



# Native woodland establishment improves soil hydrological functioning in UK upland pastoral catchments

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Running title: Native woodland improves soil hydrology in UK uplands

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/ldr.3762

## Abstract

Extreme rainfall and flood events are predicted to increase in frequency and severity as a consequence of anthropogenic climate change. In UK upland areas, historical over-grazing and associated soil compaction have further exacerbated peak flood levels and flash-flood risk along many river catchments. As a result, the reinstatement of upland woodland is increasingly seen as a key component of an integrated suite of options forming part of Natural Flood Management (NFM) associated with a 'public money for public goods' approach to European agriculture. Nevertheless, understanding the impact of native woodland establishment on upland soil hydrology remains relatively poor. We compare physical and hydrological properties from the surface soils of establishing woodland and grazed pasture across four flood vulnerable upland headwater catchments in Dartmoor National Park, SW England. We show upland native woodland establishment is a viable soil recovery option, with a doubling of soil saturated hydraulic conductivity, increased 'wetness threshold' and reduced surface soil compaction and bulk density within 15 years of establishment. Our study supports the establishment of native woodland as an effective tool to improve the hydrological functioning of soils in upland pastoral catchments and the provision of flash-flood mitigation 'ecosystem services'. We caution however, that land managers and policy makers must consider past and present management, soil type and catchment location when planning new NFM schemes if environmental benefits are to be maximised and 'public money for public goods' are to be commensurate with outcomes.

**Keywords:** Climate Change - Natural Flood Management - UK Uplands - Native woodland - Soil recovery - Soil hydrology.

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## 1 Introduction

Much of the widespread scientific concern about the environmental threat posed by anthropogenic climate change stems from acute, extreme events rather than longer-term chronic change (Rahmstorf & Coumou, 2011; Vasseur, DeLong, & Gilbert, 2014; Parmesan & Hanley, 2015). Of the many extreme climate challenges, major shifts in the intensity of extreme precipitation and concomitant increases in regional flooding along river catchments are perhaps the most pressing (Intergovernmental Panel on Climate Change [IPCC], 2014; Bevacqua et al., 2019). Globally, severe freshwater flooding has long been seen as a major economic problem for agriculture, and wider human well-being (Page & Williams, 1926; Mirza, 2002; Chau, Cassells, & Holland, 2015).

Like many regions, the United Kingdom (UK) has experienced notable summer and winter flood events in recent years, resulting in significant economic and environmental damage along river catchments (Marsh & Hannaford, 2007; Chatterton et al., 2016; Schaller et al., 2016; Marsh et al., 2016). The UK is set to see an increase in flash-flood events due to projected increases in winter, spring, and autumn precipitation and more intense rainfall events (Lavers et al., 2013; Murphy et al., 2018; Bevacqua et al., 2019). The 'uplands', typically >250 – 300m amsl in the UK (Bunce, Wood, & Smart, 2018), are particularly vulnerable and important for managing this risk. Not only have these areas experienced greater increases in precipitation compared to lowland sites (Burt & Holden, 2010; Murphy, Hanley, Ellis, & Lunt, 2019), as the source of 68% of the UK's freshwater, they

represent the principle areas of river flow generation (Van der Wal et al., 2011; Robinson, Rodda, & Sutcliffe, 2013).

Historic degradation of upland areas (Bardgett, Marsden, & Howard, 1995; Bunce et al., 2018) is therefore, of particular concern. A legacy of soil compaction from long-term over-grazing combined with high but falling livestock numbers has left many upland soils in poor condition (Sansom et al., 1999; Holden et al., 2007a; Silcock, Brunyee, & Pring, 2012). Structural degradation and soil compaction results in the loss of macro-porous structures within the soil profile, of key importance for flood risk management (Palmer & Smith, 2013; Alaoui, Rogger, Peth, & Blöschl, 2018). Indeed whilst macro-pores typically consist of 10-15% of the soil volume, they account for 74-100% of the water movement (Aloui & Helbling, 2006). The loss of connectivity between near surface and subsurface macro-pores and the alteration of pore distribution, changes the water saturation states of soils, subsequent runoff, and hydrographic characteristics after rainfall events (Meyles, Williams, Ternan, & Dowd 2003; Dixon, Sear, Odoni, Sykes, & Lane, 2016). Heavily grazed, compacted areas can become 'active source areas' for runoff generation by lowering the threshold between dry and wet soil states ('wetness threshold') (Meyles, Williams, Ternan, Anderson, & Dowd, 2006; Holden et al., 2007b). Increased runoff leads to unnaturally high flows in wet periods and decreased river base-flow in dry periods (Sansom et al., 1999; Shuttleworth et al., 2019), representing a significant challenge for mitigating the impacts of future seasonal precipitation regimes expected with climate change.

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As part of a move towards Natural Flood Management (NFM), woodland creation is increasingly seen as a way to deliver flood mitigation and attenuate peak river flows (Nisbet, Silgram, Shah, Morrow, & Broadmeadow, 2011; Dadson et al., 2017; Lane, 2017; Stratford et al., 2017). NFM attempts to deliver multiple ecosystem services and public benefits including, carbon sequestration, habitat creation, water purification and public health, whilst minimising the social, environmental and economic costs (Iacob, Brown, Rowan, & Ellis, 2014; Burgess-Gamble et al., 2017; Lane, 2017). Trees offer NFM potential via three mechanisms: 1) higher water use (transpiration) increasing the water absorption capacity within soils and reducing surface water run-off; 2) greater hydraulic 'roughness' and canopy interception increasing water losses via evaporation, and reducing the velocity of surface run-off through temporary flood water retention (including via woody debris); and 3) amelioration of soil structure enhancing water infiltration, increasing water storage, and reducing run-off (Robinson et al., 2003; Nisbet & Thomas, 2006; Nisbet et al., 2011; Birkinshaw, Bathurst, & Robinson, 2014).

