From landscapes to freshwater invertebrates: understanding the effects of peatland restoration on Atlantic Salmon (*Salmo salar*) habitat in the Flow Country.

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The Flow Country

Tanneberger et al., 2017

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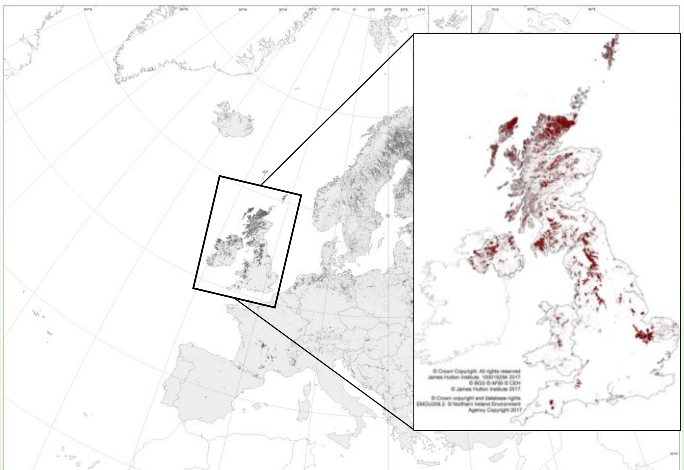
The Flow Country



Tanneberger et al., 2017

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- This was due to the outstanding nature of its actively accumulating blanket bog landscape, unique diversity of landforms and species.

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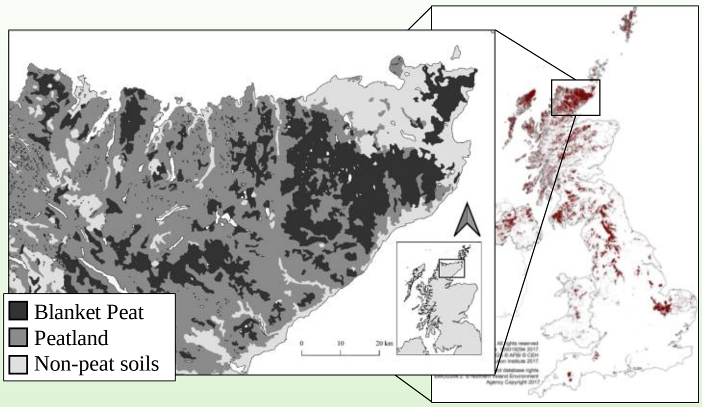

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- In 2024 it was made into a UNESCO World Heritage Site.
- This was due to the outstanding nature of its actively accumulating blanket bog landscape, unique diversity of landforms and species.
- It has been accumulating carbon for about 9,000 years.
- Some parts have peat over 8m thick!

Tanneberger et al., 2017

However, after the Second World War, large areas of peatlands were also converted into commercial forestry plantations. In the UK and Ireland in the late 20th century these plantations were established over >800 Kha of peat that required intensive drainage with deep ditches being ploughed, before the peat could be planted with the non-native crop tree species that was normally a mixture of Sitka spruce (*Picea sitchensis*) and Lodgepole pine

