The impact of semi-natural woodland and pasture on soil properties and streamflow.

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Abstract:

The increased frequency of flood events has motivated interest in natural flood management (NFM), in particular the potential for woodlands to reduce flooding. Woodlands can reduce the risk of rainfall-generated flooding through increased interception, soil infiltration, and available storage. Despite growing evidence, there is still low confidence in woodlands as a flood mitigation method due to limited empirical data available, particularly for semi-natural woodlands.

We established a correlation catchment study in Haweswater, Cumbria, UK. Nine small upland catchments, each less than 0.2 km^2 in area, were established on semi-natural broadleaf woodland sites where no stock grazing occurs or pasture with varied grazing intensity. At each site soil characteristics were investigated, namely soil moisture, permeability and bulk density. In addition, a v-notch weir was installed within in each catchment to calculate flow. The specific peak discharge (SPD), peak runoff coefficient, volume runoff coefficient and time taken to flow response was determined at each site for 28 storm events, of up to 205 mm, identified over a 13-month period.

We found that semi-natural woodland reduced SPD by 33-52 % compared with pasture, reducing SPD by 36 % during larger storms (> 1 mm/hr peak discharge). Woodland reduced the peak runoff coefficient by 31-52 % and the volume runoff coefficient by 13-22 % compared to pasture. Additionally, response to storm events took 1-4 hours longer in woodland. These differences in flood response can be somewhat explained by the more permeable woodland soils, 4.6 times greater than pasture soil. Our analysis strengthens the argument that woodlands can reduce rainfall-generated flooding as a land use management method of NFM.

Data collected here should be used to inform the parameters in flood prediction models and contribute to the evidence base for NFM.

Introduction:

Flooding has increased across the globe over the past three decades (Kundzewicz et al., 2014; Wingfield, Macdonald, Peters, Spees, & Potter, 2019) and the UK is no exception (Rogger et al., 2017). In England, flood damage costs £1.1 billion annually with 1 in 6 properties (5.4 million) at risk from flooding (Priestley, 2017). This risk is expected to further increase under future climate change (Iacob, Brown, & Rowan, 2017).

Traditional flood management methods in the UK have consisted of costly, hard-engineered structures. These flood defences have been put under immense pressure in recent years due to the persistent reoccurrence of flood events. This has contributed to the growing interest in the use of 'soft-engineered' and in most instances cheaper Natural Flood Management (NFM) strategies (Dadson et al., 2017; Stevens, Clarke, & Nicholls, 2016). NFM, also referred to as Working with Natural Processes (WWNP) or nature-based solutions, is an approach to flood management that seeks to work with natural processes whilst enhancing the flood regulatory capacity of a catchment with the addition of benefits to ecosystem services, pollution assimilation, habitat creation and carbon storage (Hankin et al., 2017). NFM can reduce flooding through a number of mechanisms, such as increasing interception, soil infiltration and soil storage capacity, and reducing water flow connectivity and overland flow velocity (*Natural Flood Management*, 2011). One of the principal ways this can be accomplished is through land use management for example, woodland creation.

Vegetation and land cover have well recognised impacts on a range of hydrological processes including interception, infiltration into the soils, and available storage (Stratford et al., 2017). Trees intercept more precipitation than other vegetation types, as trees are usually taller and have greater leaf area (I. R. Calder & Aylward, 2006; Nisbet, 2005). Woodland soils are often associated with higher infiltration and permeability rates than other vegetation types (Agnese, Bagarello, Baiamonte, & Iovino, 2011; N. A. L. Archer et al., 2013; I. Calder, Harrison, Nisbet, & Smithers, 2008; Carroll, Bird, Emmett, Reynolds, & Sinclair, 2004; Mawdsley, Chappell, & Swallow, 2017; McCulloch & Robinson, 1993; Zimmermann, Elsenbeer, & De Moraes, 2006). This is attributed to a more open structure found in woodland soils as a result of increased organic matter and the action of tree roots (TR Nisbet & Thomas, 2006). Planting trees and preventing livestock grazing can rapidly modify soil properties, with permeability rates 2.3 times higher at a depth of 10-30 cm, under 18-month old saplings compared to adjacent grazed moorland (Mawdsley et al., 2017). Permeability rates in a mature forest were 8 times higher at a depth of 12.5 cm and 4 times higher at 20 cm compared to rates observed in a pasture (Zimmermann et al., 2006). Infiltration rates were 2 times higher under 6-year old saplings and 3 times higher under mature (50-year old) forest than adjacent cropland (Wahren, 2009). Higher infiltration and permeability rates denote more water storage availability therefore reducing the likelihood of overland flow and risk of flooding.

