Likewise, the proportions are high in the HSB zone, but in the NBS zone the disturbances are not so regular, although occasionally considerable. The northern part of the NB zone, which was not included in the assessment, is likely to be least disturbed. It should also be noted that in the southern part of the NB zone, 384 large peatland patches are classified as 'not evaluated' in the SYKE air photo investigation. They were not included in the study, although it is likely that, among these patches, there are many aapa mires.

There are many possible ways of inspecting mire naturalness. An experienced interpreter can relatively reliably determine the state of mire hydrology visually from aerial images and maps (Rehell 2017). However, it is difficult to automate the interpretation work due to the variability of mire environments and because visual interpretation demands a sort of tacit knowledge that is difficult to verbalise; certain subjectivity necessarily belongs to it. In the present study, we attempted to avoid the subjectivity of visual interpretation by using a semi-automated GIS-based method. However, automated and mechanical approaches also bear risks of misinterpretation and error. In our case, the central premise is that a drained margin forms a barrier that prevents water flowing from the upper catchment to the undrained parts of the mire. This generalisation may not be strictly true, as it varies with how effectively ditches change water flow directions. For example, some ditch water may discharge back to the aapa mire via altered flow paths. Rehell (2017) estimated that this happens from some 25 % of the disturbed catchment area in the MB zone. It is also known that ditches tend to fill in by debris and vegetation and become less effective over time. This and other local details would be important to check in any individual case of interest.

Another source of uncertainty, already noted in the methods section, is related to the complexity of mire margins. The most difficult cases for our method are mires with plenty of mineral islets and complex, irregularly drained margins, but we made an effort to ensure that the method would rather underestimate than overestimate the disturbances in these difficult cases. On the whole, our results on catchment disturbances do not contradict Rehell's (2017) estimates based on visual interpretation. He suggested that 36.4 % of the area of upper catchments of wet minerotrophic aapa vegetation in the Finnish MB zone is, due to ditches, discharging no water to the aapa vegetation. In addition to this, he estimated that 12.3 % of the upper catchment area is such that it discharges water only through separate ditches. Adding these two values we obtain 48.7 % as Rehell's (2017) upper catchment disturbance percentage for the MB zone. In the present study, we did not determine the disturbance measures for the upper catchments but treated the catchments as wholes. Perhaps closest to Rehell's disturbance variable is our third variable, the proportion of the total mineral ground area within an aapa mire's catchment that is upslope of a drained margin. The numerical value is close as well (53.1 %).

Our results do not reveal the number of aapa mires that have already disappeared due to land use. Moreover, we do not know the state of the aapa mires among small peatland patches (< 50 ha). Anyway, our results concerning the margin drainage of peatlands suggest that catchment disturbances are common among smaller aapa mires, too, in the MB and HSB zones. The disturbances may have already commonly caused changes in undrained peatlands. Possibly there is an indication of this in our results. Namely, in the HSB and MB zones, the margins of non-aapa patches were more severely disturbed than the margins of aapa patches. This may indicate that some of the non-aapa patches are actually former aapa patches that have lost their aapa features because of pronounced margin drainage. This kind of changes could be confirmed by remote sensing time series or peat records (Tahvanainen 2011).

Implications for future

Our results show that land use affects the majority of peatlands in Finland. As for the catchment disturbances, based on the assumption of topographically-driven near-surface groundwater flow, the results indicate that the minerogenic water flow is likely to have decreased in most of the aapa mires in the MB and HSB zones irrespective of the conservation status of the mires. We do not yet know how this has affected the mires, but the possible implications are wide-ranging.