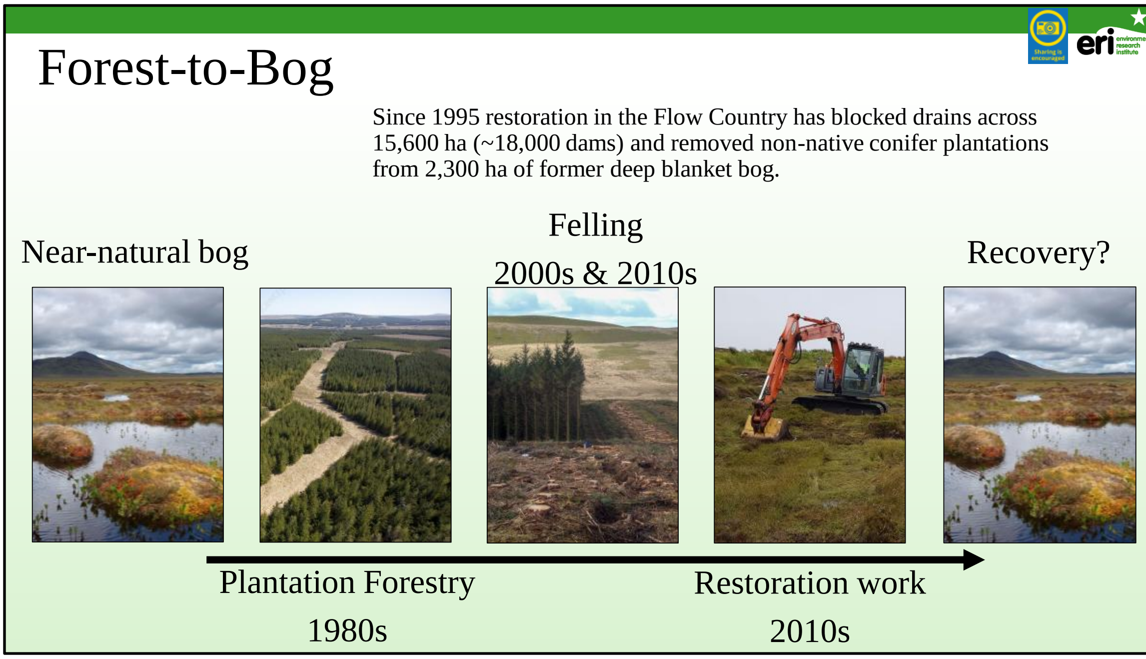
(*Pinus contorta*) (Andersen et al., 2016). The Flow Country in Northern Scotland is one of the largest Atlantic blanket bogs in the world with an area of 400000 km^2, where 67,000 km^2 underwent this afforestation during the 1970s-80s (Lindsay et al., 1988). The intensive drainage is required to lower the water table and allow tree establishment, whereby tree evapotranspiration further contributes to peat drying and reduced water table (Sarkkola et al., 2010).

The RSPB Scotland's nature reserve Forsinard within the Flow Country has formed around historic commercial forestry plantations attempting to restore extensive areas back to a near-natural bog. This push towards restoration by RSPB Scotland was driven by the loss in habitat for dunlin (*Calidris alpina*), European golden plover (*Pluvialis apricaria*) and common greenshank (*Tringa nebularia*), from both direct loss to plantation forestry and the associated avoidance edge effect in adjacent peatlands (Lindsay et al., 1988; Wilson et al, 2014; Hancock et al., 2009). Similar restoration took place on other landownership, e.g. in the state of forestry sector (Andersen & Peace, 2016).

The Flow Country – 1970s

- The Flow Country remained largely free of trees until the 1970s.
- 67,000 ha (17% of the Flow Country) were fenced off, drained, and planted with non-native conifers (Stroud et al. 1987).
- This threatened to destroy vast areas important for both wildlife and carbon storage.

Following evidence-based changes in policy, the practice of planting non-native conifers on deep peat is no longer allowed (Forestry Commission Scotland 2015), and there have been efforts and funding deployed to restore degraded peatland through interventions collectively termed “forest-to-bog” restoration. The key requirement for peatland restoration is often a recovery of natural peatland hydrology, most easily recognised as a decrease in water table depth to be near or at the surface (Anderson & Peace, 2017; Gaffney et al., 2018). It is usually expected that once the hydrology has moved towards that of a natural peatland, the peatland specialist vegetation assemblages should re-establish, albeit not necessarily linearly (Hancock et al., 2018). Restoration of natural hydrology and vegetation cover should also achieve the desired result of peatland function where it functions to sequester carbon, regulate river flows, provide a habitat for wildlife and normally cycle nutrients (Bonn et al., 2016).



But how easy is it to recover, a lot of studies have shown that many measurable features like vegetation, water quality and carbon sequestration can be done in 20 years.

Across the RSPB Forsinard reserve where this restoration has taken place many of forestry areas were restored experimentally aiming to find the most efficient route back to near natural bog. This means that there was variation within the FW and EF catchment groups in terms of felling and secondary intervention. However, the

FW and EF are still clearly divided based on initiation of restoration and intensity as described below.