It is potential impacts on soil properties which are of most relevance for the mitigation of extreme flood events. Evidence from the Pontbren catchment (Wales, UK), suggests woodland creation in former pasture systems had significant and rapid (<10 years) impacts on soil infiltration properties and flood risk (Carroll, Bird, Emmett, Reynolds, & Sinclair, 2004; Marshall et al., 2014). Nonetheless, our knowledge of how applicable results are to other upland catchments is limited (Burgess-Gamble et al., 2017) and our understanding of how trees affect soil hydraulic properties more

generally, surprisingly poor (Archer et al., 2013; Rogger et al., 2017; Stratford et al., 2017; Chandler, Stevens, Binley, & Keith, 2018). This knowledge seems particularly pertinent given the recent commitment by the UK government to plant 11 million trees by 2050 (Defra, 2018), a move which is part of a growing interest in native woodland restoration more widely, linked to a 'public money for public goods' approach to European and UK agricultural policy (Bateman & Balmford, 2018; Baldock, Hart, & Scheele, 2019). Consequently, there is a pressing need for improved understanding on the impact native woodland creation has on soil infiltration and physical properties, especially in the upland pastures where they look set to be established.

In this study we test the hypotheses that woodland establishment is associated with; a) lower surface soil compaction b) higher soil water infiltration c) increased soil macro-porosity. We examined the impact of woodland establishment (7 – 15 years without grazing) on infiltration and compaction properties in valley side and valley bottom (podzolic and gley soils) soils on four flash-flood vulnerable pastoral catchments in Dartmoor National Park (DNP), SW England.

## **2 Methods**

### **2.1 Study sites**

Dartmoor National Park (DNP), covering an area of over 900 km<sup>2</sup>, is the largest upland area in the southern part of the British Isles (Figure 1). Due to intrusion of a granite batholith, Dartmoor (621m at its highest point) represents a major topographical feature in the landscape of SW England (Perry, 2014) being on

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average 127m higher than the surrounding lowland sedimentary basin (County of Devon)([www.en-gb.topographic-map.com](http://www.en-gb.topographic-map.com)). Woodland in this area was cleared in prehistory since when the area has primarily been used for grazing livestock (Fyfe & Woodbridge, 2012). Consequently, vegetation in DNP is dominated by acid grassland and Atlantic heath with relatively sparse tree cover over most of the area (Mercer, 2009). In addition to this long history of (over) grazing and associated soil compaction (Sansom et al., 1999), the area naturally receives high levels of precipitation, with extreme rainfall events set to increase into future decades associated with climate change (Fowler & Wilby, 2010; Murphy et al., 2019). The many small streams and rivers that rise on the open moorland form 'flashy' (or 'torrential') catchments, naturally vulnerable to spate flooding (Perry, 2014). Indeed, the recent flood events in this area (Devon County Council, 2013, 2014) coupled with low woodland cover (12%) similar to the UK average (13%) (Dartmoor National Park Authority, 2017; Forestry Commission, 2019; EUROSTAT, 2019), make DNP an ideal location to test the impact of woodland establishment on soil compaction and water infiltration rates.

Four newly established woodland areas with adjacent grazed pasture (acting as a 'control' treatment) were identified (Figure 1, Table 1) on the basis of available background information (when and how densely trees were planted, former land use etc.), and position within the catchment (i.e. relevance for NFM flood risk mitigation). Three of the four sites were formerly grazed sheep, cattle and deer pasture, recently planted with native trees (*Quercus robur*, *Quercus petraea*, *Fraxinus excelsior*,



*Corylus avellana*, *Sorbus aucuparia*, *Betula pubescens*, *Crataegus monogyna*). The fourth (Higher Piles, Erme catchment), is abandoned pasture left to natural tree colonisation but supplemented with additional planted trees. All establishing woodland areas were protected from grazing by fenced exclosures (Table 1). Pasture areas were grazed with a mix of sheep, cattle and deer. Grazing intensity was quantified (appendices, Table A.1) after discussion with respective landowners, and animal to Livestock Unit (LSU) conversion followed standard UK format (Natural England, 2013).

## 2.2 Hydraulic conductivity and soil compaction

Differences in water infiltration capacities between adjacent establishing woodland and grazed pasture areas were examined over five-weeks between September and early October 2018. Eight to fourteen sample locations were selected for each establishing woodland and pasture area within catchment sites (sample number matched for each pair)(Figure 1). Micro-topographic slope variation between sample pairs, an important variable of hillslope runoff (Thompson, Katul, & Porporato, 2010; Marshall et al., 2014) was minimised (within 5° range) and recorded using an electronic spirit level. Saturated hydraulic conductivity ( $K_{sat}$ ) of soils was quantified using a portable, single ring infiltrometer (100mm x 130mm) inserted 6cm into the soil surface (Carroll et al., 2004). Soil water infiltration was measured until a 'steady state' ( $K_{sat}$ ) was reached (i.e. <10% difference between three consecutive readings) (Eijkelkamp, 2018), with minimal possible time gaps between comparable readings.

The 'wetness threshold' (Meyles et al., 2003), defined as the volume of water (cm) required for soils to transition from a 'dry state' to a 'wet state', was calculated. In the present study we define this as the volume of water required for transition from initial infiltration rates at soil field capacity (soil moisture readings, Table A.2) to Ksat.

Ten surface soil (0 – 10 cm) compaction (Kilopascal - Kpa) and eight to fourteen soil moisture content (%) measurements (upper 6cm) were taken in each area per location using an impact shear vane (SL8 10) (19mm head) and theta probe kit (AT ML2X ; [www.delta-t.co.uk](http://www.delta-t.co.uk)) respectively.