The extent of catchment directly defines the amount of rain water it receives. On the other hand, the amount of catchment-derived water controls the extent of wet minerotrophic vegetation in aapa mires (Rehell 2017). The proportion of an aapa mire's catchment that is upslope of an actively drained margin is likely to be indicative of the proportion of minerogenic water that is prevented from entering the mire, and it indicates where a decrease of wet minerotrophic vegetation can be expected. Moreover, the proportion of an aapa mire catchment's mineral ground that is upslope of a drained margin indicates probably more directly the decrease of minerogenic influence. How these variables exactly correlate with the possible changes in aapa mire vegetation is a question for further research. In principle, the sensitivity of minerotrophic vegetation to changes in water quality and flow rate makes aapa mires susceptible to hydrology-induced vegetation changes, including increased tree encroachment, hummock formation and ombrotrophication (Tahvanainen 2011).

Ombrotrophication, i.e. a fen to bog transition, is often considered to be a slow process resulting from the vertical growth of peat (e.g. Zobel 1988). However, when initiated by allogenic hydrological changes, it may take place more rapidly (Hughes & Barber 2004, Tahvanainen 2011, Finsinger *et al.* 2013, Loisel & Yu 2013). Our results, indicating commonness of hydrological isolation of aapa mires from their catchments by marginal ditching, may indicate a potential for increasing allogenic ombrotrophication, with an associated increase of *Sphagnum* mosses. These kinds of peatland ecosystem changes have linkages with climate change, as peatlands are important carbon reservoirs, estimated to hold about one-third of global soil carbon (Yu 2012, Loisel *et al.* 2014). Much of this carbon pool is formed by the remains of *Sphagnum* mosses that build peat in bogs. Fens, in the strict sense (e.g. Gorham & Janssens 1992), do not have such thick *Sphagnum* layers. The transition from fen to bog has, then, the potential to increase the sink of atmospheric CO_2. The change may also reduce CH_4 emissions, which are typically higher in fens than in bogs (e.g. Turunen *et al.* 2002). In the aapa mires of Finland, poor fens (*sensu* Sjörs 1948) with *Sphagnum* coverage prevail, while their central parts often lack a continuous moss cover (Ruuhijärvi 1960). These mires may be particularly prone to ombrotrophication, because they have low mineral alkalinity to buffer acidification, and *Sphagnum* mosses are already present in their flora (Tahvanainen 2004, 2011, van Bellen *et al.* 2013).

The shift to bog vegetation may counteract the carbon loss from organic soils that is generally anticipated for the boreal region due to climate warming (e.g. Čížková *et al.* 2013, Gong *et al.* 2013). Therefore, the Finnish national strategy (MAF 2011) to select mires with decreased naturalness (altered hydrology and changed vegetation) for peat extraction may lead to destruction of potentially increasing carbon sinks, and hence work against the goal of the strategy to cut down emissions. However, when considering ecosystem changes, all ecosystem services need to be taken into account. Possible large scale ombrotrophication of minerotrophic mires may counteract climate change, but, on the other hand, it poses a threat for biodiversity, since fens are generally more diverse environments than bogs (e.g. Rydin & Jeglum 2013). Ombrotrophication can also be conceived as an ecosystem collapse denoted in the IUCN protocol for Red List of Ecosystems (Keith *et al.* 2015, Bland *et al.* 2018).

The UN Convention on Biological Diversity has set a target to restore at least 15 per cent of degraded ecosystems (CBD 2010). The target is very ambitious in the case of Finnish peatlands, taking into account the vast amount of drained peatlands and the possible large-scale changes in the undrained peatlands. Peatland restoration has been practised in Finland since the 1980s, covering an area of about 20,000 ha, primarily in state owned nature reserves (Similä *et al.* 2014). The influence of surrounding land use on protected mires, which is evident in our results, has been increasingly acknowledged, but implementing restoration actions in the surrounding areas is complicated by conflicts of interests.

