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Research article

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.

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; Nwaishi 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

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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), felling combined with 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"; Fig. 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" (Fig. 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

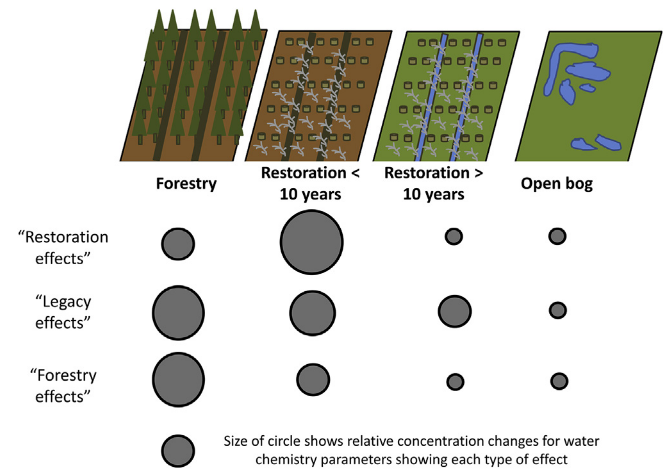

Fig. 1. Proposed patterns of changes in water chemistry following restoration of drained afforested blanket bogs.

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 hypothesised 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 (Fig. 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