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Spatial Layout of Trees on Farms Influences Magnitude and Timing of River Flow Peak

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ABSTRACT

Agroforestry, defined as farming with trees, is growing in popularity for its potential to deliver multiple landscape benefits, including natural flood management (NFM). Most NFM research has been concentrated in uplands, whereas optimising tree placement on farms for NFM in lowland catchments has not been studied. Using spatially distributed TOPMODEL, we consider rainfall-runoff changes under various agroforestry planting scenarios in a 1.75 km^2 lowland catchment in Yorkshire, UK, asking whether tree planting at densities practical for farming can significantly alter flood peaks, and which placement strategies generate the most significant effect on flood risk reduction for a fixed area of afforestation. Riparian woodland covering 2.5% of farmed area (0.6% of the catchment) attenuated flood peak by 2.6% and delayed its arrival by 6.6% (19 min). Shelterbelt or in-field copses had a more modest influence on flood peak, and linear features such as in-field tree rows or hedges had a negligible or opposing effect. Increasing tree coverage generated a diminishing return and woodland over the whole farmed area (25% of the catchment) produced only 1.6× the peak size reduction as 0.6% riparian cover in low flow scenarios, rising to 13 times the reduction for higher flows, despite requiring 40 times more land taken out of agricultural production. Our modelling therefore suggests that agroforestry sited on shallow gradients or in the riparian zone contributes to NFM without substantially impacting land available for productive agriculture. These findings demonstrate the potential capacity of agroforestry to deliver multiple landscape benefits.

1 | Introduction

Flooding is among the costliest of global natural hazards, with losses totalling $320 bn in 2024 (Munich Re 2024; Hartmann et al. 2019). Interrelated pressures such as climate forcing, intensifying resource demand and land fragmentation from infrastructure development mean that damages from flooding are growing with 'high confidence' in Europe and the United Kingdom (IPCC 2014b; Hirabayashi et al. 2013). Millions of properties and significant quantities of critical infrastructure in the United Kingdom are threatened annually by flood risk, and the frequency of autumn rainfall events exceeding 50 mm has increased by 60% since 1900 (Cotterill et al. 2021; Thorne 2014). The UK Met Office estimate extreme rainfall with a 100-year return period to be 2.5 times more likely by 2100 (Christidis et al. 2021), and according to the most recent UK Climate Change Risk Assessment (CCRA3, Sayers et al. 2021), damages from UK flooding in a 2°C future are expected to increase from £2 bn in 2021 to £2.7–3.0 bn by the 2080s, if flooding continues to be managed as it is now.

The changing nature of flood risk has prompted a move towards adaptive management and nature-based solutions. Decentralised and multifunctional green options for water management capable of delivering multiple benefits are increasingly favoured in place of traditional and capital-intensive 'grey' infrastructure solutions (Butler et al. 2017). In rural catchments, this includes natural flood management (NFM)—distributed measures which restore or enhance catchment processes to reduce flood risk, while fostering environmental benefits such as biodiversity, soil and water improvement, carbon sequestration, better agricultural productivity and greater public enjoyment of the countryside (Dadson et al. 2017). The goal of NFM is to enhance catchment hydrological functions such that the rate at which water is delivered to areas of downstream flood risk is reduced following rainfall (Lane 2017), either by delaying or desynchronising the flood peak (Kingsbury-Smith et al. 2023). Changes in land use or management are generally deployed to achieve this, with the goal of reducing overland flow velocities, promoting inline or offline water storage and improving soil conditions in favour of infiltration (Zhu et al. 2024). Afforestation might be an effective means of achieving these goals in the form of riparian, cross-slope or other strategic planting strategies (Ferguson and Fenner 2020; Marapara et al. 2020). In addition, trees in combination with understorey vegetation are known to increase surface roughness (Monger, Bond, et al. 2022) and water holding capacity (Ashwood et al. 2019) of soils, decreasing runoff when compared with unforested land uses (Farley et al. 2005).

