Measuring restoration progress using pore- and surface-water chemistry across a chronosequence of formerly afforested blanket bogs

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Abstract

During the restoration of degraded bogs and other peatlands, both habitat and functional recovery can be closely linked with nutrient cycling, which is reflected in pore- and surface-water chemistry. Several peatland restoration studies have shown that the time required for recovery of target conditions is slow (>10 years); for heavily-impacted, drained and afforested peatlands of northern Scotland, recovery time is unknown. We monitored pore- and surface-water chemistry across a chronosequence of formerly drained, afforested bog restoration sites spanning 0-17 years, using a space-for-time substitution, and compared them with open blanket bog control sites. Our aims were to measure rate of recovery towards bog conditions and to identify the best suite of water chemistry variables to indicate recovery.

Our results show progress in recovery towards bog conditions over a 0-17 year period post-restoration. Elements scavenged by trees (Mg, Na, S) completely recovered within that period. Many water chemistry variables were affected by the restoration process itself, but recovered within 11 years, except ammonium (NH$_4^+$), Zn and dissolved organic carbon (DOC) which remained elevated (when compared to control bogs) 17 years post restoration. Other variables did not completely recover (water table depth (WTD), pH), exhibiting what we term "legacy" effects of drainage and afforestation. Excess N and a lowered WTD are likely to slow the recovery of bog vegetation including key bog plants such as Sphagnum mosses.

Over 17 years, we measured near-complete recovery in the chemistry of surface-water and deep pore-water but limited progress in shallow pore-water. Our results suggest that at least >17 years are required for complete recovery of water chemistry to bog conditions. However, we expect that newer restoration methods including conifer harvesting (stem plus brash) and the blocking of plough furrows (to increase the WTD) are likely to accelerate the restoration process (albeit at greater cost); this should be evaluated in future studies. We conclude that monitoring pore- and surface-water chemistry is useful in terms of indicating recovery towards bog conditions and we recommend monitoring WTD, pH, conductivity, Ca, NH$_4^+$, phosphate (PO$_4^{3-}$), K, DOC, Al and Zn as key variables.

Highlights (85 characters max for each line, including spaces)

- After restoration, water chemistry progressed toward bog conditions over 17 years.
- pH, NH$_4^+$ and WTD had not recovered completely within 17 years.
- PO$_4^{3-}$ and K were released post-restoration, but levels recovered within 11 years.
We recommend monitoring WTD, pH, conductivity, Ca, NH$_4^+$, PO$_4^{3-}$, K, DOC, Al and Zn.

**Keywords**

Afforested peatland; peatland restoration; water chemistry; water table recovery; restoration timescale

### 1. Introduction

Restoring functionality in bogs and other peatlands, as in many terrestrial systems, depends upon the recovery of both above- and below-ground nutrient cycling, which are linked through vegetation and microbial activity (Andersen et al., 2013a, 2013b; Nwaishii et al., 2016). Nutrient cycling is a strong control on carbon cycling in bogs (Keller et al., 2006). Therefore, if nutrient cycling is restored (Andersen et al., 2013b), this should also secure peat carbon stocks and help re-initiate carbon sequestration and peat formation, all of which are all key peatland ecosystem services (Bardgett et al., 2008; Bragazza et al., 2012a).

Changes in below-ground nutrient cycling are strongly influenced by redox-conditions and therefore water table depth (WTD; Bergman et al., 1999; Waddington et al., 2015). In turn, these biogeochemical processes are reflected in pore- and surface-water chemistry (Andersen et al., 2010; Bragazza et al., 2012b). Also, pore- and surface-water chemistry strongly influence bog vegetation growth and composition (Wieder, 1985; Vitt and Chee, 1990), meanwhile changes in vegetation feedback onto water chemistry (Eppinga et al., 2009; Bragazza et al., 2012b).

One of the primary restoration approaches used to facilitate the recovery of bog vegetation (including, crucially, *Sphagnum* mosses, which include the main peat forming species) is to raise the water table, creating a near surface water table similar to that of intact bogs (Holden et al., 2004; Bellamy et al., 2012). A key question is: how much time is required, before restoration areas will once again function like bogs (Hancock et al., 2014)? This depends on how key elements of bog functioning, such as WTD, nutrients and vegetation change over time (Andersen et al., 2010; Haapalehto et al., 2014; Parry et al., 2014). If these variables change over time during restoration compared to intact sites, then they can be monitored as indicators of recovery.
In degraded peatlands across the world, progress in restoration towards intact conditions for vegetation, WTD, pore- and surface-water chemistry, below-ground microbial activity and nutrient cycling has been measured, 10 years post-restoration (Andersen et al., 2013b; Haapalehto et al., 2014). As none of these functions had fully recovered, this exemplifies the fact that full peatland restoration is a slow, and likely a multi-decadal process.

In restoration of drained, artificially afforested (formerly treeless) blanket bogs (e.g., in Scotland), blocking plough furrows (ditches between which trees were planted) and main forestry drains with peat dams was most successful in raising the water table and in promoting bog vegetation (Anderson and Peace, 2017). However, water levels were still lower than in undisturbed blanket bog ten years after restoration. Recent monitoring of 15 year old formerly afforested restoration sites have also shown more successful recovery of Sphagnum on slopes of <3° (Hancock et al., 2018), which was thought to be associated with higher water table on shallower slopes.

However, other factors might slow the recovery of the vegetation on drained and afforested blanket bogs following restoration by tree removal and drain blocking. Significant increases in pore- and surface-water dissolved organic carbon (DOC), nutrient and element concentrations occur immediately following restoration in drained afforested bogs (Muller and Tankéré-Muller, 2012; Gaffney, 2016). Some of these changes occur within a short period and could be a consequence of the biogeochemical and physical disturbance associated with restoration management (which we term "restoration effects"; Figure 1). However, if they are not, and are instead what we term "legacy effects" from the forestry plantations and associated drainage, they could last for a longer period i.e., more than ten years (Cuddington, 2011; Malcolm et al., 2014) and slow the recovery of key plants like Sphagnum mosses.

Some other elements of nutrient cycling may recover within a decade of restoration (Haapalehto et al., 2011), yet may be strongly associated with the former trees (Nisbet and Evans, 2014). Here we would term these “forestry effects” (Figure 1) given that they are faster in recovery following tree removal, rather than a lasting legacy.