Felled-to-waste (FW) was used during the first large-scale UK forest-to-bog restoration work in the late 1990s / early 2000s conducted in the Flow Country (Hancock et al., 2018). The FW method as studied here involved felling relatively young (~20 years) trees and leaving the stem, and branches on-site, as brash or “to-waste”, in the adjacent furrows. Many larger furrows and drains were blocked at this time. The “waste” was left on site for 10-12 years, as the FW method planned to return once the woody debris has become brittle and rotten with age so that it could be easily crushed into the furrows. Following this there were additional secondary interventions to further re-wet (furrow blocking) and smooth the sites (cross tracking). These sites are characterised by having large pieces of brittle brash from the felled trees, significant revegetation, almost no bare peat, and some remaining furrow-ridge features, because furrow blocking was used more than whole surface reprofiling as was more common in EF.

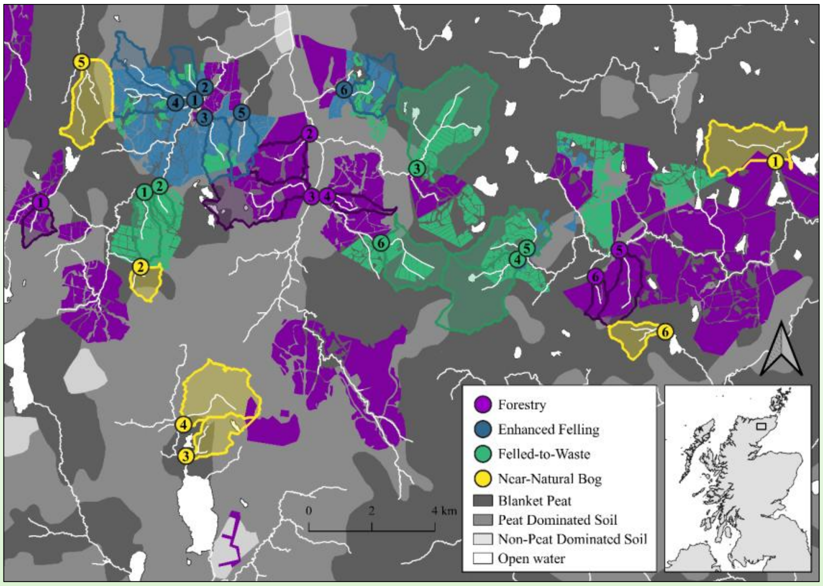
Enhanced Felling (EF) was started in the 2010s partly due to evolution of restoration techniques, but also as the trees were older (~30 years); this made conventional harvesting more viable. This reduced on-site waste as the main stem was removed for timber with only the branches and stumps were left behind. Secondary intervention was started soon after felling (1 – 3 years) with the all the brash being removed, or mechanically crushed and mulched. The stumps were flipped and compacted into furrows. Drains and furrows were blocked to re-wet the site, alongside surface smoothing, carried out by the machine tracking across the site and by some direct pushing of plough ridges into furrows. Some trees were not commercially viable, due to being very small, despite 30+ years of growth (potentially due to very wet conditions or missing fertiliser applications), so FW was still occasionally used in addition to whole tree mulching *in situ*. This greater intensity of initial disturbance by felling and rapid secondary intervention was undertaken with the aim to reach a banket bog like condition more rapidly than what was previously implemented, as activities like brash removal help prevent nutrient enrichment, which could otherwise have potentially slowed the restoration trajectory (Gaffney et al., 2022). These sites are characterised by having large quantities of brash debris that has been crushed or mulched on site, little vegetation recovery due to the forest-to-bog restoration only just recently taken place, and smoother surfaces compared to the FW sites as the furrow-ridge pattern has mostly been removed by reprofiling of the surface.

But has the water quality changed?

Forest-to-bog is a term for when a plantation, of often non-native conifer species, has been planted on what was once open peatland habitat is being restored back to the peatland it once was with the hope to recover its previous structure, function and biodiversity.
Plantation forestry on blanket bog is now largely historical due to the profound impact it has on the peatland landscape, biodiversity and carbon balance.

Previous studies have demonstrated that forest to bog restoration impacts water quality (Gaffney et al., 2022; Shah & Nisbet, 2019), but few studies have compared catchments techniques, rate of recovery or implications for water freshwater ecology. There are water quality issues with forest to bog restoration that are potentially influenced by the methods used to restore them. The felled-to-waste method leaves large quantities of decomposable material onsite, and the disturbance of the shallow peats both provide a source of significant nutrients (Gaffney et al., 2022; Anderson et al., 2016; Muller et al., 2015) in what should be a low nutrient availability blanket bog ecosystem. Additionally, these nutrients can leach into drainage waters (Gaffney et al., 2022; Shah & Nisbet, 2019; Gaffney et al., 2021; Koskinen et al., 2017), especially in catchments where trees have been mulched as they decompose more rapidly (Muller et al., 2015). Increased nutrients can lead to eutrophication, especially in oligotrophic waters. Previous instances have been recorded where algae levels increased following tree felling (Holopainen & Huttunen, 1998; Shah & Nisbet, 2019; Finnegan et al., 2014), leading to negative impacts on freshwater life, including freshwater pearl mussel populations (FIE, 2006) and macroinvertebrates (Drinan et al., 2013).