Land-use interventions for NFM include those which 'spare' land for flood risk reduction, or 'share' land for both flood mitigation and economically productive use such as agriculture. Agroforestry, defined simply as farming with trees (Woodland Trust 2022), is a land-sharing strategy known to be capable of reconciling food production and ecosystem service provision from farmland (Burgess 1999; Araujo et al. 2012; Torralba et al. 2016; Judson et al. 2023), with benefits including improved hydrological functioning of agricultural soils leading to reduced local flood risk factors (Marshall et al. 2014; Monger, Spracklen, et al. 2022). Trees may be variably sited within agroforestry systems, such as in rows with arable inter-crops, as isolated trees or copses within pasture, as shelterbelts, or in riparian zones (Nair 2005; Judson et al. 2023). As for upper-catchment NFM strategies, the effectiveness of agroforestry on flood risk reduction depends on placement strategies for trees in the farmed landscape (Marapara et al. 2020; Monger et al. 2024), and strategies will trade off with economic priorities for land depending on how placement interferes with traditional agricultural activity. Although questions surrounding flood peak sensitivity to NFM vegetation management have been addressed in upland areas (Gao et al. 2016; Kingsbury-Smith et al. 2023; Monger et al. 2024; Bond et al. 2022), spatial evaluation of agroforestry systems for NFM benefit in lowland catchments has not been undertaken. Stakeholders either planting or funding lowland agroforestry for flood benefit have the same questions as those supporting NFM in uplands, namely, optimal coverage rates to benefit effect on flood peak size (Monger et al. 2024), whether systematic strategies such as focussing on steeper or shallower areas of a catchment variably 'slow the flow' (Gao et al. 2016; Bond et al. 2022; Maske and Jain 2013), and how these factors trade off with other constraints on land use. As temperate agroforestry grows in popularity as a means of diversifying ecosystem benefit delivery from farmland, particularly in support of net-zero (Woodland Trust 2022) but also slowing or storing water in the landscape, these questions will only grow in importance.

This study asks two research questions: firstly, whether agroforestry planted at densities practical for temperate zone farming can significantly alter downstream flood risk, and secondly, which systems generate the most significant effect on flood risk reduction for a fixed area of afforestation. Understanding the effects of localised NFM interventions at catchment scale depends on thorough understanding of spatial connectivity of flow paths and timings (Rogger et al. 2017), so we use a spatially-distributed version of TOPMODEL (SD-TOPMODEL) (Gao et al. 2015) to consider a range of agroforestry planting strategies in a small (175 ha) lowland catchment in Yorkshire, UK. In this way, we address important considerations for practitioners looking to design agroforestry systems to maximise flood management benefits within financial or land-area constraints, and policy efforts to deliver multiple goods from farmed landscapes.

2 | Methodology

2.1 | Study Site

A small, 175 ha lowland catchment in the Vale of York, 11 km NE of Leeds, UK, was chosen for the study of which 25% (44 ha) comprised a livestock farm (Figure 1b) in which agroforestry scenarios were modelled. By 'lowland', we refer to a standard UK conception of lowland grasslands (appropriate in the context of a pasture farm such as this): 'grasslands that occur either in enclosed or unenclosed situations but typically below the upper level of agricultural enclosure in any area and usually below 300 m' (Jefferson et al. 2014). Mean annual precipitation (1991 to 2020) is 620 mm (December–February: 149 mm, June–August: 170 mm) and mean annual temperature is 10.0°C (December–February mean: 4.5°C, June–August mean: 15.9) (Church Fenton Met Station, 11 km away). Snow is rare and short-lived in the catchment. Elevation within the catchment ranges from 60 m in the southeast extremity to 115 m in the north and west (Figure 1a) and is hence a lowland catchment, with a mean slope of 4.9%. The entire catchment drains through the livestock farm (Figure 1), such that discharge at the outlet is maximally sensitive to land-use changes within the farm boundary. The catchment comprises arable land (39%), deciduous woodland (34%) and improved grassland (26%), with a very small area of hardstanding (1%) (Morton et al. 2023) (Figure 1c).

