*Research Article*

# DOC and $CO_2$-C Releases from Pristine and Drained Peat Soils in Response to Water Table Fluctuations: A Mesocosm Experiment

**Merjo P. P. Laine,[1] Rauni Strömmer,[1] and Lauri Arvola[2]**

[1] *Department of Environmental Sciences, University of Helsinki, Niemenkatu 73, 15140 Lahti, Finland*
[2] *Lammi Biological Station, University of Helsinki, Pääjärventie 320, 16900 Lammi, Finland*

Correspondence should be addressed to Merjo P. P. Laine; merjo.laine@helsinki.fi

Hydrological conditions are considered to be among the main drivers influencing the export of dissolved organic carbon (DOC) from terrestrial to aquatic ecosystems, and hydrology is likely to alter due to climate change. We built a mesocosm experiment by using peat profiles from a pristine and from a drained (drained in 1978) peatland. A several-week-long low water table period followed by a high water table period, that is, a setting mimicking drought followed by flood, released relatively more DOC from pristine peat than from drained peat. From pristine peat profiles DOC was released into soil water in such quantities that the concentration of DOC remained stable despite dilution caused by added spring water to the mesocosms. In drained peat the DOC concentrations decreased during the high water table period indicating stronger dilution effect in comparison to pristine peat. At the landscape level DOC load from a drained peatland to the recipient water body may, however, increase during flooding because of high water runoff out of the peatland containing high DOC concentrations relative to the forest and agricultural areas. During the high water table period neither peat type nor water table had any clear impact on carbon dioxide ($CO_2$-C) fluxes.

## 1. Introduction

Northern peatlands comprise about one-third of the world's soil organic carbon (C) pool [1]. Therefore, their important role in the global C cycle should not be underestimated. It is important to understand the decomposition and mineralization processes of organic matter and their control in peatlands, as well as factors affecting the discharge of DOC and other substances from them. This is especially crucial in the era of ongoing climate change that affects the position of the water table and discharge in boreal and subarctic areas [2]. Catchment level knowledge is essential, as the fluxes of organic matter and nutrients from terrestrial areas end up in lakes and rivers and eventually in seas and oceans.

As the decomposition and leaching of organic matter from peatlands greatly affect DOC fluxes entering water systems [3, 4], any major changes in hydrology on the peatlands and/or in the composition and properties of the peat itself modify the loading of C from these ecosystems to the recipient water bodies. This is especially important in the boreal areas where the projected change in climate seems to be considerable [5]. Although there is large storage of organic matter in peatlands, DOC concentrations and export are not necessarily convergent. An increase in export can be a consequence of increased runoff without a change in DOC concentrations, while, on the other hand, increased concentrations may occur as a result of a change in decomposition processes and production of DOC or of decreased retention of DOC in peat without changes in the hydrology [4]. Even if the export is not increased, there might be changes in the decomposition and consumption processes. If consumption outweighs or is in balance with production or the conditions are dry enough, the altered production may not be seen in DOC export at least when viewed over a short period of time.

In vast areas of Europe and North America, increasing DOC concentrations in surface waters are reported [6–11].

However, factors controlling these changes remain largely equivocal. Several hypotheses have been proposed to explain the phenomenon, including an inverse relationship between reduced acidity of the environment and DOC concentrations in surface waters [12, 13], changes in ionic strength of the soil solution [14], rising temperatures [15], changes in hydrology and biological activity [16], elevated $CO_2$-C levels [17], and combined effects of climate-related factors [9]. Rising temperatures increase both the production and microbial consumption of DOC [2]. Extreme events, as well as mineral soil quality, may also substantially affect the quantity and quality of DOC that leach into rivers [18, 19].

Peatlands and other organic soils supply most of the DOC entering boreal rivers and lakes [3, 20], and the leaching of DOC from peatlands depends on both moisture [2] and temperature [15, 21]. The combination of warming and drying is an important factor affecting the concentration of organic matter since microbial decomposition processes are expected to enhance as a consequence of improved oxygen conditions and higher temperatures [22]. Thus, any biological or physical factor that enhances decomposition may promote high DOC concentrations, although Kalbitz et al. [23] stated that variation in hydrology in organic rich soil horizons may be more important than biotic factors.

It has been predicted that precipitation will increase by 5–40% by the 2080s in Northern Europe with major changes in seasonal patterns [24] as well as in the intensity of episodic rain events [25]. Such changes are likely to affect leaching of different substances from catchment areas and the seasonality of the phenomena, since any changes in drought and rewetting periods influence decomposition and mineralization process and thus quantity and quality of DOC [26–28]. However, it is important to consider that along with changes in peatland hydrology, also $CO_2$-C or methane ($CH_4$-C) fluxes, that is, release of C to the air, may change and affect the amount of remaining DOC in the peat.

In order to analyse the significance of hydrology in controlling the DOC and $CO_2$-C fluxes in pristine and drained peatlands, a mesocosm experiment was carried out under controlled greenhouse conditions. Special emphasis was placed on successive low and high water table events, which are likely to change in frequency and timing due to climate change. In addition to DOC and $CO_2$-C fluxes, water colour and pH were analysed. The results of the release of dissolved organic nitrogen (DON), ammonium ($NH_4^+$-N), and nitrite + nitrate ($NO_2^-$ + $NO_3^-$-N) in the same experimental design are reported in Laine et al. [29]. We hypothesized that (a) a long low water table period, which mimics a period with low precipitation, enhances organic matter decomposition and (b) the following rewetting will increase DOC discharge.

## 2. Materials and Methods

### 2.1. Site Description.
This mesocosm experiment represents extreme but still realistic precipitation conditions. Four experimental mesocosm groups of the study included control (Ctrl) and fluctuating (Fluc) water table treatments with peat profiles from a pristine (Pr) peatland and a drained (Dr) peatland that was drained in 1978. They both originated from the same peatland complex called Laaviosuo in Southern Finland. The peatland types were classified according to Eurola et al. [30], and peat decomposition rates were classified according to von Post scale, which includes ten levels of peat decomposition stages (H1–H10) [31], H10 being the most decomposed one. The pristine area (61° 01′ 48″ N, 25° 01′ 38″ E, 151 m above the sea level) was classified as oligotrophic *Eriophorum vaginatum* pine bog, and the peat was composed mainly of *Carex* with a decomposition rate of H4 (i.e., peat released murky water, and after squeezing it kept its shape) at 30 cm and 50 cm depths. The peat cores of the pristine area were collected on June 2, 2009 (Table 1), from treeless low tussock places, which were dominated by *Eriophorum vaginatum*, *Vaccinium oxycoccos*, and *Carex lasiocarpa*.