CONCLUSIONS

We have explored the state of Finnish peatlands using novel data and methods. Finnish peatlands are under a bigger pressure from land use than has generally been realised. More than half of the peatland area has been drained, and the vast majority of the remaining undrained peatlands are bordered by drained areas. In the southern half of the country, the remaining seemingly undrained aapa mires are in most cases not in hydrologically natural condition, since the drainage activities in their upper catchments commonly disturb minerotrophic water discharge to the mires. In northern parts of the country, disturbances are less common, but locally they can be remarkable. Land use affects the majority of peatlands in Finland, including undrained peatlands, and also aapa mires in nature reserves. This should be taken into account in land use management, nature conservation planning and ecosystem restoration.

There is an urgent need to further investigate the changes of boreal peatland ecosystems. If extensive changes are demonstrated, the implications for ecosystem services and biodiversity are substantial.

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AUTHOR CONTRIBUTIONS

The study idea and design were conceived by AS in collaboration with TT, TK, and ST. ST provided the peatland GIS data sets. AS performed the GIS analyses and compiled the results and illustrations. AS wrote the article with significant contributions from TT and comments from ST and TK.

REFERENCES

Ahti, T., Hämet-Ahti, L. & Jalas, J. (1968) Vegetation zones and their sections in northwestern Europe. *Annales Botanici Fennici*, 5, 169–211.

Alanen, A. & Aapala, K. (eds.) (2015) Soidensuojelutyöryhmän ehdotus soidensuojelun täydentämiseksi (*Proposal of the Mire Conservation Group for Supplemental Mire Conservation*). Reports of the Ministry of the Environment 26/2015, Helsinki, 175 pp. (in Finnish).

Bland, L.M., Rowland, J.A, Regan, T.J., Keith, D.A., Murray, N.J., Lester, R.E., Linn, M., Rodríguez, J.P. & Nicholson, E. (2018) Developing a standardized definition of ecosystem collapse for risk assessment. *Frontiers in Ecology and the Environment*, 16 (1), 29–36.

CBD (2010) *Strategic Plan for Biodiversity 2011–2020*. COP 10 Decision X/2, Convention on Biological Diversity (CBD), Nagoya, Japan. Online at: https://www.cbd.int/decision/cop/?id=12268, accessed 25 Nov 2019.

Čížková, H., Květ, J., Comín, F.A., Laiho, R., Pokorný, J. & Pithart, D. (2013) Actual state of European wetlands and their possible future in the context of global climate change. *Aquatic Sciences*, 75(1), 3–26.

CLC2006 (2009) *CLC2006 Finland Final Technical Report*. Finnish Environment Institute, Helsinki, 36 pp. Online at: http://www.syke.fi/download/noname/%7BC7C849EB-3F4D-42AE-9A94-5B8069FFDFFB%7D/37641, accessed 25 Nov 2019.

CLC2012 (2015) *GIO Land Monitoring 2011–2013 in the Framework of Regulation (EU) No 911/2010: Pan-EU Component, Final Report, Finland*. Finnish Environment Institute, Helsinki, 48 pp. Online at: http://www.syke.fi/download/noname/%7B2D87A112-C054-4A79-BEC2-41F00974EBC0%7D/107966, accessed 25 Nov 2019.

EEA (2018) EUNIS habitat classification. Web document, European Environment Agency, Copenhagen. Online at: https://www.eea.europa.eu/data-and-maps/data/eunis-habitat-classification, accessed 12 Nov 2018.

Eurola, S. (1962) Über die regionale Einteilung der südfinnischen Moore (On the regional division of mires of southern Finland). *Annales Botanici Societatis Zoologicae Botanicae Fennicae "Vanamo"*, 33(2), 243 pp. (in German).

Eurola, S., Aapala, K., Kokko, A. & Nironen, M. (1991) Mire type statistics in the bog and southern aapa mire areas of Finland. *Annales Botanici Fennici*, 28, 15–36.

Finsinger, W., Schoning, K., Hicks, S., Lücke, A., Goslar, T., Wagner-Cremer, F. & Hyyppä, H. (2013) Climate change during the past 1000 years: a high-temporal-resolution multiproxy record from a mire in northern Finland. *Journal of Quaternary Science*, 28(2), 152–164.