Whilst the impacts of land cover on hydrological processes are well known (McCulloch & Robinson, 1993; Ngai, 2017), there is less confidence around the impacts of land cover on flood risk (Dadson et al., 2017; Marapara, Jackson, Hartley, & Maxwell, 2020; Rogger et al., 2017; Stratford et al, 2017). Catchment-based studies, which have been widely used to determine the impacts of land cover on food risk can be grouped into 3 main types:

- Correlation catchment studies, where streamflow is compared between different catchments that are as similar as possible in all respects other than vegetation.
- Single catchment studies, where streamflow of one catchment is related statistically to climatic variables before and after a land cover change.
- Paired catchment studies, where streamflow is measured in two similar catchments which are studied for a calibration period before the 'experimental' catchment is subject to change and the 'control' remains unchanged (McCulloch & Robinson, 1993). This approach combines the correlation and single catchment approaches.

One of the first catchment-based studies was implemented in 1900 in Switzerland, reported that a forested (99% forest, Fir, Spruce and Beech) catchment had lower annual water yields in comparison with a catchment consisting of 69% pasture and 31% forest (McCulloch & Robinson, 1993). In the UK, Law (1956) studied the Stocks reservoir catchment in Lancashire and found annual runoff was 290 mm less in a catchment planted with coniferous trees in comparison with that of an adjacent grassland catchment. These results have been confirmed by other catchment-based studies in the UK, including Plynlimon, Wales (Hudson, Gilman, & Calder, 1997; Kirby, Newson, & Gilman, 1991); Coalburn, England (Birkinshaw, Bathurst, & Robinson, 2014; Mark Robinson, 1998) and Balquhidder, Scotland (Johnson & Whitehead, 1993). Synthesis of catchment-based studies (Brown, Zhang, McMahon, Western, & Vertessy, 2005; Farley, Jobbágy, & Jackson, 2005; Zhang et al., 2017) show the response of annual runoff to forest cover change is highly variable, depending on forest type, hydrological regime and climate.

Land cover can also impact the flow peak experienced during a storm event. Further study of the Plynlimon research catchments by Kirby et al. (1991) found that whilst flow peaks were smaller in the forested catchment for smaller storms, during high flood flows there was no significant difference between the forested and grassland catchments (D. R. Archer, 2007). These results were confirmed by studies in Oregon (Beschta, Pyles, Skaugset, & Surfleet, 2000) and the Pyrenees (F. Gallart & Clotet, 1987; Francesc Gallart & Llorens, 2003) with woodlands providing a smaller reduction in peak flow for larger storms and larger catchments. M. Robinson et al. (2003) analysed 28 catchments across Europe and found impacts of forests on peak flow depend on forest type, climate and ground conditions. A meta-analysis of European studies found increasing tree cover reduced peak flow, but that additional studies were required to help understand variability and reduce uncertainty (Carrick et al., 2019).

The impact of land cover on streamflow has also be investigated using runoff coefficients, the ratio of runoff to rainfall during a storm event (Blume, Zehe, & Bronstert, 2007). Sriwongsitanon and Taesombat (2011) identified that during smaller flood events (less than 2-year annual recurrence interval) the runoff coefficient in the forest area was lower than the non-forest areas (disturbed forest and agricultural area) for the same amount of rainfall. This method is useful in identifying flood response of different land covers; however, it should be noted that runoff coefficient is also related to other factors such as topography, soil type, and geology.