Now with many plantations coming to the end of their rotation, there is an acceleration of restoration at the same time as an increase to the scale of intervention, often targeting large portions of catchments over short periods of time. IUCN UK Peatland Strategy target by 2040 is to have 20,000 km^2 of peatland in good condition, either under restoration or sustainable land management (Artz et al., 2019). While the more intense forest-to-bog restoration work offers potential for cutting years off recovery times, there remains a lack of knowledge around the consequences in the short term for fresh water and the wider ecosystems.



Sampled stream water draining catchments of:

Plantation Forestry

2010s - Enhanced Felling

2000s - Felled-to-Waste

Near-Natural Bogs.

In addition to the main river

This study took place in the Flow Country peatlands of Caithness and Sutherland, in the Scottish Highlands. The Flow Country stream sites are located in or close to the Forsinard Flows nature reserve, managed by RSPB Scotland. The study also included stream on land belonging to the Strathmore and Bighouse estates. The sampling locations were in the catchments of the rivers Halladale, Thurso, Strathy and Helmsdale. To determine water quality changes with forest-to-bog restoration we used streams that had catchments consisting of primarily felled-to-waste (FW) or enhanced felling (EF) techniques, in addition to unrestored plantation forestry and near-natural blanket bog that acted as controls, representing the plausible pre- and post-restoration states, respectively.

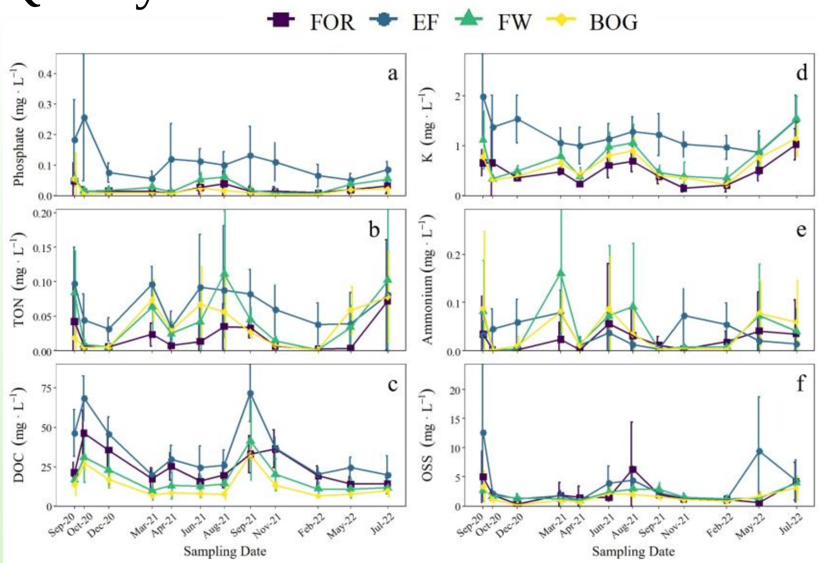
There were 24 sample streams, 6 of each land use “treatment” category, with sampling taking place over 23 months starting in September of 2020 ending in July 2022. In total water quality sampling was undertaken 12 times and occurred roughly every other month apart from winter periods where inclement weather conditions (snow / ice) often necessitated that collection could only be taken when feasible. Streams were selected based on their catchments being dominated by one of the treatments of interest: near-natural bog (BOG), plantation forestry (FOR), Felled-to-Waste (FW), and Enhanced Felling (EF). These streams also had minimal confounding land uses, which would have diluted water quality signals. In addition, three sites along the Halladale River and, five sites along its tributary, the River Dyke, were sampled throughout the period, at the same time as the streams. These river sites were to monitor water quality changes in potentially more ecologically important river systems.