FMI (2018) *Climate in Finland*. Website, Finnish Meteorological Institute, Helsinki. Online at: http://en.ilmatieteenlaitos.fi/climate, accessed 05 Apr 2018.

Frolking, S. & Roulet, N.T. (2007) Holocene radiative forcing impact of northern peatland carbon accumulation and methane emissions. *Global Change Biology*, 13 (5), 1079–1088.

Gong, J., Kellomäki, S., Wang, K., Zhang, C., Shurpali, N. & Martikainen, P.J. (2013). Modeling CO_2 and CH_4 flux changes in pristine peatlands of Finland under changing climate conditions. *Ecological Modelling*, 263, 64–80.

Gorham, E. & Janssens, J.A. (1992) Concepts of fen and bog re-examined in relation to bryophyte cover and the acidity of surface waters. *Acta Societatis Botanicorum Poloniae*, 61 (1), 7–20.

Gunnarsson, U. & Löfroth, M. (2014) *The Swedish Wetland Survey: Compiled Excerpts from the National Final Report*. Report 6618, The Swedish Environmental Protection Agency, Stockholm, 37 pp. Online at: http://www.naturvardsverket.se/ 978-91-620-6618-5, accessed 25 Nov 2019.

Hughes, P.D.M. & Barber, K.E. (2004) Contrasting pathways to ombrotrophy in three raised bogs from Ireland and Cumbria, England. *The Holocene*, 14, 65–77.

Ilvessalo, Y. (1956) Suomen metsät vuosista 1921–24 vuosiin 1951–53. Kolmeen valtakunnan metsien inventointiin perustuva tutkimus (*The Forests of Finland from 1921–24 to 1951–53. A Survey Based on Three National Forest Inventories*). Communicationes Instituti Forestalis Fenniae 47(1), 227 pp. (in Finnish).

Ingram, H.A.P. (1978) Soil layers in mires: function and terminology. *Journal of Soil Science*, 29(2), 224–227.

Ingram, H.A.P. (1983) Hydrology. In: Gore, A.J.P (ed.) *Ecosystems of the World 4A. Mires: Swamp, Bog, Fen and Moor. General Studies*. Elsevier, Amsterdam, 67–158.

Janssen, J.A.M., Rodwell, J.S. and 47 others (2016) *European Red List of Habitats. Part 2. Terrestrial and Freshwater Habitats.* Publications Office of the European Union, Luxembourg, 38 pp. Online at: https://www.iucn.org/content/ european-red-list-habitats-part-2-terrestrial-and-freshwater-habitats, accessed 25 Nov 2019.

Jenson, S.K. & Domingue, J.O. (1988) Extracting topographic structure from digital elevation data for geographic information-system analysis. *Photogrammetric Engineering and Remote Sensing*, 54(11), 1593–1600.

Joosten, H. & Clarke, D. (2002) *Wise Use of Mires and Peatlands. Background and Principles Including a Framework for Decision-making*. IMCG & IPS, Saarijärvi, Finland, 303 pp.

Joosten, H., Moen, A., Couwenberg, J. & Tanneberger, F. (2017) Mire diversity in Europe: mire and peatland types. In: Joosten, H., Tanneberger, F. & Moen, A. (eds.) *Mires and Peatlands of Europe: Status, Distribution and Conservation*. Schweizerbart Science Publishers, Stuttgart, 780 pp.

Kaakinen, E. & Salminen, P. (2006) Mire conservation and its short history in Finland. In: Lindholm, T. & Heikkilä, R. (eds.) *Finland - Land of Mires*. The Finnish Environment 23/2006, Finnish Environment Institute, Helsinki, 229–238. Online at: https://helda.helsinki.fi/handle/ 10138/37961, accessed 25 Nov 2019.