Additionally, land cover can influence the time taken to reach peak flow during a storm event (Robinson, 1998) although this has not been extensively studied for different land covers (Lana-Renault et al., 2011). Catchments that have been recently logged, typically respond more quickly compared to forested catchments (Burch, Bath, Moore, & O'Loughlin, 1987; Dubicki, 1994). Lana-Renault et al. (2011) found that an undisturbed forested catchment responded 2 to 3 times (356 min) more slowly to a storm event compared to a formerly agricultural catchment, subsequently left to naturally recolonise (131 min).

The hydrological impacts of woodland depend on forest type, age, and management (Stratford et al., 2017). In the UK, previous research has focused on impact of productive conifer plantations with little work on native semi-natural broadleaf woodlands. These woodland types are likely to have different impact on hydrological processes. Evergreen conifers retain leaves all year and intercept 25-40% of annual rainfall compared to 10-25% for broadleaf deciduous woodland (Ahmad-Shah & Rieley, 1989; TR Nisbet & Broadmeadow, 2003; Roberts & Rosier, 2005). Broadleaf trees typically have deeper root systems and higher soil infiltration rates compared to conifers (N. A. L. Archer et al., 2013). Drainage ditches and forest roads are more likely to be established when preparing land for a productive conifer plantation, which can contribute to increases in downstream peak flows (Bathurst et al., 2018; Stratford et al., 2017). Furthermore, the occurrence of periodic felling in a productive conifer plantation removes the canopy and causes soil disturbance which contributes to an increase in localised flood risk (TR Nisbet & Thomas, 2006). Despite these important differences, empirical data on the impact of semi-natural broadleaf woodlands on hydrological processes and stream flow is lacking.

Taken together these complexities mean there is still low confidence in the impacts of land and soil management as a method of flood mitigation, predominately due to the limited empirical data (Burgess-Gamble et al., 2017). More data is needed to better inform decision makers on flood management and improve flood prediction models.

The aim of this study was to establish an experimental correlation catchment study to explore differences in soil properties and streamflow response between upland pasture and native semi-natural broadleaf woodland.

Methods:

Study Area:

Fieldwork was conducted at RSPB (The Royal Society for the Protection of Birds) Haweswater in Cumbria, UK within the Lake District National Park (54°31'50.9"N, 2°45'37.3"W). The study area consists of Naddle Farm and its associated common (grazing) land, covering about 3000 hectares. In 2012, the RSPB took over the tenancies of this land and since have worked in partnership with the landowners, United Utilities, to trial a number of upland management strategies. The implementation of the Sustainable Catchment Management Programme, (SCaMP) has seen a range of interventions being delivered including tree planting, moorland drain blocking and changes to grazing (RSBP, 2015). Annual mean temperature is 11.5°C and annual mean rainfall is 1779 mm (1981-2010 mean) derived from the Shap weather station at 255 m AoD (Met Office, 2020).

Study Design:

Nine field site locations, each consisting of a small tributary to the Naddle Beck or Haweswater Reservoir were selected with regard to their land cover and management strategies to allow for a correlated catchment-like approach (Fig. 1). This field study design is motivated by a number of previous studies (Carroll et al., 2004; Chandler, Stevens, Binley, & Keith, 2018; Mawdsley et al., 2017; Wahl, Bens, Schäfer, & Hüttl, 2003) often investigating 3-6 smaller sites representative of their surrounds. Correlation studies involve catchments which are as similar as possible in all respects other than vegetation/and management (McCulloch & Robinson, 1993). Therefore, it was essential that the chosen areas with different land covers were located in areas with the same parent material. Soil in the study area are predominately Malvern and Bangor soils, over igneous rock.

