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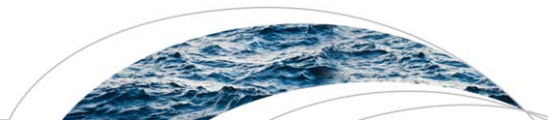
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RESEARCH ARTICLE

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Key Points:

- A BACIPS design with long-term, high-resolution water table and climate data was used to study impacts of restoration on pore water quality
- The most important variables explaining pore water quality were trophic level, peatland class, water table, and soil and air temperature
- Short postrestoration rises in DOC and nutrients in pore water were observed but declined to lower levels than in drained sites over time

Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3

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# Changes in Pore Water Quality After Peatland Restoration: Assessment of a Large-Scale, Replicated Before-After-Control-Impact Study in Finland

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**Abstract** Drainage is known to affect peatland natural hydrology and water quality, but peatland restoration is considered to ameliorate peatland degradation. Using a replicated BACIPS (Before-After-Control-Impact Paired Series) design, we investigated 24 peatlands, all drained for forestry and subsequently restored, and 19 pristine control boreal peatlands with high temporal and spatial resolution data on hydroclimate and pore water quality. In drained conditions, total nitrogen ( $N_{tot}$ ), total phosphorus ( $P_{tot}$ ), and dissolved organic carbon (DOC) in pore water were several-fold higher than observed at pristine control sites, highlighting the impacts of long-term drainage on pore water quality. In general, pore water DOC and  $N_{tot}$  decreased after restoration measures but still remained significantly higher than at pristine control sites, indicating long time lags in restoration effects. Different peatland classes and trophic levels (vegetation gradient) responded differently to restoration, primarily due to altered hydrology and varying acidity levels. Sites that were hydrologically overrestored (inundated) showed higher  $P_{tot}$ ,  $N_{tot}$ , and DOC than well-restored or insufficiently restored sites, indicating the need to optimize natural-like hydrological regimes when restoring peatlands drained for forestry. Rich fens (median pH 6.2–6.6) showed lower pore water  $P_{tot}$ ,  $N_{tot}$ , and DOC than intermediate and poor peats (pH 4.0–4.6) both before and after restoration. Nutrients and DOC in pore water increased in the first year postrestoration but decreased thereafter. The most important variables related to pore water quality were trophic level, peatland class, water table level, and soil and air temperature.

## 1. Introduction

Peatlands are ecosystems where both terrestrial and aquatic environments meet, providing unique biodiversity and ecosystem functions (Kadlec & Wallace, 2008). Although only 3% of the globe is covered by peatlands (Greenup et al., 2000), it has been reported that boreal and subarctic peatlands store approximately 30% of the total world pool of soil carbon (Yu, 2012). Natural peatlands store carbon in the form of peat, but peatlands can be a major net source of methane to the atmosphere and, when disturbed (e.g., drainage, horticulture, and peat extraction), they may become sources of carbon dioxide (Dieleman et al., 2016; Gorham, 1991; Höll et al., 2009; Waddington et al., 2010). Furthermore, peatlands (fens) which receive water and nutrients from the surrounding uplands play an important role for sustainable water management through nutrient retention facilitating plant nutrient uptake and sedimentation (Kadlec & Wallace, 2008; Kieckbusch & Schrautzer, 2007). These important services have been compromised as a result of anthropogenic disturbances to some 14–20% of the total global area of peatlands (Strack, 2008). In boreal and temperate regions, about  $15 \times 10^6$  ha of global peatland resources have been drained for forestry (Bonn et al., 2016; Koskinen et al., 2011), one third of which are located in Finland (Silfverberg & Moilanen, 2008). As a result, peatland drainage for forestry is the major source of peatland degradation in Finland (Haapalehto et al., 2011).

Runoff from degraded peatlands affects the water quality of downstream water bodies due to leaching of metals, nutrients (nitrogen and phosphorus), dissolved organic carbon (DOC), and suspended solids (Armstrong et al., 2010; Holden et al., 2004; Kløve et al., 2010; Marttila & Kløve, 2010; Prévost et al., 1999). A rise in

DOC concentrations and an increase in DOC export of about 60% following peatland drainage was reported in a recent review of 15 published studies (Evans et al., 2016). These changes affect the water quality of downstream aquatic systems (Evans et al., 2005). Peatland drainage tends to elevate the nitrate ( $\text{NO}_3^-$ ) concentration in pore water, since aeration of the uppermost peat layer further enhances mineralization and nitrification of organic nitrogen (Holden et al., 2004; Venterink et al., 2002). This can be attributed to lowered water table (WT) and increased bulk density in drained peatlands (Wells & Williams, 1996). Increased aerobic decomposition as a result of lowered WT is likely to enhance the quick breakdown of labile pools of organic phosphorus and subsequently elevate release of more inorganic phosphorus (Martin et al., 1997).

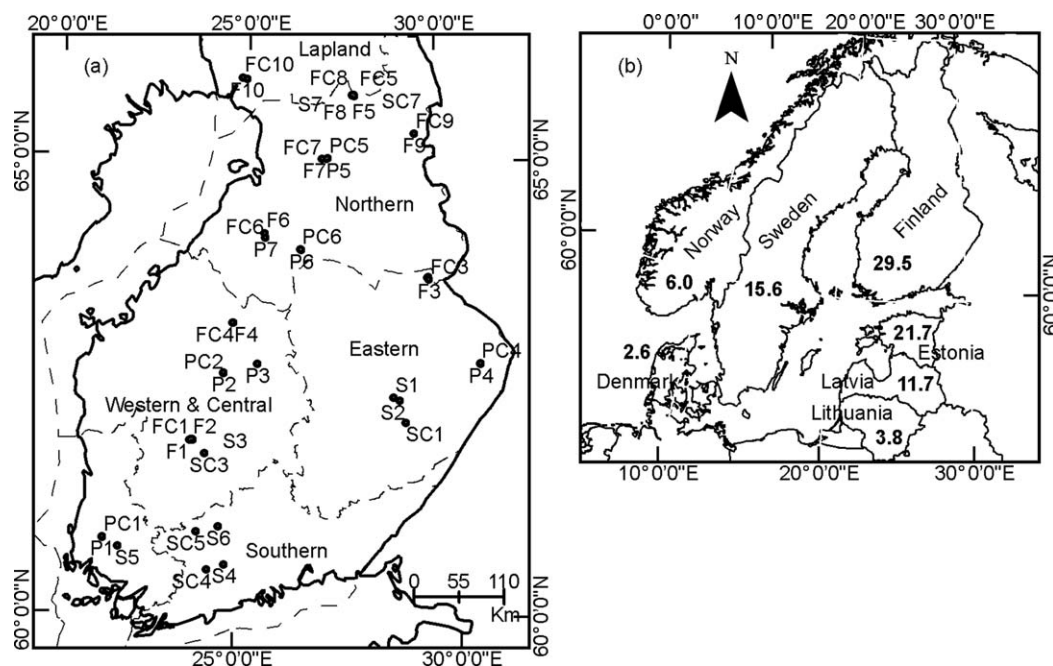
Since the natural functions of peatland ecosystems have been weakened by drainage for forestry, agriculture, peat extraction, and horticultural activities in the past 20 years, there is now growing interest in recovering the original functions through restoration (e.g., drain blocking) (Martin-Ortega et al., 2014; Menberu et al., 2016). It has been reported that restoration can restore the natural ecosystem functions of degraded peatlands (Kareksela et al., 2015; Kotiaho et al., 2016). The reestablishment of hydrological processes typical of natural peatlands is often used to measure the success of peatland restoration (Bruland et al., 2003; Haapalehto et al., 2011, 2014). This is because hydrology plays a key role in dictating redox status, pH, nutrient cycling, flora and fauna composition, and peat formation (Bridgman et al., 1991). It has been suggested that the distribution of peatland flora and fauna is restricted by their narrow tolerance to changing chemical conditions (Sjörs, 1950) and WT fluctuations (Holden et al., 2004), indicating the importance of both water quality and hydrology to measure restoration success. Thus, blocking ditches to raise the WT is likely not enough, and it is also important to restore the main sources of water inflow to peatlands. This is essential since water inflow and flow paths play a key role in transporting nutrients both toward and away from peatlands and subsequently affect the water quality.

Recent studies have shown that restoration of degraded peatlands can recover hydrological conditions typical for natural peatlands within a few years in terms of WT level (Haapalehto et al., 2011, 2014) and its fluctuations (Bruland et al., 2003; Menberu et al., 2016). This can have an instant impact on nutrient cycling (e.g., nitrogen and phosphorus; Ardón et al., 2010). However, a longer stabilization time is often required for water quality improvement, and the impact of peatland restoration on pore water quality and its interaction with changed hydrology still remains unclear. Runoff water is often studied, but there have only been a few studies on peatland drainage and subsequent restoration effects on pore water quality (Haapalehto et al., 2014). Pore water directly reflects conditions in the peat that are important to vegetation (Tahvanainen et al., 2002) and ecosystem functions. This study is one of the first attempts to include a representative set of boreal peatlands (in total 43 sites) with pore water quality and high temporal resolution WT data. In order to better understand how pore water quality recovers after boreal peatland restoration, we applied a Before-After-Control-Impact Paired Series (BACIPS) design in the 43 sites found across Finland. Although there is some evidence of negative impacts of peatland restoration operations on water quality, the sources of these impacts are still unclear: They may be due to restoration-induced hydrological alterations or to physical disturbance during restoration. Our hypothesis is that raising the WT by restoration and/or lowering it by drainage affects biogeochemical, physicochemical, and microbial cycles within the peat, and subsequently alters the water quality. Based on this hypothesis, the main aims of this study were to (1) identify the effects of peatland drainage and subsequent restoration on pore water quality and assess the trajectory of postrestoration change; (2) identify sources of water quality impact due to drainage and restoration by studying the interaction of hydrological processes, peatland classes, and trophic levels (vegetation gradients) with pore water quality parameters; and (3) assess restoration practices from a hydrological and water quality point of view.