Kaakinen, E., Kokko, A., Aapala, K., Kalpio, S., Eurola, S., Haapalehto, T., Heikkilä, R., Hotanen, J.-P., Kondelin, H., Nousiainen, H., Ruuhijärvi, R., Salminen, P., Tuominen, S., Vasander, H. & Virtanen, K. (2008) Suot (Mires). In: Raunio, A., Schulman, A. & Kontula, T. (eds.) Suomen luontotyyppien uhanalaisuus - Osa 1: Tulokset ja arvioinnin perusteet (*Assessment of Threatened Habitat Types in Finland - Part 1: Results and Basis for Assessment*). Suomen Ymparisto (The Finnish Environment) 8/2008, Suomen ympäristokeskus (Finnish Environment Institute), Helsinki, 75–109 (in Finnish). Online at: https://helda.helsinki.fi/bitstream/handle/101 38/37930, accessed 25 Nov 2019.

Kareksela, S., Moilanen, A., Tuominen, S. & Kotiaho, J.S. (2013) Use of inverse spatial conservation prioritization to avoid biological diversity loss outside protected areas. *Conservation Biology*, 27(6), 1294–1303.

Keith, D.A., Rodríguez, J.P., Brooks, T.M., Burgman, M.A. and 15 others (2015) The IUCN Red List of Ecosystems: Motivations, challenges, and applications. *Conservation Letters*, 8, 214–226.

Kontula, T. & Raunio, A. (2009) New method and criteria for national assessments of threatened habitat types. *Biodiversity and Conservation*, 18, 3861–3876.

Kontula, T. & Raunio, A. (eds.) (2018) Suomen luontotyyppien uhanalaisuus 2018, Luontotyyppien punainen kirja - Osa 1: Tulokset ja arvioinnin perusteet (*Threatened Habitat Types in Finland 2018, Red List of Habitats, Part I: Results and Basis for Assessment*). Suomen Ympäristö (The Finnish Environment) 5/2018, Suomen ympäristökeskus ja ympäristöministeriö (Finnish Environment Institute and Ministry of the Environment), Helsinki, 388 pp. (in Finnish). Online at: https://julkaisut.valtioneuvosto.fi/ handle/10024/161233, accessed 25 Nov 2019.

Laiho, R., Tuominen, S., Kojola, S., Penttilä, T., Saarinen, M. & Ihalainen, A. (2016) Heikkotuottoiset ojitetut suometsät - missä ja paljonko niitä on? (Unprofitable drained peatland forests - how much and where?) *Metsätieteen aikakauskirja*, 2/2016, 73–93 (in Finnish).

Laitinen, J., Rehell, S. & Huttunen, A. (2005) Vegetation-related hydrotopographic and hydrologic classification for aapa mires (Hirvisuo, Finland). *Annales Botanici Fennici*, 42, 107–121.

Laitinen, J., Rehell, S., Huttunen, A., Tahvanainen, T., Heikkilä, R. & Lindholm, T. (2007) Mire systems of Finland - special reference to aapa mires and their water-flow pattern. *Suo*, 58(1), 1–26.

Lindholm, T. (2015) Mikä on aapasuo? Aapamire what is it? *Suo*, 66(1), 33–38 (in Finnish and English).

Lindholm, T. & Heikkilä, R. (2006a) Destruction of mires in Finland. In: Lindholm, T. & Heikkilä, R. (eds.) *Finland - Land of Mires*. The Finnish Environment 23/2006, Finnish Environment Institute, Helsinki, 179–192. Online at: https://helda.helsinki.fi/handle/10138/37961, accessed 25 Nov 2019.

Lindholm, T. & Heikkilä, R. (eds.) (2006b) *Finland - Land of Mires*. The Finnish Environment 23/2006, Finnish Environment Institute, Helsinki, 270 pp. Online at: https://helda.helsinki.fi/handle/10138/37961, accessed 25 Nov 2019.

