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ONCE THE TREES HAVE GONE: EVALUATING CHANGES IN WATER QUALITY IN RESTORED BLANKET BOG OF THE FLOW COUNTRY, SCOTLAND

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INTRODUCTION

Covering over 4000 km^2, the Flow Country peatlands of Caithness and Sutherland are Europe‘s largest blanket bog. It is the UK‘s single largest terrestrial carbon store. It is also home to a wide range of designated species, including rare breeding waders (Lindsay *et al.*, 1988). What‘s more, it is at the source of many Atlantic salmon (*Salmo salar)* rivers; hence supports sports fishing – a critical income for rural areas in the Highlands.

In an attempt to improve productivity and grazing, a lot of hill drains were dug in those upland peatlands in the early 20th century. A more radical land-use change was initiated in the 1950s due to post-war timber shortages and, fuelled by tax-incentives, by the 1980s, around a fifth of all UK peatlands were covered in coniferous plantations. In the Flow Country, trees were planted in blocks altogether covering approximately 680 km^2, leading to the fragmentation of a once open landscape (Stroud *et al.*, 1987). Growing concerns about the impact on biodiversity and the potential losses of carbon (Cannell *et al.,* 1992) caused by this disturbance led to the first large-scale forest-to-bog restoration initiative. Between 1997and 2012, drains were blocked over 150 km^2 and trees were removed from 50 km^2 in the Flow Country.

Documenting the detrimental impact of afforestation on wader populations in adjacent open bog (Wilson *et al.*, 2014) led to changes in policy, whereby forestry needs to be removed to create buffer areas around designated peatland sites, and further planting on peat >40 cm is not permitted (FCS 2015). Recently, the Scottish Government pledged financial support to peatland restoration, with the expectation that this could contribute to meeting the reduction in greenhouse gas emission targets (Chapman *et al.,* 2012) and biodiversity and habitat directive targets (SNH peatland strategy).

Finally, with most plantations coming to the end of their growth rotation period (ca. 40 years) and now being ready for harvest, forest-to-bog restoration is likely to be a significant land-use change over the coming decade. Where initially small trees were rolled into furrows and collector drains blocked, as the trees got bigger over time, restoration methods had to change. Methods like whole tree harvest, mulching and brashing involve more machinery, which creates more initial disturbance. Sedimentation, pH alterations and metal pollution brought about by forestry and by forest-to-bog restoration could all impact freshwater biology (Ramchunder *et al.,* 2009) but this impact is poorly documented thus far. An overall better understanding of the consequences, timescales and extent of changes caused by restoration of afforested peatlands is needed to further inform management options.

Here we present our current understanding of how some of the key ecosystem processes respond to restoration. We present evidence gathered across a range of sites in the Flow Country and beyond to 1) evaluate how water quality changes over time following restoration and 2) assess the impact of restoration methods on known Atlantic salmon (*Salmo salar*) spawning sites. By documenting the short- and long-term impact of forest-to-bog restoration on ecosystem functions, we aim to provide sound evidence to support policy development, but also to feedback to practitioners which can improve the effectiveness of restoration.

METHODS

We conducted a small study in the Dyke River, a tributary of the Halladale River located in Surtherland, Scotland. The Dyke River and a number of burns and streams which feed it are known habitats for Atlantic salmon. In autumn 2014, 10 pre-identified Salmon spawning sites, known as ―redd” sites, in the Dyke River were covered with a slab to prevent spawning. They were divided as follows: four spawning sites were located upstream of a forestry plantation in an area of blanket bog (upstream), three sites were within a section of the plantation where restoration management was ongoing (forest-to-bog) and three sites were downstream of the restored area, still in the plantation (downstream) (Fig 1). Artificial arrays divided in tiers (75cm, 175cm and 275cm) were set up in the stream bed at each site while sediment baskets were set up in the upstream and downstream sites only. We measured pH, dissolved oxygen (DO), electrical conductivity (EC) and sediment accumulation periodically between

November 2014 and March 2015, covering the length of Salmon egg incubation and hatching. This also covered the period during and immediately after management, which included tree felling and harvest as well as drain blocking.