One way to measure the restoration of formerly afforested blanket bogs is to assess the temporal dynamics of pore- and surface-water chemistry over several decades to determine how long it takes before water chemistry in forest-to-bog restoration sites closely resembles that of open (treeless) bog. There are currently no studies regarding medium to long term (>5 years) changes in pore- and surface-water chemistry exclusively on the restoration of previously drained and...
artificially afforested peatlands. Here, we use a space-for-time substitution (Pickett, 1989; Thomaz et al., 2012) to address this gap, studying a chronosequence of restoration sites. Our first aim was to measure the differences in pore- and surface-water chemistry (carbon, nutrients and elements) across restoration sites of different ages (0-17 years since restoration commenced), in comparison to afforested and open bog controls, and hence infer the rate of recovery during restoration. Our second aim was to identify the key pore- and surface-water chemistry variables, which are the most useful indicators of recovery (to assess restoration progress in formerly afforested peatlands). We hypothesized that overall water chemistry would trend towards bog conditions during restoration. Further, we hypothesized that some water chemistry variables would show strong but short-lived impacts of restoration management, while others might change little after several years, leaving enduring legacies of past afforestation.
2. Methods

2.1 Site description of chronosequence restoration sites (restoration commenced between 1997 and 2015)

The Forsinard Flows National Nature Reserve (NNR; 58.357, -3.897; lat/long) is located in Sutherland in northern Scotland, and managed by the nature conservation charity the Royal Society for the Protection of Birds (RSPB). The reserve comprises a mixture of open blanket bog and land undergoing forest-to-bog restoration (the process of returning formerly drained, afforested bog into open blanket bog through tree removal and drain blocking; Hancock et al., 2014). Areas of drained afforested blanket bog (planted with non-native conifers Sitka spruce (Picea sitchensis) and Lodgepole pine (Pinus contorta) in the 1980s), remain on land adjacent to the RSPB reserve. Forest-to-bog restoration has been carried out by the RSPB since 1997 (Hancock et al., 2018), creating a series of restoration sites with a range of ages from 17 (restoration in 1997/98) to 0 (restoration in 2014/15) years; therefore, forming a chronosequence across a set of sites with a 15 km distance between the furthest east and west (Figure 2).

Within four sites of different ages in the chronosequence, we selected sampling areas intended to produce a space-for-time substitution (n = 3 replicates per age treatment). As planting mainly occurred in the 1980s but restoration was spread over 17 years, methods used for the restoration changed over time and depended on the size of the trees removed and the development of specialist machinery (Table 1). At Talaheel (restoration commenced 1997/98), trees were felled by hand (chainsaw) and were lain into the furrows as they were young and small i.e., “felled to waste” (Hancock et al., 2018). In Lonielist (restoration commenced 2003/04) trees were felled using heavy machinery and left in furrows. By this point, trees were bigger and did not fit into the furrows when felled: i.e., brash remained visible/well above the prevailing ground surface. In Raphan (restoration commenced 2011/12), and Dyke (restoration commenced 2014/15) whole tree mulching was carried out on smaller trees (across <25% of the area, reducing them to small wood-chips) but many stems were harvested for timber (brash or logging slash, was also harvested in some parts of Dyke). Stem harvesting can provide a timber income to help offset restoration costs and may improve recovery to bog conditions. Choice of sampling areas within each chronosequence site was based on restoration technique used. As there was no fell-to-waste in Dyke Forest, stem only harvest plots were included in the chronosequence, as they were the most comparable to the fell-to-waste plots in other sites (as substantial amounts of
brash remained). In each restoration site, the main forestry drains were also blocked at the time of felling, with plastic piling dams.

Standing forestry plantation controls (hereafter referred to as afforested) and open bog control plots were included in the chronosequence to represent the conditions prior to restoration and targeted end point of the restoration process respectively (Figure 2). Control plots were broadly comparable to all the chronosequence sites in terms of slope, while afforested controls had a similar species mix (Sitka spruce/Lodgepole pine) and were planted using the same methods and at the same time as the former trees on restoration sites (Table 1).

In the United Kingdom, hill drains have been placed in many bogs to improve grazing conditions (Holden et al., 2004) and some of our open bog control plots also had hill drains (spaced at least 25m apart in some areas, absent from other areas). At a study site near our control plots, Bellamy et al (2012) found that the influence of similar drains on vegetation composition was generally limited to within a few metres of the drain. Any hill drains on our open bog control sites were blocked with dams during restoration work in 1996 and 2004. This drain blocking has been effective in retaining water to dam level and encouraging revegetation of the drain. Open bog areas with this relatively minor level of past impact are our target conditions for forest-to-bog restoration sites: they represent typical near-natural open bogs in the region. Additionally, all our open bog control areas are designated as blanket bogs of high nature conservation value (Special Areas of Conservation, SAC) under the EU Habitats Directive. Thus, in nature conservation terms, they are considered among the most valuable examples of this habitat type in Britain.

*Sphagnum* mosses formed the most abundant ground vegetation cover in the open bog control sites (38% abundance at random point measurements), while in afforested controls, other mosses were most abundant (i.e., 63% Pleurocarpous and Acrocarpous mosses). Restoration sites varied in recovery towards open bog vegetation with a mean of 15% *Sphagnum* cover in the oldest site (Talaheel: Hancock et al., 2018), while Dyke, the youngest restoration site (with ≤4% *Sphagnum* abundance) was more similar to the afforested controls.

### 2.2 Pore- and surface-water sampling

Pore-water was sampled using piezometers (Wallage et al., 2006), with a 10 cm sampling zone, drilled into the polypropylene pipe. One piezometer transect was installed in each plot, which followed the slope direction and contained one dipwell (a fully drilled well) for measuring
WTD and four sampling points, each with a piezometer ‘pair’. Each ‘pair’ contained one deep and one shallow piezometer, sampling a 10 cm zone between 50-80 cm below the surface for the deep piezometers, and between 10-45 cm below the surface for the shallow piezometers.

Three plots were instrumented in each restoration site (and for both afforested and bog controls), except at Dyke (n = 6). Piezometers were emptied between four and six days prior to sample collection. Samples were collected into LDPE bottles (Nalgene) using a syringe connected to flexible PVC tubing pre-rinsed with 5 mL of sample. Surface-water was sampled from the main forestry drains in restoration and afforested control plots and from the hill drains (blocked in 1996 and 2004) in open bog control plots. Generally, one drain sample was collected from each plot, but, where more than one drain crossed a transect these were also sampled. In open bog and afforested controls, surface runoff was also sampled using crest tubes (Wallage et al., 2006). For both pore- and surface-water, measurements of temperature, pH and conductivity were made in the field (using a Hanna HI 991300 multi-parameter probe). We collected samples on three occasions (July 2014, March/April 2015 and August 2015). During the first sampling round, all Dyke sites were still afforested, as restoration began here in October 2014. In March/April 2015, only two of the three blocks in Dyke were felled. We only sampled here after blocks were felled.