## 2. Materials and Methods

### 2.1. Study Areas

A total of 43 intensively monitored peatlands (Figure 1a), comprising different spatially representative peatland types across Finland, were studied. More than half of the sites had been drained for forestry (24 sites) since the 1960s and had been restored during the monitoring period of this study, but the other study sites (19 sites) were pristine controls carefully selected to represent similar peatland type, vegetation, topography, and weather conditions as their drained (before restoration) and drained-restored (after restoration)



**Figure 1.** (a) Location and distribution of study sites across different regions in Finland and (b) percentage of peat soil cover (>30 cm peat thickness) in Nordic and Baltic countries (Montanarella et al., 2006). For site characteristics by code, see Table 1.

counterparts. This research setup enabled application of BACIPS (Osenberg & Schmitt, 1996) to study pore water quality changes and associated hydrological interactions resulting from peatland drainage and subsequent restoration on the 43 study sites. Vegetation monitoring data from the Parks & Wildlife Finland monitoring program included 134 sites, of which the 43 sites used in this study had hydrological, water quality, and vegetation data.

The study sites consisted of peatlands ranging from acidic *Sphagnum*-dominated poor fens to near-neutral rich fens, and from open to woody peatland types (supporting information Table S1). Based on the main vegetation characteristics (wood cover and ecological species groups abundance), the study sites were divided into four peatland type classes: spruce mires, pine mires, poor fens, and rich fens. Furthermore, a classification of trophic level was used to categorize sites into poor, intermediate, and rich mires (Table 1). These classes correspond, respectively, to the oligotrophic, mesotrophic, and eutrophic categories according to the Finnish peatland classification (Eurola & Huttunen, 2006). This classification reflects the degree of minerotrophic influence and, hence, pH, electric conductivity (EC), and base cations of pore water, and it is based on the presence of indicator plant species (Eurola & Huttunen, 2006; Sjörs, 1950; Tahvanainen et al., 2002). Importantly, the trophic level classification does not primarily indicate productivity or nutrient

**Table 1**  
Peatland Class, Trophic Level, and Site Code of the Different Sites

Peatland class	Trophic level	Drained/drained-restored sites	Control (C) sites
Spruce mire	Poor	S1 <sup>O</sup> , S2 <sup>O</sup> , S3 <sup>W</sup>	SC1, SC3
	Intermediate	S4 <sup>W</sup> , S5 <sup>L</sup> , S6 <sup>O</sup> , S7 <sup>W</sup>	SC4, SC5, SC7
Pine mire	Poor	P1 <sup>W</sup> , P2 <sup>L</sup> , P3 <sup>L</sup>	PC1, PC2
	Intermediate	P4 <sup>W</sup> , P5 <sup>W</sup> , P6 <sup>W</sup> , P7 <sup>W</sup>	PC4, PC5, PC6
Fen	Poor	F1 <sup>W</sup> , F2 <sup>W</sup> , F3 <sup>W</sup>	FC1, FC3
	Intermediate	F4 <sup>W</sup> , F5 <sup>W</sup> , F6 <sup>W</sup> , F7 <sup>W</sup>	FC4, FC5, FC6, FC7
	Rich	F8 <sup>W</sup> , F9 <sup>L</sup> , F10 <sup>W</sup>	FC8, FC9, FC10

Note. These site codes are also used in the location map (Figure 1a). Superscripts O, W, and L refer to sites that were hydrologically overrestored, well restored, and less well restored, respectively (Menberu et al., 2016).

availability, although a certain degree of correlation may exist with the pH/cation gradient (Tahvanainen, 2004; Tahvanainen et al., 2002). We retained the peatland class and trophic level, as these were the main basis of site selection in the original experimental plan (Aapala et al., 2012). Furthermore, based on the WT level and hydrological regime requirements of peatland vegetation species in the studied peatlands, we classified the drained-restored sites into well restored, overrestored, and less well restored (Menberu et al., 2016).

Typically, peat thickness of the studied peatlands ranged from 1 to 3 m and at some sites up to 6 m. The long-term (1981–2010) mean annual temperature in the South, Central, East, West, and North of Finland is 5.8, 3.6, 3.0, 3.8, and 2.6°C, respectively, and mean annual precipitation is 656, 641, 613, 533, and 513 mm, respectively (Finnish Meteorological Institute, 2015).

The study sites were drained during the 1960s and 1970s, with ditch spacing ranging from 30 to 50 m. The drainage networks at each study site covered typically about 60% of the total peatland area. To keep the drainage networks fully functional, the drainage networks at some of the study sites have been cleared since the 1990s. Typically, NPK-fertilizer used for a few years after drainage as routine practice in Finnish peatland forestry areas. Forest growth at these drained peatlands has generally been inefficient and no commercial logging had been done before restoration measures except at sites F1, F2, F4, and F10. Parks and Wildlife Finland (the Finnish state forest enterprise) carried out the restoration operations. The restoration operation primarily involved filling in ditches with peat and construction of peat dams across the drainage ditches by excavators using peat materials from the site, following general guidelines on restoration (Similä et al., 2014). The slope of peatlands and the amount of water flow in the ditches were taken into consideration to determine distance between peat dams, which typically ranged from 30 to 50 m, aiming at redirecting surface water flow to natural flow paths instead of the ditches. The peat dams had a maximum height of 1 m and length of 6–10 m. Furthermore, excessive tree stands were removed to create an open peatland environment promoting the recovery of characteristic peatland species (Menberu et al., 2016; Similä et al., 2014). The study sites were labeled, e.g., the first drained/drain-restored spruce mire and its pristine control site were represented as S1 and SC1, respectively, while the same system was applied to pine (P-) and fen (F-) peats (Table 1 and supporting information Table S2).

## 2.2. Hydrological and Meteorological Data

At all study sites, high temporal resolution continuous WT level data were recorded using a standpipe well of diameter 32 mm and length 1–1.5 m. The standpipe well was fully slotted from tip to center and WT was measured at 30 min resolution using a Solinst Levellogger Gold during the frost-free season (typically May–October). The standpipe well location at each study site was carefully selected near the center of the restoration areas and within a certain peatland type zone, in order to find representative local mean WT level. The standpipe well was always installed midway between ditches in drained and drained-restored plots (supporting information Figure S1). Besides WT level data, the Solinst Levellogger Gold collects high-resolution data on pore water temperature. The Finnish Meteorological Institute provided daily 10 km × 10 km gridded rainfall data. Atmospheric pressure and temperature within a 15 km radius were monitored using an automatic Solinst Barologger Gold. In order to cross-check the reliability of the logger data (especially WT level), manual measurements were made on water sampling occasions (data not shown).

## 2.3. Water Quality

The pore water samples were collected from 1 m fully slotted standpipes installed in the peat layer near the WT measuring standpipes (supporting information Figure S1). First, the old water from the standpipes was pumped out and a pause of several minutes was allowed until fresh water from the peat layer had drained into the standpipes for water sampling. The water samples collected this way were taken to be representative of the pore water in the peat layers at the study sites. Pore water quality was analyzed from water samples collected on average 4 times per year during the monitoring period, which was the same in every year (from May to October). A total of 966 water samples were analyzed during the years 2008–2014. Studies of seasonal variations in pore water chemistry had already been made at a few sites that had higher sampling frequency, and showed that pore water chemistry (e.g., DOC, pH, and total nitrogen) are quite stable and display predictable seasonal variations (Tahvanainen et al., 2003; Vitt et al., 1995). Since we had many study sites, we decided that our sampling frequency would be adequate. The total length of study period varied across the study sites, being at least 1 year before and after restoration (supporting information Table S2).

The collected pore water samples were analyzed for total concentrations of phosphorus ( $P_{\text{tot}}$ ), nitrogen ( $N_{\text{tot}}$ ), DOC, pH, electric conductivity (EC), and UV-absorbance (UV-254 nm). The specific UV absorbance (SUVA) was calculated by dividing the value UV-254 by DOC. Analyses were conducted by accredited laboratories using standard methods for  $P_{\text{tot}}$  (SFS-EN ISO 6878: 2004),  $N_{\text{tot}}$  (SFS-EN ISO 11905-1: 1998), DOC (SFS-EN 1484: 1997), pH (SFS 3021: 1979), and UV-254 (SFS-EN ISO 7887: 2012).

