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Rewilding as a Mechanism for Natural Flood Management in Upland Peaty Catchments in the Lake District

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ABSTRACT

Rewilding is an emerging conservation methodology that aims to reinvigorate natural processes to form self-sustaining ecosystems. There are close links between the aims of rewilding and natural flood management (NFM), yet the potential of rewilding to provide opportunities for mitigation of hydrological extremes alongside improving biodiversity and carbon storage is underresearched. Two catchments in the Lake District are compared to investigate and evidence the potential of rewilding to increase the water holding capacity of peaty upland landscapes. These are 'Wild Ennerdale', one of the longest running rewilding projects in the United Kingdom, and Thirlmere, which is more traditionally and intensively managed by a large private water company and its tenants. Field observations, collected during summer 2023, indicate that upland vegetation communities at Ennerdale exhibited significantly greater vegetation height and dwarf shrub cover, as well as reduced soil compaction, compared to Thirlmere. These differences were largely attributed to lower grazing intensity at Ennerdale. Both vegetation height and percentage cover of dwarf shrubs were shown to be strongly negatively correlated with compaction. More developed and woody vegetation communities increase the hydrological function of the uplands by increasing surface roughness, interception, evapotranspiration and infiltration, as well as providing better quality habitats to support biodiversity. The results show the importance of joint consideration of ecology and hydrology to evidence the value of rewilding, as traditional indexes such as species richness do not capture ecological function, and some measures of soil characteristics may take longer than 20 years of rewilding to produce a detectable signal.

1 | Introduction

Rewilding is a progressive conservation technique which restores natural processes and ecological dynamism and complexity (Lorimer 2017; Pettorelli et al. 2018; O'Mahony 2020). It can take on many forms, including active rewilding which can involve the reintroduction of key species and passive rewilding where the focus is on the reduction of human intervention (Pettorelli et al. 2018). Despite being contentious in terms of definition and practice (Pettorelli et al. 2018; Dolton-Thornton 2021), rewilding is gaining traction as it has the potential to deliver multiple ecosystem services, including boosting biodiversity, carbon storage, soil restoration and flood mitigation (Lorimer and Driessen 2014; Sandom et al. 2019; Harvey et al. 2024). To date, much of the discourse around rewilding is theoretical and there is limited explicit empirical evidence to justify its wider implementation (Carey 2016; Svenning et al. 2016). Scientific evidence on rewilding is difficult to obtain because it is relatively new as a defined practice and there are very few long-term projects. Furthermore, some

ecosystems, especially terrestrial, often require multiple decades to produce significant results from land management changes (Carver 2016; Malm et al. 2020).

Rewilding has a large, assumed potential to mitigate hydrological extremes; however, this is largely unquantified and underresearched (Harvey and Henshaw 2023). In England alone, 6.3 million properties are at risk of flooding. With climate change, this could increase to 8 million, putting one in four properties at risk by 2050 (Environment Agency 2024). The government is committed to spending £5.6 billion in England between 2021 and 2027 on the flood and coastal defence programme (DEFRA 2021). Uptake of, and funding for, rewilding schemes is likely to increase if the ecosystem services in terms of reducing flood risk can be quantified (Burnett and Bolton 2024). This is likely to be a more universally compelling argument for investment than improving an abstract 'biodiversity' (Brook 2018). Evidencing this requires a more interdisciplinary geographical approach, which brings together hydrologists and ecologists to show that rewilding can provide benefits beyond just increasing biodiversity.

Rewilding as a conservation practice and ideology aligns with the goals of natural flood management (NFM) (Rewilding Britain 2016). NFM aims to restore catchment processes impacted by human activity, especially in the upper catchment and headwaters (Environment Agency 2017; Bond et al. 2020). NFM represents a paradigm shift from traditional hard-engineering solutions to soft-engineering (Nicholson et al. 2020; Quinn et al. 2022). Similar to rewilding, NFM involves working *with* nature rather than in isolation to it (Bark et al. 2021) to deliver multiple co-benefits for society and the environment. There is strong support for wider implementation of NFM in the United Kingdom (UK, Bark et al. 2021). In 2023, Government funding of £25 million was allocated to 40 projects across England that aim to improve flood resilience through NFM (Environment Agency 2023). However, more scientific evidence on NFM's effectiveness at the catchment scale (Metcalfe et al. 2017; Nicholson et al. 2020; Bark et al. 2021), especially catchments over 10 km^2 (Quinn et al. 2022), and more evaluation of its economic viability is needed to encourage wider application (Fennell et al. 2023). Rewilding could be a mutually beneficial extension of NFM as it encourages a larger landscape scale of consideration, while simultaneously delivering on wider ecosystem services and capitalising on public and political support (Harvey and Henshaw 2023). These mutual benefits will only be realised with improved methods to evidence the joint hydrological and ecological value of rewilding as a form of NFM.

1.1 | Upland Land Use and Hydrology

In upland catchments, peatlands are often located in the headwaters and experience higher precipitation, so they are central to managing surface run-off and, therefore, flood risk (Marshall et al. 2009; Bain et al. 2011; Acreman and Holden 2013; Carver 2016; Gao et al. 2017). Peatlands are valuable and unique habitats, as they cover just 2.84% of the Earth's surface (Xu et al. 2018) yet provide over a third of soil carbon storage, river flow regulation and biodiversity (Goudarzi et al. 2021). Uplands in England cover 12% of the land area but support over half of its biodiverse Sites of Special Scientific Interest (SSSI). They store 70% of the potable water, are home to 44% of all breeding sheep and host around 70 million visits a year (Sandom et al. 2019). But this utility, especially from grazing livestock, has been extracted through intensive land use change, and only 25% of UK peatlands are considered to be in good condition (Burns et al. 2023).

Degradation of peatlands causes biodiversity loss but is also associated with higher and flashier flood peaks as damage to soil structure and vegetation cover results in increased overland flow (Acreman and Holden 2013; Dadson et al. 2017). Overgrazing has been shown to reduce and simplify vegetation cover, which causes a reduction in interception, evapotranspiration and rooting depth (Marshall et al. 2009; Marshall et al. 2014). High stock numbers also cause trampling, which compacts the soil, leading to a decrease in soil infiltration, porosity and hydraulic conductivity and an increase in bulk density (Marshall et al. 2009). Higher soil compaction is therefore associated with decreased water storage capacity and increased intensity of surface runoff in the catchment as it creates a less permeable A horizon at the top of the soil column (Figure 1) (Marshall et al. 2014). This is very important in terms of ecosystem services; economically, it is estimated that soil compaction costs the United Kingdom £472 million a year in increased flood damage as well as decreased soil productivity (Jordon 2020). Overall, intensive grazing can exacerbate runoff and contribute to increasing flooding at the plot (Marshall et al. 2009) and hillslope scale (Alaoui et al. 2018).

These hydrological processes are intertwined at the hillslope scale and interact to form a much larger hydrological cycle which determines flood risk further downstream (Figure 2). Restoration and rewilding of peatlands through rewetting, revegetation and decreased grazing pressure provide significant additional catchment surface storage (Goudarzi et al. 2021), offering potential to flatten flood hydrographs and decrease local peak flow (Pilkington et al. 2015 in Environment Agency 2017).

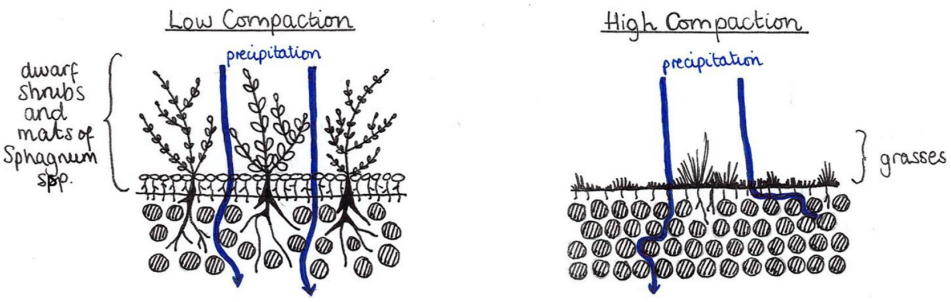

FIGURE 1 | Schematic diagram illustrating the effect of compaction on infiltration and runoff.

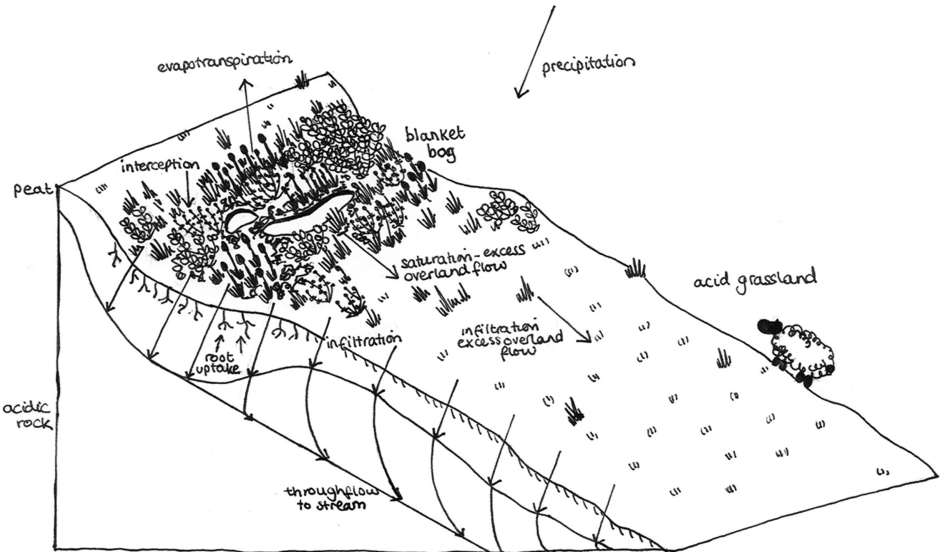

FIGURE 2 | Schematic diagram of how water moves through a peaty hillslope.