The catchment predominantly comprises fine loamy over clayey stagnogley soils up to 1 m deep from the Dunkeswick series (Cranfield University 2022). The clayey subsoil is slowly permeable making it susceptible to seasonal waterlogging and rapid runoff in winter, and land is predominantly in seasonal pasture. In the lowest lying 10% (17 ha) of the catchment, adjacent to the outlet, are calcareous brown earths extending to ~50 cm depth from the Aberford series, well-draining soils typically found on low-dipping Permian and Jurassic limestones in mid- and northern England (Cranfield University 2022). In this instance limestone from the Caedby formation underlies 43% of the catchment to the west, with the remaining 57% underlain by mud-, silt- and sandstones from the Rough Rock and Pennine Lower Coal formations (BGS 2013).

2.2 | SD-TOPMODEL

We use SD-TOPMODEL (Gao et al. 2015) to examine changes in catchment hydrological functioning derived from land-use

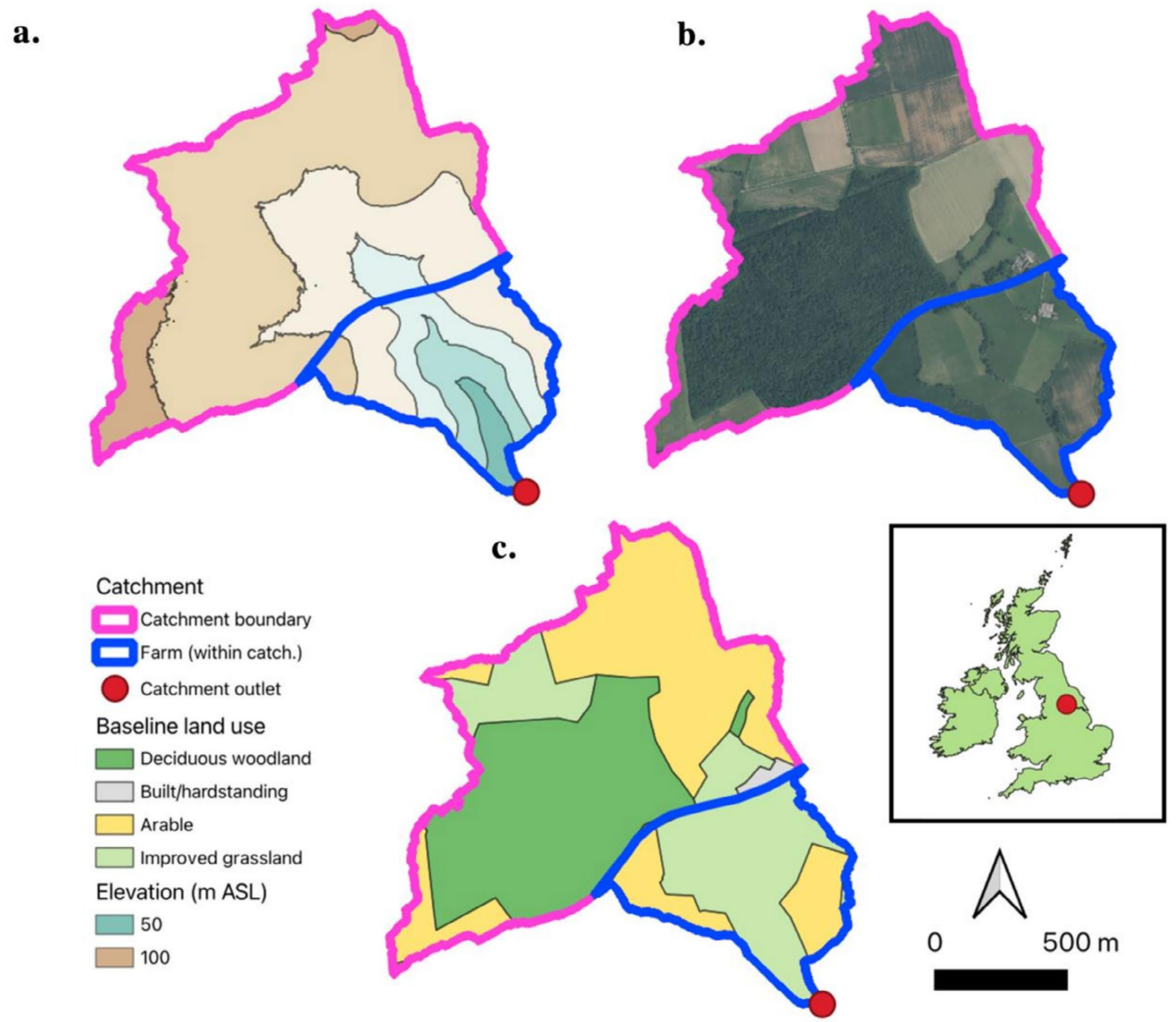

FIGURE 1 | Map of study catchment showing (a) elevation, (b) aerial photography and (c) UKCEH baseline land use. Catchment area within farm boundaries delineated in blue. Based upon Land Cover Map 2023 UKCEH 2024. Contains Ordnance Survey data Crown Copyright 2007, Licence number 100017572. Aerial photography Getmapping Ltd., accessible at EDINA Aerial Digimap Service (2022).

change scenarios within the farm boundary. SD-TOPMODEL is a spatially-distributed version of TOPMODEL (Beven and Kirkby 1979), a computationally inexpensive and parameter sparse flood-modelling algorithm using a soil water storage approach to predict saturation-excess overland flow within a catchment. This approach is particularly well-suited to UK basins in which infiltration rates are high compared with rainfall intensity, such that overland flow generation is controlled more strongly by saturation-excess rather than infiltration-excess mechanisms. Calibration of the model is achieved with three parameters for a given catchment: m—active depth for subsurface flow, K—a notional hydraulic conductivity of soil across the catchment, and k_v—an overland flow velocity constant proportional to $1/n$ where n is Manning's coefficient of roughness. Overland flow is treated as a function of rainfall intensity and saturated area within a basin, both of which vary by timestep introducing significant nonlinearity to a catchment's hydrographic response.

SD-TOPMODEL solves the original TOPMODEL runoff equations per-grid-cell across a two-dimensional user-defined grid extending uniformly across the catchment. Water is permitted to reach the saturated zone at different times according to local wetness, and is routed between cells according to local, temporal conditions (Bond et al. 2022). Importantly for this study, values for K and k_v are permitted to vary spatially by land cover type within the catchment, and