The drained part of the complex (61° 02′ 05″ N, 25° 00′ 37″ E, 149 m above the sea level, drained in 1978) was classified as peated dwarf shrub heath [30]. The area is presently covered by 5–10 metres tall Scots pines (*Pinus sylvestris*). The peat is composed mainly of *Sphagnum*. The decomposition rate at 30 and 50 cm depths was H5; that is, peat released very murky water, and unlike H4 peat, H5 peat was released a little bit through fingers when squeezed, and after squeezing the peat left in hand did not keep its shape very well [31]. The drained area peat cores were taken on June 2-3, 2009 (Table 1), from places of treeless low tussocks, which were dominated by *Eriophorum vaginatum* and Bryopsida mosses. In rainy period, there appears surface outflow in the area, indicating that the groundwater reaches the soil surface or is very close to it. However, in dry summers there is hardly any surface outflow, so the groundwater lies tens of centimetres below the soil surface.

Hourly air temperatures were recorded in a meteorological station of the Finnish Meteorological Institute (Pappila, Hämeenlinna), located at Lammi Biological Station (LBS), which also was the location of the mesocosms (see Section 2.2). During the different sampling phases the average air temperature varied from 0.6 to 15.3°C, being the highest at the beginning and the lowest at the end of the mesocosm experiment (see details in Section 3). The mesocosms stayed unfrozen during the whole experiment.

### 2.2. Mesocosm Settings.
Peat profiles were built by digging large pieces of peatland soil (dug vertically in two parts), which were then carved smaller to fit the containers. The pieces were then placed into the containers in the order they had originally been in peatlands, and the vegetation was left intact (stayed alive for the whole experiment). The experiment was then performed in an unheated greenhouse at LBS.

In the experiment there were 20 peat profiles placed in white painted plastic containers (Ø 24 cm, height 60 cm; Figure 1). Water samples were taken through small holes, blocked with rubber plugs, at different depths as indicated in Figure 1. In order to follow the water table, also a transparent plastic tube (Ø 10 cm) was installed from bottom to top alongside the outer wall of each container.

TABLE 1: Timetable of the experiment. Numbers in the sampling codes refer to calendar weeks.

| | Date (2009) | Calendar week | Water samplings (W) | | | Gas samplings (G) | | |
|---|---|---|---|---|---|---|---|---|
| | | | Date (2009) | Calendar week | Sampling code | Date (2009) | Calendar week | Sampling code |
| Building peat profiles | Jun. 2-Jun. 3 | 23 | | | | | | |
| Adjusting the water table to control levels | Jun. 3–Jun. 10 | | | | | | | |
| Low water table period (L) | Jun. 11–Sep. 20 | | Sep. 11 | 37 | WL(37) | Aug. 8 | 32 | GL(32) |
| | | | | | | Aug. 18 | 34 | GL(34) |
| | | | | | | Sep. 1 | 36 | GL(36) |
| | | | | | | Sep. 8th | 37 | GL(37) |
| Starting the water additions | Sep. 21 | 39 | | | | | | |
| High water table period (H) | Sep. 21–Oct. 30 | | Oct. 2 | 40 | WH(40) | Sep. 29 | 40 | GH(40) |
| | | | Oct. 16 | 42 | WH(42) | Oct. 13 | 42 | GH(42) |
| | | | Oct. 23 | 43 | WH(43) | Oct. 19 | 43 | GH(43) |
| | | | Oct. 30 | 44 | WH(44) | | | |

The mesocosms within each peat type were randomized and divided into two treatments, control (Ctrl) and fluctuating water table (Fluc), which differed in their temporal-magnitude variation of water table level. There were four mesocosm groups altogether, which were pristine peat profiles with control conditions (PrCtrl), pristine peat profiles with fluctuating water table (PrFluc), drained peat profiles with control conditions (DrCtrl), and drained peat profiles with fluctuating water table (DrFluc), five mesocosms of each group. Except for the water table manipulation, the external conditions were identical for all mesocosms.

Water table in the peatland potholes was measured on the next day after digging the peat cores. This was considered as a control hydrologic condition. Based on those measurements, on June 3–10, 2009 (Table 1), the water table levels were adjusted to –0 cm and –20 cm vertically down from the soil surface in pristine and drained mesocosms, respectively (Figure 1). In the control treatments, the mesocosm water table was kept stable at these initial levels (i.e., at –0 and at –20 cm) through the experiment. In order to achieve this, water was added to the mesocosms on regular basis. For water additions, spring water from a groundwater spring (Löytynlähde, 61° 02′ 53″ N, 24° 58′ 32″ E, that is, close to Laaviosuo) was used because of its stable chemical composition and because natural peatlands receive groundwater as well.

*2.3. Manipulations and Samplings.* Two successive water table manipulations, indicating low and high water tables in nature, were performed for Fluc mesocosms. During the low water table period (June 11–September 20, 2009; Table 1) only a small amount of water was added to the mesocosms in order to keep the plants alive. At the beginning of this period (June 11–June 26, 2009), 500 mL and 400 mL of soil water were released from the bottommost hole from the pristine and from the drained mesocosms, respectively. Water was lost
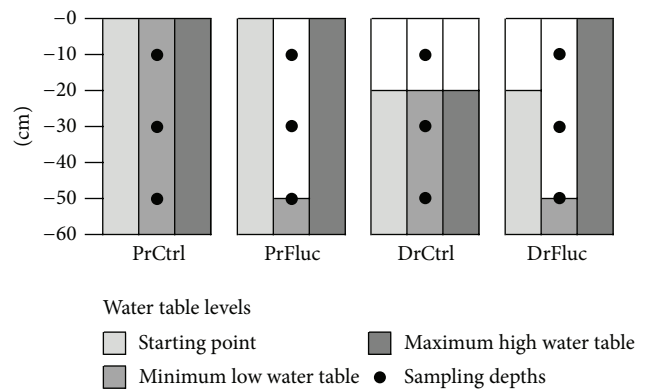


FIGURE 1: Schematic presentation of the mesocosms. $N$ = 5 for each experimental group. Pr: pristine; Dr: drained; Ctrl: control; Fluc: fluctuating water table.

from the mesocosms also by evapotranspiration and later on in water samplings.