### 2.3 Soil physical analysis

Six soil cores (60mm x 55mm) were collected from establishing woodland and grazed pasture areas at all four catchments using a Pittman corer (0200 Soil Core Sampler ; [www.soilmoisture.com](http://www.soilmoisture.com)) in December 2018. Cores were divided into upper (2 – 5cm) and lower (6 – 9cm) sections using a sharp knife, to avoid smearing. Separate cores were then saturated for three days, before being weighed and placed on sand suction tables at 0.05bar (- 50cm pressure head) until constant mass was reached; i.e. defined as no more than 100mg between readings (Hall, Reeve, Thomasson, & Wright 1977). Samples were re-weighed before drying at 100°C for 24 hours, and reweighed afterwards. The particle density of fine earth soils from each core was determined using the density bottle method (British Standards, 1990). Porosity was then determined:

$$\text{Porosity (\% of total sample)} = (1 - (\text{bulk density} / \text{particle density})) \times 100$$

Subtracting '0.05 bar' porosity from 'saturated' porosity was used as a measure of macro-porosity or 'transmission' porosity (British Standards, 1990). Samples were dry sieved to separate fine (<2 mm), small stone (> 2mm, < 16mm) and large stone (> 16mm) fractions. Soil organic matter (%) (SOM) from a subsample of the <2mm fraction, was determined using loss on ignition (LOI) (400°C for 18 hours). Dry bulk density (g cm<sup>-3</sup>) measurements including stones (>2mm) were conducted on all collected soil cores:

$$\text{Dry soil weight (g) / soil volume (cm}^{-3}\text{)}$$

#### 2.4 Soil classification

The upper soil layers (0 – 25cm) were classified by digging a hexagonal-shaped pit (40 – 50cm deep), and slices of undisturbed soil used to assess structural condition (Palmer & Smith, 2013). Soil structure is characterised by the shape, size, and degree of development of primary soil particles into naturally or artificially formed structural units, as well as the presence of voids (pores) between and within aggregates (see Hodgson (1997)). Structural degradation assessments were paired to surface compaction readings during field visits conducted at each catchment location for improved confidence in shear vane methodology (appendices, Table A.3). Samples were assigned to a 'soil series' (Clayden & Hollis, 1987) by inspection of surface and subsurface layers within pits and a 5cm wide Edelman auger to assess deeper layers. Soil classification was conducted within adjacent establishing

woodland and grazed pasture plots at each site to confirm sample locations were true pairs.

## 2.5 Statistical analysis

A Shapiro-Wilks normality test and Levene test for homogeneity of variance were performed. Despite marginally breaking normality and variance assumptions for some variables (initial infiltration, wetness threshold) parametric testing was applied to avoid potential for type II error. Results for these variables were treated and interpreted with caution (significance determined at  $p < 0.05$  rather than  $p \leq 0.05$ ) (Dytham, 2011). Differences between the establishing woodland and pasture areas ('land use'), between catchment and for interacting catchment vs 'land use' impacts were assessed via two-way ANOVA.

Statistics were performed using R studio (R Core Team 2017) and graph production and statistical packages 'GGplot2' (Wickham, 2009), 'cowplot' (Wilke, 2017) and 'Car' (Fox & Weisberg, 2011) respectively. Data available via Murphy (2020).

## 3 Results

Ksat (1.8-fold), initial infiltration (2.7-fold) and 'wetness threshold' (1.6-fold) were significantly higher in establishing woodland than grazed pasture areas ('Land Use' effect  $p < 0.001$  for all responses) (Table 2). For Ksat and initial infiltration, the impact of woodland establishment was dependent on catchment site (i.e. we found a significant 'Land use'  $\times$  'Catchment' interaction), mostly relating to higher pasture infiltration and lower woodland infiltration at the Holy Brook. The elevated wetness

threshold in woodland areas was however ubiquitous across all catchment sites (Figure 2), with no 'Land use' × 'Catchment' interaction. 'Dry state' surface soil moisture (woodland mean 29.6, SE = 4.8, pasture mean = 30.4, SE = 2.0) did not vary with land use.

Soil surface soil compaction (Kpa) (2.4-fold) and bulk density ( $\text{g cm}^{-3}$ ) (BD) (1.2-fold) were significantly higher in pasture areas ('Land Use' effect  $p < 0.001$  for both responses) (Table 3). The impact of woodland establishment on soil compaction (i.e. BD, M porosity and SOM) varied between catchments as differences in soil physical properties between establishing woodland and pasture were minimal at Holy Brook, where SOM and M porosity were comparatively low (Figure 3), small stone percentage highest (appendices, Table A.4), and historic stock density higher (Table A.1). The impact of woodland establishment in lowering surface soil compaction was greatest where SOM was higher (i.e. Colly Brook and Dean Burn) but the site with the youngest establishing woodland (Erme) evidenced the most marked changes in BD, SOM and M porosity (i.e. lower BD and increased SOM and M porosity in establishing woodland areas). For SOM and M porosity, we find catchment differences resulted in no overall 'land use' impact for these soil properties. We also observed differences in compaction, BD, percentage of small stones (%), macro-porosity (M porosity) (%) and SOM of surface soils between catchments (Table 3).

#### **4 Discussion**

The degraded nature of soils in many UK upland pastoral catchments (Sansom et al., 1999; Holden et al., 2007b), alongside elevated precipitation trends in these areas (Murphy et al., 2019) highlights the importance of hydrological integrity and soil recovery in flood risk management. Our results show that native woodland establishment in upland pasture areas offers a viable, and potentially rapid (7 – 15 years) means to reduce surface soil compaction and bulk density with concomitant benefits to Ksat and ‘wetness threshold’ (i.e. soil water holding capacity).