2.3 Sample preparation and analysis

Samples were refrigerated at 4°C on return to the laboratory and then vacuum-filtered, usually within 24 hours of collection (and always within 36 hours), through pre-combusted 0.7 µm glass fibre filters (Fisherbrand MF300) for DOC and DIC analysis (Strack et al., 2008). DOC and DIC was analysed by high temperature catalytic combustion (using a Shimadzu TOC-L instrument; Sugimura and Suzuki, 1988). A separate portion of filtrate was collected for analysis of nutrients and elements. This portion was vacuum-filtered through 0.45 µm cellulose acetate filters (Sartorius Stedim). Nutrient analysis was carried out immediately with a Seal AQ2 discrete analyser, to measure dissolved ammonium (NH₄⁺), soluble reactive phosphate (PO₄³⁻) and total oxidised nitrogen (TON), using adapted and validated methods as per ISO international water quality standards (http://www.seal-analytical.com/). Samples for macro and trace element concentrations were acidified (to 5% using trace metal grade nitric acid) and determined by inductively coupled plasma optical emission spectrometry (ICP-OES) using a Varian 720ES instrument (Clesceri et al., 1998). Samples were analysed for concentrations of Ca, Mg, Na, K, Fe, Mn, Al, S, and Zn. Certified reference materials (CRMs; MERCK nitrate
200 mg L⁻¹, Fluka PO₄³⁻ and NH₄⁺ 1000 mg L⁻¹ and multi-element CRM MAURI-09 Lot #913, Environment Canada) were used to validate each method of analysis, with recoveries ranging from 81-104% over the study period. Additionally, DOC quality was measured by absorbance at 465 nm and 665 nm using a Camspec M350 UV/Visible spectrophotometer on the 0.7 µm filtered samples (i.e., matched with the DOC analysis). The ratio of absorbance at 465 nm and 665 nm (Abs₄₆₅ nm/Abs₆₆₅ nm) were used as an approximation of the E₄,E₆ ratio (Chen et al., 1977), which is a measure of the ratio of humic to fulvic acids in the sample (Wallage et al., 2006).

2.4 Statistical analyses
All statistical analyses were performed using RStudio (Version 0.98.501, R Core Team, 2016). Samples from each plot were assigned to a treatment - open bog (BOG), afforested (FOR) or restoration (REST). Restoration treatments were labelled by the number of years since felling, as R-0, R-3, R-11 and R-17 for 2014/15, 2011/12, 2003/04 and 1997/98 respectively. For statistical analyses, results from each of the three sampling rounds were included as one treatment.

To look at the overall changes in water chemistry of the treatments over time (represented by the chronosequence), we used principal response curves (PRC; package vegan, Oksanen et al., 2016), a type of redundancy analysis (RDA). PRCs are a multivariate method, where the response variables (e.g., water chemistry) for a treatment are expressed as differences from a reference over time, and the output is displayed graphically as a response curve (van den Brink and Ter Braak, 1998, 1999).

In our analysis, we compared the water chemistry of the REST and FOR sites, to the BOG sites as our reference. The PRC specifically tested the time by treatment interaction in relation to the reference (Andersen et al., 2010), and additionally, this method displays how closely each of the individual water chemistry variables are associated with the main axis of the overall temporal trends (van den Brink and Ter Braak, 1998, 1999). The significance of the principal response curves was tested using Monte Carlo permutations (n = 999), against a null hypothesis of no treatment by time interaction.

For WTD, univariate statistical analysis was carried out by comparing treatment means, by analysing data at the plot level to determine the effect of forest-to-bog restoration between the restoration sites and the FOR and BOG controls. A generalised linear mixed model was used
(function `glmer`, package `lme4`, Bates et al., 2015), with “treatment” as the fixed factor. To account for intercorrelation between different measures taken during the same sampling round, “sampling round number” was added as a random effect. Additionally “Plot” was added as a random intercept, to account for correlation between the repeated measures within plots, i.e., within each transect. Appropriateness of model fit was checked visually by assessing normality and homoscedasticity of residuals (Crawley, 2007; Zuur et al., 2011). Having carried out, with our PRC analysis, a single hypothesis test of treatment by time interaction across all water quality variables (for each of three levels – surface-water, shallow and deep pore-water), we then examined individual water quality variable trends graphically, grouping them by the three different types of temporal response; legacy effects, restoration effects and forestry effects.
3. Results

3.1 Trends in water chemistry across the chronosequence of forest-to-bog restoration sites

Water chemistry in forest-to-bog restoration sites (REST) and afforested controls (FOR) varied significantly, when compared to the open bog control sites (BOG) for surface-water ($F = 81.6, p = 0.001$; Figure 3a), shallow pore-water ($F = 59.6, p = 0.001$; Figure 3b) and deep pore-water ($F = 42.3, p = 0.001$; Figure 3c). Surface- and shallow pore-water results implied that restoration sites diverged from BOG (and FOR) conditions initially (post-restoration), with subsequent development (over time) towards BOG conditions. Deep pore-water results suggest a gradual development towards BOG conditions throughout restoration. In terms of overall restoration progress (measured as the position of restoration sites on PRC axes between FOR and BOG conditions), this was nearly complete for deep pore-water on 17 year old sites. At the same time point, restoration was about three-quarters complete for surface-water, but for shallow pore-water chemistry, the trend was more complex, with little restoration progress beyond FOR conditions.

In surface-water the REST curve showed elevated concentrations of certain water chemistry variables (particularly $PO_4^{3-}$, Al and DOC) which occurred immediately following restoration (time = 0), but, in three-year old sites these decreased towards that of the FOR sites (Figure 3a). The inferred downward trend in REST samples then continued more gradually, as represented by the oldest restoration sites (17 years) which were closest, but still not fully aligned, with the BOG reference.

In shallow pore-water, there was a large difference in water chemistry immediately following restoration, largely associated with more than two fold increases in $PO_4^{3-}$ and lesser increases $NH_4^+$, Al and DOC (Figure 3b). These elevated concentrations began to decrease after approximately three years and the overall chemistry became more similar to FOR than to BOG sites 11 years after restoration. The PRC then suggests that no further progress in the recovery of shallow pore-water chemistry towards BOG conditions occurred within the 17-year chronosequence.