for each land-use change scenario a spatial distribution of K and k_v is incorporated to evaluate catchment response to a synthetic storm event. The model is therefore ideal for determining the extent to which land cover changes within the livestock farm boundary influence the hydrograph response of the study catchment through spatial alteration of these two parameters. Additionally, SD-TOPMODEL is well-suited to areas of shallower soil and moderate topography (Beven et al. 2021; Bond et al. 2022; Gao et al. 2015), as are found at the study catchment.

2.3 | Catchment and Rainfall Data

LiDAR elevation data were obtained at 2 m resolution (Ordnance Survey, June 2023) to generate a digital elevation model (DEM) of the study catchment (Figure 1a). This was combined with land-use data obtained from UKCEH (Morton et al. 2023), from which a baseline land cover map at the same resolution as the DEM was generated reflecting the current state of the catchment without the most recent NFM interventions included at the study site (Figure 1c).

Rainfall and runoff data for four synthetic storm events were generated for the catchment using the Revitalised Flood Hydrograph (ReFH, Kjeldsen 2007). The ReFH model is widely used to generate synthetic storms based on catchment descriptors for ungauged catchments in the United Kingdom (Faulkner and Barber 2009), and has been used to validate several applications of SD-TOPMODEL elsewhere (Gao et al. 2016; Kingsbury-Smith et al. 2023; Bond et al. 2022). We use combinations of two storm durations (4-h and 10-h) and two return periods (10-year and 50-year) (Table 1). A 4 h length was chosen as it is the recommended storm duration for the study catchment (Kjeldsen 2007), and an alternative, 10-h duration and two respective intensities were chosen to maximise consistency of model performance (Monger et al. 2024). Observations for these storms were at 15-min intervals (timesteps). The purpose of using synthetic storms was to calibrate initial parameter values of K, k_v and m for the catchment, after which performance of chosen parameter values was validated using field measurements at the study catchment. Additionally, a baseflow value for the catchment was estimated using ReFH and applied at calibration, validation and scenario testing stages. As in previous work with SD-TOPMODEL (Bond et al. 2022; Kingsbury-Smith et al. 2023), storm events were chosen such that specific return period events could be represented, and rainfall for each storm was distributed with a Gaussian profile typical of winter frontal storm events in which rain falls continuously with peak intensity midway through the storm. Typical evapotranspiration levels of 1–2 mm day^{-1} found in the United Kingdom (Blyth et al. 2019) were treated as negligible compared with storm intensity for these events (min. 80 mm day^{-1}) and therefore excluded from the model.