Difference in soil wetness thresholds have considerable impact on the steepness of river flow hydrograph peaks, with wet state ‘active source areas’ quickly converting rainfall into either saturated overland flow or subsurface flow runoff (Meyles et al., 2003). During this ‘wet state’, the water at hillslope scale can become highly connected, with topography and slope angle dominating (appendices, Table A.5). This connectivity results in the rapid conversion of water to stream discharge via a network of ephemeral channels and rapid flow pathways, often associated with animal tracks and areas of high compaction (Meyles et al., 2006; Meijles, Dowd, Williams, & Heppell, 2015). It is likely therefore, that establishing woodland offers effective NFM by reducing the number of wet source areas, the connectivity of hillslope moisture, and the conversion of rainfall to stream discharge.

Our study is the first to measure comparable differences in the water infiltration rates of soils between establishing native woodland and pasture sites across multiple (more than two) UK upland catchments. Although not as high as the 12-fold increase in Ksat reported by Chandler et al. (2018), our average 1.8-fold increase in

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establishing woodland versus grazed pasture areas was broadly similar to Marshall et al. (2009) (2.5-fold) and Archer et al. (2013) (4.5-fold). Nonetheless, catchment-specific differences highlight the importance of local soil conditions and corroborate the view that the positive impact of trees on soil permeability ( $K_{sat}$ ) is dependent on a range of interacting factors (Chandler & Chappell, 2008).

The ability of soils to accept rainwater is highly dependent on soil type, with less permeable ('stagnant') soils reaching 'wet state' quickly, and freely draining soils such as brown earth podzols, rarely reaching saturation if in good condition (Brady & Weil, 2008). Indeed, the catchment specificity of our results, specifically the negligible recovery of  $K_{sat}$  for the site with highest past grazing intensity (Holy Brook), suggests soils can reach a 'point of no return' if the elastic limit is exceeded. It is also worth bearing in mind that recovery from long-term soil compaction can range from just six months to more than 50 years. Specifically, the resistance (vulnerability) and resilience (recovery) of soils to compaction depend on management impacts and natural soil properties (Brady & Weil, 2008, Gregory et al., 2009), involving a complex interaction between clay content (%), SOM, water content, soil texture, biological activity, and past and previous management (Pulleman, Six, Uyl, Marinissen, & Jongmans, 2005; Gregory et al., 2009, Bonetti, Anghinoni, de Moraes, & Fink, 2017).

The most noticeable beneficial effect of woodland establishment on  $K_{sat}$  occurred where SOM was highest (i.e. Colly Brook and Dean Burn), supporting the view that higher SOM is linked to increased soil resilience (Bonetti et al., 2017). Our study

suggests therefore, that woodland NFM schemes will be most effective in areas where soils are more resilient. Heavily degraded soils with low resilience likely require remediation if the benefits of woodland establishment are to be maximised. Indeed, in the Holy Brook catchment, where historic stock density was highest (appendices, Table A.1), steady-state water infiltration ( $K_{sat}$ ) in establishing woodland was no different to pasture areas, with negligible treatment impacts on bulk density, compaction and macro-porosity, despite the greater age and density of planting. This finding highlights the important role of historic stock density, soil type and management in determining potential woodland NFM outcomes and soil remediation requirements. Moreover, it should not be assumed that woodland creation will always improve soil health, hydrology, and peak flows (Soulsby, Dick, Scheliga, & Tetzlaff, 2017). Indeed, whilst long-term evidence from upland catchments typically links higher tree cover to reductions in river discharge (Robinson et al., 2003; Birkenshaw, Bathurst, & Robinson, 2014; Evaristo & McDonnell, 2019), records for effective attenuation of peak flows for the most severe river flooding by woodland at catchment scale is limited (Burgess-Gamble et al., 2017; Dadson et al., 2017; Soulsby et al., 2017). Consequently, it is important that realistic NFM expectations are communicated to the public and policy makers.

Our study demonstrates the potential of native woodland restoration in upland pasture systems to improve the hydrological functioning of soils needed to mitigate the increasing flash-flood risk expected with climate change. Establishment of native woodland where naturally freely draining soils have suffered long-term soil



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compaction through (over) grazing offers the highest potential increases in infiltration rates. These compacted soils are typical of mid-slope valley pastures in UK catchment headwaters. Here not only may native woodland establishment reduce surface runoff on site, but crucially, 'soak up' runoff generated further up the hillslope (Chandler et al., 2018). Indeed, the strategic placement of native woodland will be critical to reduce surface run-off generated by both saturation excess (run-off when soil saturated) and infiltration excess (rainfall intensity greater than infiltration rate). Flash-flooding can result from both these processes (individually and in combination), and the flood mitigation potential of native woodland will be defined by its placement (soil type, soil condition, slope angle), character (extent, tree density, tree species, management), and the seasonal climate (rainfall patterns, evaporation potential) at respective catchments.

Additionally, changes in land management will likely demand trade-offs between ecosystem service benefits (Iacob et al., 2014; Cord et al., 2017). Whilst our study shows grazing cessation and woodland establishment aids soil recovery, and may significantly benefit carbon sequestration (Perks, Nagy, Meir, & Auld, 2010; Uri et al., 2017; Bastin et al., 2019), lower grazing may reduce grassland species richness (Evans et al., 2015; Mitchell et al., 2017; Pakeman, Fielding, Everts, & Littlewood, 2019). The large impact of the location and type of woodland expansion on ecosystem service provision (such as on river base-flow, Nisbet et al., 2011) further complicates trade-offs, and highlights the importance of ensuring 'the right trees, are in the right place' (NCC, 2020).