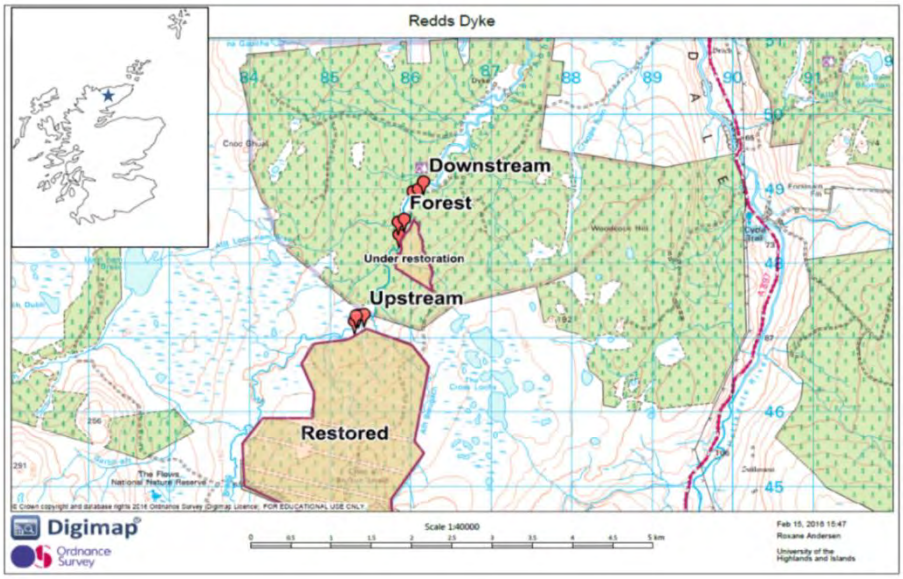

Figure 2: Map of the sampling locations: four sampling points upstream of the Dyke forest, receiving water from open bog and restored (2003-2004) area, three sampling points receiving water from the area under restoration and three points downstream, receiving water from forestry.

All the water samples were taken in the same stretch of river, hence are not independent from each other and this spatial auto-correlation can be modelled and taken into account in the comparison of sites. To do so, we constructed an asymmetric eigenvector map (AEM) and created a matrix of spatial variable describing the spatial connectivity between each sampling point as dictated by the direction of the flow (upstream to forest to downstream) (Blanchet *et al.,* 2010). We then used a redundancy analysis (RDA) to test whether any of the spatial variables generated were significantly related to the four physico-chemical parameters. This allowed us to understand whether a sampling point was likely to be influenced by what happened upstream of it and if so, how far the effect was likely to extend to. We also used redundancy analysis to assess whether stage height was related to the physico-chemical parameters. As it was significantly related, we then tested how the chemical parameters varied across depths within sites over time once the influence of stage height had been taken into account.

RESULTS AND DISCUSSION

Summary of impact from restoration on water and water courses

Many studies have looked at the impact of drainage and/or drain blocking on stream properties (e.g. Ramchunder *et al.,* 2009), but fewer have looked at the impact of tree removal and drain blocking combined. Some studies have shown increases in sediment load and water run-off following conifer afforestation; a consequence of the mechanical (e.g. digging) and the physical disturbances (e.g. cracking, drying) of the peat mass and the mineral soil underneath (Ratcliffe and Thompson, 1988; Ramchunder *et al.,* 2009; Clarke *et al.,* 2015). The disturbance associated with restoration could trigger similar responses. A notable impact of forest-to-bog on water quality is the increased nutrient (N, P) concentration and export related to decomposition of brash and needle litter left on site (Table 1). This impact has been noted both in the pore water (Asam *et al.,* 2014) and in stream water in catchments where restoration work was undertaken (Smith, 2015, O'Driscoll *et al.,* 2014a, Rodgers *et al.*, 2010; Clarke *et al.*, 2015), but usually subsides after two to four years. O'Driscoll *et al.* (2014b) suggested that buffer areas between forestry and rivers could be a potential option to reduce phosphorus (P) load and potential harm to freshwater organisms. As well as nutrients, in some cases, increased metal (Al, Fe) concentrations and exports have been observed (Müller *et al.*, 2012) and have been related to changes in pH and organic matter, and to chemical composition of the peat.