2.4 | Parameter Sources

Land use for different agroforestry scenarios was represented by spatially-variable values of K and k_v specific to each land cover. As elsewhere (Gao et al. 2015; Bond et al. 2022; Kingsbury-Smith et al. 2023; Zhu et al. 2025), these were estimated using literature sources and expressed as relative values (Table 2) to be multiplied by calibrated factors determined in Section 2.5. We also express values of K and k_v relative to a single land cover (Deciduous Woodland) for ease of comparison (Table 2, values in parentheses).

TABLE 1 | Synthetic storm events (derived from the Revitalised Flood Handbook) used for model calibration.

Storm duration (h)	Storm recurrence interval (years)	Total rainfall (mm)	Mean rainfall intensity (mm h^{-1})	Maximum rainfall intensity (mm h^{-1})
4	10	24.89	5.86	15.10
4	50	34.57	8.64	20.96
10	10	33.27	3.33	8.55
10	50	45.00	4.50	11.57

TABLE 2 | Land-use parameters for model calibration and testing hydrograph response of spatially-explicit land-use scenarios.

Land cover	Baseline cover (%)	Current cover (ha)	k_v	K	m	Interception (%)
Deciduous woodland	34	59.70	0.8 (1.0)	0.90 (1.00)	1.0	20
Improved grassland	26	43.95	2.4 (3.0)	0.55 (0.61)	1.0	0
Arable	39	65.69	2.4 (3.0)	0.55 (0.61)	1.0	0
Suburban/hardstanding	1	1.41	10.0 (12.5)	0.10 (0.11)	1.0	0
Silvopasture/Copse	—	0.04	1.0 (1.25)	0.80 (0.89)	1.0	20
Shelterbelt	—	0.93	1.0 (1.25)	0.80 (0.89)	1.0	20
Riparian woodland	—	1.28	1.0 (1.25)	0.80 (0.89)	1.0	20
Hedge	—	0.60	1.0 (1.25)	2.00 (2.22)	1.0	20

Note: Relative differences in parameter values between land cover types are estimated from field measurements and literature sources (for ease of comparison, these are given relative to Deciduous Woodland in parentheses for K and k_v).

TABLE 3 | Parameter bounds and step size used for model calibration, including calibrated values.

Parameter	Minimum value	Maximum value	Step	Calibrated value
K	4.0	8.0	1.0	5.0
k_v	2.5	15	2.5	5.0
m	0.010	0.020	0.002	0.014

In order to understand trade-offs between land-use scenarios and differing placement of trees, only one set of parameters was used to model all types of woodland used for agroforestry (silvopasture, shelterbelt and riparian woodland, Table 2). Previous studies using SD-TOPMODEL (Bond et al. 2022; Kingsbury-Smith et al. 2023) differentiate between deciduous woodland of different ages or types when assigning parameter values, reflecting differences in establishment or understorey cover, and we do so only in differentiating between well-established woodland included in UKCEH baseline land cover and more recent broadleaf woodland established for NFM. The purpose of the study is not to describe current hydrological characteristics of the catchment in detail, but to hypothesise more generally about differences between planting scenarios which could be replicated elsewhere and to compare the effectiveness of planting an equivalent area of trees in different parts of the catchment. We therefore choose equivalent parameters for all agroforestry systems modelled, assuming that the trees are deciduous, well-established and fenced from livestock to allow spontaneous development of understorey vegetation. This allows us to preserve model simplicity and prevent overfitting. We nonetheless note that parameter choice represents the most significant source of uncertainty in the model (Kingsbury-Smith et al. 2023), and more work is needed to harmonise parameter estimates across land covers.