In deep pore-water samples, the chemistry of REST was initially closer to FOR than BOG in the most recent restoration sites, but the difference from BOG decreased in older chronosequence sites, implying a decline in concentrations over time (Figure 3c). There were several variables associated this trend. The highest scoring was $NH_4^+$, which decreased over time, while DIC showed the opposite trend, implying an increase over time.
### 3.2 Effects of forest-to-bog restoration on hydrology and water chemistry

#### 3.2.1 Hydrological effects

Forest-to-bog restoration resulted in a raising of the water table over time, with the most recent restoration sites having WTD closer to that of the FOR controls and the oldest restoration sites most similar to the BOG sites (Figure 4). There was a significant treatment (i.e., inferred time) effect on WTD ($p < 0.001$); therefore WTD varied significantly between the controls and restoration sites. Mean WTD on the R11, R17 and BOG sites was higher than the FOR sites (at 22, 26 and 34 cm higher, respectively). However, WTD at R11 and R17 sites remained, on average, 12 and 8 cm lower than the BOG controls, respectively.

#### 3.2.2 Water chemistry variables showing a “legacy effect”

In pore- and surface-water, pH and Ca both exhibited marked differences between FOR and BOG sites, with a trend for values in REST sites to move towards open bog conditions with time since restoration (Figure 5). However, recovery to BOG was either not reached or only reached by the oldest restoration sites. This pattern was termed a “legacy effect”.

The values for pH showed a similar trend to WTD, with the lowest values in FOR and the highest in BOG (Figure 5a-c). In surface-water, there was a general pH increase with time since restoration, while in shallow and deep pore-water, high pH was also found in the 11-year-old restoration site (R-11).

For Ca, only the R-17 site had similar concentrations to the open bog (Figure 5e-g). In shallow pore-water, Ca increased slightly following restoration (R-0), while in surface and deep pore-water, Ca decreased from FOR to REST to BOG.

In deep pore-water, Al and NH$_4^+$ exhibited similar patterns, with higher concentrations in FOR sites and in recently restored sites than in BOG. For Al, concentrations had almost recovered 11 years post restoration (Figure 5d), but although NH$_4^+$ decreased through time, it did not recover fully to that of BOG (Figure 5h).
"Restoration effects" were defined here, as a marked change (increase or decrease) in water chemistry following restoration, outside the range of FOR and BOG controls. This trend was exhibited by DOC, E4:E6 ratio, NH$_4^+$, PO$_4^{3-}$, K, Al, and Zn (Figure 6). In most cases, these show a pattern implying a concentration increase in surface- and shallow pore-water in the period 0-3 years after restoration, which then reduces over time.

Immediately following restoration, DOC concentrations in surface- and shallow pore-water increased to a mean of ≥ 100 mg L$^{-1}$, from < 50 mg L$^{-1}$ in FOR sites (Figure 6a-b). DOC concentrations then decreased with time since restoration, recovering to levels similar to FOR after 17 years (post-restoration), but they remained higher than BOG. The E4:E6 ratio in surface-water following restoration (0-3 years) was similar to BOG and FOR. However, by 11 years post-restoration, it had increased by a factor of 1.5 and then began to decrease towards BOG conditions in the oldest restoration site (Figure 6c).

In surface- and shallow pore-water, PO$_4^{3-}$ and K exhibited a similar trend post-restoration. Sharp increases in PO$_4^{3-}$ were observed in early restoration sites (R-0) with 40-fold higher concentrations in surface-water than in FOR sites and an increase of 330-fold in shallow pore-water compared to FOR sites (Figure 6e-f). Potassium concentrations increased by five-fold, in both surface- and shallow pore-water compared to FOR sites (Figure 6g-h). For both PO$_4^{3-}$ and K, concentrations remained high in three-year old restoration sites, but results implied recovery to typical FOR and BOG levels within 11 years post-restoration. In slight contrast, NH$_4^+$ was elevated in youngest restoration sites (in shallow pore-water) but three-year-old post-restoration sites had concentrations triple that of FOR sites (Figure 6d). Results suggested that NH$_4^+$ continued to decrease with time following restoration but did not recover to match BOG sites within 17 years.

Aluminium concentrations also increased immediately post-restoration in surface- and shallow pore-water and did not recover to concentrations similar to BOG until 17 years post-restoration (Figure 6i-j). However, in this case, FOR sites were higher than BOG, showing in part the legacy effect of forestry in restoration sites.

Zinc exhibited an effect of restoration in surface- and pore-water, with the highest mean concentrations seen either three years post-restoration (shallow pore-water; Figure 6k), 11 years post-restoration (surface-water; Figure 6l) or 17 years post-restoration (deep pore-water; not shown). Compared to FOR sites, peak mean concentrations were up to 11-fold higher. FOR
and BOG had similar Zn concentrations but the oldest restoration site still remained relatively high at all depths in comparison to both.

3.2.4 Water chemistry variables mostly influenced by conifers – “forestry effects”

"Forestry effects" were defined, as variables with highest concentrations in forest controls which then decreased over time following restoration, with recovery to bog conditions by 11 years i.e. roughly a decade. Magnesium, Na, S, and conductivity were higher in FOR sites, than REST or BOG sites. Shortly after restoration (R-0), levels were largely similar to FOR sites. In some cases and particularly in surface-water, recovery to concentrations similar to BOG was visible by the three-year post-restoration point. By 11 years post-restoration, all were more similar to BOG than FOR (Figure 7). Thus, these variables exhibited the short-medium term influence of forestry. These effects were present at all depths (in surface- and pore-water) and Mg, Na and S showed a very similar trend, in terms of recovery over time from forestry, following restoration.
4. Discussion

There were clear differences in the water chemistry of afforested (FOR) and open bog (BOG) sites in terms of surface- and both shallow and deep pore-water samples (Figure 3). This confirms that water chemistry is a useful measure when considering recovery in forest-to-bog restoration sites. In general, we found three types of pattern in the inferred trends in water chemistry with variables showing: 1) long term legacy effects, i.e., moving from FOR to BOG but recovering only after 17 years or more, 2) restoration effects, i.e., marked changes in concentrations, generally within 3 years of restoration, that fell outside the range of both FOR and BOG controls, 3) short/medium term forestry effects, i.e., rapid recovery moving from FOR to BOG (within 3 - 11 years) in surface- and pore-water following tree removal. This confirms our hypothesis that some water chemistry variables would show strong but short-lived impacts of restoration management, while others might change little after several years, leaving enduring legacies of past afforestation.