The nine field sites are between 260-390 m AoD and can be divided into three-subgroups dependent on their land cover/management (Table 1). Semi-natural upland woodland (W) sites have no stock grazing. Woodlands consisted of mixed broadleaf species, predominantly oak, ash, alder, birch and hazel (W7, W9, W11 NVC woodland classifications). Pasture sites are described as either commons grazing (CG) land, where sheep grazing occurs all year round at a maximum ewe intensity of 0.12 livestock units (LU)/ha and low-density grazing (LG); with a maximum grazing of 0.10 LU/ha, removal of grazing in winter and scattered tree planting. In addition, light grazing by Red and Roe deer occurs at all sites.

Data Collection:

Soil data collection:

Permeability (Kfs or Ksat), soil moisture and bulk density measurements, were measured over a 12-month period (July 2018- July 2019).

Bulk density:

To calculate bulk density, soil samples (approximately 31 samples at each site) were taken from the first 5 cm of soil, just below the vegetation layer, using Eijelkamp bulk density rings. The soil samples were removed from the bulk density ring into pre-weighed and pre-labelled containers and placed into an oven at 105°C for a minimum of 16 hours. They were then be placed into a desiccator to cool before weighing. The bulk density (ρ, g/cm^3) was calculated using equation (1) below:

$$\rho = \frac{M}{V} \quad (1)$$

Where;

M is the mass of soil (g);

V is volume (cm^3).

Topsoil permeability:

An Eijelkamp Permeameter, was used to calculate the topsoil saturated permeability (m/s). Soil samples (approximately 29 samples at each site) taken from the first 5 cm of soil, just below the vegetation layer, using bulk density rings.

Subsoil permeability:

An Engineering Technologies Canada Ltd. (ETC) pask (constant head well) permeameter was used to measure subsoil permeability (m/s) following the constant head well permeameter (CHWP) method described by Reynolds (2008) and Elrick and Reynolds (1986). Measurements (approximately 13 at each site) are taken at 0.15 m and an auger used to ensure the same dimensions. A brush was then used to reduce the problem of smearing. The method set out by dynamic monitors was adapted. A pre-wetting phase was included to reduce the time to reach steady state flow and ensured that each measured point was saturated. The Eijelkamp permeameter was unsuitable for the subsoil measurements due to the rocky nature of the ground.

Soil moisture:

Soil moisture content was measured using a Delta-T Ltd ‘theta probe’ (approximately 225 readings were taken at each site). The ‘theta probe’ uses a simplified Time-Domain Reflectometry (TDR) technique to derive values of volumetric moisture content (Delta-T, 1999).

Stream flow data collection:

At each site, a v-notch weir was established to collect flow data every 5 minutes over a 13-month period (January 2019 - February 2020). Rainfall data was collected using a HOBO RG3 data logging tipping bucket rain gauge, recording the number of tips every 5 minutes. This allows for the isolation of rainfall events for hydrograph analysis.

The v-notch weir was installed at a point in the stream less than 1 m across. The weir itself was constructed by removing a small proportion of the stream banks before rebuilding them to offer support to a pre-cut 1.6 mm sheet of galvanised metal (Fig. 2a). A Rugged Troll Level Logger was placed within an adapted section of pipe casing which allowed for the free movement of water and positioned in the now-formed stilling pool (Fig. 2b).

The V-notch weir uses the basic principle that discharge is directly related to water depth above the bottom of the V and is referred to as the head (h) (IOFS, 1980). The

Rugged TROLL level logger records water level depth every 5 minutes which allows for the determination of head. A V-notch weir was chosen over other types of weir, such as the rectangular weir, as a large change in depth represents a small charge is discharge so produces far more accurate discharge measurements. In addition, the use of a Rugged BaroTROLL logger allowed for correction of absolute level sensor data to eliminate barometric pressure effects from the measurements, which will additionally improve the accurately of discharge. The depth corrected values were used to calculate the effective head (h_e). River flow (Q, $m^3/s \times 10^{-1}$) was calculated using the Kindsvater-Shen equation (2):

$$Q = C_d \frac{8}{15} \tan\frac{\propto}{2} \sqrt{2g}\, h_e^{5/2}$$

Where;

C_d is discharge coefficient;

h_e is the effective head (m);

g is acceleration due to gravity (m/s^2);

α is angle of V-notch (°).