Table 1: Summary impacts of forest-to-bog restoration on pore and stream water chemistry DOC = Dissolved Organic Carbon, P = Phosphorus, N = Nitrogen, SRP = Soluble Reactive Phosphorus,

Variable impacted	**Pore water**	**Receiving burns and streams**
DOC	[DOC] in shallow afforested peat	Export depends on catchment properties
P	↑ [P] during the first 2-4 years as needles and brash decay	↑ Export total and SRP during first 2 years; Buffer zone method could be used efficiently in peatland forestry to moderate ↑ [P] concentrations
N	↑ [N] and mineralisation rates	↑ NO_3 export
Suspended solids (SS)	N/A	↑ total SS during peak flow events, substantial ↑ SS during windrowing
Metals	↑ [Al], [Mn]	Export of Fe and Al; dependent on peat characteristics Changes in seasonal cycles of biologically active (C, Si, P) and organically complexed (Fe, Al) elements.
References	*Asam et al., 2014; Gaffney et al., 2014; Müller & Tankere Müller, 2012;Smith 2015*	*Vinjinli, 2012; Asam et al 2014; Rodgers et al 2010; Clarke et al., 2015; O'Driscoll et al., 2014a; Müller & Tankere Müller, 2012; Müller et al., 2015*

Influence of connectivity

In this case, we found that the spatial connectivity between the 10 sampling sites was not significantly related to the water chemistry parameters measured (F=0.28, p=0.99). A possible explanation is that each stretch of the river sampled receives water from different subsidiary burns but also from near-surface through flow and overland flow, thereby creating a dilution effect. This is the case in many other UK rivers which drain areas of upland blanket peat (Holden and Burt, 2003). Thus, it seems that the immediate influence of those micro-catchments may be important in determining the chemistry of a given sampling location. Similar results have been observed by Shah (2015) in a study looking at the impact of afforestation on water chemistry in the Halladale River, in which the Dyke River flows.

Differences in chemistry between sites

For EC, DO and pH, the three sites presented the same behaviour over time, which suggests that restoration management (felling and drain blocking) has little or no influence on the water quality over the very short term (months). The temporal patterns were similar across depths (only surface data shown). For EC and DO, the values were highest in January and February in all sites. The pH values were inversely related to stage height (Fig. 2), with higher pH at low stage heights and vice-versa. The opposite trend was observed for EC and DO. It is known that during low flows, acidity can be neutralized by calcium carbonate ($CaCO_3$) in streambed sediments (Miller *et al.,* 2001).

Differences in sediment load between sites

The mass of the sediments in the sediment basket also appeared more influenced by the season and inherent catchment characteristics than by management. Generally, there was a decrease in sediments in both sites (upstream and downstream) over time, with proportionally greater reductions in the downstream site. Overall, the upstream sites, which mostly drain open blanket bog and older restored sites, received more sediments than the downstream sites, which drain afforested and restored sections (Fig. 3). This could be related to sediment traps installed along the collector drains as part of the restoration management, which appear to effectively mitigate any potential impact of the machinery and the physical disturbance.