Loisel, J. & Yu, Z. (2013) Recent acceleration of carbon accumulation in a boreal peatland, south central Alaska. *Journal of Geophysical Research: Biogeosciences*, 118, 41–53.

Loisel, J., Yu, Z., Beilman, D.W. and 58 others (2014) A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. *The Holocene*, 24(9), 1028–1042.

LUKE (2017) Forest resources. Web document, Natural Resources Institute Finland, Helsinki. Online at: http://stat.luke.fi/en/tilasto/6221, accessed 04 Dec 2017.

MAF (2011) Ehdotus soiden ja turvemaiden kestävän ja vastuullisen käytön ja suojelun kansalliseksi strategiaksi (*Proposal for a National Strategy for the Sustainable and Responsible Use of Mires and Peatlands*). Working group memorandum MMM 2011:1, Ministry of Agriculture and Forestry (MAF), Helsinki, 159 pp. (in Finnish). ISBN 978-952-453-625-7.

Masing, V., Botch, M. & Läänelaid, A. (2010) Mires of the former Soviet Union. *Wetlands Ecology and Management*, 18(4), 397–433.

McCarter, C.R.P. & Price, J.S. (2017) Experimental hydrological forcing to illustrate water flow processes of a subarctic ladder fen peatland. *Hydrological Processes*, 31, 1578–1589.

Myllys, M. & Soini, S. (2008) Cultivation of mires in Finland. In: Korhonen, R., Korpela, L. & Sarkkola, S. (eds.) *Finland - Fenland: Research and Sustainable Utilisation of Mires and Peat*. Finnish Peatland Society, Helsinki, 93–95.

NLS (2018) *Topographic Database*. Web resource, National Land Survey of Finland (NLS), Helsinki. Online at: https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/expert-users/product-descriptions/topographic-database, accessed 26 Nov 2019.

NWWG (1988) *Wetlands of Canada*. Ecological Land Classification Series 24, National Wetlands Working Group (NWWG), Environment Canada, Ottawa and Polyscience Publications, Montreal, 452 pp.

O'Callaghan, J.F. & Mark, D.M. (1984) The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics and Image Processing*, 28, 323–344.

Päivänen, J. & Hånell, B. (2012) *Peatland Ecology and Forestry - a Sound Approach*. Publications 3, Department of Forest Sciences, University of Helsinki, 267 pp.

Raunio, A., Schulman, A. & Kontula, T. (eds.) (2008) Suomen luontotyyppien uhanalaisuus - Osa 1: Tulokset ja arvioinnin perusteet (*Assessment of Threatened Habitat Types in Finland - Part 1: Results and Basis for Assessment*). Suomen Ymparisto (The Finnish Environment) 8/2008, Suomen ympäristokeskus (Finnish Environment Institute), Helsinki, 75–109 (in Finnish). Online at: https://helda.helsinki.fi/bitstream/handle/10138/37930, accessed 25 Nov 2019.

Rehell, S. (2017) Ilmastotekijöiden ja vesitalouden vaikutus minerotrofisten rimpipintojen esiintymiseen boreaalisissa suosysteemeissä (The effect of climate factors and catchment area on the occurrence of minerotrophic wet level in boreal mire systems). *Suo*, 68(2–3), 41–66 (in Finnish with English summary).

Rehell, S., Sallantaus, T., Tahvanainen, T., Haapalehto, T. & Joensuu, S. (2014) The hydrology of peatlands. In: Similä, M., Aapala, K. & Penttinen, J. (eds.) *Ecological Restoration in Drained Peatlands - Best Practices From Finland*. Metsähallitus Parks & Wildlife, Vantaa and Finnish Environment Institute SYKE, Helsinki, 16–20. Online at: https://julkaisut.metsa.fi/ julkaisut/show/1733, accessed 26 Nov 2019.