<u>Data Analysis:</u>

<u>Soil data analysis:</u>

Statistical analysis including normality tests, the non-parametric Kruskal-Wallis and post hoc tests were used to identify significant differences between sites.

<u>Stream data analysis:</u>

Storm events were defined when more than 20 mm of rain occurred during a 24-hr period. The end of the event was defined as 6 hours with no rain. During a 13-month period (January 2019 - February 2020), 28 storms were identified including both winter and summer time storms (Appendix A). The site’s response to each storm has been analysed in four ways; the specific peak discharge, peak runoff coefficient, volume runoff coefficient and the time taken for the site's streamflow to respond to the first instance of rainfall.

The specific peak discharge (SPD) indicates the highest discharge during the storm event with the influence of catchment area removed. This allows for comparisons of different sized catchments. The specific peak discharge is calculated using the following equation (3):

$$\frac{Q}{A} \times 3600 \qquad (3)$$

Where;

Q is discharge (m^3/s);

A is area (m^2).

The maximum SPD (mm/hr) from the storm's duration is taken.

Both the peak runoff coefficient and volume runoff coefficient are dimensionless coefficients relating the amount of runoff to the amount of precipitation received and useful for catchment comparisons to understand how different landscapes impact runoff (Young, McEnroe, & Rome, 2009). A larger runoff coefficient can indicate a catchment with lower infiltration rates that is more susceptible for flash flooding, whilst a smaller value suggests a more permeable area.

Peak runoff coefficient is calculated for each storm event using equation (4):

$$C = \frac{Q}{iA} \qquad (4)$$

Where:

Q is peak rate of runoff (m^3/s),

i is maximum rainfall intensity (m/s),

A is catchment area (m^2).

To determine the volume runoff coefficient for each storm, baseflow is removed from the storm hydrograph and the total storm runoff calculated. The volume runoff coefficient is then calculated by equation (5):

$$\frac{\text{Total storm runoff (mm)}}{\text{Total storm rainfall (mm)}} \qquad (5)$$

The time taken for streamflow to respond is calculated as the number of hours between when the rainfall event starts to when the streamflow responds, determined as the time when flow has increased by a factor of 3. In instances when the flow does not increase by this amount, the number of hours to the peak flow is determined.

In addition, the changes in flow at each site over a duration longer than one storm is also analysed. The duration selected was chosen based on the availability of data at all 9 sites, when little to no evapotranspiration can be assumed. The cumulative sum of flow above thresholds (1 and 2 mm/hr) was calculated between 03.03.2019 – 17.03.2019.

Statistical analysis including normality tests, Kruskal-Wallis and post hoc tests were used to identify any significant differences between sites.

Results

Table 2 summarises the mean and standard error of streamflow and soil properties in the different land covers.

Soil properties

Figure 3 reports soil properties for each land cover (breakdown of soil properties at each site in Appendix B & C).

The lowest bulk density soils were measured at the LG sites (0.36 g/cm^3) compared with CG (0.46 g/cm^3) and W sites (0.50 g/cm^3) (Fig. 3a). The bulk density at site LG3 was significantly different ($P<0.05$) from all other sites.

The woodland sites typically exhibit higher permeability compared to the pasture sites (Fig. 3b) ($P<0.05$). Mean topsoil permeability across the woodland sites was 0.0046 m/s, compared to 0.0010 m/s in the grazed sites (LG = 0.0007 m/s, CG = 0.0013 m/s) (Table 2).

There was no significant difference between subsoil permeability at the different sites ($P<0.05$, Fig. 3c). Mean subsoil permeability across the woodland sites was 2.21E-06 m/s, 2.47E-06 m/s in the CG sites and to 2.25E-06 m/s in the LG sites.