## 5. Conclusions

Our study provides supports for the establishment of native woodland as an effective tool to improve the hydrological functioning of soils in upland pastoral catchments and the provision of flash-flood mitigation 'ecosystem services'. We caution however, that land managers and policy makers must consider past and present management, soil type and catchment location when planning new NFM schemes if environmental benefits are to be maximised and 'public money for public goods' are to be commensurate with outcomes.

Despite the likelihood that upland land-use policy will increasingly promote woodland establishment within pasture systems to mitigate lower-catchment flooding, it is vital that land managers and policy makers consider the context in which NFM outcomes are expected. We recommend long term monitoring of river flows in upland catchments to clarify and refine realistic NFM outcomes associated with native woodland establishment. Furthermore, consultation and co-operation with farmers and land managers with local soil knowledge will be essential if environmental benefits are to be maximised, and to ensure the sensitive implementation of nature-based solutions to climate change (Seddon et al, 2020).

## 5 Acknowledgments

This work was funded by the Environment Agency and the University of Plymouth as part of the Dartmoor Headwaters pilot project. Consequently, we would like to thank the flood and coastal risk management team (Exeter, UK) and the University of

Plymouth for financial and technical support. Particular thanks to Dr Richard Smith (Environment Agency) for his guidance and technical soils expertise. We also gratefully acknowledge Moor Trees (moortrees.org) for access to sites and landowners (Cyril Pearse, Hugh Bourne, Henry White and John Howell) for their help and co-operation. Authors have no conflict of interest to declare.

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## 7 Tables

**Table 1** – Site characteristics of four river catchments located on Dartmoor, SW England, used to assess the impact of establishing woodland on soil hydrology. Details include location (latitude:longitude), time since planting (woodland age) and composition (tree density and species, planting method). Soil series and descriptive information were classified using field soil pit observations and ‘The Soils Guide’ (Cranfield University, 2019).

	Catchment			
	Erme (ER)	Colly Brook (CB)	Dean Burn (DB)	Holy Brook (HB)
Location (Lat:Long)	50.4382: -03.9110	50.5779: -04.0657	50.4831: -03.8391	50.5024: -03.8575
Tree density (ha <sup>-1</sup> )	1083	945	686	1557
Altitude (m)	250m	319m	286m	281m
Woodland age (years)	7	10	11	15
Dominant tree species	Oak	Oak	Oak	Oak & Ash
Method of establishment	Natural colonisation with planting	Planted	Planted	Planted
Position within catchment (Slope angle °)	Valley bottom (0)	Valley bottom (0)	Valley slope (7.0)	Valley slope (9.1)

Soil series	Laployd	Wilcocks 2	Denbigh	Manod
Soil description	Stagnohumic gley soils	Stagnohumic gley soils	Brown Earth, Podzolic	Brown earth, Podzolic
Natural Hydrology	Seasonally waterlogged	Seasonally waterlogged	Freely draining	Freely draining

**Table 2** – The influence of newly established woodland on surface soil hydrological properties along four study river catchments located in Dartmoor, SW England. Mean ( $\pm$ SE and SD) values of saturated hydraulic conductivity ( $\text{cm}^{-\text{hr}}$ ) ('Ksat'), initial infiltration rate ( $\text{cm}^{-\text{hr}}$ ) ('Infiltration'), wetness threshold ( $\text{cm}^{-\text{hr}}$ ) ('W threshold'), and surface soil moisture (%) of soils in establishing 'woodland' sites are compared with control grazed 'pasture' areas using two way ANOVA with significant ( $p \leq 0.05$  except Infiltration and W threshold =  $p < 0.05$ ) differences denoted in bold font. The F-statistic ( $F$ ) and  $p$ -values ( $p$ ) are reported.  $n = 4$ .

Soil property	Land use	Mean	SE	SD	Results of Two-way ANOVA					
					Land use (df = 1)		Catchment (df = 3)		Interaction (df = 3)	
					$F$	$p$	$F$	$p$	$F$	$p$
Ksat ( $\text{cm}^{-\text{hr}}$ )	Woodland	1052.5	276.5	552.9	<b>15.9</b>	<b>&lt; 0.001</b>	<b>3.5</b>	<b>0.019</b>	<b>6.2</b>	<b>&lt; 0.001</b>
	Pasture	574.1	134.5	268.9						
Infiltration ( $\text{cm}^{-\text{hr}}$ )	Woodland	1849.8	347.5	797.4	<b>39.5</b>	<b>&lt; 0.001</b>	<b>3.4</b>	<b>0.022</b>	<b>5.1</b>	<b>0.003</b>
	Pasture	693	137.0	273.9						
W threshold (cm)	Woodland	29.4	2.3	4.6	<b>24.1</b>	<b>&lt; 0.001</b>	2.0	0.124	1.8	0.164
	Pasture	18.8	1.3	2.7						
Soil moisture (%)	Woodland	29.6	2.4	4.8	0.9	0.330	2.2	0.094	2.2	0.100
	Pasture	30.4	1.0	2.0						

**Table 3** – The influence of newly established woodland on surface soil physical properties along four study river catchments located in Dartmoor, SW England. Mean ( $\pm$ SE and SD) values of surface soil compaction (Kpa), bulk density with stones ( $\text{g cm}^{-3}$ )(BD), macro-porosity (%) (M porosity), percentage of small stones (%) and organic matter (%) (SOM) of soils in establishing ‘woodland’ sites are compared with control grazed ‘pasture’ areas using two way ANOVA with significant ( $p \leq 0.05$ ) differences denoted in bold font. The F-statistic ( $F$ ) and  $p$ -values ( $p$ ) are reported.  $n = 4$ .