4.1 Hydrology and chemistry feedbacks

The step-wise increase in WTD following restoration highlighted how this system partially recovered over time and clearly showed the difference between FOR and BOG land uses. The largest increase in mean WTD was between the FOR controls and the most recent restoration site (R-0), which was similar to that observed in formerly forested Finnish peatlands in a study covering 10 years post-restoration (Haapalehto et al., 2011). In our study, WTD in the oldest restoration site was still lower than the BOG (8 cm on average) and crucially, unlike in the bog, it did still fall below 25 cm on several occasions. This suggests a long-term legacy effect related to drainage and afforestation on WTD, where also the range of water table fluctuation remained greater than in the bog controls. Therefore, blocking only the main collector drains was not sufficient to fully raise the water table, within the time period of this study.

This implies that older restoration techniques (as used on the R-17 site) may not be completely effective even after 17-18 years post-restoration, and that further management intervention (at additional cost) may be needed e.g. blocking of the plough furrows. In addition to furrow blocking, surface smoothing, where the plough ridge created during tree planting is flattened, may help to convey water more evenly across restoration areas. Others have aided rewetting
by building dams high (50 cm) above the height of the peat surface (Koskinen et al., 2017), as peat can subside close to drain edges (Strack et al., 2008).

However, recent work has shown that overall moisture conditions indicated by plants have recovered on our oldest restoration site (R-17), therefore it is clear that restoration is progressing (Hancock et al., 2018). Feedbacks between mosses and water table (Waddington et al., 2015) may additionally help to restore a high water table similar to open bog conditions, as bog vegetation recovers.

WTD is a major influence on peatland pore- and surface-water chemistry (Mandernack et al., 2000) especially through changes caused in redox conditions. For instance, a higher WT is associated with the reduction or limited oxidation of certain S, Fe and N phases/compounds - changing their soluble concentration balance in pore-water (Steinmann and Shotyk, 1997; Mandernack et al., 2000).

4.2 Water chemistry variables showing a “legacy” effect

The increase in pH over time in restoration sites relates to the slow but incomplete recovery of the system from the legacy of the acidifying effect of forestry. Forestry can acidify soils through a number of mechanisms such as base cation uptake and formation of an acid humus layer (Nisbet and Evans, 2014), and this is one of its principal and long-lasting impacts on water quality (Malcolm et al., 2014). However, in coastal areas, the primary causes are aerial scavenging of atmospheric S and N (Fowler et al., 1989; Nisbet and Evans, 2014); and additionally, forests enhance sea salt deposition, (i.e., marine sourced Na and Mg), which through cation exchange displace acid cations in soil ($\text{H}^+$, $\text{Al}^{3+}$), thus contributing to the acidity of pore- and surface-waters (Evans et al., 2001).

Calcium concentrations also showed a legacy effect in surface- and pore-water, which may be related to displacement of Ca from peat exchange sites by marine sourced Mg and Na under forestry (Evans et al., 2001). In general, Ca inputs to surface- and pore-water in bogs are not influenced as strongly by regional precipitation differences as with marine sourced cations (Mg and Na; Glaser, 1992). However, atmospheric Ca may be intercepted and concentrated by the tree canopy enhancing Ca in throughfall and therefore in pore- and surface-water in afforested sites (Schmitt and Stille, 2005).

Following restoration, both displacement and atmospheric capture of Ca ceased, hence, concentrations could have started to decrease from the maxima in the FOR sites, although
dilution of Ca from pore-water was a slow process, recovering only in the 17 year old site. However, we also observed a slight increase in shallow pore-water Ca immediately following restoration (R-0). This may have been related, at least in part, to disturbance of the soil surface by tree-felling machinery, which may have exposed / introduced mineral material. The legacy effect of Ca concentrations, may present a barrier to Sphagnum colonisation, in the first decade post-restoration, when concentrations were elevated above BOG sites. Sphagnum species are known to have different niche overlaps in terms of Ca tolerance (Bragazza, 1997), but in general, growth can be impaired under elevated Ca concentrations (Spatt and Miller, 1981).

The highest NH$_4^+$ concentrations in this study were generally in the deep pore-water (where oxygenation is likely at its lowest), in FOR sites. This was also shown by the PRC, where NH$_4^+$ scored highest. Following planting, exudation by active conifer roots (Wieder, 1985) and mineralisation of organic N pools during periods of WTD drawdown (Daniels et al., 2012) could both have contributed to increasing the NH$_4^+$ pool. In all the restoration sites, NH$_4^+$ concentrations appeared higher than in the BOG controls, perhaps aided through release from decomposed peat through re-wetting (Zak and Gelbrecht, 2007).

4.3 Water chemistry variables showing a “restoration” effect

Following forest-to-bog restoration, DOC concentrations in surface- and shallow pore-water increased immediately, which concurs with results from other re-wetted or restored peatlands (Chow et al., 2003; Koskinen et al., 2017). DOC concentrations may be influenced by abiotic factors following rewetting; the increase in pH (increasing DOC solubility) and desorption of DOC from mineral elements in peat, may both play a role (Grybos et al., 2009; Clark et al., 2012). However, as pH increased only very slightly in the year following restoration (≤0.1 units in surface- and shallow pore-water), where maximum DOC concentrations occurred, other mechanisms may be more important.

The large increase in DOC following rewetting, is likely in part due to the stimulated enzyme activity that is commonly observed in drought-rewetting cycles (Fenner et al., 2011). Immediately following restoration (R-0 site), brash decomposition will likely also contribute significantly to enhanced DOC concentrations in pore- and surface-water (Palviainen et al., 2004; Gaffney, 2016).

In the longer-term, DOC concentrations in restoration sites have been observed to decrease below those of equivalent unrestored drained sites (Wallage et al., 2006; Höll et al., 2009), or,
naturally forested sites (Haapalehto et al., 2014). In our restoration sites, DOC concentrations decreased over time but only surface-water DOC was lower than that of FOR sites, 17 years post-restoration. A major influence on decreasing DOC concentrations over time may be the relative (between-season) stabilisation of the water table (Höll et al., 2009; Andersen et al., 2010), when compared to the rapid (19 cm) WTD rise observed in the first year following restoration. At the 17-year-old restoration site, mean DOC concentrations still remained ~two fold higher than BOG sites in both surface- and pore-water. As no restoration sites reached mean DOC concentrations as low as the BOG controls, this suggests continued enhanced microbial activity was occurring in restoration sites when compared to BOG (Bardgett et al., 2008). However, the slight increase in the E4:E6 ratio with time since restoration in surface- and shallow pore-water indicated that the DOC pool may be less humified and therefore younger. This could suggest that restoration releases younger carbon, from more recently laid down peat, but has little effect on deeper, older peat (Wilson et al., 2011).