The high water table period lasted from September 21 to October 30, 2009 (Table 1). At the beginning of this period, two litres of water was added three times a week to the Fluc mesocosms, until they were saturated with water (Figure 1). After reaching the water saturation, water was added occasionally to maintain the high water table. Magnitude of the suitable water additions was estimated on the basis of the earlier precipitation data of the meteorological station at LBS. In order to avoid disturbance, five days without adding water preceded all water samplings. As water table determines the aerobic/anaerobic conditions of the soil, target water levels were employed instead of standard water volume additions to the mesocosms, and, as a consequence, there was slight variation in the total amounts of added water within each experimental group. The added water volumes, transformed

TABLE 2: Spring water volumes (transformed per m$^2$) added to each experimental group during the low water table (L) and high water table (H) periods within the five-month experiment.

| Experimental group | Period | Added water (L m$^{-2}$) | | $n$ |
| | | Mean | SE | |
| --- | --- | --- | --- | --- |
| PrCtrl | L | 192 | 18 | 5 |
| | H | 46 | 2 | 5 |
| PrFluc | L | 55 | 0 | 5 |
| | H | 263 | 28 | 5 |
| DrCtrl | L | 250 | 35 | 5 |
| | H | 51 | 4 | 5 |
| DrFluc | L | 55 | 0 | 5 |
| | H | 323 | 22 | 5 |

Pr: pristine, Dr: drained, Ctrl: control, and Fluc: fluctuating water table.

per m$^2$ (itemised for low and high water table periods for each experimental group), are presented in Table 2.

The two water table periods included altogether five water sampling phases: WL(37) (i.e., "water sampling (W)," "low water table (L)" (calendar week)) WH(40), WH(42), WH(43), and WH(44) (H meaning "high water table"). Timetable of these sampling phases is presented in Table 1. The codes of low and high water table periods are used also when Ctrl mesocosms are considered in order to indicate the timing, despite the actual stable water table level in the Ctrl mesocosms.

From the water samples, DOC, pH, and water colour were analysed. DOC samples were taken through the container holes (Figure 1) using 0.15 $\mu$m porous lysimeters (Eijkelkamp Agrisearch Equipment 192121, Rhizon soil moisture sampler, type MOM). pH samples were taken by syringes, and the samples were left unfiltered. Water taken from the three sampling depths (Figure 1) was pooled for a composite sample. The WL(37) sample volume was not enough for all water analyses. Laine et al. [29] analysed also DON, NH$_4^+$-N, and NO$_2^-$ + NO$_3^-$-N from the same water samples as DOC and water colour of this study.

CO$_2$-C and CH$_4$-C samples were taken from both the Ctrl and Fluc mesocosms. Gas samplings are indicated as G (gas sampling), L/H (low/high water table), and calendar week in brackets. The timetable of the gas samplings is presented in Table 1. The samples were taken by placing a gas chamber with a volume of 10.2 dm$^3$ on top of the mesocosm container and by sucking with a syringe 30 mL gas samples into vacuumed gas vials at times of 2, 7, 12, 17, and 22 minutes after closing the chamber.

*2.4. Laboratory Analyses.* DOC concentrations, water colour, and pH were measured from water samples using standard laboratory protocols at Lammi Biological Station. DOC was analysed by using a standard method SFS-EN 1484 (Shimadzu TOC 5000A analyzer). pH was measured with an Orion pH meter and water colour with a Shimadzu UV Spectrophotometer UV-1800. Colour was analysed by photometrically measured water absorbance at 420 nm wavelength.

The absorbance readings were calibrated against platinum-cobalt standards. DOC concentration and pH of the spring water used for water additions were analysed once in 2009 and in 2011. DOC and pH of the pothole water in peatlands, where the peat profiles were taken from, were also analysed.

CO$_2$-C and CH$_4$-C flux analyses were performed with a gas chromatograph (Agilent 6890N GC, TCD detector for CO$_2$-C, and FID detector for CH$_4$-C) [32]. The flux result (g m$^{-2}$ 24 h$^{-1}$) was accepted when the coefficient of determination was $\geq$0.95 in a time series of 20 minutes. In a few cases, one or two CO$_2$-C measurements were discarded, but if more samples failed, the whole flux result was discarded. Empty spaces between the peat surface and the edge of the containers (max 8 cm) were taken into account in the flux calculations (added to the gas chamber volume). Majority of the CH$_4$-C analyses failed.

*2.5. Statistical Analyses.* Differences between the experimental groups (PrCtrl, PrFluc, DrCtrl, and DrFluc) and between phases and interactions between the groups and phases on DOC, DOC/DON ratios, and pH during the phases WH(40–44), and CO$_2$-C fluxes separately for phases GL(32–37) and phases GH(40–43), were analysed by using SAS 9.2./Proc mixed with repeated statement method [33]. DON data was the same as in Laine et al. [29]. In "Proc mixed" method, different model covariance structures are tested in order to find the best model fit. As a result, AIC (Akaike information criterion) values with those different covariance structures are given in the program. For the final analysis, the model with the lowest AIC value was used. The chosen covariance structures were unstructured in analysing DOC and pH, autoregressive in analysing DOC/DON ratios, heterogeneous compound symmetry in analysing CO$_2$-C fluxes for phases GL(32–37), and heterogeneous autoregressive in analysing CO$_2$-C fluxes for phases GH(40–43). Contrasts between the experimental groups (PrCtrl versus DrCtrl, PrFluc versus DrFluc, PrCtrl versus PrFluc, and DrCtrl versus DrFluc) were tested when the experimental group effect in the model, explained above, was significant. Phase WL(37) was not included in any of the statistical tests presented above. pH values were converted to H$^+$ concentrations (mol H$_3$O$^+$ L$^{-1}$) before the statistical analyses.

Based on the interaction results, we considered testing the different phases separately for DOC and pH. Interactions become significant when the measured values of the replicates within each independent variable (experimental group) are at about the same level at the starting point (small standard error (SE)), and the change in the measured value within time is similar in all experimental groups. This was the case in our experiment with DOC and pH in general (see Figures 2 and 3). This indicates that the replicates were homogeneous, and therefore there was no reason to test DOC concentrations and pH separately for each phase.