Ruuhijärvi, R. (1960) Über die regionale Einteilung der nordfinnischen Moore (On the regional division of mires of northern Finland). *Annales Botanici Societatis Zoologicae Botanicae Fennicae "Vanamo"*, 31 (1), 1–360 (in German).

Ruuhijärvi, R. (1983) The Finnish mire types and their regional distribution. In: Gore, A.J.P. (ed.) *Ecosystems of the World 4B. Mires: Swamp, Bog, Fen and Moor. Regional Studies*. Elsevier, Amsterdam, 47–67.

Rydin, H. & Jeglum, J.K. (2013) *The Biology of Peatlands*. Second edition, Oxford University Press, Oxford, 382 pp.

Sallantaus, T. (2006) Mire ecohydrology in Finland. In: Lindholm, T. & Heikkilä, R. (eds.) *Finland - Land of Mires*. The Finnish Environment 23/2006, Finnish Environment Institute, Helsinki, 105–118. Online at: https://helda.helsinki.fi/handle/10138/37961, accessed 25 Nov 2019.

Seppälä, M. (1986) Korkeussuhteet (Topography). In: Alalammi, P. (ed.) *Suomen kartasto* (*Atlas of Finland*), Folio 121–122, National Board of Survey & Geographical Society of Finland, 1–5.

Similä, M., Aapala, K., & Penttinen, J. (eds.) (2014) *Ecological Restoration in Drained Peatlands - Best Practices from Finland*. Metsähallitus Parks & Wildlife, Vantaa and Finnish Environment Institute SYKE, Helsinki, 84 pp. Online at: https://julkaisut.metsa.fi/julkaisut/show/1733, accessed 26 Nov 2019.

Sjörs, H. (1948) Myrvegetation i Bergslagen (Mire vegetation in Bergslagen area, Sweden). *Acta Phytogeographica Suecica*, 21, 1–380 (in Swedish).

SOJT_09b1 (2009) Raster data set of drainage status of Finnish peatlands. Seppo Tuominen/Finnish Environment Institute SYKE, Helsinki.

Solantie, R. (2006) Climate of Finland and its effect on mires. In: Lindholm, T. & Heikkilä, R. (eds.) *Finland - Land of Mires*. The Finnish Environment 23/2006, Finnish Environment Institute, Helsinki, 17–21. Online at: https://helda.helsinki.fi/handle/10138/37961, accessed 25 Nov 2019.

Tahvanainen, T. (2004) Water chemistry of mires in relation to the poor–rich vegetation gradient and contrasting geochemical zones of the north-eastern Fennoscandian Shield. *Folia Geobotanica*, 39, 353–369.

Tahvanainen, T. (2011) Abrupt ombrotrophication of a boreal aapa mire triggered by hydrological disturbance in the catchment. *Journal of Ecology*, 99(2), 404–415.

Tahvanainen, T. (2016) D3.2 Aapa mire. Factsheet, European Red List of Habitats - Mires Habitat Group, 10 pp. Online at: http://forum.eionet.europa.eu/european-red-list-habitats/library/terrestrial-habitats/d.-mires-and-bogs/d3.2-aapa-mire, accessed 26 Nov 2019.

Tahvanainen, T. (2017) Euroopan suohabitaattien uhanalaisuusarviointi - European mire habitats red list. *Suo*, 68(1), 13–26 (in Finnish with English summary).

Tahvanainen, T., Sallantaus, T. & Heikkilä, R. (2003) Seasonal variation of water chemical gradients in three boreal fens. *Annales Botanici Fennici*, 40(5), 345–355.

Tikkanen, M. (2006a) Unsettled weather and climate of Finland. In: Lindholm, T. & Heikkilä, R. (eds.) *Finland - Land of Mires*. The Finnish Environment 23/2006, Finnish Environment Institute, Helsinki, 7–16. Online at: https://helda.helsinki.fi/handle/10138/37961, accessed 25 Nov 2019.