In surface- and shallow pore-water, the elevated PO$_4^{3-}$ and K concentrations in the year following restoration (R-0) likely resulted from needle and brash decomposition, respectively (Asam et al., 2014b; Kaila et al., 2014). Increased pore-water PO$_4^{3-}$ concentrations following rewetting has also been attributed to release from labile peat in nutrient poor peatlands (bogs), where there are low concentrations of Fe and Al hydroxides which bind phosphorus in a less available form (Kaila et al., 2016), therefore some PO$_4^{3-}$ may be released by the peat itself following the post-restoration water table rise. However, we believe brash and needle decomposition to be the dominant source of both PO$_4^{3-}$ and K, given the large increases in concentrations of both during a short-term laboratory study (Gaffney, 2016). Despite the fast release of both PO$_4^{3-}$ and K, concentrations decreased in the R-3 site and continued to decrease to BOG levels by the 11-12 year post-restoration point.

In shallow pore-water, maximum NH$_4^+$ concentrations were measured in the R-3 site, suggesting a slower release of N (compared to P and K), which has previously been demonstrated for conifer litter (Moore et al., 2011). The timing of NH$_4^+$ release following rewetting was similar to the results of a Finnish study, which also found maximum concentrations three years post-restoration (Koskinen et al., 2017), although in this case trees remained standing.

Even 17-18 years after restoration, NH$_4^+$ concentrations in shallow pore-water were still 11-fold higher than in the BOG controls (7.5 fold in R-11); therefore, under current restoration
management, more time appears to be required for recovery of N to BOG state, as it is released more slowly during decomposition (Moore et al., 2011). Increased levels of N can increase bacterial biomass but induce microbial P limitation, stimulating further N release and P retention by microbes (Bragazza et al., 2012a). This in turn can encourage vascular plant growth, whilst discouraging Sphagnum (Xing et al., 2011). The remaining NH$_4^+$ in shallow pore-water may contribute to the variable recovery of Sphagnum at the oldest restoration site, e.g. by favouring competing plant species such as grasses (R-17; Hancock et al., 2018).

In the shorter term, following restoration (R-3), there were elevated concentrations of PO$_4^{3-}$ and K when NH$_4^+$ began to increase. An excess of N, P and K together has been found to have a stronger positive effect on vascular plants and negative effect on Sphagnum mosses, than N alone (Bubier et al., 2007; Larmola et al., 2013). This suggests that the starting point in terms of forest-to-bog restoration is very important, i.e., sites may be more conducive to recovery to a bog vegetation state if obvious sources of excess nutrients (conifer brash and stems) are removed.

The peak in Al in surface- and shallow pore-water immediately following restoration (R-0 sites) may be related to releases from needle decomposition in the early restoration period (Asam et al., 2014a), although others have found mostly Al accumulation during needle decomposition (Kaila et al., 2012). There were also signs of legacy effects on deep pore-water Al, which may be a long lasting effect caused by disturbance through ploughing (Muller and Tankéré-Muller, 2012), or, displacement of Al from cation exchange sites by scavenged cations from conifers (Evans et al., 2001).

Increasing trends in Zn were also found over time, with higher concentrations in older restoration sites. As Zn is normally present as a micronutrient in trees, obtained mainly from atmospheric sources (Boardman and McGuire, 1990), some release may be expected during decomposition of brash and needles. Other studies have found both Zn accumulation and release from conifer needles (Asam et al., 2014a), and, increased concentrations in surface-water following clear felling (Kuikkilä et al., 2014). However, this is the first time (to our knowledge) that an effect of this length has been documented in peatlands undergoing restoration. Increased Al and Zn concentrations in watercourses draining peatlands can be associated with deleterious effects on aquatic fungi, primary producers and salmonid fish (Niyogi et al., 2002; Duarte et al., 2004; Kroglund et al., 2008) - however, stream water concentrations for these elements have been found to be substantially lower than they are in pore-water (Gaffney, 2016).
4.4 Water chemistry variables showing a “forestry” effect

Concentrations of Mg, Na and S were highest in FOR sites (when compared to all other sites) and decreased through time. For all three elements, concentrations mostly recovered to levels similar to BOG sites within a decade post-restoration, indicating that they were more strongly influenced by the presence of the trees themselves, rather than by legacy effects from the forestry. Indeed, concentrations of all three elements are enhanced by forest capture (Harriman and Morrison, 1982; Evans et al., 2001) and here, due to coastal proximity, will be associated with marine sources (Harriman et al., 1995, 2001). A similar trend in recovery of Na in peat forest restoration sites was found by Haapalehto et al. (2014), in Finland. The trend in electrical conductivity across the chronosequence also reflected these elements, as a summative measure of ions (Vogt et al., 2010), showing it usefulness an indicator of “forestry” effects.

In FOR sites, high S concentrations could be due both to scavenging of S by conifers (Nisbet and Evans, 2014) and to hydrological feedbacks (Clark et al., 2005). Where WTD is lower, sulphate is produced by the oxidation of reduced inorganic/organic sulphur species (Adamson et al., 2001; Chapman et al., 2005), which then contributes to higher concentrations of S in pore-water (in FOR and recent REST sites). Conversely, when the WTD rises, anaerobic bacteria reduce sulphate back to less soluble states (hydrogen sulphide, reduced inorganic sulphur, organic bound sulphur; Mandernack et al., 2000; Adamson et al., 2001), which may help explain the concentration declines we observed with time.

4.5 Management implications for restoration success

In our study, the restoration method of fell-to-waste and drain blocking was effective in initiating bog recovery, however, it would appear that at least >17 years are required to align with BOG pore- and surface-water chemistry. When considering all our water chemistry variables together (measured by the PRC), the greatest recovery towards open bog conditions was achieved in surface-water (~75%) and deep pore-water (~90%), with more limited recovery made in shallow pore-water. This suggests that shallow pore-water was most disturbed by the restoration and afforestation process, most likely through a combination of the following factors: 1) continued water table fluctuation, 2) physical disturbance of surface peat by harvesting machinery and 3) vertical leaching from decomposing brash/tree material (including tree root plates, which decompose more slowly below-ground; Chen et al., 2001). Therefore, future management techniques should seek to address these barriers to enhance recovery.
Current forest-to-bog management techniques in the United Kingdom use harvesting of stems and sometimes of whole trees, rather than felling-to-waste as trees are older/larger and income from the timber can help offset some of the restoration costs (Anderson, 2010). Further enhancements to forest-to-bog restoration are also now being trialled (i.e., furrow blocking, surface smoothing, brash crushing, stump flipping) to assess the most effective method (Andersen et al., 2016; Anderson and Peace, 2017; Hancock et al., 2018). However, we consider there may be a trade-off between speed of recovery, and cost of management intervention.