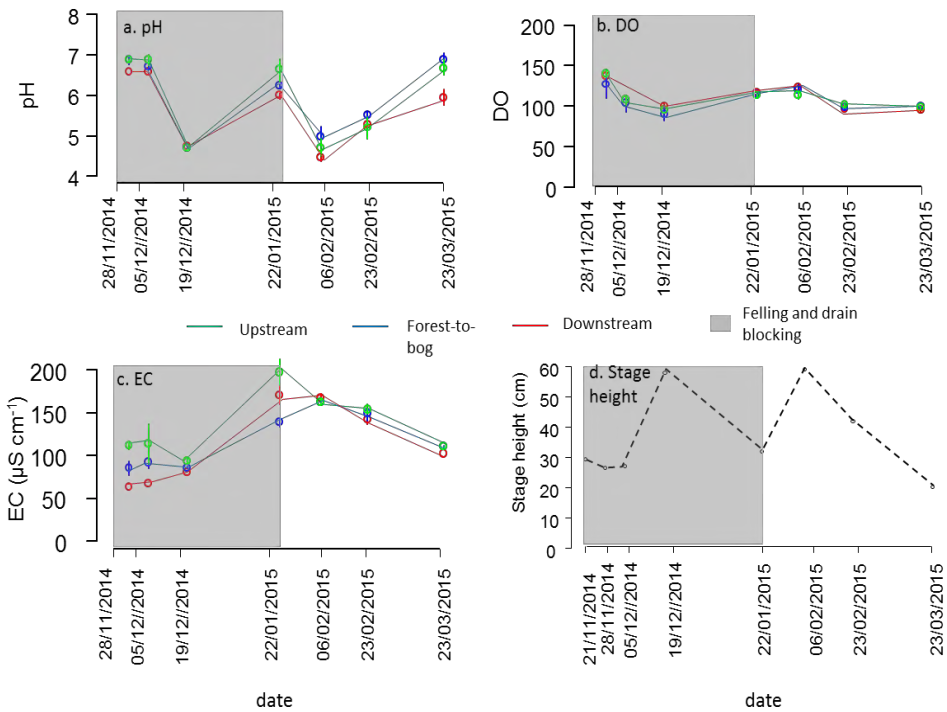

Figure 3: Temporal trends for a) surface pH, b) surface oxygen (DO), c) surface electrical conductivity (EC) and d) Stage height (height of water in the river) measured in the River Dyke in sites upstream, within and downstream of the restoration work between November 2014 and March 2015. Samples were taken prior, during and after the restoration work.

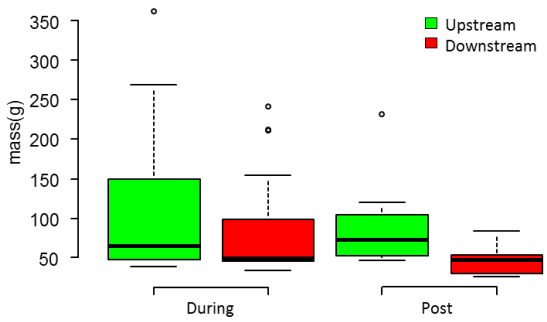

Figure 4: Changes in sediment mass in the Dyke river bed in sites upstream and downstream of restoration work between November 2014 and March 2015. Samples were taken during and post management (felling and drain blocking).

CONCLUSION

While there are documented impacts of forest-to-bog restoration on the water quality both *in situ* and in receiving water course, our study demonstrates no immediate impact of management on sediment load on the river bed, nor on EC, DO and pH in the river Dyke at known spawning sites. We noted that compared to open and older restored bog, forested areas could increase the sediment export but sediment traps appear effective at reducing the load associated with management and disturbance. We also observed an influence of seasonality on the physico-chemistry of the river associated with stage height, and a notable influence of the micro-catchment properties, which might have been misinterpreted if we had not had a control-impact design.

In summary, short-term changes associated with management are likely to be catchment-specific and influenced by local climatic conditions. From a freshwater biodiversity perspective, management should aim to minimise and mitigate short-term changes/impacts for example through installing sediment traps. In any case, it may be argued that short-lived ecosystem changes resulting from disturbance and improved water quality arising from restoration may still be better than longer-term chemical and physical alteration to water courses caused by continued forestry plantations. Further research should aim to assess the direct responses of freshwater organisms to forest-to-bog restoration management, and understand the hydrological processes driving the chemical changes at a wider catchment scale and over longer time-periods.

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