#### 2.4. Replicated Before-After-Control-Impact Paired Series Design

The BACIPS design (Osenberg & Schmitt, 1996; Stewart-Oaten et al., 1986) was used in this study for replicated pore water quality data samples collected before and after restoration at control, drained, and drained-restored study sites. The BACIPS design is a robust method that helps to eliminate hydrological differences between study years. Taking into account natural variation in WT and pore water quality is important, since hydrological conditions vary widely in Finland. The analysis was performed for all aggregated data, each pair of study sites and aggregated pore water quality parameters based on peatland class and trophic level regardless of time after restoration. Furthermore, pore water quality recovery since restoration time analyzed at each postrestoration year to understand time dependence of pore water quality recovery. Typically, nutrient concentrations at drained-restored sites can be expected to increase immediately after restoration, due to disturbances caused during ditch blockage. Elevated water color and DOC concentrations have been reported during the first 10 months of restoration (Worrall et al., 2007). Since there may have been certain immediate effects after restoration, such as the release of suspended fine material by digging or release/flushing of the pool of dissolved material accumulated during the drainage phase, we discarded first year postrestoration data in the BACIPS analysis. Thus, our data had the potential to reveal altered dynamics which were not caused by the immediate physical effects and settling of hydrology to the new conditions but may still include variations because we expect that it takes some time for these parameters to stabilize. For each pore water quality parameter, we calculated the absolute difference between the control and drained ( $\Delta b$ ) before restoration and the control and drained-restored ( $\Delta a$ ) after the given amount of time after restoration in the time since restoration analysis or for the average value of years 2–6 for the aggregated analysis. The average effect size (Es) of perturbation (Osenberg et al., 1994) was also calculated (average of  $\Delta a$  – average of  $\Delta b$ ) because Es transforms the effect of drainage and restoration on pore water quality parameters to a value with a straight-forward interpretation. A positive value of Es indicates an increase (rise) and a negative value indicates a decrease (fall) in the pore water quality parameter in question following restoration. Furthermore, the standardized effect size index (Esl), free from the original pore water parameter units, was evaluated by dividing the absolute value of Es by the variability (standard deviation). Conventional definitions indicate that the effect is small, medium, and large when Esl is between 0 and 0.20, 0.20 and 0.50, and more than 0.5, respectively (Cohen, 1977).

#### 2.5. Statistical Analyses

The pore water quality parameters were aggregated based on peatland class and trophic level in order to understand the general behavior of the data and find guidelines for restoration measures. Statistically significant changes were tested using the Student's *t* test and Mann-Whitney *U* test. Pearson's correlation coefficient (*r*) was used to study the relationship between pore water quality parameters before and after restoration. The relationships between each pore water quality parameter and antecedent data on rainfall (PPT), atmospheric temperature ( $T_{\text{air}}$ ), soil temperature ( $T_{\text{soil}}$ ) and hydrological conditions (e.g., WT) were also analyzed. The antecedent conditions considered for this analysis were 1 and 4 days mean and standard deviation (SD), 7 days mean and SD, 14 days mean and SD, and 30 days mean and SD, but for rainfall, the total instead of the mean was calculated.

We explored main patterns of variation in pore water quality parameters between all sites, and separately for drained, drained-restored, and pristine control sites, and also between peatland classes and trophic levels using principal component analysis (PCA). Prior to running PCA, we standardized the end products to have zero mean and unit variance on the covariance matrix. The final number of PCs was determined using the broken-stick model (widely applied in ecological studies due to its effectiveness and ease of calculation), in which eigenvalues from a PCA are compared with the broken-stick distribution (Jackson, 1993). Since each eigenvalue of a PCA represents a measure of a component's variance, a component is retained if its eigenvalue is larger than the value given by the broken-stick model.

We used multivariate clustering methods to generate groups of peatlands with maximum similarity in pore water quality. We made separate analysis for the following groups: drained, drained-restored, and pristine control. Ward's hierarchical clustering (Legendre & Legendre, 2012) was used for standardized pore water quality data and the final number of clusters was based on manual truncation of the dendrogram. The cluster analysis divided the individual pore water quality samples into four groups with all treatments, with the number of measurements per cluster varying from 6 to 22, 30 to 121, and 7 to 97 for drained, Drained-restored, and pristine control, respectively.

The results from clustering were further utilized in a Random Forest (RF) model (Breiman, 2001) in order to assess which environmental factors best explained the clustering (i.e., variations in pore water quality). As explanatory variables in RF, we used trophic levels, peatland classes, and variables characterizing WT levels, soil and atmospheric temperatures, and local precipitation values of the sampling date and 7 and 30 days prior to the sampling date. We also tested conditions at 3, 14, and 20 days prior to sampling, but we did not find any meaningful differences and thus they were excluded from further analysis. RF models make no assumptions about the type of relationship (linear or nonlinear) between the predictor and response variables. We used the R-program implementation of RF to build the models (Liaw & Wiener, 2002). RF models integrate the combined output of many decision tree models (i.e., the "forest," here 5000), each using a different bootstrap sample from the original data. The predictions of the final RF model are an average of the predictions of the forest. For the "forest," each tree is tested on samples not used in building the tree, providing an out-of-bag (OOB) estimate of the model error. The selection of the final RF model was based on visual examination of the variable importance plots (Cutler et al., 2007). We used mean decrease in accuracy as the primary criterion of model fit. Higher values indicate variables that are more important for the classification.

### 3. Results

#### 3.1. Water Quality in Pristine Control Peatlands

The pristine control sites showed variation in pore water quality when the data were grouped based on peatland classes. The highest mean pore water  $N_{\text{tot}}$  and  $P_{\text{tot}}$  were observed in spruce mires ( $P_{\text{tot}} = 94.5 \mu\text{g L}^{-1}$ ,  $N_{\text{tot}} = 1,047 \mu\text{g L}^{-1}$ ) while fens had the lowest  $N_{\text{tot}}$  ( $619 \mu\text{g L}^{-1}$ ) and DOC ( $28.1 \text{ mg L}^{-1}$ ). Generally,  $N_{\text{tot}}$  and DOC processes were strongly interconnected and significant positive correlations ( $r = 0.46\text{--}0.91$ ,  $r_{\text{mean}} = 0.70$ ) were found when peatland class and trophic level were considered separately. Both DOC and  $N_{\text{tot}}$  were moderately correlated with  $P_{\text{tot}}$  ( $r = 0.21\text{--}0.81$ ,  $r_{\text{mean}} = 0.50$ ). Additionally, moderate correlations between  $P_{\text{tot}}$ ,  $N_{\text{tot}}$ , UV, and DOC ( $r = 0.31\text{--}0.84$ ) were observed for the whole dataset of pristine control peatlands.

Measured pore water concentrations also varied between different trophic levels. The lowest  $N_{\text{tot}}$ ,  $P_{\text{tot}}$ , and DOC were observed for the sites classified as rich (all were rich fens) and the highest  $N_{\text{tot}}$  and DOC for the intermediate (mesotrophic level) and poor (oligotrophic level) trophic level sites. Unexpectedly, peatlands of the poor class (oligotrophic level) showed on average the highest  $P_{\text{tot}}$  in pore water. Pristine control spruce forest mires from the main peatland class had the highest median pH and mean EC, followed by fens and pine mires, whereas on the trophic level gradient the highest values were observed for the rich level, followed by the intermediate and the poor levels (Table 2).

#### 3.2. Pore Water Quality Since the Time of Restoration

Data from 3 years before and after restoration were compared to assess pore water quality stabilization after restoration by aggregating all study sites together to find generalizable patterns in recovery of water quality after restoration regardless of peatland classes or trophic levels. Comparison of the 1 year prerestoration and postrestoration pore water  $P_{\text{tot}}$ ,  $N_{\text{tot}}$ , and DOC revealed that the postrestoration concentrations were 60%, 27%, and 13% higher, respectively. However, pore water nutrients and DOC started to decrease during subsequent postrestoration years (Table 3), indicating stabilization of peatland systems after restoration (Figures 2a–2c and supporting information Figure S2). Two years after restoration, the pore water  $N_{\text{tot}}$  and DOC had decreased by 30% and 26%, respectively, from the situation 2 years before restoration, and the increase in  $P_{\text{tot}}$  was also reduced from 60% to 15%. After 3 years of restoration,  $N_{\text{tot}}$  and DOC were reduced by 49% and 41%, respectively, compared with the situation 3 years before restoration and the increase in  $P_{\text{tot}}$  was limited to 5% only (Table 3). Furthermore, the pore water recovery since restoration

**Table 2**  
Characteristics of Pore Water Quality (Mean ± 1SE) Summarized Based on Study Site Peatland Class and Trophic Level for All Treatment Periods