Soil properties	Land use	Mean	SE	SD	Land use (df = 1)		Catchment (df = 3)		Interaction (df = 3)																																																						
					$F$	$p$	$F$	$p$	$F$	$p$																																																					
Compaction (Kpa)	Woodland	21.8	6.8	13.7	<b>194.3</b>	<b>&lt; 0.001</b>	<b>3.9</b>	<b>0.011</b>	<b>18.9</b>	<b>&lt; 0.001</b>																																																					
	Pasture	52.0	2.7	5.4							BD ( $\text{g cm}^{-3}$ )	Woodland	0.67	0.05	0.09	<b>22.6</b>	<b>&lt; 0.001</b>	<b>10.8</b>	<b>&lt; 0.001</b>	<b>6.1</b>	<b>0.001</b>	Pasture	0.80	0.06	0.12	M porosity (%)	Woodland	9.8	1.0	2.0	2.4	0.128	<b>34.5</b>	<b>&lt; 0.001</b>	<b>10.5</b>	<b>&lt; 0.001</b>	Pasture	9.3	0.9	1.8	Small stones (%)	Woodland	32.4	11.2	22.4	0.6	0.458	<b>229.1</b>	<b>&lt; 0.001</b>	2.2	0.108	Pasture	33.5	11.4	22.7	SOM (%)	Woodland	15.4	1.2	2.3	2.4	0.129	<b>21.9</b>
BD ( $\text{g cm}^{-3}$ )	Woodland	0.67	0.05	0.09	<b>22.6</b>	<b>&lt; 0.001</b>	<b>10.8</b>	<b>&lt; 0.001</b>	<b>6.1</b>	<b>0.001</b>																																																					
	Pasture	0.80	0.06	0.12							M porosity (%)	Woodland	9.8	1.0	2.0	2.4	0.128	<b>34.5</b>	<b>&lt; 0.001</b>	<b>10.5</b>	<b>&lt; 0.001</b>	Pasture	9.3	0.9	1.8	Small stones (%)	Woodland	32.4	11.2	22.4	0.6	0.458	<b>229.1</b>	<b>&lt; 0.001</b>	2.2	0.108	Pasture	33.5	11.4	22.7	SOM (%)	Woodland	15.4	1.2	2.3	2.4	0.129	<b>21.9</b>	<b>&lt; 0.001</b>	<b>6.4</b>	<b>0.001</b>	Pasture	14.3	2.3	4.7								
M porosity (%)	Woodland	9.8	1.0	2.0	2.4	0.128	<b>34.5</b>	<b>&lt; 0.001</b>	<b>10.5</b>	<b>&lt; 0.001</b>																																																					
	Pasture	9.3	0.9	1.8							Small stones (%)	Woodland	32.4	11.2	22.4	0.6	0.458	<b>229.1</b>	<b>&lt; 0.001</b>	2.2	0.108	Pasture	33.5	11.4	22.7	SOM (%)	Woodland	15.4	1.2	2.3	2.4	0.129	<b>21.9</b>	<b>&lt; 0.001</b>	<b>6.4</b>	<b>0.001</b>	Pasture	14.3	2.3	4.7																							
Small stones (%)	Woodland	32.4	11.2	22.4	0.6	0.458	<b>229.1</b>	<b>&lt; 0.001</b>	2.2	0.108																																																					
	Pasture	33.5	11.4	22.7							SOM (%)	Woodland	15.4	1.2	2.3	2.4	0.129	<b>21.9</b>	<b>&lt; 0.001</b>	<b>6.4</b>	<b>0.001</b>	Pasture	14.3	2.3	4.7																																						
SOM (%)	Woodland	15.4	1.2	2.3	2.4	0.129	<b>21.9</b>	<b>&lt; 0.001</b>	<b>6.4</b>	<b>0.001</b>																																																					
	Pasture	14.3	2.3	4.7																																																											

## 8 Figure legends

**Figure 1** – a) Location of study area (Dartmoor National Park, southwest England) within north-western Europe. b) Locations of catchment sites in relation to the 300m 'upland' isoline. c) Example (Holy Brook) of sampling approach to compare soil hydrological and physical properties in establishing woodland (circles) and pasture areas (crosses).

**Figure 2** – The influence of newly established woodland on surface soil hydrological properties along four study river catchments located in Dartmoor, SW England. Mean ( $\pm$ SE) infiltration rate ( $\text{cm}^{-\text{hr}}$ ) by cumulative water volume of soils in establishing woodland sites compared with control grazed pasture areas.

**Figure 3** – Site-specific difference in surface soil physical properties between establishing woodland and grazed pasture areas along four study river catchments in Dartmoor, SW England. Values show the mean ( $\pm$ SE) surface soil compaction (Kpa), bulk density ( $\text{g cm}^{-3}$ ), macro-porosity (%) ('M porosity) and organic matter (%) ('SOM') recorded in establishing woodland and grazed pasture areas.

## 9 Appendices

**Table A.1** – Details of current (2018/2019) and previous grazing intensity for summer and winter seasons in upland catchments. Details include current (2018/2019) and previous grazing intensity in summer (May – October) and winter (December – March) seasons along four study river catchments in Dartmoor, SW England. Grazing intensities are presented in livestock units per hectare (LSU ha<sup>-1</sup>).

	Catchment									
	Erme		Colly Brook		Dean Burn		Holy Brook			
	Current grazing intensity (LSU ha <sup>-1</sup> )									
Land use	Woodland	Pasture	Woodland	Pasture	Woodland	Pasture	Woodland	Pasture		
Summer	0	0.20	0	0.72	0	0.18	0	0.66		
Winter	0	0.01	0	0	0	0.18	0	0.66		
	Previous grazing intensity (LSU ha <sup>-1</sup> )									
Time period covered	2004 – 2015		2002 - 2016		Pre 2002		N/a		1991 - 2013	
Summer	0.21‡		0.29		3.93		-		1.46	
Winter	0.08‡		0 (3.15†)		3.93		-		1.46	

† March – April, ‡ Averaged from 2009 and 2015 audits.