1.2 | Upland Vegetation Characteristics and Hydrology

The physical structure of vegetation has an important role in determining hydrological response in the uplands. Better structured vegetation communities, or those with greater vegetation height and complexity, contribute to reducing and slowing surface run-off through improving root structure, increasing interception and evapotranspiration, and increasing surface hydrological roughness (Bond et al. 2020). While better vegetated peat soils do not directly increase catchment storage, they produce less flashy hydrographs than degraded peatlands (Shepherd et al. 2013; Allott et al. 2015; Goudarzi et al. 2021). Furthermore, natural regeneration of vegetation, associated with greater height and later successional plant communities, is linked with changes in hydrological processes (Harvey and Henshaw 2023; Harvey et al. 2024). In the uplands, natural succession leads to the increased cover of dwarf shrubs (Natural England Lake District Team 2020). The development of woody vegetation, such as dwarf shrubs, is particularly valuable for NFM as it is strongly linked with increased interception, infiltration and reduced surface run-off (Harvey and Henshaw 2023). While the emergence of scrub and the development of shrubland habitats is common across rewilding projects, there is a lack of research on the joint hydrological and ecological value of these habitats (Harvey et al. 2024).

1.3 | Barriers to Passive Rewilding in the Uplands

Extensive grazing has been encouraged by governmental subsidies (Carver 2016). The phasing out of the Common Agricultural Policy (CAP) as the United Kingdom leaves the EU offers potential for change (Bark et al. 2021; L. Malm and Evans 2020), however, addressing these upland land management issues in terms of passive rewilding for flood management is highly contentious as these landscapes are tightly bound in cultural tradition and power dynamics. Many studies that look at the impact of decreasing human intervention by reducing livestock pressure and using natural processes to improve flooding mitigation in upland temperate regions, such as the 'Upstream Thinking Project' on Exmoor and 'Pumlumon Living Landscape Project', do not label this management style as a form of 'rewilding' (Rewilding Britain 2016). This could be because they either do not realise this passive management can constitute rewilding in the confused discourse, or because the association with rewilding would be a hindrance to communication.

Passive rewilding is particularly contentious in the Lake District as the area is characterised by historical traditions and small family-run farms (Schofield 2023). Two thirds of the Lake District High Fells Special Area for Conservation (SAC) is 'common land' (Natural England Lake District Team 2020), which allows 'rights of the common' over it, including grazing rights for traditionally poorer communities who did not own land of their own (Foundation for Common Land 2023). Grazing sheep here is called 'hefting', and this represents a deeper metaphor for people's connection to place and sense of belonging (Olwig 2016; Brook 2018). While there is an acknowledgement that overgrazing is a serious anthropogenic threat to the SAC (Natural England Lake District Team 2020) and that the Lake District has been severely impacted by recent flooding (Rhodes 2020), the idea of removing or reducing sheep and consequently 'abandoning' the land in passive rewilding to combat this is met with many concerns. For some, 'there could be no greater sacrilege' (Schofield 2023, 17) as it would be as a type of virtual enclosure and a way of removing the 'rights of the common' (Olwig 2016). Therefore, when considering rewilding and restoration in culturally saturated landscapes, such as the Lake District, it is poignant to engage effectively with various stakeholders to address conflicts of interest. Gathering more evidence on the benefits of rewilding is pivotal to increasing government funding and increasing societal understanding of the importance and role of the uplands in flood mitigation within a changing climate.

1.4 | Study Aims

This research seeks to provide evidence of the value of upland rewilding to mitigate hydrological extremes. Two catchments in the Lake District are compared, 'Wild Ennerdale', one of the longest-running rewilding projects in the United Kingdom, and Thirlmere, which is more traditionally and intensively managed by a private water company, United Utilities, and its tenants. Vegetation and soil hydrology data on peaty soils were collected during fieldwork in summer 2023 and are used to develop an understanding of the joint ecosystem benefits provided by rewilding. The potential for rewilding to deliver NFM is evidenced by investigating how differing land management schemes affect the ability of upland catchments to store water. The specific research questions are as follows:

- Is there a difference in the upland vegetation communities between Ennerdale and Thirlmere that provides value for flood mitigation?
- Is there a difference in the soil hydrology and characteristics of shallow and deep peat between Ennerdale and Thirlmere that increases the ability of catchments to store water?
- Is there a relationship between vegetation communities and soil characteristics at Ennerdale and/or Thirlmere?

2 | Details of Study Location

This study will compare the Ennerdale reservoir and Thirlmere reservoir catchments (River Ehen and St John's Beck respectively) in the Lake District National Park in north-west England (Figure 3). The catchments are geographically proximate and similar in terms of annual rainfall, size and characteristics. Both catchments are underlain by similar igneous acidic rocks, predominantly from the Borrowdale Volcanic Series and Skiddaw Slates. They are also both dominated by grassland, which covers nearly one third of the catchments, with smaller areas of mountain/heath/bog and woodland (Moody et al. 2018; JNCC 2023).

Land management is the main difference between the two catchments. The Ennerdale catchment was traditionally dominated by sheep grazing and forestry, but since 2002, it has been managed as the 'Wild Ennerdale' project by the landowners, the National Trust, Forestry England and United Utilities, and supported by Natural England (Moody et al. 2018). Wild Ennerdale covers an area of 4400 ha and aims to work across land ownership collaboratively to restore natural processes to form a self-sustaining environment which supports wildlife and people. There is low-level intervention, with lower intensity naturalistic grazing, predominantly cattle grazing, and passive rewilding (Moody et al. 2018; Sandom et al. 2019);

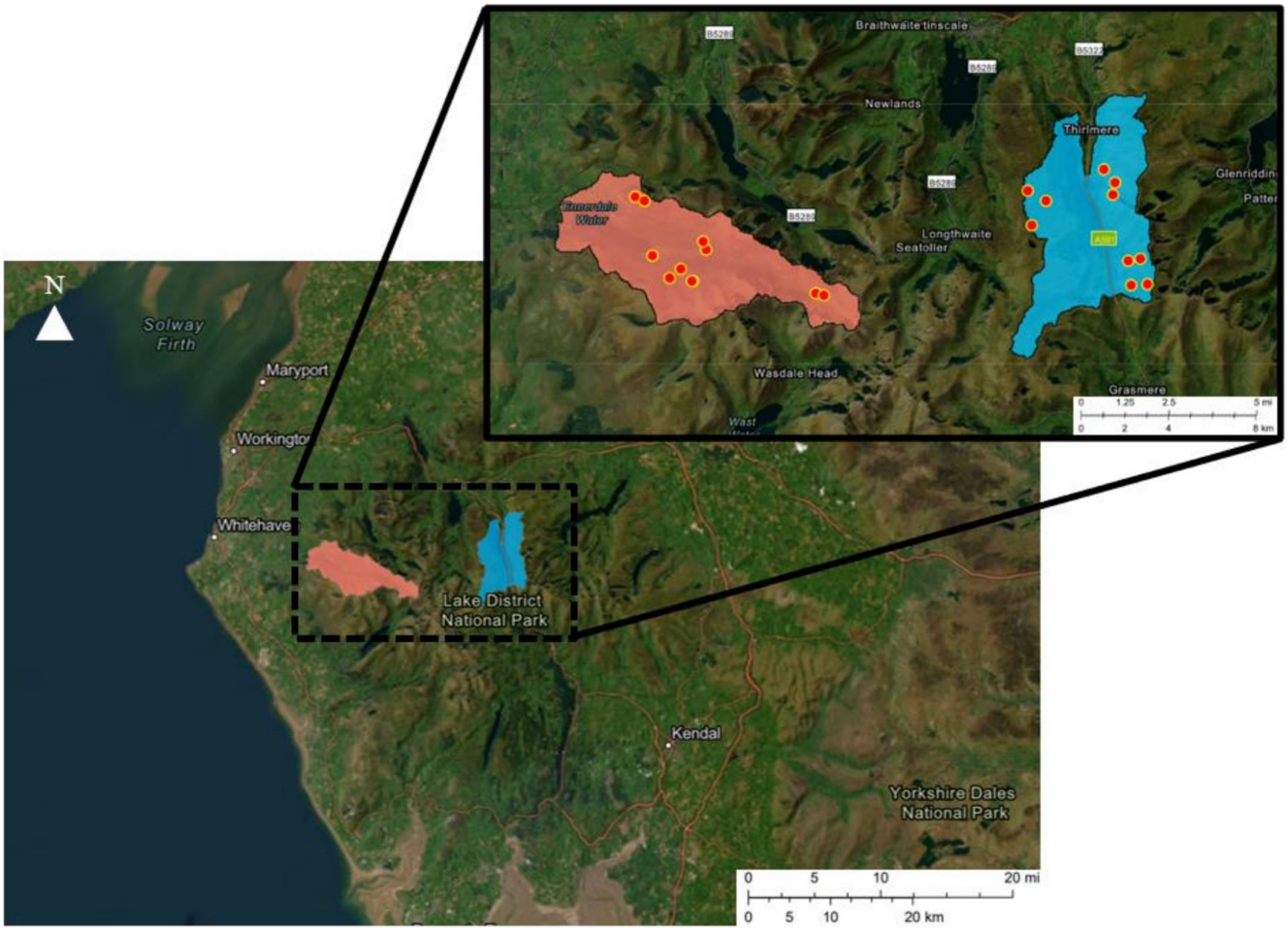

FIGURE 3 | Map of Ennerdale (pink) and Thirlmere (blue) catchments within the Lake District, with an insert of locations of the study sites (red points).

however, it is recognised that significant interventions may be needed to restore natural processes. It is one of the first major rewilding projects in the United Kingdom (Rewilding Europe 2023) and offers a rare and valuable opportunity to assess the long-term impacts of rewilding. By contrast, Thirlmere reservoir catchment is managed more traditionally, with moderate to heavy sheep grazing carried out by United Utilities and its tenants. The Thirlmere Resilience Project was set up in 2020 between United Utilities, Natural England, Cumbria Wildlife Trust and the John Muir Trust to less intensively manage the catchment for people and nature (John Muir Trust 2024); however, substantial changes have not yet been recorded in the catchment.