The highest mean soil moisture occurs at the woodland sites (49%), compared to LG (46%) and CG (33%) with significant differences between the soil moisture at the different sites ($P<0.05$, Fig. 3d).

Streamflow:

Figure 4 shows streamflow properties for each land cover (breakdown of streamflow properties at each site in Appendix D & E).

Mean SPD is lower across semi-natural woodland sites (1.80 mm/hr) compared to CG (2.71 mm/hr) and LG (3.72 mm/hr) sites. Woodland sites had significantly lower SPD compared to CG and LG sites ($P<0.05$) (Fig .4a).

The mean peak runoff coefficient of semi-natural woodland sites (0.87) is lower than CG (1.27) and LG (1.83) sites. Woodland sites had significantly different runoff coefficients compared to the pasture sites ($P<0.05$) (Fig. 4b).

Mean volume runoff coefficient is lower across semi-natural woodland sites (0.40) compared with CG (0.46) and LG (0.51) sites. Whilst there were some significant differences between sites (Fig. 4c), there was no significant difference between land covers.

The mean time to flow in semi-natural woodland (9 hrs) is lower than CG (8 hrs) and LG (5 hrs) sites (Fig. 4c). Woodland sites had significantly different time taken to flow response compared to the LG, but not CG sites ($P<0.05$) (Fig. 4d).

We also compared flow responses over a duration longer than one storm. The cumulative sum of flow above thresholds (1 mm/hr and 2 mm/hr) was calculated between 03.03.2019 – 17.03.2019, see Table 3. Overall woodland sites exhibited the lowest cumulative flow at both thresholds compared with pasture sites.

Discussion

Comparison of semi-natural woodland and pasture

We found that woodland sites typically had lower specific peak discharge compared to grazed pasture sites. These results are in line with findings from a review of 72 papers by Stratford et al., (2017), which concluded that increasing tree cover of a catchment decreases flood peaks. However, Stratford et al., (2017) notes whilst there is strong evidence that afforestation reduces peak discharge during small events, studies often find little or no significant difference during larger flood events. One such study by Kirby et al. (1991) at the Plynlimon research catchments identified lower peak flows in a wooded catchment compared to a grassland catchment during smaller storms (discharge peaks < 1 mm/hr), but little difference during larger storms (discharge peaks > 1 mm/hr). Due to storm selection in our study, the majority of storm responses would be classified according to Kirby et al. (1991) as larger storms. For these larger storms only, we find the woodland exhibited lower mean SPD (2.35 mm/hr) compared with pasture (3.67 mm/hr). Our study focused on semi-natural woodlands consisting of native broadleaf trees species without any drainage. In contrast the woodland investigated by Kirby et al. (1991) was a conifer plantation with drains established prior to tree planting which may explain the difference in storm response. Additionally, we found the cumulative flow above a certain threshold during a 14-day period in winter was lower at the woodland sites compared with pasture.

We found a significant difference between peak runoff coefficients estimated for the woodland and pasture sites. Woodland sites exhibited lower runoff coefficients than both the CG sites and LG sites, by 31% and 52% respectively. Whilst the volume peak runoff coefficient was 13 – 22 % lower for woodland than pasture. These results support findings from Sriwongsitanon and Taesombat (2011) where lower runoff coefficients were calculated for a forested area in comparison with an agricultural area.

The average time taken for flow to respond to storm events was longer in the woodland compared to pasture sites. Woodland sites took 13% longer to respond than CG sites and 80% longer than LG sites. Similar results were found by Lana-Renault et al. (2011) where an undisturbed forested catchment responded 2 to 3 times more slowly than a formerly agricultural catchment, subsequently left to naturally recolonise (171% longer). The impact of land cover on flood timing parameters is a relatively new method, which could be easily replicated on established streamflow records from research catchments. This would contribute to creating a more robust evidence base on whether land cover may contribute to ‘slowing the flow’ for NFM.