The dependence of added spring water volumes on $\delta$ DOC (change in DOC concentration between phases) along consecutive phases WL(37)–WH(40), WH(40–42), WH(42–43), and WH(43–44) was also tested, as well as the dependence of DOC on water colour (including phases WH(40–44)). These analyses were performed by regression analyses
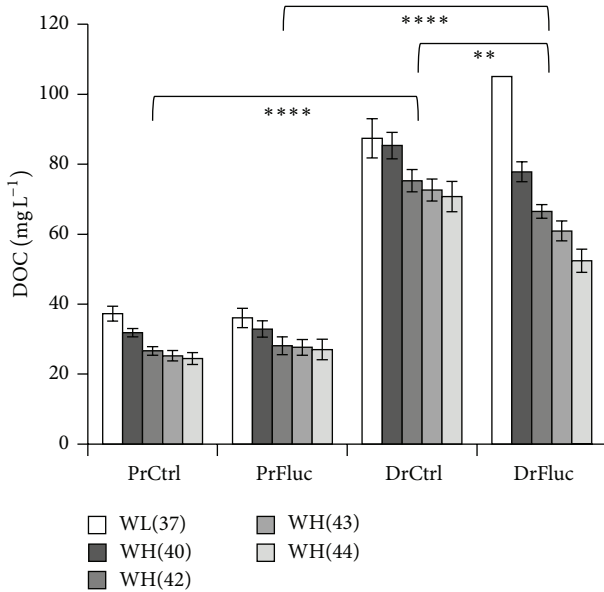
FIGURE 2: Mean (±SE) concentrations of DOC in different experimental groups at phase WL(37) and phases WH(40–44). $N = 5$ for each experimental group and each phase except for DrFluc at phase WL(37), where $n = 1$. For statistical tests only phases WH(40–44) were included. Significant differences between the experiment groups are indicated with asterisks ([**]$P < 0.01$; [****]$P < 0.0001$). W: water sampling; L: low water table; H: high water table; (xx): calendar week number. Pr: pristine; Dr: drained; Ctrl: control; Fluc: fluctuating water table.
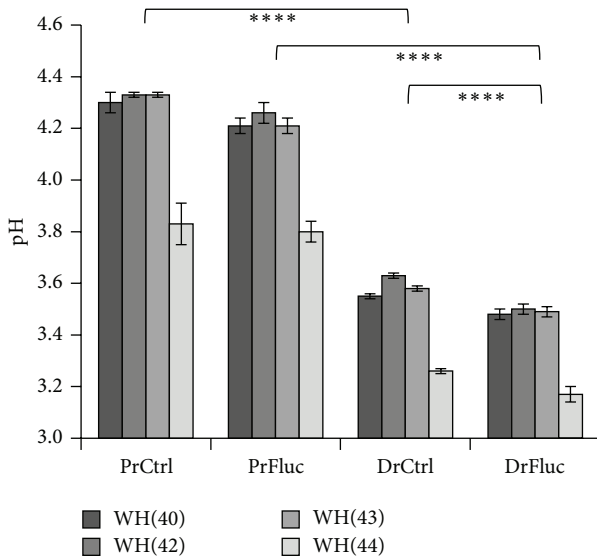


FIGURE 3: Mean (±SE) soil water pH in different experimental groups at different phases of the study. $N = 5$ for each experimental group and each phase. pH values were converted to $H^+$ concentrations (mol $H_3O^+ L^{-1}$) before the statistical analysis. Significant differences between the experiment groups are indicated with asterisks ([****]$P < 0.0001$). W: water sampling; H: high water table; (xx): calendar week number. Pr: pristine; Dr: drained; Ctrl: control; Fluc: fluctuating water table.

separately for each experimental group in IBM SPSS Statistics 21 [34].

## 3. Results

*3.1. DOC Concentrations in the Mesocosm Water.* Compared to the spring water, which was used for water additions to the mesocosms, DOC concentrations in mesocosm soil waters were 10 to 50 times higher, indicating that substantial amounts of DOC were released from the peat. DOC concentrations were 1.9–2.9 times higher in the drained peat (Dr) mesocosms than in the pristine peat (Pr) mesocosms (Figure 2). In the Ctrl mesocosms, the average DOC concentrations were 2.3–2.9 times higher in Dr than in Pr mesocosms at phases WL(37) and WH(40–44) (Figure 2). This was similar to the difference found between pristine and drained peatlands, from where the peat was collected, as DOC concentration was approximately 3 times higher in drained than in pristine peatland pothole water samples. At the end of the low water table period (WL(37)), DOC concentrations in PrCtrl and PrFluc mesocosms were at about the same level (Figure 2). In DrFluc mesocosms, we could only take one sample at this time.

During phases WH(40–44), that is, at the high water table period, DOC concentrations differed between the experimental groups (Num DF = 3; Den DF = 16; $F = 105.48$; $P < 0.0001$) and between phases (Num DF = 3; Den DF = 16; $F = 60.14$; $P < 0.0001$). There was also an interaction between the groups and phases (Num DF = 9; Den DF = 16; $F = 8.23$; $P < 0.0002$). The significance of the contrasts between the experimental groups (PrCtrl versus DrCtrl, PrFluc versus DrFluc, and DrCtrl versus DrFluc) is presented in Figure 2 with asterisks.

Dr mesocosms differed also when considering the effect of the low and high water table manipulation, as DrCtrl mesocosms had significantly higher DOC concentrations in comparison to DrFluc mesocosms, but no difference between PrCtrl and PrFluc mesocosms was found (Figure 2). DOC concentrations declined in all experimental groups with time and the variation in DOC concentration within the replicates was low (Figure 2).

Importantly, DOC concentration decreased along with the spring water additions in DrFluc mesocosms (Figure 4), where the volume of added water explained 47% of the variation of changes in DOC concentrations ($\delta$ DOC) during the experiment (regression analyses for DrFluc: $n = 16$, $F = 12.61$, $P = 0.003$, $R^2 = 0.47$, and $b = -4.36$). In the other experimental groups, no relationship between the added water volumes and $\delta$ DOC was found.

DOC/DON ratios differed between the experimental groups (Num DF = 3; Den DF = 16; $F = 51.13$; $P < 0.0001$). There was no difference between phases or interaction between treatments and phases. Results of the pairwise comparisons are presented in Figure 5.