Anecdotally, the differing land use management practices in the two catchments have been suggested by local land managers as possible reasons for differing catchment responses to heavy rainfall (Martynoga 2023). Major flooding in the Lake District in 2009 and 2015 illustrated this as Thirlmere experienced damaging flooding and highly turbid flows, but Ennerdale's floodwaters were clear and contained on its floodplains (Carver 2016; Rewilding Britain 2016). Moody et al. (2018) investigated the flood regimes of Ennerdale and Thirlmere and concluded that Ennerdale has a higher discharge for the lowest 90% of flows, but in the most extreme storms, Thirlmere had the greatest relative flow response; however, the lack of data on soil hydrology restricted their ability to evidence the reasons for this difference.

Within the study catchments, study sites (Figure 3) were selected to represent the two main soil types in the catchments, deep peat and shallow peat. These soil types were chosen because of their prevalence in the Lake District and the academic interest in their potential to deliver multiple ecosystem services, from water regulation to carbon sequestration and reducing biodiversity loss (Goudarzi et al. 2021). Blanket bogs are mainly found on deep peat and are particularly important as they are named as a priority habitat under the UK's Biodiversity Action Plan (1999) (Bain et al. 2011). Soil types were defined by the 'Soilscapes' classifications from Cranfield University which are produced from the simplification of the National Soil Map (NATMAPvector) (2023).

Deep peat, defined as 'Soilscape 25' (Cranfield University 2023) and as a peat soil over 0.4 m by Natural England, is formed from decomposing vegetation, so it is very acidic (Bain et al. 2011; Natural England Lake District Team 2020; Scott 2021). It is typically of low fertility (Cranfield University 2023) and saturated with a high water table, 5–10 cm from the surface in a healthy ecosystem (Shepherd et al. 2013). This forms a blanket bog habitat, which has a complex and distinct hydrology (McCarter et al. 2024). The top 'active' layer of an intact blanket bog is called the acrotelm and is composed largely of spongy *Sphagnum* spp. mosses, which have high hydraulic conductivity (Shepherd et al. 2013). Beneath this is a layer of more compacted, decaying vegetation, called the catotelm. This forms a permanently waterlogged, anaerobic layer of peat, which has low hydraulic conductivity (Bain et al. 2011; Shepherd et al. 2013) (Figure 4). The relative thinness of the acrotelm means water storage capacity in deep peat habitats is low, and therefore, the predominant response to

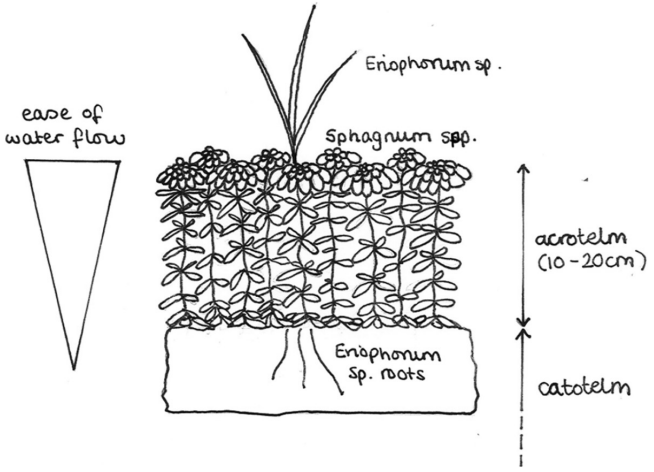

FIGURE 4 | Schematic diagram of naturally functioning peat soil structure, based on diagrams from Bain et al. (2011).

rainfall events is saturation-excess overland flow (Shepherd et al. 2013; Goudarzi et al. 2021), which Holden et al. (2008), states contributes to up to 80% of the water movement here. Deep peat is often characterised by Annex 1 plant communities, which are considered of conservation importance under the European Habitats Directive 1992, such as 'North Atlantic wet heath (4010)' and 'Blanket bog (7130)' and these are dominated by *Erica tetralix* and *Eriophorum* spp. (JNCC 2023).

Shallow peat soils, described as 'Soilscape 2', are shallow acidic peaty soils over rock which often have low fertility and more variable drainage (Cranfield University 2023). Characteristic plant communities here can also include wet heaths on flushes, but acid grasslands and dry heaths are more prevalent with key species such as *Calluna vulgaris* and *Deschampsia flexuosa* (JNCC 2023). This soil type covers a large area of the Lake District and these areas are considered more suitable for grazing compared to deep peat due to their typically drier nature and greater prevalence of productive species, such as grasses (Natural England Lake District Team 2020). However, overgrazing on shallow peat soils can damage vegetation communities and lead to erosion of topsoil (Cranfield University 2023), which is why shallow peat is perhaps more vulnerable to oxidisation and desiccation (Natural England Lake District Team 2020).

3 | Methodology

3.1 | Study Sites

At each catchment, five sites were surveyed for each soil type, which amounted to 20 survey sites in total (Figure 2). Study sites were randomly selected within the area of each soil type to remove bias, but inappropriate sites that were not safe or accessible for fieldwork were discounted. The distribution of soil types was identified using Cranfield University's 'Soilscapes' maps (2023) which were produced with support from the Department for Environment, Food & Rural Affairs (DEFRA). These were further refined by using expert local knowledge of the catchments and ground truthing through measuring peat depth in the field.

3.2 | Data Collection

Surveying was conducted over two weeks in June and July of 2023. The weather in the Lake District at the beginning of June was largely dry and warm, followed by localised heavy rainfall in the second half of June and into July (Barker et al. 2023; Sefton et al. 2023). Antecedent conditions were moist; over the two weeks preceding surveying at each catchment, 61.8 mm of rain fell at Ennerdale and 54.2 mm fell at Thirlmere St John's Beck (DEFRA 2025), over half of the monthly average for the Lake District (MetOffice 2025). During surveying at each catchment, the same sites recorded 38 and 39 mm, respectively. At each site, soil and vegetation properties were surveyed in five 1 m × 1 m quadrats organised into a standard 'W-shape' within a 10 m x 10 m macro quadrat to account for the high heterogeneity within soil sampling (Parfey 2017). To maintain as much consistency as possible in soil hydrology and runoff processes, slope was moderated as much as possible (Monger et al. 2022), and all sites had a slope within the range of 0°–19°, and fieldwork was not undertaken in heavy rain.

3.3 | Ecological Vegetation Surveying

Within each 1 m × 1 m quadrat, sampling on the vegetation was conducted first as subsequent soil sampling would disrupt these measurements. Vegetation height was calculated by measuring the sward depth using a tape measure held perpendicular to the ground (Bond et al. 2020; Malm et al. 2020). Ecological surveying was then undertaken, and vascular plants were identified to their species level, and mosses were identified to species or genus level. Species were then given an estimated percentage cover across the quadrat. The total percentage cover was allowed to exceed 100% under the understanding that understorey plants provide multiple layers of vegetation (Pilkington et al. 2015). Structural composition of vegetation communities was also recorded by organising species and their associated percentage cover into structural groups (Table 1).

Species richness was calculated by identifying the number of discrete species present in each sample (Krebs 1999; Begon et al. 2014). Community structures, such as dominance or rarity were investigated using the Shannon–Weiner's Diversity Index (H, Equation (1)), which is a measure of diversity formed from species richness and each species' proportional abundance (Ricklefs and Miller 1999; Magurran 2004; Begon et al. 2014).

TABLE 1 | Different plant structure types used and their definitions.

Plant structure group	Description
A	Mosses, e.g., *Sphagnum* spp.
B	Groundcover plants, e.g., *Vaccinium oxycoccos*
C	Low plants (< 15 cm), e.g., *Potentilla erecta*
D	Tall plants (> 15 cm), e.g., *Deschampsia flexuosa*
E	Dwarf shrubs, e.g., *Calluna vulgaris*

$$H = -\sum_{i=1}^{s} p_i ln(p_i) \quad (1)$$

where s is the number of species and p_i is the proportion of the entire communities made up of species i.

3.4 | Compaction

Compaction measurements were taken with a handheld penetrometer (Gao et al. 2015; Moody et al. 2018). This was pushed on top of the vegetation, replicating how rain would fall onto the surface, until the tip was sunken into the soil and the measurement at this point was recorded. Five repeated measurements in each 1 m × 1 m quadrat were taken to reduce the effect of small-scale soil variability. In total, 500 compaction measurements were taken across the two catchments. The handheld penetrometer was chosen as it had a good balance between portability for use at remote sites and accuracy, with a resolution of 0.5 kg/cm^3.

3.5 | Infiltration

Infiltration of water directly into the soil surface was recorded using a mini disk infiltrometer (Marshall et al. 2014) set to the lowest suction setting of 0.5 as peaty soils are inherently saturated and slow infiltrators. Measurements of the volume of water in the infiltrometer were taken at the beginning of recording and then every 30 s after for 2 min. Infiltration rate (cm^3/s) was then calculated from the total volume of water infiltrated, divided by 120.

3.6 | Volumetric Soil Moisture

A theta probe kit was used in the field to take volumetric soil moisture readings (Murphy et al. 2021; Monger et al. 2022). The theta probe kit was calibrated for 'organic' soils when surveying deep peat and for 'mineral' soils when surveying shallow peat. Three repeated measurements of soil moisture in each 1 m × 1 m quadrat were taken to mitigate the effects of small-scale heterogeneity.

3.7 | Gravimetric Soil Moisture and Bulk Density From Soil Samples

Within each quadrat, soil cores were taken from the A horizon, 2–8 cm deep, using a handheld metal corer with a diameter of 46 mm. It can be difficult to collect good quality peat soil samples (Bonnett et al. 2009), and in this study, the depth of soil core taken varied, and the content of vegetation collected differed due to the varying structural integrity of samples; therefore, the depth of the soil core was recorded. The five cores taken for each study site were then pooled together and stored in an airtight bag. The saturated weight of the soil samples was recorded, and then the samples were taken to the laboratory for further analysis. These samples were dried in an oven at 60°C until all water had evaporated and mass was constant. The gravimetric soil moisture content of the samples was then calculated (Gao et al. 2015). The bulk density was also calculated from this

analysis by dividing the dry weight of the soil by the volume of the soil samples taken (Meyles et al. 2006; Marshall et al. 2014; Jordon 2021; Murphy et al. 2021; Monger et al. 2022).