The lower specific peak flow, lower runoff coefficient and longer response time of woodlands in an upland catchment contributes to reducing the peak flow downstream and highlights the importance of understanding upland land cover and land use as a method of NFM. We analysed the impacts of land cover during both winter and summertime storms (Appendix A). Woodlands had lower SPD and runoff coefficients compared to pasture in both summer and winter, with the largest differences in winter (Appendix F). An increase in heavy wintertime rainfall across Northern England in recent decades, highlights the need for flood management during winter months (Burt & Ferranti, 2012; Orr & Carling, 2006).

The difference in streamflow response by woodland and pasture sites, particularly in winter when differences in interception and transpiration will be more limited, can in part be explained by differences in their soil properties. Lower peak flows, lower runoff coefficients and longer times to flow response all indicate a more permeable catchment. This is confirmed from the topsoil permeability recorded in the woodland catchments, which have an average topsoil permeability 4.6 times greater than the pasture sites. Our results confirmed previous work showing woodlands have a topsoil (< 10 cm) permeability 1.8 to 6 times that of gazed pasture (Table 4). Many previous studies also found higher permeability in woodland soils, whereas we found no significant difference in soil permeability at 15 cm depth between woodland and pasture soils. This is likely due to the relatively thin soils in our upland sites, with the action of tree roots limited in the development of open pores more limited below 15 cm.

We found LG and woodland sites had significantly higher soil moisture when compared to CG sites. The sparse tree planting in the LG may also have contributed to the higher soil moisture in this area. This supports recent research by Mawdsley et al. (2017) which identified that the ‘sponge effect’ can develop in a relatively short timeframe, 18 months after tree planting. Furthermore, higher levels of soil moisture are often attributed to lower levels of grazing (Xu, Xie, & Wang, 2014). Wallace and Chappell (2020) found that application of fertiliser and slurry to agriculturally improve pasture resulted in reduced summer soil moisture but increased autumn soil moisture potentially increasing downstream flood risk.

Some previous studies have found woodland soils to have 10-30 % lower bulk density than other vegetation types (Agnese et al., 2011; Sharrow, 2007; Wahren, 2009). In contrast, Upson, Burgess, and Morison (2016) found woodland soils had greater bulk density compared to pasture. We found woodlands exhibited the highest bulk density values, 0.5 g/cm^3 compared to 0.36 and 0.46 g/cm^3, with a significant difference between woodland soils and LG soils.

In our study the pasture sites were grazed by livestock whereas the woodland sites did not have any livestock grazing. The number of sheep in the UK has changed substantially in recent decades, increasing from 19.7 million in 1950 (Fuller & Gough, 1999) to 44.5 million in 1990, before declining around the turn of the century to 33.5 million in 2019 (DEFRA, 2020). Sheep numbers in the nearby Lune catchment (Cumbria) increased by a factor of 5 from 100 000 in 1860 to 500 000 in 1990 (Orr & Carling, 2006). These large changes in livestock numbers are likely to have caused substantial impacts. Stock grazing and the changes in vegetation structure and composition that it results in, can lead to soil compaction and a reduction in soil permeability (Alaoui, Rogger, Peth, & Blöschl, 2018) and soil water storage (Meyles, Williams, Ternan, Anderson, & Dowd, 2006) as well as changes in nutrient cycling and vegetation structure and diversity (Milligan, Rose, & Marrs, 2016). Loss of vegetation and soil compaction can increase flood risk, with simulated flood peak in a UK upland catchment increased by 33% under light grazing and 82% under heavy grazing (Gao, Holden, & Kirkby, 2017). The lower grazing levels found in our Lower-density Grazing (LG) sites would be anticipated to lead to higher soil permeability and lower peak flow. In contrast, we found lower rates of permeability and higher SPD and runoff coefficients at the LG sites. Overall grazing pressure across both the CG and LG pasture sites in our study were relatively similar at around 0.1 livestock unit per hectare (Table 1), with the main difference being less wintertime grazing in the LG sites. Our study does not provide any information on the impacts of higher grazing pressure that is found across much of the UK uplands, exceeding 4 sheep per hectare in some locations (Orr & Carling, 2006). Variability in grazing pressure within a site can result in areas favoured for grazing experiencing more compaction (Orr & Carling, 2006) reducing the downward mixing of organic material, decreasing permeability. In our study reduced grazing was introduced fairly recently (~ 7 years ago) and whilst relatively little is known about the effects of reducing stock grazing pressures, it may take 48-62 years to see the benefits of reducing sheep grazing due to the long-term degradation caused by historical sheep-grazing and slow rates of recovery (Robert H. Marrs et al., 2020; Robert H Marrs et al., 2018). High grazing pressure by sheep in the uplands replaces heather with short grass (Orr & Carling, 2006). The recovery of vegetation after a reduction in grazing should reduce rates of overland flow (Bond, Kirkby, Johnston, Crowle, & Holden, 2020), with impacts on downstream flooding.