Briefly at each site an *in situ* measurements of water pH, electrical conductivity and temperature were taken using a pre-washed Hanna Waterproof probe connected to a pH/EC meter (Hanna Instruments, HI-991300). The water sample for measuring turbidity and suspended solids was collected in a 1L (Fisherbrand™ Polypropylene Wide-Mouth Bottle) bottle. The water sample for measuring TOC, colour, NH4, PO4, NO2 and NO3 was filtered before being stored in 50ml plastic tubes (Fisherbrand™ Polypropylene Centrifuge Tubes). A 50ml syringe (BD Plastipak 50ml Luer-Lok Syringe) was rinsed with the sample stream's water three times before attaching a 0.45 µm syringe filter (Whatman syringe filter, 0.45 µm cellulose acetate filter membrane, until January 2021 when Fisherbrand 25mm Syringe filter, 0.45 µm Nylon was used).

Stream Water Quality

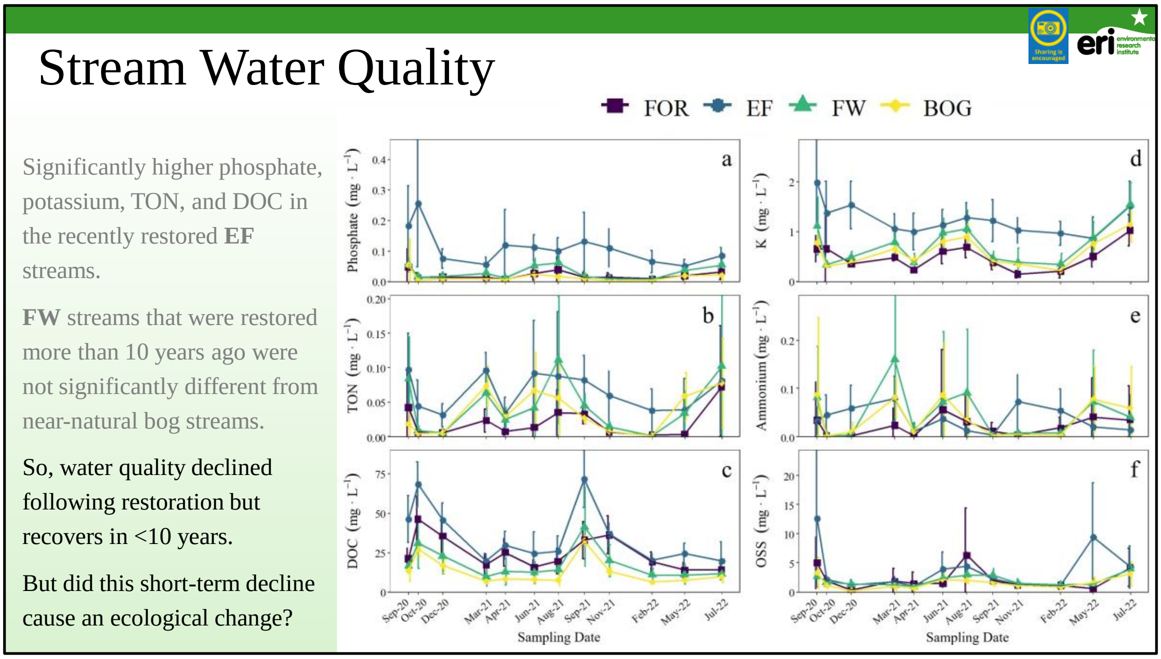
Significantly higher phosphate, potassium, TON, and DOC in the recently restored **EF** streams.

FW streams that were restored more than 10 years ago were not significantly different from near-natural bog streams.