Trophic level	Treatment	$P_{tot}$ ( $\mu\text{g L}^{-1}$ )	$N_{tot}$ ( $\mu\text{g L}^{-1}$ )	DOC ( $\text{mg L}^{-1}$ )	pH <sup>a</sup>	EC ( $\mu\text{S/m}$ )	SUVA	WT (cm)	N	No. of sites
Rich		53.1 ± 12.3	769 ± 73.5	18.2 ± 1.5	6.4 ± 0.06	67.5 ± 5.4	4.3 ± 0.2	-10.3 ± 1.3	69–79	6
	Drained	150 ± 61.0	1,660 ± 317	33.5 ± 4.5	6.6 ± 0.2	87.1 ± 15.3	4.0 ± 0.5	-32.9 ± 7.6	7–12	3
	Drained-restored	71.8 ± 19.6	913 ± 70.5	21.3 ± 2.0	6.2 ± 0.1	72.2 ± 12.1	5.5 ± 0.3	-11.1 ± 0.8	27–29	3
	Pristine control	10.7 ± 2.4	402 ± 45.4	10.9 ± 1.6	6.5 ± 0.07	57.9 ± 4.0	3.6 ± 0.1	-5.2 ± 1.0	35–38	3
Intermediate		107.8 ± 10.5	1,596 ± 76.5	53.6 ± 1.7	4.6 ± 0.7	30.2 ± 0.9	4.6 ± 0.1	-14.1 ± 0.7	464–495	22
	Drained	156.5 ± 32.6	2,652 ± 191	80.9 ± 4.4	4.5 ± 0.6	36.4 ± 2.1	4.1 ± 0.1	-26.8 ± 1.9	88–103	12
	Drained-restored	161.7 ± 20.5	1,982 ± 143	60.1 ± 3	4.5 ± 0.6	31.8 ± 1.4	4.9 ± 0.1	-10.6 ± 1.1	167–173	12
	Pristine control	43.9 ± 6.9	819 ± 61	35.7 ± 1.2	4.7 ± 0.7	26.1 ± 1.2	4.8 ± 0.1	-11.5 ± 0.7	206–219	10
Poor		127.7 ± 13	1,471 ± 83.4	54.8 ± 1.5	4.1 ± 0.5	22.9 ± 1.3	4.2 ± 0.1	-16.4 ± 0.7	353–383	15
	Drained	141.6 ± 26.1	1,901 ± 153.4	69.7 ± 2.9	4.0 ± 0.8	28.7 ± 3.0	4.0 ± 0.1	-31.8 ± 1.9	62–79	9
	Drained-restored	176.7 ± 25.3	1,800 ± 163.8	61.5 ± 2.7	4.0 ± 0.4	23.7 ± 1.7	4.5 ± 0.1	-13.8 ± 0.9	166–170	9
	Pristine control	59.1 ± 8.7	817.3 ± 29.8	37.6 ± 1.2	4.2 ± 0.4	18.8 ± 2.3	4.0 ± 0.1	-12.2 ± 0.8	125–134	6
<i>Peatland class</i>										
Fen		44.4 ± 5.1	948 ± 44.1	38.1 ± 1.2	4.3 ± 0.05	27.2 ± 1.5	4.3 ± 0.1	-11.9 ± 0.49	404–410	19
	Drained	71.5 ± 15.2	1,475 ± 119	54.3 ± 2.4	4.1 ± 0.1	28.3 ± 3.5	4.2 ± 0.1	-21.5 ± 1.4	83–87	10
	Drained-restored	45.5 ± 5.9	1,043 ± 77.9	40.8 ± 2.2	4.2 ± 0.08	27.5 ± 3.1	4.7 ± 0.1	-9.6 ± 0.7	143–144	10
	Pristine control	30.4 ± 7.7	619 ± 40.0	28.1 ± 1.4	4.7 ± 0.07	26.6 ± 1.7	4.0 ± 0.1	-10.0 ± 0.53	178–179	9
Pine mire		130 ± 227	1,810 ± 104	66.6 ± 2.2	4.2 ± 0.03	26.3 ± 1.0	4.4 ± 0.1	-14.9 ± 0.87	285–289	12
	Drained	187 ± 27.3	3,018 ± 249	93.1 ± 5.4	4.4 ± 0.8	40.0 ± 2.5	3.8 ± 0.2	-30.9 ± 2.4	60–62	7
	Drained-restored	200 ± 27.4	2,135 ± 160	74.0 ± 3.2	4.1 ± 0.6	29.2 ± 1.6	4.7 ± 0.1	-13.7 ± 1.1	115–116	7
	Pristine control	26.0 ± 4.8	790 ± 97.5	43.6 ± 1.5	4.2 ± 0.02	16.1 ± 0.7	4.5 ± 0.1	-8.2 ± 0.7	110	5
Spruce mire		200 ± 21.6	1,974 ± 130	54.7 ± 2.4	4.7 ± 0.05	40.5 ± 1.8	4.7 ± 0.1	-18.7 ± 1.2	243–258	12
	Drained	263 ± 76.8	2,950 ± 248	82.8 ± 5.8	4.8 ± 0.1	51.2 ± 4.7	3.9 ± 0.2	-41.1 ± 3.0	38–44	7
	Drained-restored	277 ± 38.2	2,516 ± 261	62.6 ± 4.1	4.5 ± 0.06	38.5 ± 2.4	4.9 ± 0.1	-13.7 ± 1.5	104–112	7
	Pristine control	94.5 ± 10.8	1,047 ± 51.3	33.9 ± 1.4	5.2 ± 0.07	38.2 ± 3.2	4.8 ± 0.2	-16.1 ± 1.4	101–102	5

<sup>a</sup>Median ± 1SD, N is total number of samples analyzed and SE is standard error of mean.

analysis by peatland class and trophic level as well revealed a decreasing trend in  $P_{tot}$ ,  $N_{tot}$  and DOC concentrations and moved toward pristine control conditions (Figures 3a–3c and 4a–4c).

### 3.3. Impact of Drainage and Subsequent Restoration on Pore Water Quality

The BACIPS design analyses of each pair of study sites revealed that treatment (drainage and restoration) had variable impacts on pore water quality (supporting information Figure S3). In general, pore water quality in drained peatlands differed from that in pristine control peatlands (Table 2). The measured  $P_{tot}$ ,  $N_{tot}$ ,

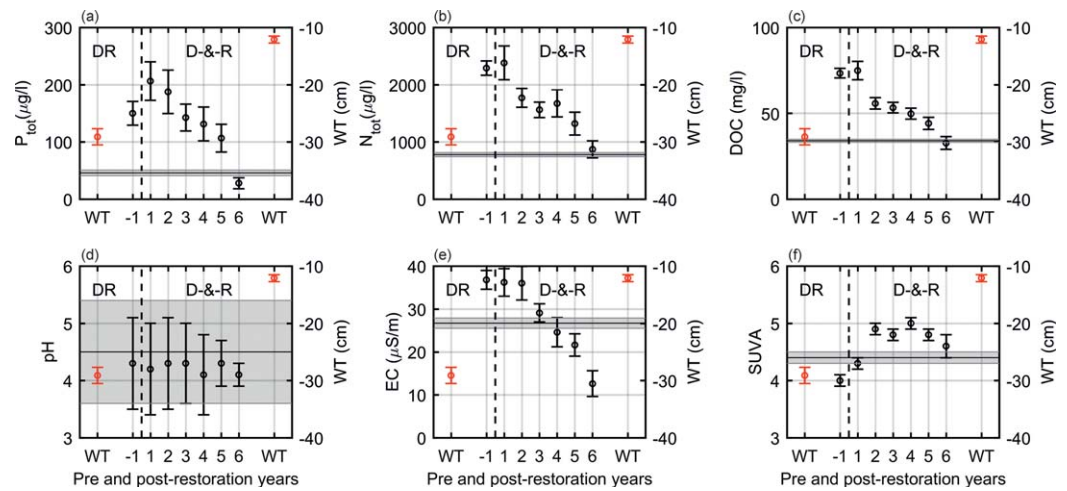
**Table 3**  
Summary of Mean and Range of Pore Water Quality Before and After Restoration, Mean Concentrations for Pristine Control Sites, Restoration Success Groups (Menberu et al., 2016), and Years After Restoration

Treatment	$P_{tot}$ ( $\mu\text{g L}^{-1}$ )	$N_{tot}$ ( $\mu\text{g L}^{-1}$ )	DOC ( $\text{mg L}^{-1}$ )	pH <sup>a</sup>	EC ( $\mu\text{S/m}$ )	SUVA	WT (cm)	N	No. of sites
Drained	150 ± 20.6	2,290 ± 124	73.4 ± 2.8	4.3 ± 0.8	36.8 ± 2.2	4.0 ± 0.1	-29.1 ± 1.4	157–194	24
Drained-restored	161 ± 15.1	1,813 ± 101	57.7 ± 1.9	4.2 ± 0.7	31.3 ± 1.5	4.7 ± 0.1	-12.1 ± 0.6	362–372	24
Pristine control	45.9 ± 4.9	778 ± 36.6	34.0 ± 0.9	4.5 ± 0.9	26.7 ± 1.2	4.4 ± 0.1	-11.1 ± 0.5	366–391	19
Well restored	143 ± 17.3	1,698.4 ± 108	56.4 ± 2.6	4.2 ± 0.8	29.8 ± 2.0	4.8 ± 0.1	-8.5 ± 0.7	220–227	17
Overrestored	460.5 ± 77.3	3,915.8 ± 572	88.3 ± 7.9	4.6 ± 0.4	50.9 ± 4.8	4.7 ± 0.2	-3.8 ± 1.3	40	3
Less well restored	62.5 ± 10.2	1,464 ± 99	51 ± 3.1	4.1 ± 1.1	37.2 ± 4.9	4.5 ± 0.1	-25 ± 1.6	47–53	4
Drained <sup>b</sup>	63.7–163.7	1,740–3,073	56.3–90	4.2–4.4	18.9–39	3.8–4.4	-33.2 to -17.9	3–85	1–24
1 year after restoration	206.3 ± 33.6	2,381.1 ± 294.8	74.9 ± 5.4	4.2 ± 0.8	36.2 ± 3.2	4.3 ± 0.1	-9.5 ± 1.2	91–94	24
2 years after restoration	187.6 ± 37.8	1,771.5 ± 164.1	55.8 ± 3.3	4.3 ± 0.8	36 ± 3.9	4.9 ± 0.1	-10.8 ± 1.3	97–100	24
3 years after restoration	142.6 ± 23.4	1,562.1 ± 135.4	53.3 ± 3.1	4.3 ± 0.7	29.1 ± 2.1	4.8 ± 0.1	-10.8 ± 1.2	92–97	22
4 years after restoration	131.3 ± 29.6	1,671.6 ± 234.7	49.8 ± 3.2	4.1 ± 0.7	24.6 ± 3.4	5.0 ± 0.1	-16.9 ± 1.7	51–52	11
5 years after restoration	106.6 ± 24.3	1,319.2 ± 199.9	44.1 ± 3.5	4.3 ± 0.4	21.6 ± 2.6	4.8 ± 0.1	-17.9 ± 1.6	26–27	4
6 years after restoration	27.8 ± 9.7	871.3 ± 147.8	32.7 ± 3.7	4.1 ± 0.2	12.6 ± 3	4.6 ± 0.2	-18.3 ± 2.8	4	1

<sup>a</sup>Median ± 1SD, N is total number of samples analyzed and SE is standard error of mean.