Water colour, that is, the absorption of light at 420 nm, increased significantly along with the DOC concentration in all experimental groups except in DrFluc. The slopes of regressions were within a narrow range (6.5–8.8) in PrCtrl, PrFluc, and DrCtrl. In a case of DrFluc, two outliers resulted
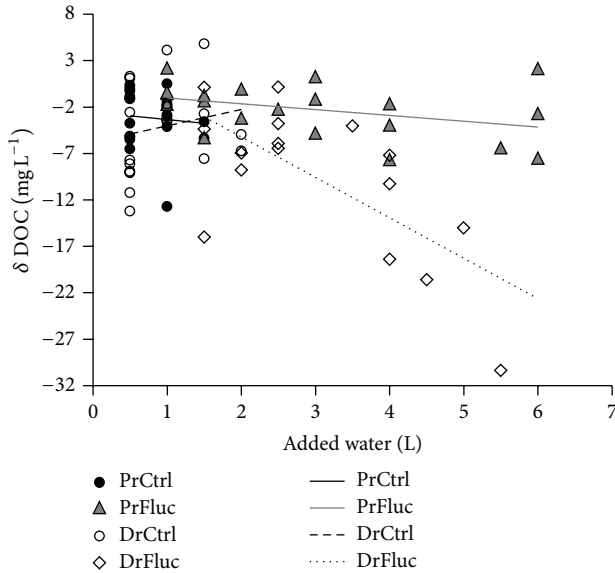
FIGURE 4: $\delta$ DOC in relation to the volume of added water in different experimental groups during phases WL(37)–WH(40), WH(40)–WH(42), WH(42)-WH(43), and WH(43)-WH(44) and their linear fitted lines. For PrCtrl, PrFluc, and DrCtrl $n = 20$ (so five per phase). For DrFluc $n = 16$ (one sample at WL(37)). Pr: pristine; Dr: drained; Ctrl: control; Fluc: fluctuating water table.
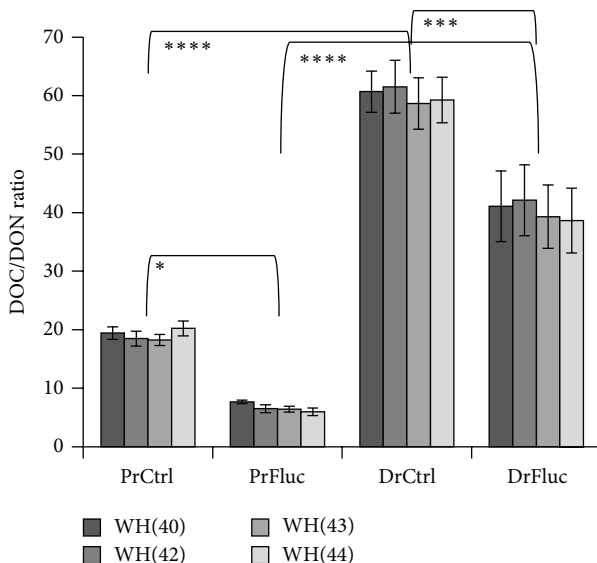


FIGURE 5: Mean ($\pm$SE) DOC/DON ratios in different experimental groups at different phases of the study. $N = 5$ for each experimental group and each phase except for DrCtrl at phases WH(43) and WH(44), where $n = 4$. Significant differences between the experimental groups are indicated with asterisks ($^*P < 0.05$; $^{***}P < 0.001$; $^{****}P < 0.0001$). W: water sampling; H: high water table; (xx): calendar week number. Pr: pristine; Dr: drained; Ctrl: control; Fluc: fluctuating water table.

in a very low $R^2$ value, but if the outliers were omitted, the dependence of DOC on water colour was significant also in DrFluc mesocosms.

### 3.2. Water pH.
Water pH was clearly higher in spring water (pH $\geq$ 6) than in any of the mesocosm soil waters (Figure 3). pH differed between the experimental groups (Num DF = 3; Den DF = 16; $F = 574.80$; $P < 0.0001$) and between phases (Num DF = 3; Den DF = 16; $F = 185.18$; $P < 0.0001$). There was also an interaction between the groups and phases (Num DF = 9; Den DF = 16; $F = 17.70$; $P < 0.0001$). pH was higher in Pr than in Dr mesocosms, while it did not vary between the Ctrl and Fluc mesocosms in pristine peat (Figure 3). pH was slightly but significantly higher in DrCtrl than in DrFluc mesocosms. There was a similar pattern in pH over time in all experimental groups as parallel increase or decrease was noticed in all experimental groups (Figure 3).

### 3.3. Carbon Dioxide and Methane Fluxes.
During the low water table period, that is, at phases GL(32–37), $CO_2$-C fluxes differed between the experimental groups (Num DF = 3; Den DF = 16; $F = 5.72$; $P < 0.01$) and between phases (Num DF = 3; Den DF = 47; $F = 26.49$; $P < 0.0001$). At this period, $CO_2$-C fluxes were higher in DrCtrl than in PrCtrl (Figure 6). During the high water table period, that is, at phases GH(40–43), there were no differences between the experimental groups, but the phases differed (Num DF = 2; Den DF = 29; $F = 38.46$; $P < 0.0001$). There was a clear decline in $CO_2$-C fluxes from phase GL(36) to phase GH(43) in all experimental groups in parallel (Figure 6). In addition, the temporal pattern in $CO_2$-C flux was parallel from phase GL(32) to phase GL(36) in all experimental groups, so the fluxes decreased at first and then increased (Figure 6). There was no interaction between the groups and phases neither at low nor at high water table periods.

In addition, it is noteworthy that the mean values of the $CO_2$-C fluxes during phases GL(32)–GH(40) were higher in PrFluc than in PrCtrl but lower in DrFluc than in DrCtrl (Figure 6), so the pattern was opposite in pristine and drained mesocosms. This indicates that the dry period in Pr mesocosms favored C mineralization as compared to controls, but in Dr mesocosms the control water level was more favorable for C mineralization than the very dry conditions in DrFluc mesocosms.

$CH_4$-C fluxes contributed less than two per cent of the respective $CO_2$-C fluxes. We were unable to obtain sufficient data for evaluating differences in the $CH_4$-C fluxes among the experimental groups.

### 3.4. Air Temperature.
Air temperatures were relatively stable during the gas sampling phases GL(32–34), GL(34–36), GL(36-37), and GL(37)–GH(40), the average values being 15.3, 13.7, 14.4, and 11.2°C, while during phases GH(40–42) and GH(42-43) the average air temperatures were 2.9 and 0.6°C, respectively (Finnish Meteorological Institute 2009). During the water sampling phases WH(40–42), WH(42-43), and WH(43-44), the average air temperatures were 2.2, 2.0, and 2.9°C, respectively.
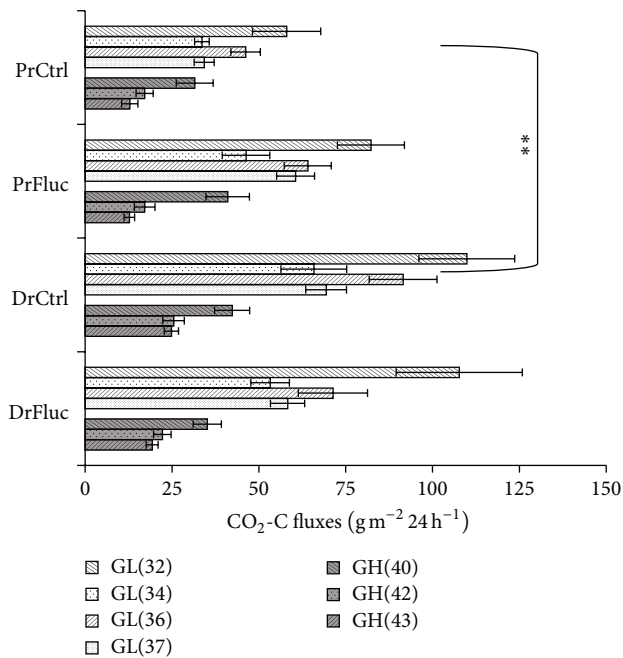
FIGURE 6: Mean (±SE) $CO_2$-C fluxes in different experimental groups at phases GL(32–37) and phases GH(40–43). $N = 5$ except in DrCtrl at phase GL(37), in DrFluc at phase GH(40), and in PrCtrl and PrFluc at phase GH(43), where $n = 4$. Significant difference between the experiment groups is indicated with asterisks ($^{**}P <$ 0.01). G: gas sampling; L: low water table; H: high water table; (xx): calendar week number. Pr: pristine; Dr: drained; Ctrl: control; Fluc: fluctuating water table.