As our results suggest, elevated $\text{NH}_4^+$ in the oldest restoration sites (R-17) is one of the main barriers to recovery, removing the source of nutrients (by harvesting brash and stems) is, in theory, a good solution. However, enhanced harvesting methods may not be entirely without negative impacts. In the first year following stem plus brash harvest, nutrient release may be enhanced by the extra surface disturbance caused by brash harvesting machinery (Gaffney, 2016). Nonetheless, the longer-term benefits of brash harvest might outweigh such short term/negative impacts.

In order for vegetation to recover and become comparable to intact bogs (i.e., hold abundant Sphagnum and other bog plants), a stable hydrology allowing high soil moisture and soil water pressure must be present throughout the year (Price and Whitehead, 2001). As yet, 17-18 years post-restoration, these conditions are not quite attained. Therefore, blocking of plough furrows can also be undertaken to further raise and stabilize the WTD, which, along with correcting nutrient levels, is key to Sphagnum recovery (Bragazza, 1997; Bragazza et al., 2012a).

Inevitably, a degree of caution must be applied to our findings, as trees on the various restoration sites studied here were of different ages when felled. This may have shortened recovery time in older restoration sites. For example, the quantities of nutrients released by trees in the R-17 and R-11 sites may be somewhat less than if these sites had held mature stands - due to the greater quantity of above/belowground biomass left on site (e.g. Saarsalmi et al., 2010). Also, the most-recent restoration sites may be more disturbed as they spent a longer period under drainage and forestry, leading to a greater loss of bog vegetation and greater decomposition of peat (Laine et al., 1995). Further, sampling was limited spatially and temporally and may not be applicable to all forest-to-bog sites; and, certain site-specific factors will inevitably create variation (i.e., peat depth, underlying geology, proximity to coast). We also acknowledge a temporal limitation from sampling only three occasions over one year (covering spring and summer). However, there is a strong seasonal pattern in nutrient release.
to pore-water in this region (Muller and Tankéré-Muller, 2012; Gaffney, 2016), where seasonal decomposition cycles are more active in warmer months. Therefore, we aimed to capture this by sampling over the growing season.

Nevertheless, our results show that pore- and surface-water chemistry are indeed useful indicators of recovery in the restoration of afforested peatlands, especially when carried out across decadal timescales in comparison to control sites. It is important to monitor water chemistry variables which are contrasting between FOR and BOG sites (before restoration even starts), as well as those which do not differ initially (but then are affected by restoration). Therefore, to identify the key pore- and surface-water chemistry variables, which are the most useful indicators of recovery (to assess restoration progress in formerly afforested peatlands), we chose variables showing either of these patterns. This allowed identification of a suite of water chemistry variables (Table 2). We first selected those, which appeared strongest on the PRC axis for each sampling depth (surface-, shallow or deep pore-water). Secondly, individual parameters were selected, which showed a “legacy” or “restoration” effect, which were also closely linked to other key bog functions e.g. vegetation recovery. Variables showing “forestry” effects were generally considered less essential to bog function, although conductivity was included as useful summative measure of water chemistry.
5. Conclusion

Currently, our results suggest that at least >17 years is likely required for complete recovery of water chemistry to bog conditions. Over sites representing 0-17 years post-restoration, we measured greatest recovery towards open bog conditions in surface-water (~75%) and deep pore-water (~90%), with more limited recovery in shallow pore-water. However, newer restoration methods, including conifer harvesting (stem plus brash) and blocking of plough furrows (to increase the WTD), may be able to remove some key barriers to recovery (i.e., hydrology and elevated N levels) and accelerate the entire restoration process. In this way, forest-to-bog restoration sites may return to functioning blanket bogs more quickly. We conclude that monitoring of surface-water and pore-water chemistry is very useful in terms of indicating recovery to bog conditions and we recommend monitoring (as a minimum) WTD, pH, conductivity, Ca, NH$_4^+$, PO$_4^{3-}$, K, DOC, Al and Zn as key variables.

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Hancock, M.H., Cowie, N., Field, R., 2014. The science of peatland restoration, RSPB Centre


Larmola, T., Bubier, J.L., Kobyljanec, C., Basiliko, N., Juutinen, S., Humphreys, E., Preston,


Spatt, P.D., Miller, M.C., 1981. Growth conditions and vitality of Sphagnum tundra community along the Alaska Pipeline Haul Road. Arctic 34, 48–54.


Sugimura, Y., Suzuki, Y., 1988. A high-temperature catalytic oxidation method for the determination of non-volatile dissolved organic carbon in seawater by direct injection of


Zak, D., Gelbrecht, J., 2007. The mobilisation of phosphorus, organic carbon and ammonium in the initial stage of fen rewetting (a case study from NE Germany). Biogeochemistry 85, 141–151.

Table 1: Sample site characteristics

<table>
<thead>
<tr>
<th>treatment</th>
<th>restoration year</th>
<th>age</th>
<th>code</th>
<th>n*</th>
<th>restoration method</th>
<th>drainage density</th>
<th>tree planting species / years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open bog</td>
<td>1996/2004</td>
<td></td>
<td>BOG 3</td>
<td>3</td>
<td>Hill drains blocked</td>
<td>&gt;25 m</td>
<td>-</td>
</tr>
<tr>
<td>Afforested controls</td>
<td>-</td>
<td>0</td>
<td>FOR 3</td>
<td>3</td>
<td>Felling and stem harvesting by excavator + drain blocking</td>
<td>2-4 m</td>
<td>Pinus contorta / Picea sitchensis 1984, 1989</td>
</tr>
<tr>
<td>Dyke</td>
<td>2014/15</td>
<td>0</td>
<td>R-0 6</td>
<td></td>
<td>Fell-to-waste by excavator + drain blocking</td>
<td>2-4 m</td>
<td>Pinus contorta / Picea sitchensis 1982-1984</td>
</tr>
<tr>
<td>Raphan</td>
<td>2011/12</td>
<td>3</td>
<td>R-3 3</td>
<td>3</td>
<td>Fell-to-waste by excavator + drain blocking</td>
<td>2-4 m</td>
<td>Pinus contorta / Picea sitchensis 1985-1989</td>
</tr>
<tr>
<td>Lonielist</td>
<td>2003/04</td>
<td>11</td>
<td>R-113</td>
<td>3</td>
<td>Fell-to-waste by hand (chainsaw)+ drain blocking</td>
<td>2-4 m</td>
<td>Pinus contorta / Picea sitchensis 1981</td>
</tr>
<tr>
<td>Talaheel</td>
<td>1997/98</td>
<td>17</td>
<td>R-173</td>
<td>3</td>
<td>Fell-to-waste by hand (chainsaw)+ drain blocking</td>
<td>2-4 m</td>
<td>Pinus contorta / Picea sitchensis 1983-1985</td>
</tr>
</tbody>
</table>