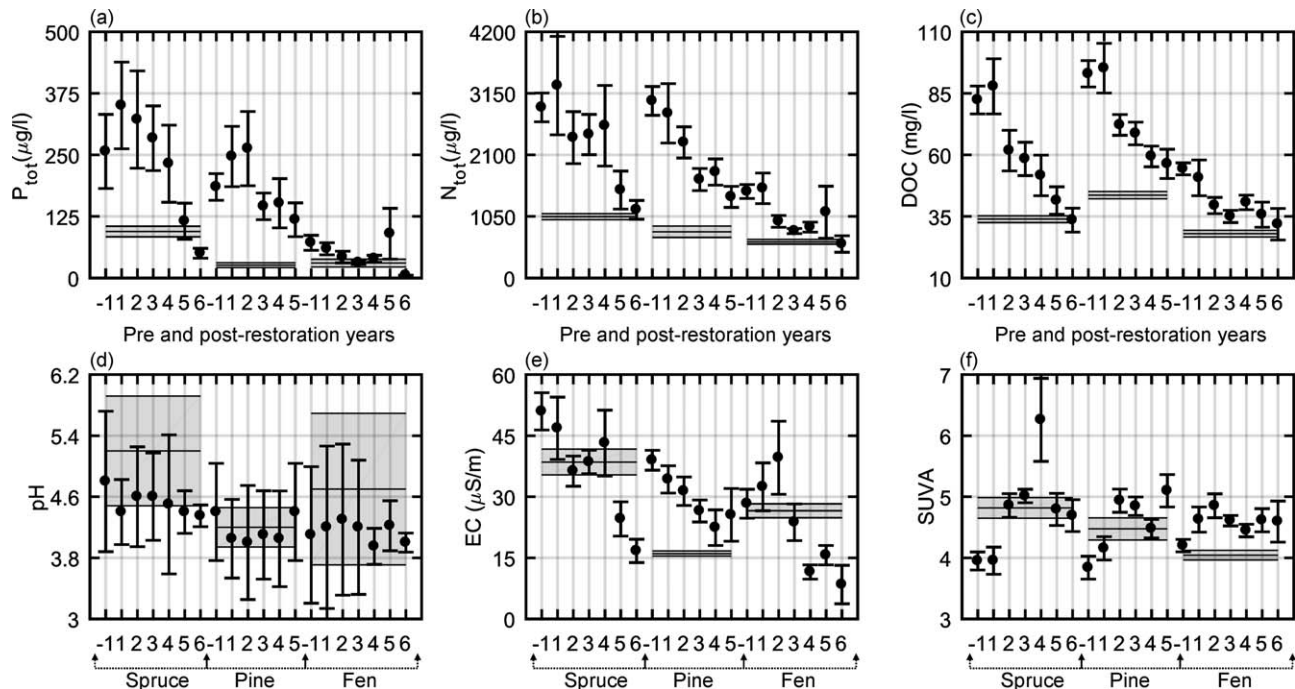
<sup>b</sup>Range of mean values for drained conditions for years 1–4.



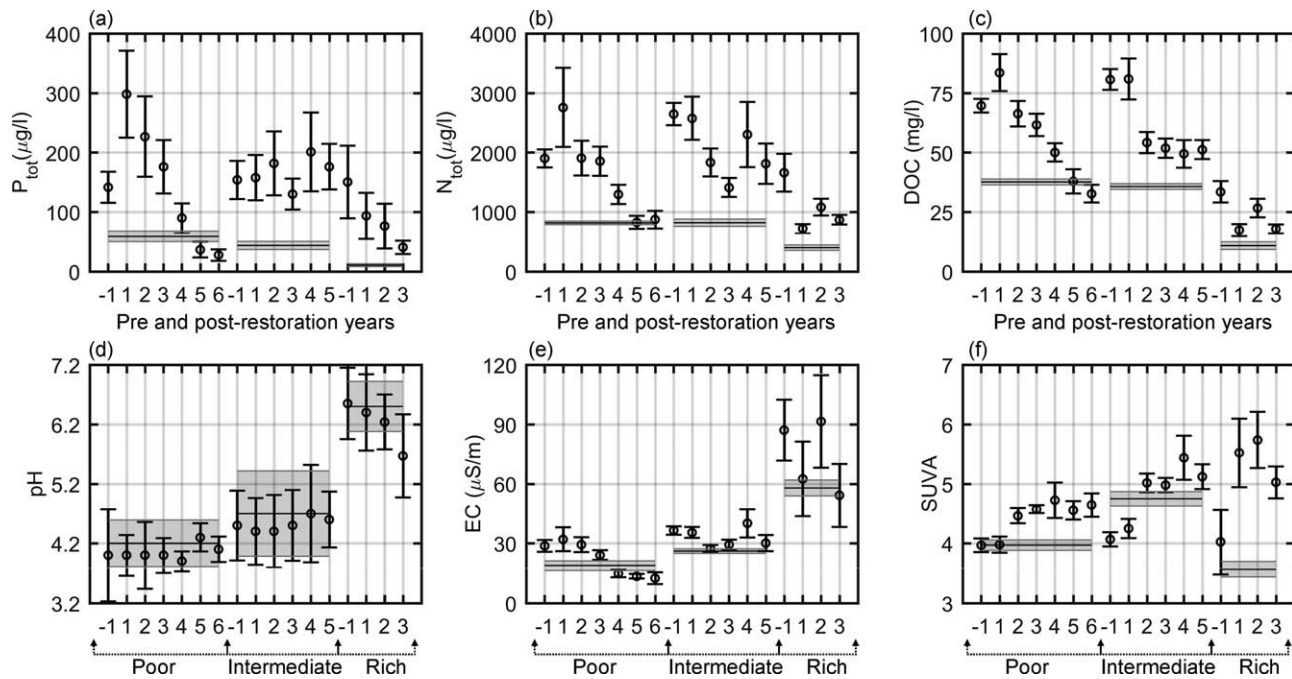


**Figure 2.** Trajectory of postrestoration change in mean (a) total phosphorus ( $P_{tot}$ ), (b) total nitrogen ( $N_{tot}$ ), (c) dissolved organic carbon (DOC), (d) pH, (e) electric conductivity (EC), and (f) SUVA for the entire study site and bars show standard error of mean. DR, drained; D-&R, drained-restored; WT, average water table (red bars); -1 represents drained condition; 1-6 represent postrestoration years; and shaded region represent mean values and standard error of mean for each parameter at pristine control sites, except for pH where median and standard deviation shown. The total number of samples analyzed in drained-restored sites for postrestoration year 1 = 91-94, year 2 = 97-100, year 3 = 92-97, year 4 = 51-52, year 5 = 26-27, and year 6 = 4.

and DOC for different peatland types and trophic levels under drained conditions was 2-14, 2.4-4.0, and 1.9-3.1 times higher, respectively, than measured at the pristine control sites. The measured  $P_{tot}$ ,  $N_{tot}$ , and DOC under drained-restored conditions also maintained high values and was 1.5-7.7, 1.7-2.7, and 1.0-2.0 times higher, respectively, than measured at the pristine control sites, respectively (Table 2).