3.8 | Statistical Testing

Statistical analysis and tests were undertaken on the survey data to decipher trends and differences, and the significance of these results was determined at the 95% confidence level. The Shapiro–Wilk test was used to check the normality of each data set. For normal data, a two-sample *t* test was conducted to test for statistical differences between the averages ($p < 0.05$). If one or both of the data sets were not normal, a Wilcox test was performed as the non-parametric alternative. Pearson's correlation coefficients were calculated for normal datasets, and Spearman's Rank was performed for non-parametric data. Statistical tests were conducted in RStudio Version 4.1.1.

4 | Results and Discussion

4.1 | Comparing Ecological Vegetation Characteristics

Three main habitat types were identified when surveying the vegetation communities: blanket bog/wet heath, which was mainly found on the deep peat soils, and dry heath and acid grassland types, which were typical on shallow peat soils. However, some degraded blanket peat was so dried out that the habitat resembled acid grassland; conversely, some shallow peat soils located near a flush were more representative of wet heath habitats. Table 2 shows the dominant species of each habitat and the distribution of the habitat types between the study catchments and soil types.

Averages of ecological diversity indexes were calculated from the five sites for both deep and shallow peat soils in each of the study catchments (Table 3).

It was hypothesised that Ennerdale would have higher ecological indexes following the implementation of lower grazing levels and a change from sheep to cattle-dominated grazing. This would echo other rewilding schemes where an increase in biological diversity has been recorded as human intervention is reduced and natural processes and habitats are restored (Tree 2018; Stewart et al. 2020). However, using traditional ecological metrics, there was no evidence of higher ecological richness at sites in Ennerdale, and weak evidence of a higher average site species richness was observed at Thirlmere on peat (result of Wilcox test: $p = 0.465$) and shallow peat (result of Wilcox test: p value $= 0.081$). The average Shannon Weiner Diversity Index at sites was very similar on peat soils (result of two-sample *t* test: p value $= 0.940$), but on shallow peat soils, the Shannon Weiner Diversity Index was higher at Thirlmere than Ennerdale (result of two-sample *t* test: p value $= 0.034$). This may partly be because diverse and sensitive species, such as lichens and liverworts, which require specialist identification, were not recorded in this study (Milligan et al. 2016). Other potential considerations include the time taken after different grazing regimes are implemented for change to be detected and the role of grazing in surpressing natural succession and preventing fast-growing species from dominating, creating a less developed but more heterogeneous community (Malm and Evans 2020).

Traditional ecological metrics do not allow consideration of the type of species present and may misrepresent ecological health, especially for unique habitats such as those found on peatlands. For example, some of the species recorded at Thirlmere were non-indicators of peaty soil ecosystem health, such as *Polytrichum* spp. mosses, and on the eastern slopes, on Willie Wife Moor, acid grassland species like *Deschampsia flexuosa* were recorded on peat over 1 m deep where blanket bog would be expected. This indicates poor ecosystem function and drying out, leading to a loss and simplification of the characteristic bog vegetation. This may help explain the vulnerability of Thirlmere in past flooding events because, on its eastern slopes, the vegetation is particularly degraded and grazed, and this is exacerbated by exposure to predominant westerly rainfall. Furthermore, this reflects national issues as 51% of England's upland peatlands by area are affected by non-peat forming vegetation (Natural England 2010). This is a particularly important finding for this study as it suggests that traditional heavy grazing can degrade and desiccate peatland habitats, reducing the amount of water they can store and therefore potentially increasing surface runoff and flood risk downstream.

In peatland ecosystems it is important to consider indicator species which demonstrate natural ecological function. Natural England outlines indicator species for different habitats; for this study, indicator species of blanket bog were used for peat soils, and indicator species of blanket bog as well as heath and acid grassland were used for shallow peat soils (Crowle et al. 2025; McCullagh et al. 2025). The average indicator species richness was higher at Ennerdale compared to Thirlmere on both peat and shallow peat soils (result of Wilcox test: p value $= 0.094$, p value < 0.001). Of the indicator species of particular interest was *Sphagnum* spp., as they help form peat itself but they are particularly vulnerable to overgrazing and trampling as they are physically delicate (Lindsay et al. 2014; Natural England Lake District Team 2020). *Sphagnum* spp. provide the highest value for surface roughness to reduce the speed of overland flow compared to other blanket bog species due to their long branching structure (shown in Figure 4) (Holden et al. 2008; Allott et al. 2015). Despite this, there was no statistically significant difference in *Sphagnum* spp. cover recorded between study catchments.

The general lower average site richness, but better ecological health shown by a greater prevalence of indicator species at Ennerdale, demonstrates a better natural hydrological regime here. This is not captured by comparing diversity metrics alone but requires analysis of specific species, demonstrating the importance of joint ecological and hydrological consideration of peatland ecosystem function.

4.2 | Comparing Physical Vegetation Characteristics

Average vegetation height was higher at Ennerdale compared to Thirlmere on deep peat soils by 4.3% (result of two-sample *t* test: p value $= 0.537$) and on shallow peat soils by 61.0% (result of Wilcox

TABLE 2 | Main habitats surveyed with key species identified from JNCC 2023 and Turrill 1963 and their distribution across habitat and soil types.

Habitat type	Dominant species	Example site	Number and distribution of study sites of each habitat type			
			Peat		Shallow peat	
			Ennerdale	Thirlmere	Ennerdale	Thirlmere
Blanket bog/ wet heath	• *Erica tetralix* • *Sphagnum* spp. • *Scirpus cespitosus* • *Molinia caerulea* • *Narthecium ossifragum*		4	4	1	1
Dry heath	• *Calluna vulgaris* • *Vaccinium myrtillus* • *Galium saxatile*		1	0	3	1

(Continues)

TABLE 2 | (Continued)

Habitat type	Dominant species	Example site	Number and distribution of study sites of each habitat type			
			Peat		Shallow peat	
			Ennerdale	Thirlmere	Ennerdale	Thirlmere
Acid grassland	• *Nardus stricta* • *Deschampsia flexuosa* • *Potentilla erecta* • *Festuca* spp.		0	1	1	3

test: p value < 0.001) (Figure 5). Vegetation height on shallow peat displayed a greater difference between study catchments than deep peat, and this suggests that the habitats here were more notably structurally affected by land management, perhaps because they are more vulnerable to cropping through preferential grazing.

There is a large difference in the percentage cover of dwarf shrubs between the two catchments, with the mean percentage cover of dwarf shrubs approximately threefold at Ennerdale compared to Thirlmere on each soil type. Therefore, there is strong evidence that Ennerdale has a higher average percentage cover of dwarf shrubs on both deep peat and shallow peat (result of Wilcox test: p value = 0.010, p value < 0.001, Figure 6). Thirlmere has a distinct lack of dwarf shrubs, with a median of 0% on both soil types. Outliers in Figures 5 and 6 are indicative of the variability in vegetation within sites due to areas of restricted grazing and changes in elevation, shelter and rocky terrain. Furthermore, there are fine-scale spatial differences in vegetation communities, particularly at Thirlmere. Here, the eastern slopes are relatively heavily grazed, but areas of the western slopes, near Armboth Fell, have experienced peatland restoration through restricted grazing (Natural England Lake District Team 2020) and, more recently, the replanting of blanket bog species under the 'Fix the Fells' collaborative initiative (Cumbria Wildlife Trust 2022).

More intensive grazing can reduce sward height as well as reduce the cover of and prevent the regeneration of dwarf shrubs, which are more sensitive to grazing pressure than grassy species (Natural England Lake District Team 2020). Overall, the rewilded areas at Ennerdale demonstrate a taller, more developed vegetation community at a later stage of succession compared to Thirlmere, which can be at least partly attributed to the different land management and grazing pressures. This echoes other experimental studies in the Scottish Highlands and at Glen Finglas, where un-grazed areas showed greater vegetation height and shrub cover after just over 25 years and 10 years, respectively, when compared to areas with conventional and light grazing regimes (Hope et al. 1996; Malm and Evans 2020).

4.3 | Comparing Soil Characteristics and Hydrology

Average compaction was lower at Ennerdale than Thirlmere on deep peat soils by 45.1% (result of two-sample t test: p value < 0.001) and on shallow peat soils by 26.9% (result of Wilcox test: p value = 0.018) (Figure 7). Of all the soil characteristics surveyed, compaction displayed the greatest difference between Ennerdale and Thirlmere. For example, the minimum compaction at Ennerdale was a third of the minimum at Thirlmere on peat (0.4 kg/cm^3 compared to 1.2 kg/cm^3) and less than half of the minimum on shallow peat (0.9 kg/cm^3 compared to 1.7 kg/cm^3).

Average compaction was higher on shallow peat than deep peat soils at Ennerdale (result of Wilcox test: p value = 0.025) and Thirlmere (result of two-sample t test: p value < 0.001). This was hypothesised as shallow peat is often preferentially grazed and therefore is more at risk of trampling by livestock, which can result in higher compaction. Shallow peat is also associated with a higher risk of desiccation of the top organic layer, and this can further increase compaction (Natural England Lake

TABLE 3 | Comparing averages of ecological indexes on deep and shallow peat soils between Ennerdale and Thirlmere. Grey shading indicates significant differences at 95% confidence level between catchments.