**Table A.2** – Soil moisture (%) readings at field capacity (24 – 48 hours after rainfall) in establishing native woodland and grazed pasture sites along four study river catchments in Dartmoor, SW England.

Land use	Soil moisture (%)							
	Erme		Colly Brook		Dean Burn		Holy Brook	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Woodland	30.6	2.5	22.7	3.6	33.6	2.2	31.6	1.6
Pasture	27.5	1.3	30.8	2.1	32.2	2.3	30.9	2.6

**Table A.3** - Relationship between surface shear vane compaction measurements and visual assessment of soil structure conducted along four study river catchments in Dartmoor, SW England.

Surface soil compaction (Kpa)	Visual assessment of soil structure
0 – 30	Excellent
30 – 45	Good
45 – 60	Moderate
60 – 90	Moderate to Poor
90 – 130	Poor
130+	Very poor

**Table A.4** – Differences in the physical properties of surface soils along four study river catchments. Details show the mean ( $\pm$ SE) values of surface soil organic matter (%) (SOM), bulk density with stones ( $\text{g cm}^{-3}$ )(BD), percentage of ‘small stones’ (%) and macro-porosity (%) (M porosity) recorded along four study catchments in Dartmoor, SW England.  $n = 12$ .

	Catchment							
	Erme		Colly Brook		Dean Burn		Holy Brook	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
SOM (%)	11.9	1.2	16.6	0.9	18.5	0.6	12.3	0.3
BD ( $\text{g cm}^{-3}$ )	0.79	0.06	0.69	0.03	0.63	0.02	0.81	0.02
Small stones (%)	14.4	1.6	12.9	1.6	48.8	1.5	55.6	1.4
M porosity (%)	9.3	0.6	11.8	0.3	9.5	0.3	7.6	0.2

**Table A.5** – Relationship between catchment slope angle and saturated hydraulic conductivity ( $K_{\text{sat}}$ ). Reported are the Pearson’s correlation coefficient ( $r$ ), significance ( $p$ -value =  $p$ ), and model fit ( $r^2$ ) between mean values of slope angle and  $K_{\text{sat}}$  in establishing woodland and grazed pasture areas along four study river catchments in Dartmoor, SW

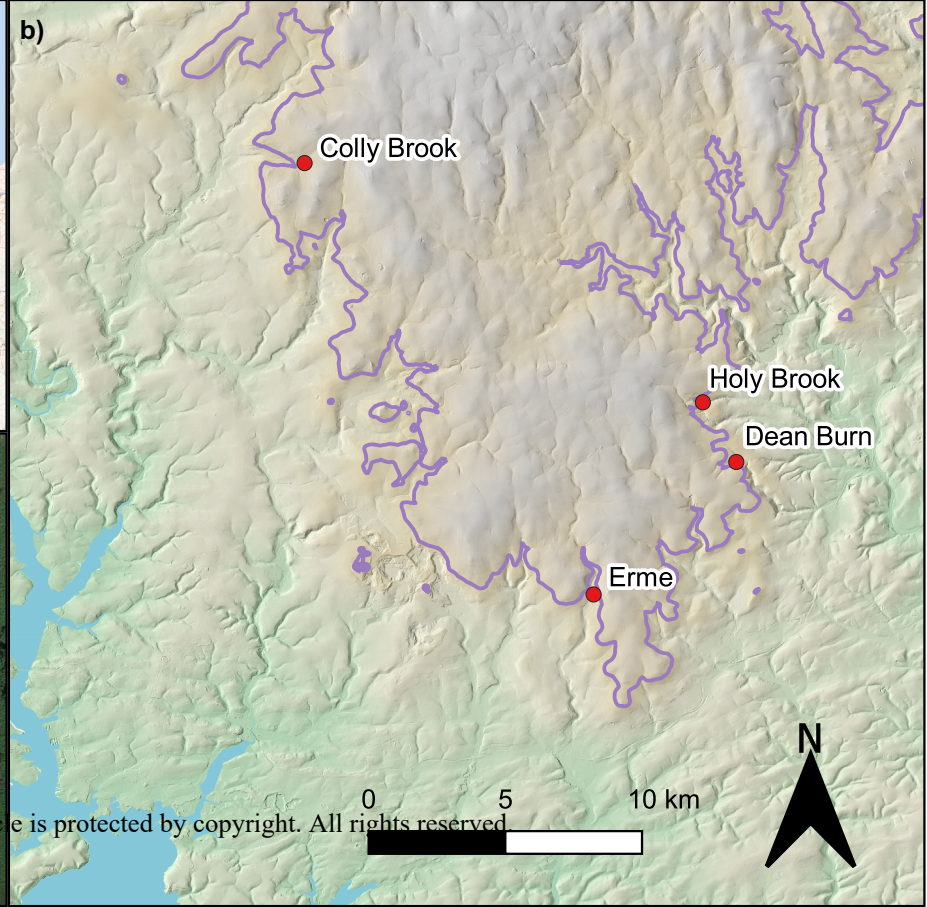
England. Statistically significant relationships ( $p \leq 0.05$ ) are denoted in bold.  $n = 4$ .