<u>Implications for Policy</u>

Our study provides some of the first information of the impacts of mature semi-natural woodlands in the UK on streamflow in small (< 0.2 km^2) catchments. Data collected here can be used to inform parameter choice in flood prediction models, which can then be used to upscale results to understand the impacts of semi-natural woodlands on downstream flooding in larger catchments (Gao et al., 2017). We show that semi-natural woodland has more permeable soils resulting in lower peak flood discharge compared to pasture grazed by sheep, the dominant land use in much of the UK uplands. All the pasture sites in our study had relatively low grazing intensity (~0.1 sheep / hectare) - the difference in streamflow between woodland and pasture may be even greater for pasture with the higher grazing intensity more typical of the UK uplands (DEFRA, 2020). Our study suggests that restoring or converting upland pasture to semi-natural woodland would help reduce downstream flood risk. Previous studies have found that soil permeability can increase rapidly after tree planting (Mawdsley et al., 2017) so the benefits to reduced flooding could be realised quickly. In contrast, reductions in grazing without tree planting may result in relatively slow changes in soil properties suggesting tree planting may be necessary in many locations if rapid changes are needed. In the UK, agricultural subsidies have supported upland sheep farming in recent decades and many landowners have not adopted alternative land management strategies (Hardaker, 2018). Changes in agricultural subsidy and the need to mitigate climate change and reach net-zero carbon emissions, both in the UK and internationally (Paris Agreement, 2015), provide challenges to upland farming and may increase future interest in woodland creation. An integrated policy perspective combining climate and flood mitigation alongside the other benefits of woodlands is required to maximise benefits for society. Future work is needed to identify the most beneficial locations for woodland creation in terms of flood mitigation and to understand how climate and flood mitigation vary for different woodland types.

Conclusion

The aim of this study was to explore the potential flood mitigation impacts of semi-natural broadleaf woodlands. We established an experimental correlation catchment study at Haweswater, Cumbria, to identify differences in streamflow and soil properties between semi-natural woodland and pasture. Sites were selected with similar soil type and geology but different land use.

We found that semi-natural broadleaf woodlands can reduce runoff coefficients by 31-52% compared with pasture and specific peak discharge (SPD) by 33-52 %. Crucially, we found that woodlands exhibit lower SPD during larger storms (> 1 mm/hr). Woodland sites take longer to respond to storm events (1-4 hours) than that of the pasture. Differences in flood response can be explained by the more permeable woodland soils, 2.3 to 8 times greater than pasture soil irrespective of the higher bulk density measured. These results strengthen the case that semi-natural broadleaf woodlands can reduce rainfall-generated flooding as a land use management method of NFM.

Our study contributes vital empirical data from a correlation catchment study to an insufficient NFM evidence base. The development of new research catchments has offered a different insight into the potential of upland catchment management for NFM. The longevity of the project should be considered to investigate the long-term impact of reduced grazing levels and tree planting on streamflow and soil properties.

Data Availabilty Statement

The data that support the findings of this study are openly avaible in the University of Leeds repository at https://doi.org/10.5518/950.

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