	Peat		Shallow peat	
Ecological index	**Ennerdale**	**Thirlmere**	**Ennerdale**	**Thirlmere**
Species richness	7.4	7.92	7.72	8.32
Shannon–Weiner Diversity Index	1.67	1.68	1.68	1.83
Indicator species richness	4.76	3.52	3.84	1.88

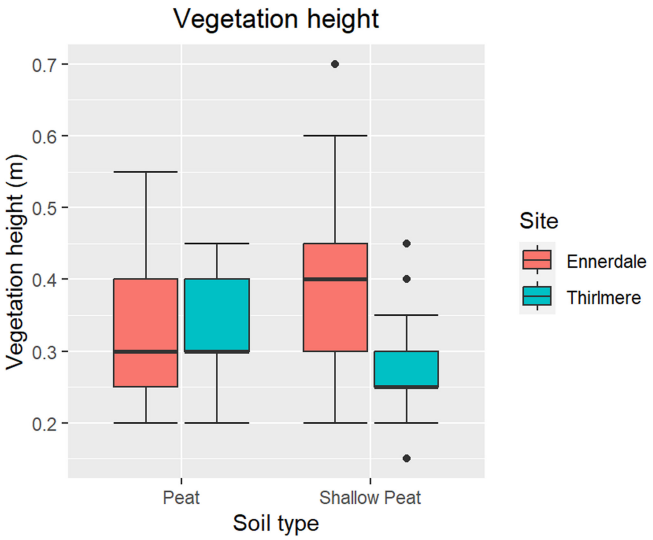

FIGURE 5 | Boxplot comparing study catchments for the different soil types in terms of vegetation height.

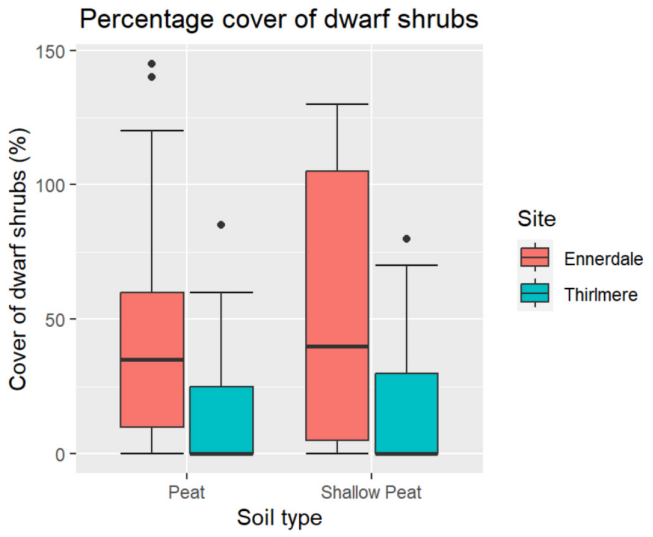

FIGURE 6 | Boxplot comparing study catchments for the different soil types in terms of percentage cover of dwarf.

District Team 2020). Furthermore, due to its hydrology, deep peat is more likely to have a top permeable layer of peat (acrotelm), which is largely made of spongy *Sphagnum* spp. (Bain et al. 2011) and has very low compaction.

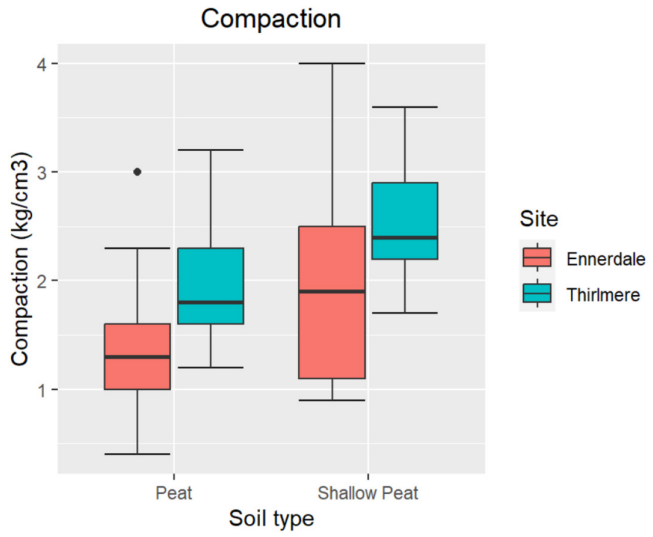

FIGURE 7 | Boxplot comparing study catchments for the different soil types in terms of compaction.

The lower compaction recorded at Ennerdale is assumed to be a consequence of the less intensive land management which leads to higher and more woody vegetation that improves soil structure by adding organic matter and increasing root penetration. Reduced trampling by livestock at Ennerdale also improves soil structure and decreases compaction. This data is particularly valuable as it adds evidence to the scarce database of compaction on UK upland soils (Gao et al. 2015) and builds on understandings of the timescales for rewilding impacts. Current estimates suggest a wide range for recovery from long-term soil compaction from just 6 months to over 50 years (Murphy et al. 2021), but this investigation demonstrates rewilding can help produce a significantly lower compaction after, at the most, around 20 years and likely much before this.

There was weak evidence of higher average infiltration at Ennerdale compared to Thirlmere on peat soils and shallow peat soils (result of Wilcox test: p value = 0.838, p value = 0.183, Figure 8a). The data for volumetric soil moisture demonstrates multiple outliers decreasing confidence in the data (Figure 8b). Variability in rainfall and antecedent conditions over the survey period is likely to have influenced the data.

Lower bulk density is assumed to be developed in ecological restoration through reduced trampling and increased soil organic matter due to regeneration of vegetation (Meyles et al. 2006). However, there was weak evidence that bulk density was lower at

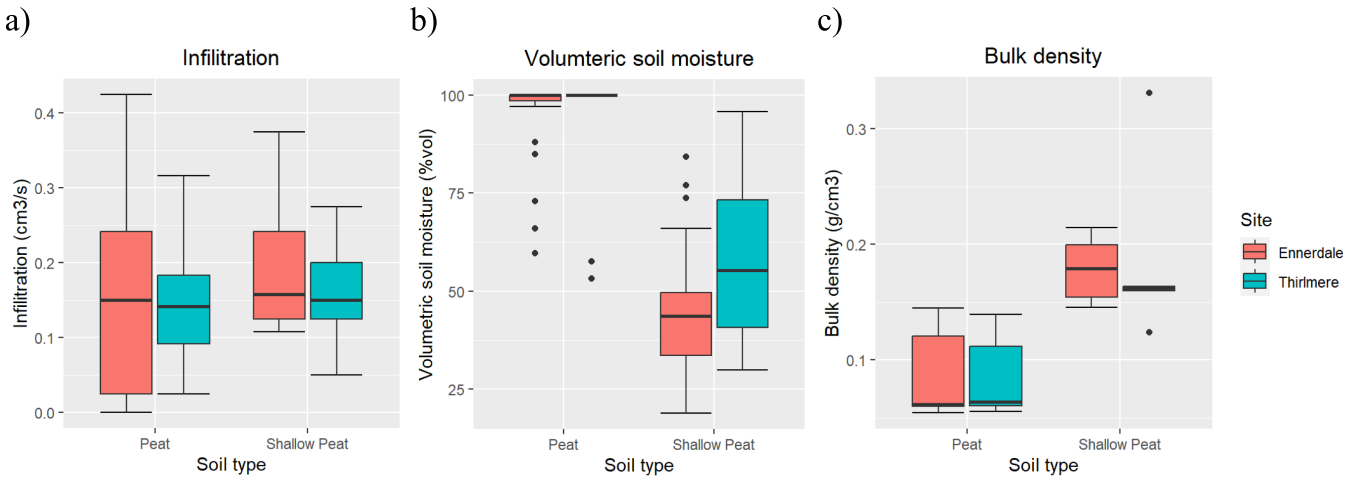

FIGURE 8 | Boxplot comparing study catchments for the different soil types in terms of (a) infiltration, (b) volumetric soil moisture and (c) bulk density.

Thirlmere compared to Ennerdale on peat (result of two-sample *t* test: *p* value = 0.940) and was lower at Ennerdale compared to Thirlmere on shallow peat (result of Wilcox test: *p* value = 0.841) (Figure 8c). Bulk density was lower on deep than shallow peat soils at Ennerdale (result of two-sample *t* test: *p* value = 0.005) and Thirlmere (result of Wilcox test: *p* value = 0.016). Higher bulk density on shallow peat soils was hypothesised because they are at a greater risk of drying out (Natural England Lake District Team 2020) perhaps as they have more variable drainage and are often preferentially grazed, so experience more trampling.

These findings are important as they demonstrate the complexity of soil hydrological systems and suggest that some soil hydrological indices could take longer than a 20-year rewilding period to demonstrate a significant difference. Long-term studies on the moisture holding capacity of soils to accurately assess the hydrological impacts of different land management regimes at the plot and catchment scale are therefore needed. In the absence of such studies, these results show the value of integrating analysis of soil hydrology with ecological indices to assess the benefits of NFM.

4.4 | Identifying Relationships Between Vegetation Communities and Soil Characteristics

The hydrological regime of a catchment is determined by multiple interacting factors, including soil properties and the vegetation community. Deciphering the key relationships is important to improve understanding and implement targeted management. Statistical tests for correlation between variables were performed separately for each soil type, and the strongest relationships are presented here.

Ennerdale and Thirlmere had negative relationships between vegetation height and compaction on peat soils, with a statistically significant relationship found at Ennerdale (Figure 9a). On shallow peat soils, both catchments showed statistically significant relationships (Figure 9b). This indicates a negative relationship between vegetation height and compaction, especially at Ennerdale. This empirically supports theoretical assumptions that as vegetation height increases, there is a more developed root structure and a higher organic matter content, which makes the soil less compact. Furthermore, greater vegetation height is associated with a lower grazing density, and this promotes lower compaction through reduced trampling.

The relationship between the percentage cover of dwarf shrubs and compaction on both soil types and study catchments was negative, and on deep peat at Thirlmere and shallow peat at Ennerdale, the relationship is statistically significant and particularly strong (Figure 10). Therefore, this evidences a negative relationship between the percentage cover of dwarf shrubs and compaction across both catchments and statistically supports understandings that a higher percentage cover of dwarf shrubs creates a greater density of roots, more porosity, and a less compact soil structure. A more developed vegetation community, indicated by a greater prevalence of woody species, also implies that it has suffered less from heavy grazing pressure (Natural England Lake District Team 2020), which further contributes to its reduced compaction.