Tikkanen, M. (2006b) The landforms of Finland. In: Lindholm, T. & Heikkilä, R. (eds.) *Finland - Land of Mires*. The Finnish Environment 23/2006, Finnish Environment Institute, Helsinki, 27–38. Online at: https://helda.helsinki.fi/handle/10138/37961, accessed 25 Nov 2019.

Tomppo, E. (1999) Forest resources of Finnish peatlands in 1951–1994. *International Peat Journal*, 9, 38–44.

Tuhkanen, S. (1984) A circumboreal system of climatic-phytogeographical regions. *Acta Botanica Fennica*, 127, 1–50.

Turunen, J., Tomppo, E., Tolonen, K. & Reinikainen, A. (2002) Estimating carbon accumulation rates of undrained mires in Finland - application to boreal and subarctic regions. *The Holocene*, 12(1), 69–80.

van Bellen, S., Garneau, M., Ali, A.A., Lamarre, A., Robert, É.C., Magnan, G., Asnong, H. & Pratte, S. (2013) Poor fen succession over ombrotrophic peat related to late Holocene increased surface wetness in subarctic Quebec, Canada. *Journal of Quaternary Science*, 28, 748–760.

Wu, Y., Chan, E., Melton, J.R., Verseghy, D.L. (2017) A map of global peatland distribution created using machine learning for use in terrestrial ecosystem and earth system models. *Geoscientific Model Development Discussions*, 2017/07/13, 1–21.

Yu, Z. (2012) Northern peatland carbon stocks and dynamics: a review. *Biogeosciences*, 9, 4071–4085.

Zobel, M. (1988) Autogenic succession in boreal mires: a review. *Folia Geobotanica & Phytotaxonomica*, 23(4), 417–445.

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Supplementary material: Aapa catchment properties (Excel file; key to column headings in Appendix)

Appendix: Explanation of the supplementary Table 'Aapa catchment properties'

No	Identification number
Study_area	Areal division; HSB = hemiboreal and southern boreal zone, MB = middle boreal zone, NBS = southern part of northern boreal zone
Name	Name in the SYKE database of undrained peatland patches
Lat_WGS84	Latitude coordinate (in WGS 84 coordinate system, in decimal form) of the center point of the undrained part of aapa mire
Lon_WGS84	Longitude coordinate (in WGS 84 coordinate system, in decimal form) of the centere point of the undrained part of aapa mire
Munic_2015	Municipality in 2015
SLT09_ID	Identification number in the SYKE database of undrained peatland patches
Catch_area	Extent of aapa mire's catchment, including the mire, in hectares
Sub_catch	Number of sub-catchments having their own discharge directions
Peat_pct	Percentage of peatland in the catchment according to the Finnish National Land Survey's Topographic Database
Lake_pct	Percentage of open water in the catchment according to the Finnish National Land Survey's Topographic Database
Mineral_pct	Percentage of mineral ground areas in the catchment, calculated by subtracting the peatland area and open water area from the catchment area
Catch_drain_pct	Percentage of drained peatland in the catchment according to SYKE drainage status raster
Peat_drain_pct	Percentage of drained peatland among peatlands of the catchment according to SYKE drainage status raster
Aapa_comp_area	Extent of aapa mire complex, in hectares
Aapa_undr_area	Extent of the undrained part of aapa mire complex, in hectares
Aapa_comp_drain_pct	Percentage of drained peatland in aapa mire complex
Disc_catch_pct	'Disconnected catchment percentage', i.e. the proportion (%) of an aapa mire's catchment that is upslope of a drained margin
Disc_mineral_pct	'Disconnected mineral ground percentage', i.e. the proportion (%) of the total mineral ground area within an aapa mire's catchment that is upslope of a drained margin
Aapa_undr_Natura_pct	The proportion (%) of the undrained part of an aapa mire that is located in European Union's Natura 2000 network of nature protection areas