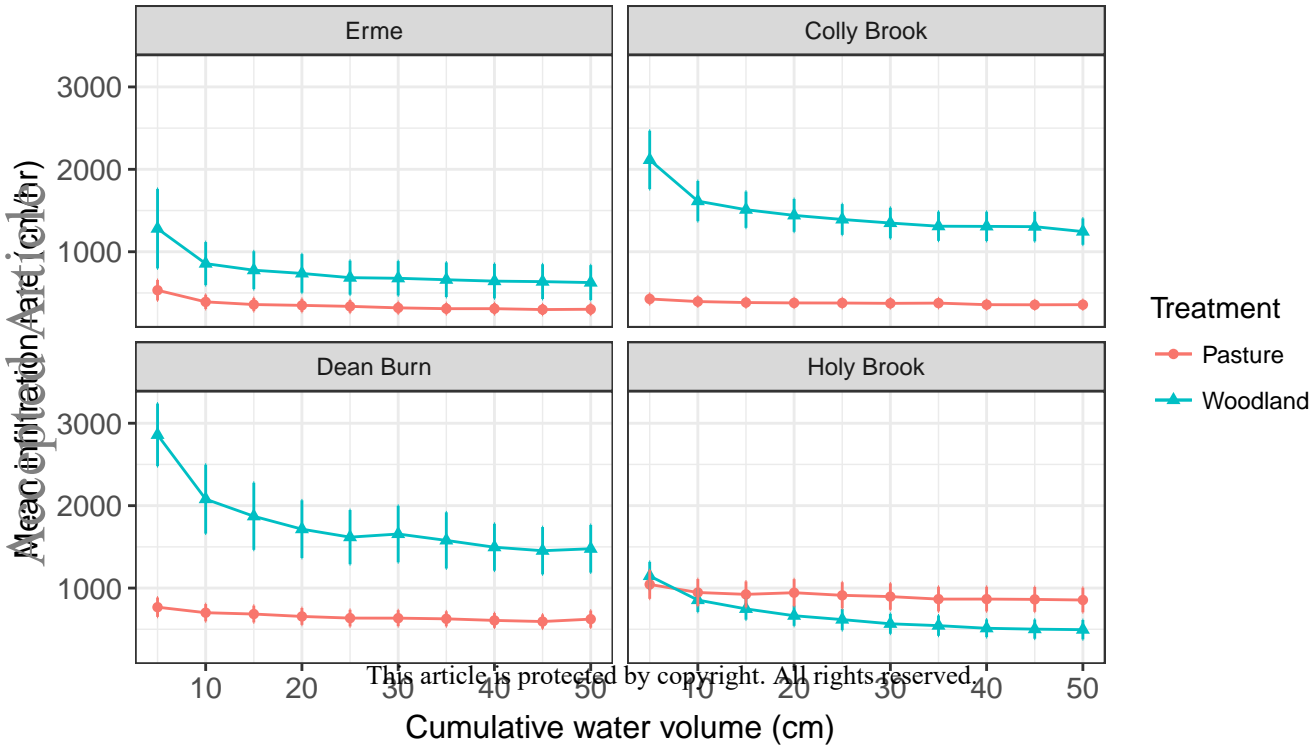
Slope angle vs Ksat					
Woodland			Pasture		
$r$	$p$	$r^2$	$r$	$p$	$r^2$
-0.167	0.832	0.028	<b>0.978</b>	<b>0.021</b>	<b>0.957</b>

## 10 Data Availability Statement

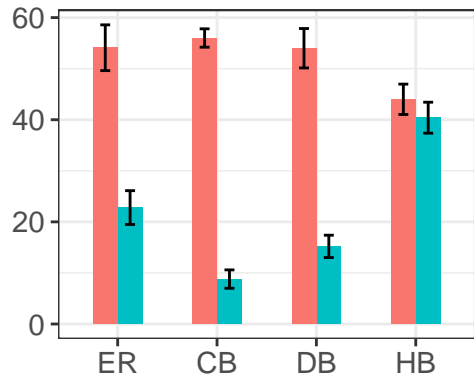
The data that support the findings of this study are openly available in Mendeley Data, at <http://dx.doi.org/10.17632/mc2rxtzk4n.2>.



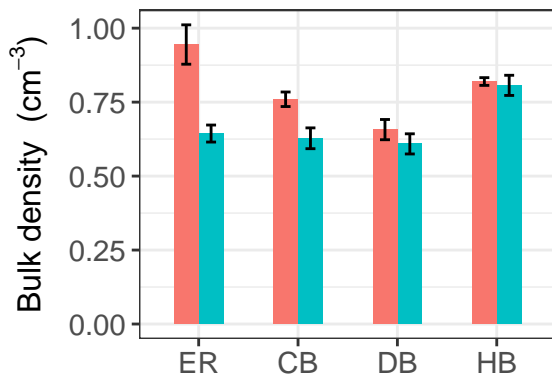




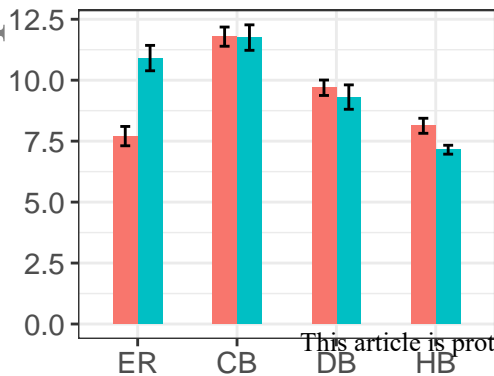
## Compaction



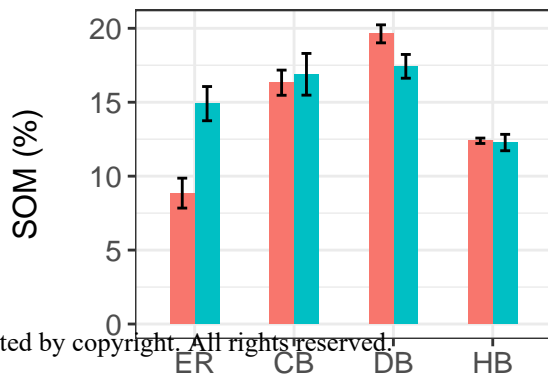
## Bulk Density



## M porosity



## SOM



## Treatment

Pasture

Woodland