5 | Considerations for Future Research

This study offers a valuable joint consideration and data collection of ecological and hydrological properties. The lack of past joint studies in the Lake District and elsewhere means that there is a lack of baseline data to compare these results to. Harvey et al. (2024) call for an increase in the number of before-and-after comparisons of the hydrological benefits of rewilding and for longer-term studies. This is important because ecological communities are highly dynamic, individual and complex. While the data presented here suggests that 20 years is sufficient for upland habitat regeneration in the Lake District, without data on the species and habitats present before rewilding started in 2002, it is challenging to understand the recolonisation rates and therefore the current levels of habitat development (Natural England Lake District Team 2020). Soil hydrology measurements presented here relate to the two-week sampling period within which the

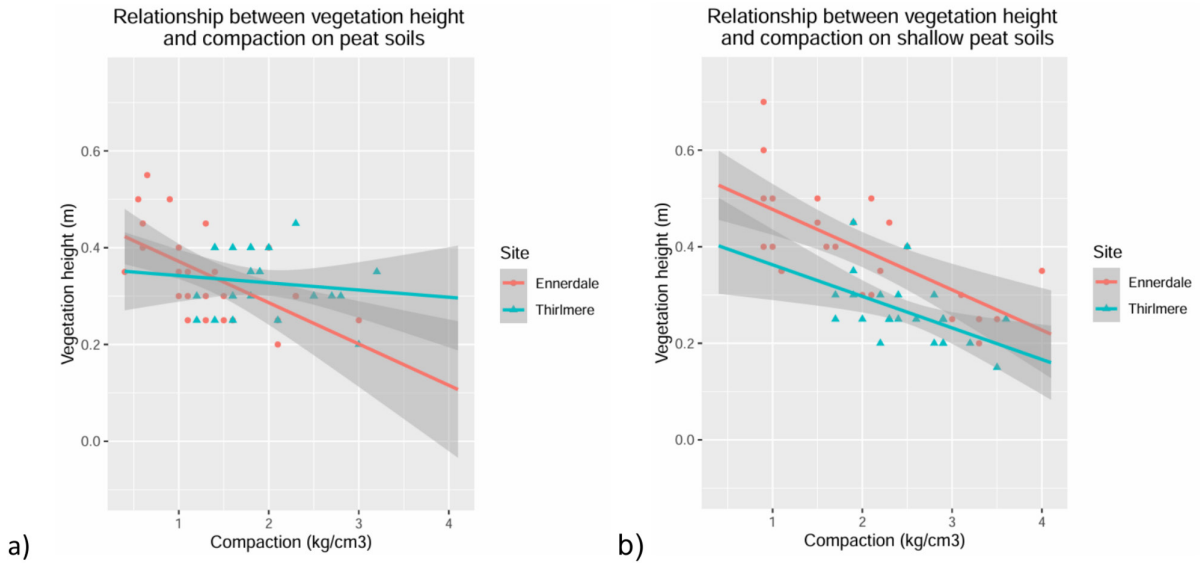

FIGURE 9 | Graphs plotting the relationship between vegetation height and compaction at both study catchments, with fitted regression lines and 95% confidence interval bands in grey for (a) peat soils and (b) shallow peat soils (Results for peat soils: Ennerdale using Pearson's correlation coefficients $\beta = -0.595$ and p value $= 0.002$, Thirlmere using Pearson's correlation coefficients $\beta = -0.130$ and p value $= 0.534$. Results for shallow peat soil: Ennerdale using Spearman's Rank $\beta = -0.699$, p value < 0.001, Thirlmere using Spearman's Rank $\beta = -0.559$, p value $= 0.004$)

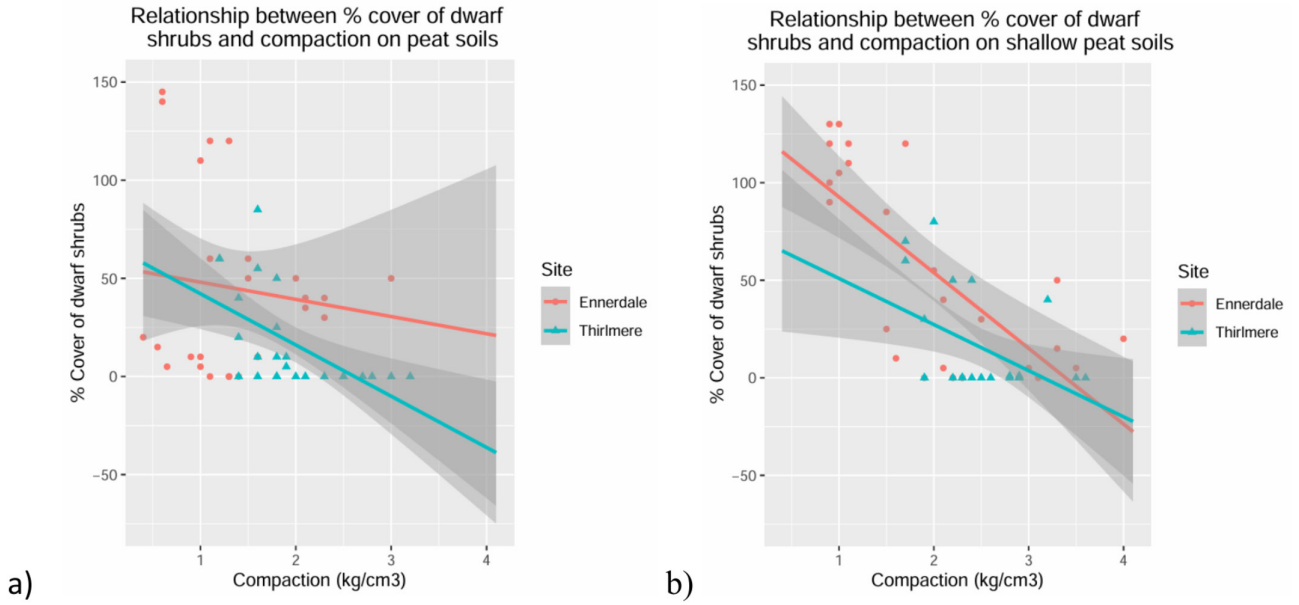

FIGURE 10 | Graphs plotting the relationship between percentage cover of dwarf shrubs and compaction at both study catchments, with fitted regression lines and 95% confidence interval bands in grey for (a) peat soils and (b) shallow peat soils (Results for peat soils: Ennerdale using Spearman's Rank $\beta = 0.010$ and p value $= 0.961$, Thirlmere using Spearman's Rank $\beta = -0.687$ and p value < 0.001. Results for shallow peat soils: Ennerdale using Spearman's Rank $\beta = -0.714$ and p value < 0.001, Thirlmere using Spearman's Rank $\beta = -0.382$ and p value $= 0.060$)

fieldwork was conducted and therefore are specific to the relatively wet climate conditions directly before and at the time of surveying. However, soil hydrology is also sensitive to the effects of legacies of land management and use. Therefore, longer-term studies would address the need to capture a full range of hydrological conditions including flood extremes (Harvey et al. 2024) and evidence the magnitude and speed of landscape recovery, which can support NFM.

This study shows the complex nature of rewilding and highlights the need for combined consideration of hydrological and ecological properties to assess the multidimensional benefits of rewilding. Further analysis is also needed to isolate and untangle the complex effects of specific vegetation types on hydrological regimes to improve confidence in the conclusions drawn (Marshall et al. 2009; Natural England Lake District Team 2020). Looking forward, it would be valuable to combine

compaction, a key result of this study, with hydrological modelling to project flood hazard (Gao et al. 2017) and identify areas of compaction which have the highest impact on flood risk to support targeted rewilding interventions (Gao et al. 2015). On a larger scale, it would also be beneficial to assess and model the magnitude of impact that rewilding and land management regimes have on flood management across whole catchments and investigate how flood risk propagates downstream (Alaoui et al. 2018).

6 | Conclusion

Existing discourse on rewilding is highly contested and largely theoretical. This study is the first known holistic investigation into the soil hydrology and vegetation communities at the rewilded Ennerdale and more traditionally managed Thirlmere reservoir catchments in the Lake District. It presents quantitative research that evaluates the potential of rewilding as a mechanism for NFM through habitat regeneration and soil restoration.

In terms of the ecology at both study catchments, traditional diversity indexes were shown to underrepresent the potential value of rewilding. Peat habitats can be naturally species-poor and therefore were better assessed in terms of indicator species such as *Erica tetralix* and *Eriophorum* spp.. Considering this, Ennerdale exhibited better ecological function and a more naturalised hydrological regime. The higher vegetation height and percentage cover of dwarf shrubs in the rewilded Ennerdale catchment also indicated significantly more developed upland vegetation communities following reduced grazing. Soil structure was also improved due to the more developed vegetation community and reduced trampling, as evidenced by the significantly lower compaction of both deep and shallow peat soils at Ennerdale.

The resulting increase in surface roughness, interception, evapotranspiration and root penetration and improved soil structure increases the catchment's ability to store water in the uplands. Rewilding in Ennerdale is therefore shown to help decrease the intensity of surface run-off and peak flow in the catchment, as well as providing better quality habitats to support biodiversity. This study, therefore, celebrates the remarkable collaboration between landowners and stakeholders at 'Wild Ennerdale' in a traditionally fragmented landscape and the co-benefits for nature and society it nurtures.

Other soil properties were measured, including infiltration, soil moisture and bulk density, and while averages suggested Ennerdale was more capable of holding water in the landscape, not all comparisons between Ennerdale and Thirlmere produced significant differences. Given the complexity of soil structures, these inconclusive results suggest that some physical soil characteristics may take longer than around 20 years to show a consistent detectable difference following rewilding. This disparity between the speed of the effect of rewilding on soil characteristics compared to ecology makes the assessment of combined benefits challenging. Our results show the compaction recovers quickest from land management change, and therefore, assessment of soil compaction offers potential as a prospective indicator of the hydrological value of rewilding in the short to medium term.

The ongoing take up of rewilding will be dependent on evidencing the capacity of rewilding to provide multiple ecosystem services. This study outlines a detailed and accessible methodology based on the best practice of soil and ecological surveying, which provides a valuable baseline from which to organise and compare future long-term and before-and-after monitoring of rewilding schemes in the context of flood risk management. Increasing the evidence base on rewilding would ensure that rewilding is effectively integrated into national policy as a key agent of NFM.