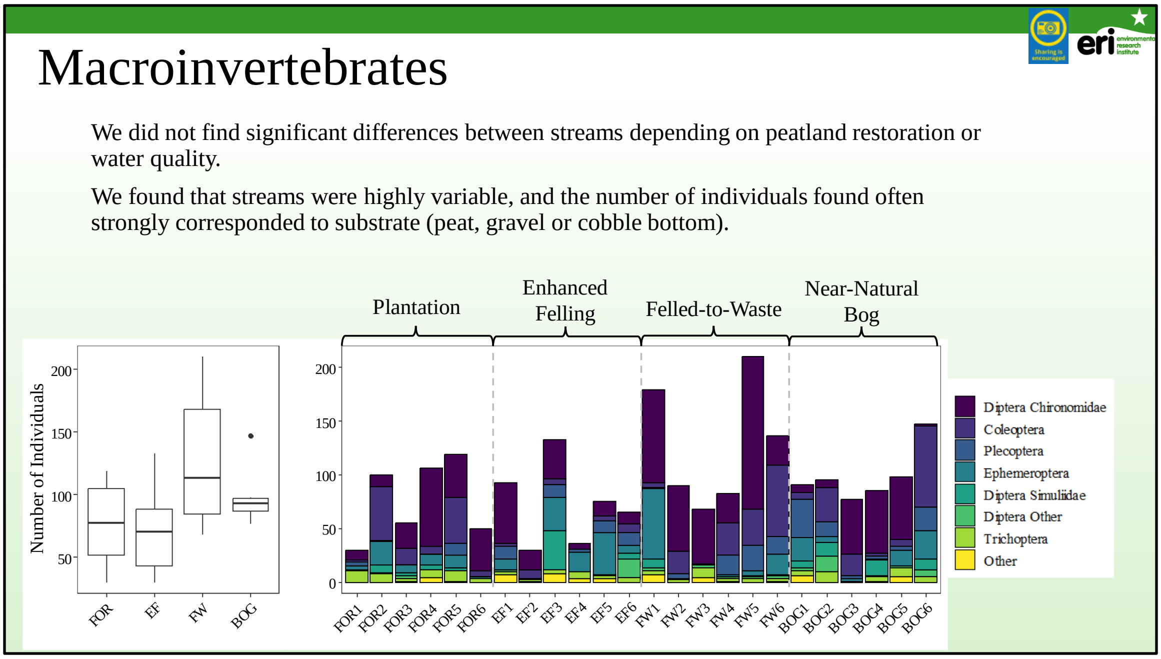


Principal response curves (PRC) were used for multivariate analysis of the data. PRC is a multivariate method that compares the overall change in a data set, over time, in relation to an *a priori* control or reference (Van den Brink & Ter Braak, 1998). The chosen reference in this study was the streams draining near-natural bog that had undergone little human interference within their catchments either by plantation forestry or drainage. This statistical method was used to compare the water chemistry differences between near natural bog catchments against afforested and restored catchments. Variables in concentrations were transformed by 1+log10 for standardisation. The PRC graphical output demonstrates the deviations over time of the catchment groups: afforested (FOR), Enhanced Felling (EF), and Fell-to-Waste (FW) in relation to the near-natural bog (BOG) streams. Significance testing was by ANOVA – Monte Carlo permutations (*n*=999). Both axis 1 and 2 were found to be significant ($p = <0.05$) and were therefore plotted, the first axis representing the stronger treatment x time interaction (the way in which treatments differed over time) within the water quality data.

Water quality variables that were found to be influential to the PRC were tested for significant differences between the stream treatments (BOG, FOR, FW, EF) using linear mixed-effects models (LMERs) (package nlme, Pinheiro et al., 2016). The water quality variables normality was tested for using histograms and QQ-plots. Non-normal data was corrected for by using log transformations for phosphate, ammonium, DOC, Abs_{400}, K, OSS, Al, Fe. Temperature represented a near-normal distribution, but incomplete, and did not require log transformation. The stream pH demonstrated a bimodal distribution that is common in peatland streams due to calcium/carbonate change over, its model residuals demonstrated normal distribution and therefore did not require transformation. LMERs allowed for us to account for the treatment, and random variables (sampling stream and date). We built two models per WQ parameter, with one including the predictor variable, and tested the difference between the models (ANOVA base R function, with Bonferroni correction) ability to describe variance. If the stream catchment treatment was found to explain a significant degree of variation, then the Tukey post-hoc test was used to identify between which pair of treatments this difference occurred.