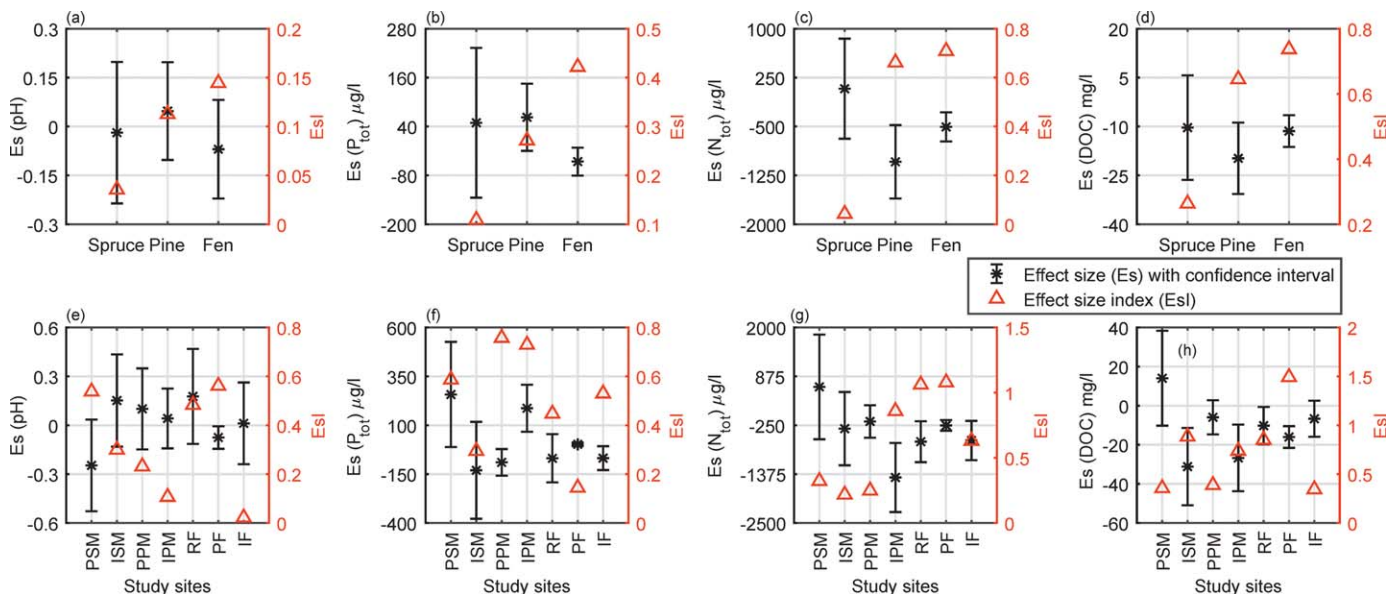


**Figure 3.** Trajectory of postrestoration change in mean (a) total phosphorus ( $P_{tot}$ ), (b) total nitrogen ( $N_{tot}$ ), (c) dissolved organic carbon (DOC), (d) pH, (e) electric conductivity (EC), and (f) SUVA grouped based on peatland classes and bars show standard error of mean. Where -1 represents drained condition, 1-6 represent postrestoration years, and shaded region represent mean values and standard error of mean for each parameter at pristine control sites except for pH where median and standard deviation shown.



**Figure 4.** Trajectory of postrestoration change in mean (a) total phosphorus ( $P_{tot}$ ), (b) total nitrogen ( $N_{tot}$ ), (c) dissolved organic carbon (DOC), (d) pH, (e) electric conductivity (EC), and (f) SUVA grouped based on trophic levels and bars show standard error of mean. Where -1 represents drained condition, 1–6 represent postrestoration years, and shaded region represent mean values and standard error of mean for each parameter at pristine control sites except for pH where median and standard deviation shown.

The highest  $P_{tot}$  levels were observed in the spruce mires and poor sites (Table 2). The mean  $P_{tot}$  generally increased (decreased only among rich fen groups) after restoration, but decreased with time at many sites (Table 3 and Figures 3b and 4b). This could be seen in the BACIPS design analysis, which produced positive  $Es_{P_{tot}}$  values for the spruce forest and pine mires, while fens showed negative  $Es_{P_{tot}}$  on average (Figure



**Figure 5.** Mean restoration effect size (Es) and effect size index (Esi) of (a, e) pH level and (b, f) total phosphorus ( $P_{tot}$ ), (c, g) total nitrogen ( $N_{tot}$ ), and (d, h) dissolved organic carbon (DOC) concentration in pore water for different peatland classes (Figures 5a–5d) and trophic levels (Figures 5e–5h) regardless of time after restoration (bars show 95% confidence interval of Es). PSM, poor spruce mires; ISM, intermediate spruce mires; PPM, poor pine mires; IPM, intermediate pine mires; RF, rich fens; PF, poor fens; and IF, intermediate fens.

5b). However, only the decline ( $EsP_{tot} = -46.2 \mu\text{g L}^{-1}$ ) in fens was statistically significant. In general, mean pore water nutrient concentrations were lowest in rich fens when the whole study period (drained and drained-restored) was considered. Under drained conditions, pine mires had the highest mean pore water  $N_{tot}$  and DOC, followed by spruce forest mires and fens. The DOC concentration in drained-restored conditions was highest in pine mires, followed by spruce forest mires and fens (Table 2).

Restoration gave a statistically significant decline in  $N_{tot}$  and DOC in pore water in pine mires and fens, but not in spruce forest mires when post restoration years aggregately considered. The largest restoration-induced pore water  $N_{tot}$  and DOC decline was observed for pine mires, followed by fen and spruce mires (Figures 5c and 5d). Postrestoration  $Es$  of DOC in pine mires, fens, and spruce forest mires was  $-19.8$ ,  $-11.4$ , and  $-10.4 \text{ mg L}^{-1}$ , respectively, which indicated that restoration had reduced the pore water DOC in all three types of peatlands. On average,  $N_{tot}$  also decreased in pine mires ( $Es = -1,041.8 \mu\text{g L}^{-1}$ ) and fens ( $Es = -506.1 \mu\text{g L}^{-1}$ ), while in spruce mires  $N_{tot}$  slightly increased on average after restoration ( $Es = 79.4 \mu\text{g L}^{-1}$ ; Figures 5c and 5d). In spite of the evident decrease in pore water  $N_{tot}$  and DOC after restoration, the concentrations remained significantly higher than at the pristine control sites (Table 3).

The results of the analysis for  $N_{tot}$  and DOC were more consistent than for  $P_{tot}$ . Restoration caused pore water  $N_{tot}$  and DOC to decrease (negative  $Es$ ) at all trophic levels and to increase only in poor spruce mires (PSM). The postrestoration  $N_{tot}$  decline in intermediate pine mires (IPF), rich fens (RF), intermediate fens (IF), and poor fens (PF) and the DOC decline in intermediate spruce mires (ISM), IPM, RF, and PF were statistically significant (large negative  $Es$ ; Figures 5f–5h).

### 3.4. Impact of Hydrology and Temperature on Pore Water Quality

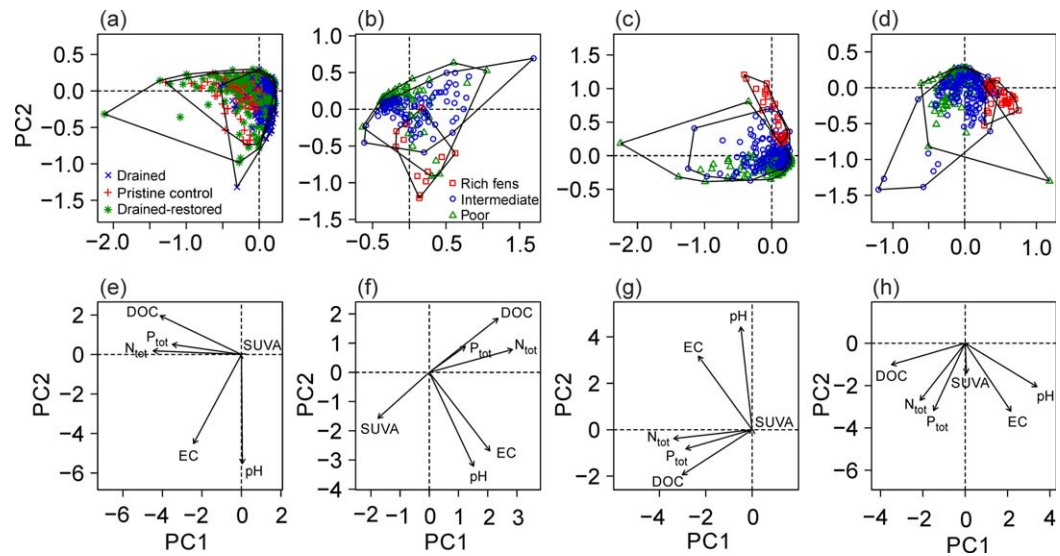
In the peatlands studied, warmer weather (higher  $T_{air}$ ) was linked to higher  $P_{tot}$  ( $r = 0.22\text{--}0.96$ ),  $N_{tot}$  ( $r = 0.27\text{--}0.75$ ), and DOC ( $r = 0.20\text{--}0.88$ ), whereas  $T_{soil}$  had an effect only on  $N_{tot}$  ( $r = 0.25\text{--}0.95$ ). The pore water concentrations and 14 day antecedent mean  $T_{air}$  showed the strongest correlation. In addition to this, under drained conditions, where the WT level was deeper at the study sites, the pore water  $N_{tot}$  and DOC increased as the WT level dropped ( $r$  of  $N_{tot} = 0.28\text{--}0.83$ ,  $r$  of DOC =  $0.20\text{--}0.88$ ) across different peatland classes and trophic levels as hypothesized. However, under drained-restored conditions, this was not seen, as the WT level was significantly raised and fluctuations were gentle. Furthermore, the analyses on all aggregated data further reaffirmed the  $N_{tot}$  and WT level correlation ( $r = 0.24\text{--}0.74$ ). When the success of hydrological restoration was considered, overrestored sites (inundated) showed the highest mean  $P_{tot}$ ,  $N_{tot}$ , and DOC and higher median pH, followed in sequence by well-restored and less well-restored sites (Table 3).