Author Contributions

E.M.: conceptualisation, fieldwork, data analysis, producing figures, writing initial manuscript and reviewing and editing. L.S.: project supervision, supporting data interpretation, writing initial manuscript and reviewing and editing. S.W.: conceptualisation and fieldwork support and reviewing and editing.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Acreman, M., & J. Holden, (2013). How Wetlands Affect Floods. *Wetlands*, 33 (5), 773–786. https://doi.org/10.1007/s13157-013-0473-2.

Alaoui, A., M. Rogger, S. Peth, and G. Blöschl. 2018. "Does Soil Compaction Increase Floods? A Review." *Journal of Hydrology* 557: 631–642. https://doi.org/10.1016/j.jhydrol.2017.12.052.

Allott, T., E. Shuttleworth, M. Evans, et al. 2015. *Restoration of Blanket Bogs; Flood Risk Reduction and Other Ecosystem Benefits Annex 5. Flood Risk Final Report of the Making Space for Water project*. Available from: https://www.moorsforthefuture.org.uk/__data/assets/pdf_file/0032/80789/Making-Space-for-Water-Annex-5.Flood-Risk_0.pdf.

Bain, C. G., A. Bonn, R. Stoneman, et al. 2011. *IUCN UK Commission of Inquiry on Peatlands*. IUCN UK Peatland Programme Available from: https://pearl.plymouth.ac.uk/cgi/viewcontent.cgi?params=/context/gees-research/article/1829/&path_info=IUCN_20UK_20Commission_20of_20Inquiry_20on_20Peatlands_20Full_20Report_20spv_20web.pdf.

Bark, R. H., J. Martin-Ortega, and K. A. Waylen. 2021. "Stakeholders' Views on Natural Flood Management: Implications for the Nature-Based Solutions Paradigm Shift?" *Environmental Science & Policy* 115: 91–98. https://doi.org/10.1016/j.envsci.2020.10.018.

Barker, L., R. Armitage, F. O'Callaghan, A. McKenzie, and S. Clemas. 2023. *Hydrological Summary for the United Kingdom: June 2023*. UK Centre for Ecology & Hydrology 12pp. (UKCEH Project no. C06944). Available from: https://nora.nerc.ac.uk/id/eprint/535432.

Begon, M., R. W. Howarth, and C. R. Townsend. 2014. *Essentials of Ecology*. 4thed. John Wiley & Sons.

Bond, S., M. J. Kirkby, J. Johnston, A. Crowle, and J. Holden. 2020. "Seasonal Vegetation and Management Influence Overland Flow Velocity and Roughness in Upland Grasslands." *Hydrological Processes* 34, no. 18: 3777–3791. https://doi.org/10.1002/hyp.13842.

Bonnett, S. A. F., S. Ross, C. Linstead, and E. Maltby. 2009. *A Review of Techniques for Monitoring the Success of Peatland Restoration*. University of Liverpool Natural England Commissioned Reports, Number 086. Available from: https://publications.naturalengland.org.uk/publication/46013.

Brook, I. 2018. "Restoring or Re-Storying the Lake District: Applying Responsive Cohesion to a Current Problem Situation." *Environmental Values* 27, no. 4: 427–445. https://doi.org/10.3197/096327118X15251686827750.

Burnett, N., and P. Bolton. 2024. *Flood Risk Management and Funding*. House of Commons Library Report no 7514. Available from: https://researchbriefings.files.parliament.uk/documents/CBP-7514/CBP-7514.pdf [Accessed 20/12/2024].

Burns, F., S. Mordue, N. al Fulaij, et al. 2023. *State of Nature 2023*. Available from: https://stateofnature.org.uk/wp-content/uploads/2023/09/TP25999-State-of-Nature-main-report_2023_FULL-DOC-v12.pdf.

Carey, J. 2016. "Rewilding." *Proceedings of the National Academy of Sciences of the United States of America* 113, no. 4: 806–808. https://doi.org/10.1073/pnas.1522151112.

Carver, S. 2016. "Flood Management and Nature - Can Rewilding Help?" *ECOS* 37, no. 1: 32–43. Available from: https://www.ecos.org.uk/wp-content/uploads/2016/05/ECOS-37-1-32-Flood-management-and-nature.pdf.

Cranfield University. 2023. *Soilscapes Soil Types Viewer - Cranfield Environment Centre*. Cranfield University Available from: https://www.landis.org.uk/soilscapes/index.cfm [Accessed 7/10/2023].

Crowle, A., I. Diack, D. Glaves, D. Key, and R. Lindsay. 2025. *Definition of Favourable Conservation Status for Blanket bog. RP2967*. Natural England Available from: https://publications.naturalengland.org.uk/publication/4818679880220672.

Cumbria Widlife Trust. 2022. Planting on damaged peatland at Armboth Fell will help tackle climate change and restore habitat for wildlife. Available from: https://www.cumbriawildlifetrust.org.uk/news/planting-damaged-peatland-armboth-fell-will-help-tackle-climate-change-and-restore-habitat.

Dadson, S. J., J. W. Hall, A. Murgatroyd, et al. 2017. "A Restatement of the Natural Science Evidence Concerning Catchment-Based "Natural" Flood Management in the UK." *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 473, no. 2199: 20160706. https://doi.org/10.1098/rspa.2016.0706.

DEFRA. 2021. *Flood and Coastal Erosion Risk Management: An Investment Plan for 2021 to 2027*. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1006447/Flood_coastal_erosion_investment_plan_2021.pdf.

DEFRA (2025). *Hydrology Data Explorer*. Available from: https://environment.data.gov.uk/hydrology/landing [Accessed 14/09/2025].

Dolton-Thornton, N. 2021. "Rewilding and Repeopling in Scotland: Large-Scale Land Managers' Perspectives and Practices." *Journal of Rural Studies* 86: 36–45. https://doi.org/10.1016/j.jrurstud.2021.05.010.

Environment Agency. 2017. *Working With Natural Processes to Reduce Flood Risk- 1 Page Summaries*. Available from: https://assets.publishing.service.gov.uk/media/6036c730d3bf7f0aac939a47/Working_with_natural_processes_one_page_summaries.pdf [Accessed 21/09/2025].

Environment Agency. 2023. *Natural Flood Management Programme*. Available from: https://www.gov.uk/guidance/natural-flood-management-programme [Accessed 28/08/2024].

Environment Agency (2024). *National Assessment of Flood and Coastal Erosion in England 2024*. Available from: https://www.gov.uk/government/publications/national-assessment-of-flood-and-coastal-erosion-risk-in-england-2024/national-assessment-of-flood-and-coastal-erosion-risk-in-england-2024 [Accessed 20/12/2024].

Fennell, J., C. Soulsby, M. E. Wilkinson, R. Daalmans, and J. Geris. 2023. "Time Variable Effectiveness and Cost-Benefits of Different Nature-Based Solution Types and Design for Drought and Flood Management." *Nature-Based Solutions* 3: 100050. https://doi.org/10.1016/j.nbsj.2023.100050.

Foundation for Common Land. (2023). *A Guide to Common Land and Commoning — Foundation for Common Land*. Available from: https://foundationforcommonland.org.uk/a-guide-to-common-land-and-commoning#what-are-commons-banner [Accessed 7/10/2023].

Gao, J., J. Holden, and M. Kirkby. 2017. "Modelling Impacts of Agricultural Practice on Flood Peaks in Upland Catchments: An Application of the Distributed TOPMODEL." *Hydrological Processes* 31, no. 23: 4206–4216. https://doi.org/10.1002/hyp.11355.

Gao, J., M. Kirkby, R. Grayson, and J. Holden. 2015. *Flood Modelling and Compaction Studies for the Upper Ure Project. Final Report to Yorkshire Dales National Park Authority, Project UUCP1/2015*. University of Leeds Internal report.

Goudarzi, S., D. G. Milledge, J. Holden, et al. 2021. "Blanket Peat Restoration: Numerical Study of the Underlying Processes Delivering Natural Flood Management Benefits." *Water Resources Research* 57, no. 4: 1–25. https://doi.org/10.1029/2020WR029209.

Harvey, G. L., A. T. Hartley, A. J. Henshaw, et al. 2024. "The Role of Rewilding in Mitigating Hydrological Extremes: State of the Evidence." *WIREs Water* 11, no. 3: e1710. https://doi.org/10.1002/wat2.1710.

Harvey, G. L., and A. J. Henshaw. 2023. "Rewilding and the Water Cycle." *WIREs Water* 10, no. 6: e1686. https://doi.org/10.1002/wat2.1686.

Holden, J., M. J. Kirkby, S. N. Lane, et al. 2008. "Overland Flow Velocity and Roughness Properties in Peatlands." *Water Resources Research* 44, no. 6: 1–11. https://doi.org/10.1029/2007WR006052.

Hope, D., N. Picozzi, D. C. Catt, and R. Moss. 1996. "Effects of Reducing Sheep Grazing in the Scottish Highlands." *Journal of Range Management* 49, no. 4: 301. https://doi.org/10.2307/4002587.

JNCC. (2023). *Lake District High Fells - Special Areas of Conservation*. Available from: https://sac.jncc.gov.uk/site/UK0012960 [Accessed 7/10/2023].

John Muir Trust. (2024). *Thirlmere Resilience Partnership Update*. Available from: https://www.johnmuirtrust.org/whats-new/news/1677-thirlmere-resilience-partnership-update [Accessed 27/10/2024].

Jordon, M. W. (2020). Does mixed vs separate sheep and cattle grazing reduce soil compaction? *Soil Use and Management*, 37 (4), 822–831. Portico. https://doi.org/10.1111/sum.12659.

Krebs, C. J. 1999. *Ecological Methodology*. 2nded. Benjamin/Cummings.

Lindsay, R., R. Birnie, & J Clough, (2014). *IUCN UK Committee Peatland Programme Briefing Note No7 Grazing and Trampling*. https://doi.org/10.13140/2.1.2920.6729.

Lorimer, J. 2017. "Probiotic Environmentalities: Rewilding With Wolves and Worms." *Theory, Culture and Society* 34, no. 4: 27–48. https://doi.org/10.1177/0263276417695866.