## 4. Discussion

In disagreement with our hypothesis and some previous studies [35, 36], in mesocosms with peat from the drained peatland (Dr), DOC concentrations were lower in fluctuating water table mesocosms (Fluc) than in control mesocosms (Ctrl), where water level was kept constant. This can be supposed to result from added spring water and dilution of the existing soil water in DrFluc mesocosms, as indicated by the negative correlation between the added water volume and $\delta$ DOC. Still, we suggest that in boreal peatland dominated drainage basins the DOC load in runoff water can increase irrespective of the dilution effect because during floods water volumes are large. A decrease in DOC concentration in soil water may have only a minor influence for total loads especially in spring and after heavy precipitation events in summer and autumn (see [37]).

It was evident that the rewetting event effectively released DOC from pristine peat, as DOC concentrations remained equally high in PrFluc compared to PrCtrl despite the dilution effect along with the added spring water. This indicates that the release of DOC was large enough to overcome the dilution effect in Pr mesocosms, which in these experimental conditions did not happen in Dr mesocosms. The result supports our hypothesis that an extended dry period followed by rewetting increases the release of DOC in pristine peat soil

water. Laine et al. [29] observed also a considerable DON and $NH_4^+$-N release from peat originating from pristine peatland into soil water when rewetted after a dry period. When evaluating the phenomenon in natural water ecosystems on a catchment scale, it is important to consider the whole drainage basin through which water is transported, as, for example, downstream lakes can receive DOC less from their own surroundings than from the upper parts of the drainage basin [19].

In addition to studying the consequences of the fluctuating water table, another subject of interest was the differences between the peat types in present and in altered climate conditions. The latter is interesting not only when considering draining peatlands but also when evaluating the possible benefits of remediating drained peatlands closer to their initial conditions preceding drainage. We observed distinctly higher DOC concentrations in drained than in the pristine peat mesocosms which is in line with previous results that a deep aerobic layer promotes DOC release [38]. However, it is noteworthy to realize that this difference between the peat types depended largely on the initial DOC concentrations seen already in the natural peatland pothole water. In line with the presumption of aerobic layer promoting microbial activity, we hypothesized that low water table conditions enhance organic matter decomposition and mineralization. Due to difficulties to obtain water samples from the DrFluc mesocosms at the end of the low water table period (phase WL(37)), we cannot reliably estimate the effect of low water table on DOC concentrations in Dr mesocosms. In Pr mesocosms, DOC concentrations at this period were approximately on the same level in Ctrl and Fluc mesocosms. It must be also noted that both a fall and a rise in the water table level may eventually increase organic C loads into water systems, as decomposition of organic C increases due to improved aerobic conditions during a drought, while a flood increases discharge [36]. A severe drought and subsequent rewetting can also destabilize peatland C stocks [39].

There was a decline in DOC in all experimental groups along with time. It cannot be explained by air temperature because during the water samplings (phases WH(40–42), WH(42-43), and WH(43-44)) the air temperature was rather stable. Instead, the decline in DOC concentration with time indicated that dilution effect along with several spring water additions started to accumulate slowly, decreasing slightly the DOC concentrations towards the end of the experiment. It should be kept in mind, however, that reequilibration after disturbance due to preparation of the mesocosms may have also affected these results.

Humic substances, a major fraction of dissolved organic matter in boreal peat soils [40, 41], and carboxyl acids [19, 42] are largely responsible of the low pH of DOC. This is consistent with the finding that pH was lower and DOC higher in drained peat than in pristine peat in our experiment. It has been discovered in other studies as well that drainage can lower pH in the top layer of the peat profile in fens [43, 44] and in bogs [45].

Combining the data of this study and the study of Laine et al. [29] shows that the DOC/DON ratios were clearly

higher in drained than in pristine mesocosms and higher in Ctrl than in Fluc mesocosms (Figure 5). The difference between the peat types is explained by the fact that the gap between Pr and Dr mesocosms was larger in DOC than in DON. In Pr mesocosms, there was a remarkably higher DON concentration in PrFluc than in PrCrl mesocosms, discussed in Laine et al. [29], that caused the lower DOC/DON in PrFluc than in PrCtrl.

We also studied the quality of DOC in peat soil water based on water colour. We expected that the dependence of DOC on water colour would be quite different in pristine and drained mesocosms, as the environmental conditions may affect the composition of DOC, which in turn may influence the chromatic properties of organic matter [46], and because chemical and environmental factors can affect the strength of this relationship [19]. However, the relationship between DOC and water colour was very similar in pristine and drained peat mesocosms.

As expected, we found higher $CO_2$-C flux in DrCtrl than in PrCtrl during the low water table period, most likely due to 20 cm lower water table level in DrCtrl than in PrCtrl. Also Martikainen et al. [47] found that a deeper aerobic layer promotes an increase in $CO_2$-C emissions. The $CO_2$-C fluxes in all experimental groups and the air temperature changed in parallel, which emphasizes that air temperature was a key factor regulating $CO_2$-C fluxes out of the mesocosms.

Compared to previous results, $CO_2$-C flux results of this study were high. For example, Salm et al. [48] estimated the emissions of $CO_2$-C, for example, from Estonian natural mires and drained peatlands. $CO_2$-C emissions from the mires (median values) were approximately $0.4 \, g \, m^{-2} \, 24 \, h^{-1}$ and from the drained peatlands approximately $0.5 \, g \, m^{-2} \, 24 \, h^{-1}$. Ojanen et al. [49] estimated $CO_2$ fluxes of $3$–$12 \, g \, m^{-2} \, 24 \, h^{-1}$ (equivalent with $0.8$–$3.3 \, g \, m^{-2} \, 24 \, h^{-1}$ $CO_2$-C) in boreal forestry-drained peatlands.