The water quality parameters that were found to be most influential on the PRC were further tested with linear mixed-effect models (LMERs) using catchment treatment as a fixed effect, and sampling date and stream as random effects. Significant differences between treatment means using Tukey Tests are reported in Table 3.2. For the water quality parameters appearing to cause the seasonal trend away from near natural bog streams in Axis 1 (phosphate, ammonium, TON, DOC, OSS, Fe, Mn, K) we found that in terms of nutrients, phosphate, phosphorus (P), and K were significantly higher in concentration in EF compared to BOG streams, but ammonium and TON were not significantly different from BOG levels. These trends of enriched phosphate and K in EF streams compared to all others are maintained throughout the study period (Figure above a & d), with phosphate ~10x, and K ~2x greater in EF compared to all other stream catchment types. The EF streams were also on average higher in TON (0.7 mg/l) compared to all other stream types but were only significantly higher than the FOR streams (0.02 mg/l) (Fig b). There was no significant differences between average ammonium in streams, and there were no clear trends throughout the study (Fig e). The BOG, FOR, and FW streams increased in their average phosphate, K, and TON during the dry periods summer periods of the study, with EF streams showing less seasonality (Fig a, b & d) this could explain the trend in PRC Axis 1 where these summer periods are associated with all stream catchment types becoming more similar in terms of water parameters.

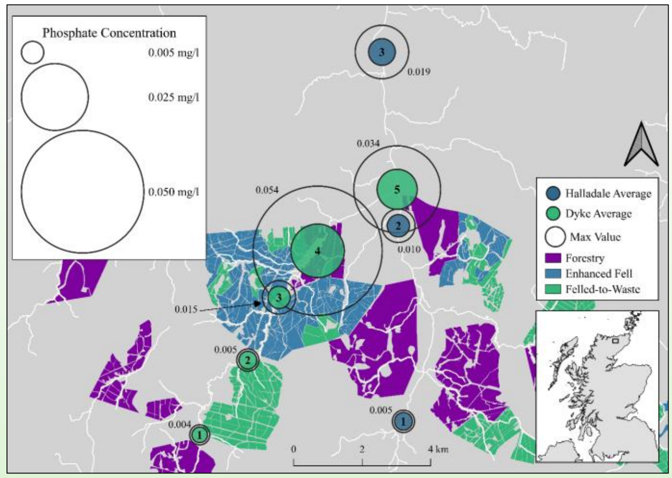


Our study provided the first detailed description of freshwater macroinvertebrates communities in different streams in the Flow Country blanket bog comparing between different land uses within their catchment areas with various types and stages of forest-to-bog restoration. We believe that there would be different assemblages of macroinvertebrates in streams due to the water quality differences, as previous studies have found the water quality impacts due to drainage, burning within catchments, and water source affect freshwater macroinvertebrates (Ramchunder et al., 2013 & 2012; Vuori & Joensuu, 1996; Friberg et al., 2001; Fierro et al., 2017; Vuori et al., 1996). However, our study found no significant changes in the stream macroinvertebrate community composition that could be attributable to variations in water quality parameters. Despite significant differences in water quality metrics observed mainly between EF and near-natural BOG streams these variations did not result in notable changes in the macroinvertebrate communities.

River Phosphate

When testing in the larger rivers we found that there was little change due to restoration.

Except for phosphate which was significantly influenced by upstream restoration on the River Dyke (AEM, F = 13.2, and p = 0.001). Though would still be "good" water quality.



Blanchet et al., 2008. Modelling directional spatial processes in ecological data

Scotland River Basin District Standards

Asymmetric eigenvector maps (AEM) were used to test if there was a significant relationship between water quality and the position of the sampling points on the river Dyke and where the Dyke met the greater Halladale River. As previously demonstrated with modelling by Blanchet, Legendre and Borcard (2008), we used the "adespatial" package (Dray et al., 2015). This was to determine if there was upstream influence on water quality that could be caused by restoration streams entering the larger river network, as previously demonstrated by Andersen et al., (2018). The water quality parameters used were ammonium, phosphate, TON, pH, conductivity, temperature, Abs_{400}, TSS, OSS, ISS, DOC, DIC, and dissolved elements Al, Fe, K, Mg, Mn, P, S, and Zn with all values in measured in mg/l using their natural logarithm for AEM analysis. The AEM was analysed with canonical redundancy analysis (RDA) and then by the “ANOVA” permutation test function, in the “vegan” package (Oksanen et al., 2007). Accounting for each sampling time (as “blocks” in the RDA). This analysis was to find if the water quality at downstream river positions was significantly related to upstream river sampling sites, that could be caused by forest-to-bog streams entering the river higher in the catchment, and altering water quality.

River Temperature

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The only troubling result was the high temperatures (24°C+) in the summer where salmon are likely to be at risk to future warming.