Lorimer, J., and C. Driessen. 2014. "Wild Experiments at the Oostvaardersplassen: Rethinking Environmentalism in the Anthropocene." *Transactions of the Institute of British Geographers* 39, no. 2: 169–181. https://doi.org/10.1111/tran.12030.

Magurran, A. E. 2004. *Measuring Biological Diversity*. Blackwell.

Malm, L., & D. Evans. (2020). *Rewilding: Rare Birds Return When Livestock Grazing Has Stopped*. Available from: https://theconversation.

com/rewilding-rare-birds-return-when-livestock-grazing-has-stopped-137948 [Accessed 11/10/2023].

Malm, L. E., J. W. Pearce-Higgins, N. A. Littlewood, et al. 2020. "Livestock Grazing Impacts Components of the Breeding Productivity of a Common Upland Insectivorous Passerine: Results From a Long-Term Experiment." *Journal of Applied Ecology* 57, no. 8: 1514–1523. https://doi.org/10.1111/1365-2664.13647.

Marshall, M. R., C. E. Ballard, Z. L. Frogbrook, et al. 2014. "The Impact of Rural Land Management Changes on Soil Hydraulic Properties and Runoff Processes: Results From Experimental Plots in Upland UK." *Hydrological Processes* 28, no. 4: 2617–2629. https://doi.org/10.1002/hyp.9826.

Marshall, M. R., O. J. Francis, Z. L. Frogbrook, et al. 2009. "The Impact of Upland Land Management on Flooding: Results From an Improved Pasture Hillslope." *Hydrological Processes* 23, no. 3: 464–475. https://doi.org/10.1111/j.1753-318X.2008.00009.x.

Martynoga, B. 2023. *Keeping Taps on and Boosting Wildlife: The Race to Protect the Lake District's Water*. Guardian Available from: https://www.theguardian.com/uk-news/2023/oct/11/keeping-taps-on-and-boosting-wildlife-the-race-to-protect-the-lake-districts-water?ref=inkcapjournal.co.uk [Accessed 24/10/2023].

McCarter, C. P. R., V. Golubev, and P. Whittington. 2024. "Modelling the Ecohydrological Plasticity in Soil Hydraulic Properties of *Sphagnum* Mosses." *Ecohydrology* 17, no. 7: e2701. https://doi.org/10.1002/eco.2701.

McCullagh, F., I. Alonso, S. Hedley, et al. 2025. *Definition of Favourable Conservation Status for Blanket bog - RP2967 Natural England*. Available From: https://publications.naturalengland.org.uk/publication/6212544182878208.

Metcalfe, P., K. Beven, B. Hankin, and R. Lamb. 2017. "A Modelling Framework for Evaluation of the Hydrological Impacts of Nature-Based Approaches to Flood Risk Management, With Application to In-Channel Interventions Across a 29-km^2 Scale Catchment in the United Kingdom." *Hydrological Processes* 31, no. 9: 1734–1748. https://doi.org/10.1002/hyp.11140.

MetOffice (2025). *Keswick Location-Specific Long-Term Averages*. Available from: https://www.metoffice.gov.uk/research/climate/maps-and-data/location-specific-long-term-averages/gcty8njjs [Accessed 14/09/2025].

Meyles, E. W., A. G. Williams, J. L. Ternan, J. M. Anderson, and J. F. Dowd. 2006. "The Influence of Grazing on Vegetation, Soil Properties and Stream Discharge in a Small Dartmoor Catchment, Southwest England, UK." *Earth Surface Processes and Landforms* 31: 622–631. https://doi.org/10.1002/esp.1352.

Milligan, G., R. J. Rose, and R. H. Marrs. 2016. "Winners and Losers in a Long-Term Study of Vegetation Change at Moor House NNR: Effects of Sheep-Grazing and Its Removal on British Upland Vegetation." *Ecological Indicators* 68: 89–101. https://doi.org/10.1016/j.ecolind.2015.10.053.

Monger, F., S. Bond, D. V. Spracklen, and M. J. Kirkby. 2022. "Overland Flow Velocity and Soil Properties in Established Semi-Natural Woodland and Wood Pasture in an Upland Catchment." *Hydrological Processes* 36, no. 4: 1–13. https://doi.org/10.1002/hyp.14567.

Moody, C., S. Carver, J. Holden, 2018. Ennerdale and Thirlmere Rainfall-Runoff Sediment-Response Scoping Study. Final report. University of Leeds. Internal report.

Murphy, T. R., M. E. Hanley, J. S. Ellis, and P. H. Lunt. 2021. "Native Woodland Establishment Improves Soil Hydrological Functioning in UK Upland Pastoral Catchments." *Land Degradation & Development* 32, no. 2: 1034–1045. https://doi.org/10.1002/ldr.3762.

Natural England. 2010. *England's Peatlands: Carbon Storage and Greenhouse Gases (NE257)*, 1–11. Available from: https://publications.naturalengland.org.uk/publication/30021.

Natural England Lake District Team. 2020. *Grazing Regimes for Nature Recovery: Experience From 25 Years of Agri-Environment Agreements in the Lake District's High Fells Natural England Lake District Team, 2020*. Available from: https://www.wildennerdale.co.uk/wp-content/uploads/2020/11/Grazing-Regimes-for-Nature-Recovery-7.7.20-.pdf.

Nicholson, A. R., G. M. O'Donnell, M. E. Wilkinson, and P. F. Quinn. 2020. "The Potential of Runoff Attenuation Features as a Natural Flood Management Approach." *Journal of Flood Risk Management* 13, no. S1: 1–14. https://doi.org/10.1111/jfr3.12565.

Olwig, K. R. 2016. "Virtual Enclosure, Ecosystem Services, Landscape's Character and the 'Rewilding' of the Commons: The 'Lake District' Case." *Landscape Research* 41, no. 2: 253–264. https://doi.org/10.1080/01426397.2015.1135320.

O'Mahony, K. 2020. "Blurring Boundaries: Feral Rewilding, Biosecurity and Contested Wild Boar Belonging in England." *Conservation and Society* 18, no. 2: 114–125. https://doi.org/10.4103/cs.cs_19_39.

Parfey, S.. (2017). *Strategies for Soil Sampling*. Available from: https://www.soilassociation.org/farmers-growers/farming-news/2017/strategies-for-soil-sampling/ [Accessed 21/10/2023].

Pettorelli, N., J. Barlow, P. A. Stephens, et al. 2018. "Making Rewilding Fit for Policy." *Journal of Applied Ecology* 55, no. 3: 1114–1125. https://doi.org/10.1111/1365-2664.13082.

Pilkington, M., J. Walker, & R. Maskill, 2015. *Restoration of Blanket Bogs; Flood Risk Reduction and Other Ecosystem Benefits. Annex 2: The Development of Plant Diversity. Final Report of the Making Space for Water Project: Moors for the Future Partnership*. Available from: https://www.moorsforthefuture.org.uk/__data/assets/pdf_file/0020/84215/Annex-2.Diversity.a.pdf.

Quinn, P. F., C. J. M. Hewett, M. E. Wilkinson, & R. Adams, (2022). The Role of Runoff Attenuation Features (RAFs) in Natural Flood Management. *Water*, 14 (23), 3807. https://doi.org/10.3390/w14233807.

Rewilding Britain. 2016. *How Rewilding Reduces Flood Risk*. Available from: https://www.rewildingbritain.org.uk/about-us/what-we-say/research-and-reports/how-rewilding-reduces-flood-risk.

Rewilding Europe. (2023). *Wild Ennerdale*. Available from: https://rewildingeurope.com/rew-project/wild-ennerdale/ [Accessed 15/12/2023].

Rhodes, D. 2020. *Flood Defences in England Get 1% of Infrastructure Spending*. BBC News Available from: https://www.bbc.co.uk/news/uk-england-51463267 [Accessed 21/10/2023].

Ricklefs, R. E., and G. L. Miller. 1999. *Ecology*. 4thed. Freeman.

Sandom, C. J., B. Dempsey, D. Bullock, et al. 2019. "Rewilding in the English Uplands: Policy and Practice." *Journal of Applied Ecology* 56, no. 2: 266–273. https://doi.org/10.1111/1365-2664.13276.

Schofield, L. 2023. *Wild Fell*. Doubleday.

Scott, E. 2021. *Peatland Burning: New Regulations for Blanket bog Habitats*. House of Lords Library Available from: https://lordslibrary.parliament.uk/peatland-burning-new-regulations-for-blanket-bog-habitats/ [Accessed 7/10/2023].

Sefton, C., A. Kumar, S. Turner, F. O'Callaghan, J. Bloomfield, and S. Clemas. 2023. *Hydrological Summary for the United Kingdom: July 2023*. UK Centre for Ecology & Hydrology 12pp. (UKCEH Project no. C06944). Available from: https://nora.nerc.ac.uk/id/eprint/535593.

Shepherd, M. J., J. Labadz, S. J. Caporn, et al. 2013. *Natural England Review of Upland Evidence - Restoration of Degraded Blanket bog*. Available From: https://publications.naturalengland.org.uk/publication/5724822.

Stewart, B. D., L. M. Howarth, H. Wood, et al. 2020. "Marine Conservation Begins at Home: How a Local Community and Protection of a Small Bay Sent Waves of Change Around the UK and Beyond." *Frontiers in Marine Science* 7: 1–14. Frontiers Media S.A. https://doi.org/10.3389/fmars.2020.00076.

Svenning, J.-C., P. B. M. Pedersen, C. J. Donlan, et al. 2016. "Science for a Wilder Anthropocene: Synthesis and Future Directions for Trophic Rewilding Research." *Proceedings of the National Academy of Sciences of the United States of America* 133, no. 4: 898–906. https://doi.org/10.1073/pnas.1502556112.

Tree, I. 2018. *Wilding: The Return of Nature to a British Farm*. Picador.

Turrill, W. B. 1963. *British Plant Life*. 3rded. Collins.

Xu, J., P. J. Morris, J. Liu, and J. Holden. 2018. "PEATMAP: Refining Estimates of Global Peatland Distribution Based on A Meta-Analysis." *Catena* 160: 134–140. https://doi.org/10.1016/j.catena.2017.09.010.