In the PCA and RF model analysis, in total two or three principal components (PCs), in different treatment PCAs (all data, drained, drained-restored, pristine control) explained 42–83% of the variance in pore water quality at the study sites (Table 4). Different trophic levels (rich, intermediate, and poor) had different chemical characteristics in all treatments (Figures 6b–6d). Typically,  $N_{tot}$ ,  $P_{tot}$ , and DOC correlated in the same

**Table 4**  
Summary of Principal Component Analysis (PCA) on Pore Water Quality for All Data, Drained, Drained-Restored, and Pristine Control Sites

	All data		Drained			Drained-restored		Pristine control		
	PC1	PC2	PC1	PC2	PC3	PC1	PC2	PC1	PC2	PC3
Eigenvalue	1.54	1.01	2.51	1.55	0.91	2.51	1.02	2.07	1.01	0.76
% Explained	0.26	0.17	0.42	0.26	0.15	0.42	0.17	0.34	0.17	0.13
Cumulative % explained	0.26	0.42	0.42	0.68	0.83	0.42	0.82	0.34	0.51	0.64
pH	<b>3.373</b>	-0.107	0.955	<b>-2.071</b>	0.224	<b>0.229</b>	0.174	<b>2.411</b>	0.342	0.087
EC	<b>2.543</b>	-0.011	<b>1.718</b>	-1.476	-0.340	<b>1.740</b>	0.012	<b>1.833</b>	0.793	-0.194
$P_{tot}$	<b>-0.272</b>	0.007	1.000	0.358	<b>2.093</b>	<b>2.188</b>	-0.001	-0.132	-0.639	<b>-1.382</b>
$N_{tot}$	-0.203	<b>0.216</b>	<b>2.153</b>	0.415	-0.257	<b>2.527</b>	-0.267	-0.744	1.052	<b>1.389</b>
SUVA	0.020	<b>3.557</b>	<b>-1.291</b>	-0.970	-0.174	0.011	<b>-2.800</b>	0.484	<b>-2.071</b>	1.034
DOC	<b>-1.230</b>	-0.294	<b>1.818</b>	1.106	-0.767	<b>2.341</b>	0.276	<b>-1.904</b>	0.303	-0.261

Note. The highest loadings for each component are shown in bold.

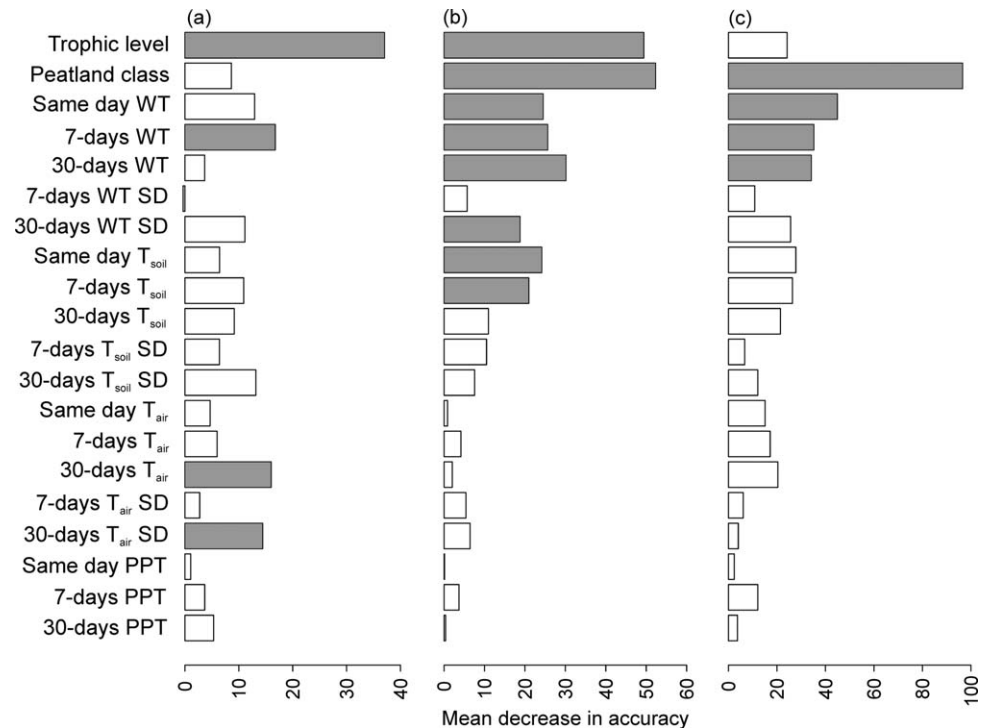


**Figure 6.** Principal component analysis of pore water quality for (a) all data, (b) drained, (c) drained-restored, and (d) pristine control conditions for (a) all conditions and (b–d) for different peatland trophic levels (rich, intermediate, and poor). Vector length indicates the explanatory power of the corresponding variable.

direction, but were determined by the treatment applied. Rich fens formed a clear group in all treatments and were separated along the pH and EC gradients (Figures 6b–6d). Treatment situations (drained and drained-restored) and the intermediate and poor sites formed separate groups with slight overlapping.

**3.5. Random Forest Model on Predictors of Water Quality Variation**

The most important variables in the preliminary RF model including all predictor variables showed some differences between treatments (Figure 7). For analysis of drained data, the most important variables were



**Figure 7.** Random Forest model results for variable importance with (a) drained conditions, (b) drained-restored conditions, and (c) pristine control sites. This was used to predict patterns in pore water quality. Gray bars denote the variables selected for the final model, SD is standard deviation, PPT is rainfall,  $T_{air}$  is air temperature, and  $T_{soil}$  is soil temperature.

trophic level, 7 days WT, 30 days  $T_{air}$ , and 30 days  $T_{air}$  SD (Figure 7a). For drained-restored data, the most important variables were trophic level, peatland class, same day WT, 7 days WT, 30 days WT, 30 days WT SD, same day  $T_{soil}$  and 7 days  $T_{soil}$  (Figure 7b) while for the pristine control data they were peatland class, same day WT, 7 days WT and 30 days WT (Figure 7c). The final best models suggested that the classification accuracy was 52%, 62%, and 53%, for pore water quality parameters of drained, drained-restored, and pristine control, respectively. Restoration brought parameter values closer to pristine conditions.

#### 4. Discussion

This study of pore water quality provided new insights into the impact of restoration on peatland ecosystems. Pore water quality is important to vegetation, which in turn forms one major ecosystem structure, affects biogeochemical cycles through effects on e.g., decomposition and therefore can indicate development of ecosystem functions. Pore water also indicates the potential risk of nutrient flushing to watercourses. In this study, the aggregated mean pore water  $P_{tot}$ ,  $N_{tot}$ , and DOC in different peatland classes and trophic levels of drained sites were several-fold higher than those observed at their respective pristine control sites. This highlights the long-term impacts of drainage on pore water concentrations in drained peatland forestry areas. In general, the results in this study showed a decrease in  $P_{tot}$ ,  $N_{tot}$ , and DOC following restoration measures. We found that  $N_{tot}$  and DOC in peat pore water decreased already within a few years following restoration (Figures 2b, 2c, 3b, 3c, 4b, and 4c and Table 3) and we consider that these findings on pore water quality indicate that nutrient runoff to downstream water courses can also be reduced. The postrestoration pore water quality recovery for the first 3–4 years were very reliable since there were enough number of sites with postrestoration data. However, the postrestoration recovery trajectory analysis of the pore water quality after 5 and 6 years become less reliable since there were fewer sites with postrestoration data (Figures 2–4).

The  $P_{tot}$  changes after restoration were not so dramatic in pore water. However, pore water  $P_{tot}$  increased in the first year postrestoration, but was observed to decline with time since restoration (Table 3 and Figures 2a, 3a, and 4a). A previous study reported an increase in  $P_{tot}$  in runoff water for 5 years after restoration, but thereafter it started to decrease and 10 years after restoration was close to the concentration at pristine control sites (Haapalehto et al., 2014). The main peat matrix restoration area (between ditches) is typically assumed to be the main leaching pool for potential  $P_{tot}$  exports. However, taking into account the results of this study, the reported  $P_{tot}$  rise in runoff water several years after restoration may be attributable to some other sources than the main peat matrix. These potential sources are most likely to be the more disturbed areas along the filled/dammed drainage ditches, which could result in long-lasting leaching of nutrients from runoff water, as discussed in Haapalehto et al. (2014). Hence, we recommend that disturbed ditch areas be built to mimic conditions in the undisturbed peatland main area, but unfortunately this has not been considered at all in previous and current restoration practices. For example, we suggest (1) promoting *Sphagnum* moss cover on active restoration ditch areas by planting moss fragments or just making it a practice to shovel surface peat with plant propagules from surrounding peat to restoration ditch areas and (2) directing the water flow from blocked ditches to interditch areas, so that unwanted nutrient and DOC leaching immediately after restoration can be minimized.

##### 4.1. Water Table and Temperature Effects on Pore Water Quality

In understanding the effects of WT and temperature on peatland restoration, knowledge of biogeochemical dynamics is critical, in particular because these driving factors are expected to be affected by climate change. We found clear connections between restoration changes in hydrology and pore water quality. The WT level, its fluctuations, and antecedent conditions were observed to have strong impacts on pore water quality. In particular, same day, weekly (7 days) and monthly term WT level (30 days) and standard deviation of WT fluctuation during 30 days were important variables in RF models of drained-restored and pristine control sites (Figures 7b and 7c), explaining variations in pore water quality. WT level affects oxidation and redox conditions in the peat matrix, and thus it can be assumed to be one primary physicochemical factor behind variations in nutrient and DOC concentrations. While the importance of WT has been reported previously (Höll et al., 2009; Strack et al., 2008; Wallage et al., 2006), our study is the first to show the general effect of WT conditions on pore water quality using high temporal resolution data from various areas representative of boreal peatlands. The results of this study demonstrated the importance of 7 days WT for pore water quality under drained conditions. This indicates that the role of WT fluctuations is significant,

especially under drained conditions but is also important after restoration. Thus, the stability of WT level after restoration needs to be ensured in successful restoration to promote stabilization of the whole peatland system.