Decomposition and mineralization of organic matter release DOC and $CO_2$-C, respectively. Even if the DOC concentrations in soil water would increase, a similar increase in DOC export to the surrounding water systems may not necessarily be seen especially in a short term if the conditions are very dry. The reason is that part of the DOC may be further mineralized to $CO_2$-C. This did not show during our experiment because of the air temperature, discussed above. Therefore, it was not meaningful to explore how much DOC turnover was equivalent to $CO_2$-C fluxes. Also, as the results suggest a burst in DOC export can emerge later on as a consequence of changing hydrological conditions. It is known that the role of DOC production in relation to DOC export increases as the time between rain events increases [50].

In conclusion, our results indicate that long dry periods favor $CO_2$-C producing microbial activity more in pristine than in drained peatlands. The following heavy rain events cause high DOC loads especially from pristine peatlands to recipient aquatic systems when the hydrological conditions are sufficient for element transport. In this kind of environmental conditions, total DOC load can be high also from drained peatlands, as the DOC content of the peatland is high.

## References

[1] E. Gorham, "Northern peatlands: role in the carbon cycle and probable responses to climatic warming," *Ecological Applications*, vol. 1, no. 2, pp. 182–195, 1991.

[2] J. Pastor, J. Solin, S. D. Bridgham et al., "Global warming and the export of dissolved organic carbon from boreal peatlands," *Oikos*, vol. 100, no. 2, pp. 380–386, 2003.

[3] P. Kortelainen, S. Saukkonen, and T. Mattsson, "Leaching of nitrogen from forested catchments in Finland," *Global Biogeochemical Cycles*, vol. 11, no. 4, pp. 627–638, 1997.

[4] N. Roulet and T. R. Moore, "Environmental chemistry: browning the waters," *Nature*, vol. 444, no. 7117, pp. 283–284, 2006.

[5] M. C. Serreze and J. A. Francis, "The arctic amplification debate," *Climatic Change*, vol. 76, no. 3-4, pp. 241–264, 2006.

[6] D. T. Monteith, C. D. Evans, and S. Patrick, "Monitoring acid waters in the UK: 1988–1998 trends," *Water, Air, and Soil Pollution*, vol. 130, no. 1–4, pp. 1307–1312, 2001.

[7] B. L. Skjelkvåle, C. Evans, T. Larssen, A. Hindar, and G. G. Raddum, "Recovery from acidification in European surface waters: a view to the future," *Ambio*, vol. 32, no. 3, pp. 170–175, 2003.

[8] F. Worrall, R. Harriman, C. D. Evans et al., "Trends in dissolved organic carbon in UK rivers and lakes," *Biogeochemistry*, vol. 70, no. 3, pp. 369–402, 2004.

[9] C. D. Evans, D. T. Monteith, and D. M. Cooper, "Long-term increases in surface water dissolved organic carbon: observations, possible causes and environmental impacts," *Environmental Pollution*, vol. 137, no. 1, pp. 55–71, 2005.

[10] D. T. Monteith, J. L. Stoddard, C. D. Evans et al., "Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry," *Nature*, vol. 450, no. 7169, pp. 537–540, 2007.

[11] F. Worrall and T. P. Burt, "Trends in DOC concentration in Great Britain," *Journal of Hydrology*, vol. 346, no. 3-4, pp. 81–92, 2007.

[12] C. D. Evans, C. L. Goodale, S. J. M. Caporn et al., "Does elevated nitrogen deposition or ecosystem recovery from acidification drive increased dissolved organic carbon loss from upland soil? A review of evidence from field nitrogen addition experiments," *Biogeochemistry*, vol. 91, no. 1, pp. 13–35, 2008.

[13] M. Erlandsson, N. Cory, S. Köhler, and K. Bishop, "Direct and indirect effects of increasing dissolved organic carbon levels on pH in lakes recovering from acidification," *Journal of Geophysical Research G: Biogeosciences*, vol. 115, no. 3, Article ID G03004, 2010.

[14] G. F. Vance and M. B. David, "Effect of acid treatment on dissolved organic carbon retention by a Spodic horizon," *Soil Science Society of America Journal*, vol. 53, no. 4, pp. 1242–1247, 1989.

[15] C. Freeman, C. D. Evans, D. T. Monteith, B. Reynolds, and N. Fenner, "Export of organic carbon from peat soils," *Nature*, vol. 412, no. 6849, p. 785, 2001.

[16] L. J. Tranvik, M. Jansson, C. D. Evans et al., "Climate change—Terrestrial export of organic carbon," *Nature*, vol. 415, no. 6874, pp. 861–862, 2002.

[17] C. Freeman, N. Fenner, N. J. Ostle et al., "Export of dissolved organic carbon from peatlands under elevated carbon dioxide levels," *Nature*, vol. 430, no. 6996, pp. 195–198, 2004.

[18] M. J. Hinton, S. L. Schiff, and M. C. English, "Sources and flow-paths of dissolved organic carbon during storms in two forested watersheds of the Precambrian Shield," *Biogeochemistry*, vol. 41, no. 2, pp. 175–197, 1998.

[19] L. Arvola, M. Rask, J. Ruuhijärvi et al., "Long-term patterns in pH and colour in small acidic boreal lakes of varying hydrological and landscape settings," *Biogeochemistry*, vol. 101, no. 1–3, pp. 269–279, 2010.

[20] L. Arvola, "The load of organic carbon, nitrogen and phosphorus from two large drainage basins (River Kitka and River Oulanka) in NE Finland," *Fennia*, vol. 177, no. 1, pp. 17–25, 1999.

[21] M. D. Preston, M. C. Eimers, and S. A. Watmough, "Effect of moisture and temperature variation on DOC release from a peatland: conflicting results from laboratory, field and historical data analysis," *The Science of the Total Environment*, vol. 409, no. 7, pp. 1235–1242, 2011.

[22] E. Tipping, C. Woof, E. Rigg et al., "Climatic influences on the leaching of dissolved organic matter from upland UK moorland soils, investigated by a field manipulation experiment," *Environment International*, vol. 25, no. 1, pp. 83–95, 1999.

[23] K. Kalbitz, S. Solinger, J.-H. Park, B. Michalzik, and E. Matzner, "Controls on the dynamics dissolved organic matter in soils: a review," *Soil Science*, vol. 165, no. 4, pp. 277–304, 2000.

[24] K. Jylhä, H. Tuomenvirta, and K. Ruosteenoja, "Climate change projections for Finland during the 21st century," *Boreal Environment Research*, vol. 9, no. 2, pp. 127–152, 2004.