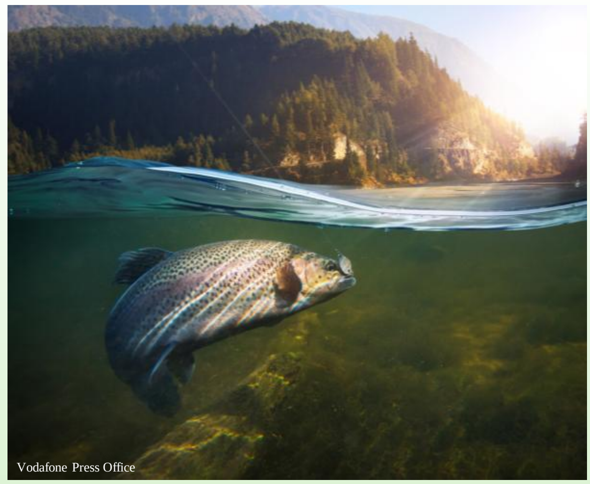
Blanchet et al., 2008. Modelling directional spatial processes in ecological data

Pronounced like Fey khoroon vor
Native tree species in the Flow Country like birch, oak, rowan and willow are not bog colonising species like the non-native lodgepole pine or Sitka spruce so can be reestablished in the riparian area. However high grazing pressure have historically caused a decline of woodland area, as we can see what happened in the Armadale burn with far less historic pressure.

We found that large upland tributaries like the River Dyke were getting very warm in the summer months, close to 25°C. These temperatures are stressful to the cold adapted freshwater life, and these temperatures can be expected to become more common under climate change scenarios (Parmesan, 2006; Lenoir & Svenning, 2015). Scotland is expected on average to get hotter and drier summers and milder and wetter winters (Werritty & Sugden, 2012), this increases the risk rivers are at low flow or at high temperatures. There are initiatives that could help increase the resistance of these freshwater habitats against climate change. Peatland restoration is often cited as a way of improving the flow of water, reducing peak flows and retaining water, however studies have demonstrated that even restored blanket bogs are still flashy systems (and do not act like sponges as is often implied) (Parry et al., 2014; Price 2016). The revegetation of hagged, degraded, or bare peat can increase the surface roughness, reducing the overland flow, and this has been demonstrated to be effective at reducing peak flows (Shuttleworth et al., 2019; Holden et al., 2008). But this level of degraded peat is not common in the Flow Country, so reasonable reductions in peak water flow are unlikely to be seen from peatland restoration alone (Andersen et al., 2024; Hancock et al., 2018b; Howson et al., 2021). Additional methods that could be effective in the Flow Country are the recovery of riparian woodlands (Revell et al., 2021; Monger et al., 2022), and the installation of “leaky” dams (Barnes et al., 2023; Villamizar et al., 2024). Dams are often removed due to negative impacts on the river ecosystem but leaky dams, made of large woody debris above the baseflow water level, can mimic the natural obstruction, caused by fallen trees, at high water flows. Naturally Eurasian beavers (*Castor fiber*) would have construct leaky dams in the Flow Country that can slow the flow and create refuge ponds in droughts (Puttock et al., 2021; Malison et al., 2014); however, they are extinct in the Flow Country. Reintroductions are happening in Scotland, but they require riparian woodlands, a habitat that has also been lost across the Highlands (Smout, 2007). Therefore, their reintroduction would necessitate the native woodland establishment decades prior. Larger artificial dams could also be constructed such as the Loch More dam, designed to control the Thurso River water level for the benefit of the salmon population. This dam is clearly effective as the Thurso River had the fewest days at low flow (<5%). If a large dam was to be constructed in the upper reaches of a Flow Country river to regulate water flow the only reasonable candidate would be the Wick River due to its clear ecological declines relating to due to low flows. The other rivers do not show the same extreme ecological problems with low flows and dam construction should be limited to leaky wooden dams as larger dams are more likely to do more harm than good for the environment.

Conclusions

- Stream water quality declined in catchments recently undergoing forest-to-bog restoration.
- These declines did not alter the macroinvertebrate community.
- River water quality declined from "Excellent" to "Good" in terms of phosphate*.
- We intend to do more intensive sampling (weekly) for ensuring any short-term declines or flushes are not missed that could impact salmon.



*Scotland River Basin District Standards


Thank you for your time!