n* number of plots sampled

Table 2: Key pore- and surface-water chemistry variables, which are the most useful indicators of recovery to assess restoration progress in formerly afforested peatlands. WTD is included as a strong influence on water chemistry.

<table>
<thead>
<tr>
<th>variable</th>
<th>strong PRC (&gt;0.5)</th>
<th>effect</th>
<th>recovery time*</th>
<th>key function</th>
</tr>
</thead>
<tbody>
<tr>
<td>WTD</td>
<td>n/a</td>
<td>legacy</td>
<td>&gt;17</td>
<td>strongly influences water chemistry</td>
</tr>
<tr>
<td>pH</td>
<td>n</td>
<td>legacy</td>
<td>&gt;17</td>
<td>vegetation recovery / water quality</td>
</tr>
<tr>
<td>Conductivity</td>
<td>n</td>
<td>forestry</td>
<td>11</td>
<td>summative water quality indicator</td>
</tr>
<tr>
<td>Ca</td>
<td>n</td>
<td>legacy</td>
<td>17</td>
<td>vegetation recovery</td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>y</td>
<td>restoration</td>
<td>&gt;17</td>
<td>vegetation recovery</td>
</tr>
<tr>
<td>PO₄³⁻</td>
<td>y</td>
<td>restoration</td>
<td>11</td>
<td>vegetation recovery</td>
</tr>
<tr>
<td>K</td>
<td>n</td>
<td>restoration</td>
<td>11</td>
<td>vegetation recovery</td>
</tr>
<tr>
<td>DOC</td>
<td>y</td>
<td>restoration</td>
<td>&gt;17</td>
<td>carbon cycling</td>
</tr>
<tr>
<td>Al</td>
<td>y</td>
<td>restoration/legacy</td>
<td>17</td>
<td>water quality</td>
</tr>
<tr>
<td>Zn</td>
<td>n</td>
<td>restoration</td>
<td>&gt;17</td>
<td>water quality</td>
</tr>
</tbody>
</table>

* recovery time until all depths have recovered e.g. for pH shallow and deep pore-water may be faster (~11 years)
Graphical Abstract (colour – web version only)

Figure 1: Proposed patterns of changes in water chemistry following restoration of drained afforested blanket bogs.
Figure 2: Chronosequence of forest-to-bog restoration sites selected for pore- and surface-water sampling. Dark shaded (blue) plots are forest-to-bog restoration areas, within which light shaded (orange) plots are sampling sites. In Dyke, (felled 2014/15) each orange plot contained one sampling transect, while in the other restoration areas, each orange plot contained the three sampling transects for that site. Line hatched (yellow) plots are afforested controls and chequered (grey) plots are open bog controls (to interpret references to colour, the reader is referred to the web version of this article).
Width – 1.5 columns

Figure 3: Principal Response Curves (PRC) for water chemistry following restoration for (a) surface-water, (b) shallow pore-water and (c) deep pore-water using a space-for-time substitution. The curve shows the main axis of variation in water chemistry in the forest-to-bog restoration sites of different ages (REST) relative to the open bog control sites (BOG; reference state), along with the afforested control sites (FOR), as an additional reference line. The overall chemistry of the REST and FOR sites are expressed as canonical coefficients on the first principal component axis (PC1), relative to the reference BOG sites, represented by the zero line. The right hand axis shows canonical coefficients for all the water chemistry variables interpreted. Here, a higher positive value shows a stronger relationship with the curve, i.e., the top scoring parameters vary most when comparing REST and FOR sites with the BOG reference. Conversely, a strongly negative value indicates a trend opposite to that of the curve. The graph represents the period from 0-1 year following restoration (2014/15) to 17-18 years following restoration (1997/98).
produce this analysis, it was assumed that the BOG and FOR sites remain constant over time. However, both BOG and FOR reference lines are constructed from separate sites \(n = 3\), on three sampling occasions.

Figure 4: Water table depth (WTD) in each of the forest-to-bog restoration ages and in open bog (BOG) and afforested (FOR) control plots, measured five times over a one-year period. Boxplots show median and interquartile range with means (●). The x-axis labels show each site treatment. Restoration sites use the prefix “R” followed by age in years at time of sampling.
Figure 5: Response of water chemistry variables to forest-to-bog restoration which show a “legacy effect” of drainage and afforestation: defined by 1) a marked difference between afforested (FOR) and open bog (BOG) controls; and 2) restoration sites (over time) moving from conditions similar to FOR to become more similar to BOG and 3) across the restoration sites recovery to BOG
Boxplots show median and interquartile range with means (●) in either surface-water, shallow pore-water or deep pore-water, in each of the forest-to-bog restoration ages (denoted R-age) and in BOG and FOR control plots.

Figure 6: Response of water chemistry variables to forest-to-bog restoration, which show a "restoration effect": defined by a sharp change across restoration sites - indicating a marked
increase or decrease in concentrations outside the range for afforested (FOR) and open bog (BOG) controls. Boxplots show median and interquartile range with means (●) in either surface-water or shallow pore-water, in each of the forest-to-bog restoration ages (denoted R-age) and in BOG and FOR control plots.

Figure 7: Response of water chemistry variables to forest-to-bog restoration which show a “forestry effect”: defined by 1) a marked difference between afforested (FOR) and open bog (BOG) controls and 2) restoration sites moving from conditions similar to FOR towards that of BOG within 3-11 years (whereupon, complete recovery is achieved). Boxplots show median and interquartile range with means (●) for surface-water, shallow pore-water and deep pore-water, in each of the forest-to-bog restoration ages (denoted R-age) and in BOG and FOR control plots.