It is well known that drainage (WT position changes and fluctuation) increases soil aeration, leading to higher nutrient mineralization (Bridgham et al., 1998; Cabrera, 1993; Kalbitz et al., 2002; Ramchunder et al., 2009; Worrall et al., 2007), which has been linked to increased N availability (Paul & Tu, 1965). Responses in DOC and N concentrations to WT levels and fluctuations can be sensitive, e.g., lowering the WT in a boreal-rich fen by only 3 cm caused a 21.8% increase in DOC production (Hribljan et al., 2014; Kane et al., 2010). In drained peatlands, peat aeration promotes microbial processes and solubility and increases peat mineralization, resulting in a rise in DOC (Gough et al., 2016) and the organic-bound N pool. When nutrients and DOC are soluble, there is also a risk of nutrients being leached to downstream waters during rainfall. Indeed, peatland restoration has been carried out in many areas with the aim of reducing the nutrient load to downstream water bodies (Shenker et al., 2005; Venterink et al., 2002; Wallage et al., 2006). Furthermore, it has been reported that a rise in DOC in surface waters of glaciated landscapes could be due to a decline in atmospheric sulfur deposition (Monteith et al., 2007), which changes soil biogeochemical conditions. On the other hand, nitrogen deposition in Finland is low (Dirnböck et al., 2014) and it is unlikely to have a significant effect on our dataset that would significantly mask the effects of drainage and restoration. Moreover, a study on the relationships between peat soil DOC concentration and changes in atmospheric deposition in the United Kingdom reported no significant correlation (Worrall et al., 2008).

Phosphorus concentrations in pore water were rather high at many sites immediately after restoration. The results from our study revealed increased  $P_{\text{tot}}$ , especially in spruce and pine mires, after restoration (Figure 5b), which agrees with previous findings (Koskinen et al., 2017). This is probably caused by a higher WT rise than in fens after restoration and associated changes in conditions in the peat matrix and could potentially lead to a risk of P leaching to downstream waters during high rainfall events, as suggested by Koskinen et al. (2017). Kaila et al. (2016) also observed increased P export from Fe-rich peat after restoration. Both treatments had significantly higher  $P_{\text{tot}}$  concentrations than their pristine control counterparts (Table 3). This could be due to varying soil moisture conditions resulted from transitioning from dry (before restoration) to wet (after restoration), and vice versa, causing increased pore water  $P_{\text{tot}}$  in the drained and/or drained-restored sites (Martin et al., 1997; Rupp et al., 2004). Another possible reason for higher  $P_{\text{tot}}$  in drained and/or drained-restored sites could be fertilization (e.g., with wood ash) at sites drained for forestry. However, there is no detailed information available about possible fertilizer application at our sites. Typically, NPK-fertilizer is used for a few years after drainage as routine practice in Finnish peatland forestry areas, but it is difficult to say if it has any impact many decades later. The typical rise in nutrient concentrations after restoration was short lived, however, giving hope that harmful impacts are limited and predictable, lasting only a few years. In any case, our results stress that stabilization of nutrient levels in drained-restored peatland sites is likely to take decades until the natural water quality of the pristine control counterparts is recovered.

Our analysis showed existence a threat from rising temperature, as air temperature (30 days  $T_{\text{air}}$  and 30 days  $T_{\text{air}}$  SD) were among the most important variables explaining pore water DOC in drained conditions. Under drained-restored conditions, sites behaved more similarly to pristine control sites and soil temperature (same day  $T_{\text{soil}}$  and 7 day  $T_{\text{soil}}$ ) were among the most important explanatory variables. In one mechanism, carbon storage in peatlands is regulated by the enzyme phenol oxidase and a rise in temperature increases enzymatic activity, which then facilitates release of DOC in the soil matrix (Freeman et al., 2001; Reddy & DeLaune, 2008). In northern latitudes with low temperature regimes, organic matter decomposition is more sensitive to changes in temperature than in warmer regions (Vanhala et al., 2008). Under projected global warming, this is likely to increase DOC and greenhouse gas release in the future, especially from drained peatlands. Drained sites appear to be more sensitive to changes in air temperature than their pristine control counterparts and drained-restored sites, which means that restoration may act to buffer effects of predicted temperature rise due to climate change, thus potentially affecting DOC and  $N_{\text{tot}}$  concentrations in particular, e.g., via effects on decomposition.

#### 4.2. Hydrochemical Changes Differ Between Peatland Classes

We found strong dependence between peatland class, trophic level, hydrology (e.g., WT fluctuation), and pore water quality (Figure 7). In the RF model, vegetation gradient (trophic level), peatland class, and WT

were the most important predictor parameters of pore water quality. The data included a wide variety of peatland vegetation, varying from wet, open fens to closed peatland forest vegetation of spruce mires, and from near-ombrotrophic communities of acidic poor fens to typical rich fen vegetation. Considering the wide range of variation, it is not surprising that trophic levels and peatland class governed the analyses as explanatory variables for water quality variations. The hydrochemical response to drainage and restoration varied between different peatland types. The mean WT response to restoration was highest in spruce mires, moderate in pine mires and lowest in fens, as reported in more detail in a previous hydrological study at the same sites (Menberu et al., 2016). However, restoration had the largest mean impact on pore water DOC and  $N_{\text{tot}}$  in pine mires, followed by fens and spruce mires (Figures 5c and 5d) regardless of time after restoration. Spruce mires generally have thinner peat layers (often <100 cm), and a more humified peat matrix than fens and pine mires (Seppä, 2002).

Rich fens are characterized by high mineral cation but low nutrient levels, and they are rich in vegetation that requires a low-productivity calcareous habitat (e.g., rare and endangered vascular plants and bryophytes; Sjörs, 1950). In this study, rich fens showed the lowest mean pore water  $P_{\text{tot}}$ , DOC, and  $N_{\text{tot}}$  before and after restoration, while the highest concentrations were seen at intermediate and poor sites. Lower DOC concentrations in rich fens are almost certainly attributable to the dilution of high-DOC water coming directly from the peat with low-DOC water entering the fen from adjacent mineral soil or groundwater. Another reason is that nutrient availability is controlled by pH, which in turn is mainly controlled by flow patterns of minerogenic waters within peatland areas and from surrounding catchments. In organic soils, a pH range of 5.0–6.0 generally results in the highest availability of P and N to plants (Lucas & Davis, 1961). Sites in this study categorized as poor and intermediate were more acidic (median pH range 4.0–4.6) and rich fens were very close to neutral (median pH range 6.2–6.6) both before and after restoration (Table 2).

Water movement in the peat matrix of poor and intermediate sites with *Sphagnum* peat is slow, allowing DOC and poorly available organically bound nutrients to accumulate with longer residence time in the pore water than in rich fens. Rich fens typically have better water movement in peat and well-connected upper and surrounding catchments, which provides groundwater input and additional nutrients to the mire (Sjörs, 1950) and inevitably causes; e.g., dilution of high-DOC water from the peat and incoming low-DOC water. This creates suitable conditions for peatland plant species to utilize available nutrients during the growing season and allows nutrient storage in vegetation biomass. Hence, higher movement of water in the peat matrix in rich fens could potentially allow leaching of nutrients in runoff water, leaving behind fewer nutrients in the pore water. A study of water movement in 53 mires in Canada found increased pH levels and oxygen concentrations with faster rates of water movement in moderately rich fens (Sparling, 1966). Rich fen vegetation needs to have a good water flow rate in order to create the required high mineral cation concentrations and alkalinity (Tahvanainen et al., 2002). In this study, higher pH levels were seen in vegetation-rich fens that showed the presence of better water movement and oxygen concentration than at poor and intermediate sites. During restoration planning, possible water flow paths from surrounding catchments should also be taken into consideration, as conservation of waterways is essential in peatland ecosystem restoration.

## 5. Conclusions

Various peatland types (in total 43 sites), high quality pore water quality data, high temporal resolution WT data, and a replicated Before-After-Control-Impact Paired Series (BACIPS) approach were used to assess peatland restoration success. Restoration effect size (Es) was largest in pine mires, followed by fens and spruce mires. With respect to pore water DOC and  $N_{\text{tot}}$ , the BACIPS design analysis revealed that spruce mires were the least affected by drainage and restoration, and showed only a slight impact before and after restoration compared with pine mires and fens. In general, variations in pore water quality in the whole dataset were great and were mainly related to vegetation gradients and peatland classes. Some treatment-related variation was identified: drained sites had higher  $P_{\text{tot}}$ , N, and DOC than pristine control sites and, after a very short postrestoration rise, concentrations declined mainly to a lower level than at drained sites. Restoration recovery time had a significant effect on pore water quality. Pore water concentrations greatly increased during the first years after restoration, mainly decreased after a few years, but have not yet fully stabilized even after 6 years. Hence, it is recommended to allow a longer monitoring period when planning monitoring of the impacts of peatland restoration measures. Local hydroclimate, peatland class, and trophic

level were observed to have an effect on pore water DOC and nutrients. Water table level and temperature conditions (air and soil), their fluctuations, and antecedent conditions were also observed to have an impact on pore water quality. The WT levels (same day, 7 days, and 30 days) and the standard deviation of WT fluctuations during 30 days were especially important variables explaining variations in pore water quality. Besides hydroclimate conditions, peatland class (mainly acidity level) also played a significant role in pore water quality. Hydrologically overrestored sites (inundated) had significantly higher concentrations of nutrients and DOC than well-restored and less well-restored sites, indicating the importance of achieving a hydrological regime typical of peatlands when planning peatland restoration operations. In this pore water study, unwanted water quality changes did not last as long as reported in some previous runoff studies. This indicates that negative impacts on runoff water quality after restoration are most probably caused by processes in the disturbed areas along blocked ditches and not necessarily in the main peat matrix itself. Hence, identifying and dealing with such hotspots is important in future peatland restoration planning.

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