[25] R. P. Allan and B. J. Soden, "Atmospheric warming and the amplification of precipitation extremes," *Science*, vol. 321, no. 5895, pp. 1481–1484, 2008.

[26] P. S. Naden and A. T. McDonald, "Statistical modelling of water colour in the uplands: the Upper Nidd catchment 1979–1987," *Environmental Pollution*, vol. 60, no. 1-2, pp. 141–163, 1989.

[27] N. Fenner, C. Freeman, S. Hughes, and B. Reynolds, "Molecular weight spectra of dissolved organic carbon in a rewetted Welsh peatland and possible implications for water quality," *Soil Use and Management*, vol. 17, no. 2, pp. 106–112, 2001.

[28] J. M. Clark, P. J. Chapman, J. K. Adamson, and S. N. Lane, "Influence of drought-induced acidification on the mobility of dissolved organic carbon in peat soils," *Global Change Biology*, vol. 11, no. 5, pp. 791–809, 2005.

[29] M. P. P. Laine, R. Strömmer, and L. Arvola, "Nitrogen release in pristine and drained peat profiles in response to water table fluctuations: a mesocosm experiment," *Applied and Environmental Soil Science*, vol. 2013, Article ID 694368, 7 pages, 2013.

[30] S. Eurola, A. Huttunen, and K. Kukko-oja, *Oulanka Reports 14—Suokasvillisuusopas*, University of Oulu, Oulanka Biological Station, Oulu, Finland, 1995, (Finnish).

[31] Lappalainen, C.-G. Stén, and J. Häikiö, "Turvetutkimusten maasto-opas," Opas 12, Geologian Tutkimuskeskus, Espoo, Finland, 1984.

[32] A. Ojala, J. L. Bellido, T. Tulonen, P. Kankaala, and J. Huotari, "Carbon gas fluxes from a brown-water and a clear-water lake in the boreal zone during a summer with extreme rain events," *Limnology and Oceanography*, vol. 56, no. 1, pp. 61–76, 2011.

[33] Anonymous, *SAS/STAT, 9.2 User's Guide*, SAS Institute, Cary, NC, USA, 2008.

[34] Anonymous, *IBM SPSS Statistics 21 Core System User's Guide*, IBM, 1989, 2012.

[35] D. J. Chittleborough, K. R. J. Smettem, E. Cotsaris, and F. W. Leaney, "Seasonal changes in pathways of dissolved organic carbon through a hillslope soil (Xeralf) with contrasting texture," *Australian Journal of Soil Research*, vol. 30, no. 4, pp. 465–476, 1992.

[36] D. F. Jager, M. Wilmking, and J. V. K. Kukkonen, "The influence of summer seasonal extremes on dissolved organic carbon export from a boreal peatland catchment: evidence from one dry and one wet growing season," *Science of the Total Environment*, vol. 407, no. 4, pp. 1373–1382, 2009.

[37] L. Arvola, M. Järvinen, and I. Hakala, "Nutrient export from small boreal catchment areas: the influence of annual and seasonal hydrology," in *Proceedings of the International Association of Theoretical and Applied Limnology*, J. Jones, Ed., vol. 29, pp. 2031–2034, 2006.

[38] F. Worrall, T. Burt, and R. Shedden, "Long term records of riverine dissolved organic matter," *Biogeochemistry*, vol. 64, no. 2, pp. 165–178, 2003.

[39] N. Fenner and C. Freeman, "Drought-induced carbon loss in peatlands," *Nature Geoscience*, vol. 4, no. 12, pp. 895–900, 2011.

[40] S. M. Ilina, O. Y. Drozdova, S. A. Lapitskiy et al., "Size fractionation and optical properties of dissolved organic matter in the continuum soil solution-bog-river and terminal lake of a boreal watershed," *Organic Geochemistry*, vol. 66, pp. 14–24, 2014.

[41] Z. Wei, X. Zhao, C. Zhu, B. Xi, Y. Zhao, and X. Yu, "Assessment of humification degree of dissolved organic matter from different composts using fluorescence spectroscopy technology," *Chemosphere*, vol. 95, pp. 261–267, 2014.

[42] D. N. Kothawala, C. Roehm, C. Blodau, and T. R. Moore, "Selective adsorption of dissolved organic matter to mineral soils," *Geoderma*, vol. 189-190, pp. 334–342, 2012.

[43] K. Minkkinen, H. Vasander, S. Jauhiainen, M. Karsisto, and J. Laine, "Post-drainage changes in vegetation composition and carbon balance in Lakkasuo mire, central Finland," *Plant and Soil*, vol. 207, no. 1, pp. 107–120, 1998.

[44] H. Toberman, R. Laiho, C. D. Evans et al., "Long-term drainage for forestry inhibits extracellular phenol oxidase activity in Finnish boreal mire peat," *European Journal of Soil Science*, vol. 61, no. 6, pp. 950–957, 2010.

[45] J. Laine, H. Vasander, and R. Laiho, "Long-term effects of water level drawdown on the vegetation of drained pine mires in southern Finland," *Journal of Applied Ecology*, vol. 32, no. 4, pp. 785–802, 1995.

[46] Z. E. Wallage, J. Holden, and A. T. McDonald, "Drain blocking: an effective treatment for reducing dissolved organic carbon loss and water discolouration in a drained peatland," *Science of the Total Environment*, vol. 367, no. 2-3, pp. 811–821, 2006.

[47] P. J. Martikainen, H. Nykänen, J. Alm, and J. Silvola, "Change in fluxes of carbon dioxide, methane and nitrous oxide due to forest drainage of mire sites of different trophy," *Plant and Soil*, vol. 168-169, no. 1, pp. 571–577, 1995.

[48] J.-O. Salm, M. Maddison, S. Tammik, K. Soosaar, J. Truu, and Ü. Mander, "Emissions of $CO_2$, $CH_4$ and $N_2O$ from undisturbed, drained and mined peatlands in Estonia," *Hydrobiologia*, vol. 692, no. 1, pp. 41–55, 2012.

[49] P. Ojanen, K. Minkkinen, J. Alm, and T. Penttilä, "Soil-atmosphere $CO_2$, $CH_4$ and $N_2O$ fluxes in boreal forestry-drained peatlands," *Forest Ecology and Management*, vol. 260, no. 3, pp. 411–421, 2010.

[50] F. Worrall, H. S. Gibson, and T. P. Burt, "Production vs. solubility in controlling runoff of DOC from peat soils—the use of an event analysis," *Journal of Hydrology*, vol. 358, no. 1-2, pp. 84–95, 2008.