Significant variability exists between studies in parameter estimates, with estimates for K and k_v in some cases differing by an order of magnitude or more for similar land cover descriptions. Given that relative differences between empirical values are necessary for the model we prioritised consistency of literature sources over breadth, such that estimates were derived from the same methodology where possible. Lowland estimates for k_v were not available for land cover types in this study. In the manner of Kingsbury-Smith et al. (2023), we therefore base estimates on literature values for Manning's n from Chow et al. (1988), with k_v proportional to $1/n$, in order to preserve consistency of methodology between estimates aiding relative comparisons. As with Kingsbury-Smith et al. (2023), we distinguish between prior, established woodland and agroforestry planted for NFM.

We obtained relative values of K using field measurements by Kingsbury-Smith et al. (2023) in N Yorkshire, UK. These included relative values for established deciduous woodland, woodland planted for NFM and improved grassland. Arable land use for the catchment was set to the same K value as improved grassland. We used measurements from Holden et al. (2019) at a site less than 5 km from this study site on a farm with similar topography and soil type to obtain a relative value of K for hedge cover. For hardstanding, we set K to the model's minimum value (Bond 2022).

Interception values for the land cover types studied (Table 2) also vary considerably between estimates from temperate, broadleaf studies such as 13% (Dolman 1987) or 25% (Herbst et al. 2008). A conservative, intermediate value of 20% was therefore set for hedgerows and all woodland types. As in Bond et al. (2022), values for winter were used as a conservative estimate of interception, given that the values were not derived at the same site. Interception for land cover without woody vegetation was set to zero.

As elsewhere (Bond 2022; Beven and Kirkby 1979), m was treated as a scaling parameter only and held constant across the catchment. Although m is related to soil depth in that, it is a measure of the rate at which flow reaches zero with increasing depth, many other soil physical properties influence its spatial variability (K. J. Beven 2012). Intrinsic soil hydraulic properties are known to exert a stronger influence on soil water storage than vegetation type (Geris et al. 2014; Rodgers et al. 2005; Hrachowitz et al. 2009; Soulsby and Tetzlaff 2008); while soil from the Dunkeswick series is typically deeper (1 m), it is slowly permeable in subsoil and therefore well-draining to an approximately equivalent depth (50 cm) as soils in the Aberford series (Cranfield University 2022).

2.5 | Calibration

A baseline land cover map of the catchment (Morton et al. 2023) with 10 m grid cells was used to calibrate the model. Calibration refers to establishing three multipliers corresponding to K, k_v and m specific to the study catchment ('calibrated values', Table 3), which are used to transform relative values specific to each land cover given in Table 2. The UKCEH baseline land cover was used as it most closely represents land cover assumed by ReFH design storms.

Model performance was evaluated for the calibration stage by comparing the flood hydrograph predicted by SD-TOPMODEL with the four chosen ReFH synthetic storms (Figure 2). ReFH design storms are widely used in this way to estimate discharge for ungauged UK catchments based on known catchment characteristics (Monger et al. 2024). Goodness of fit was determined by Nash–Sutcliffe Efficiency (NSE), a commonly used measure of model performance (Ritter and Muñoz-Carpena 2013; Bond et al. 2022; Gao et al. 2015).

Parameter sets for calibration were chosen by scanning the parameter space uniformly between minimum and maximum values (Table 3) (Gao et al. 2015). Choice of reasonable figures for minimum and maximum values was guided by prior studies using SD-TOPMODEL, and 720 simulations (180 per storm) were used in which each parameter set was applied to the four synthetic storms (Table 3). The best parameter set was chosen to be that which resulted in the highest average NSE value between the four storms (Figure 2).

2.6 | Validation

The fully calibrated model was validated for its performance against empirical rainfall (Table 4) and river level (Figure 3) data measured between April and December 2024 at the study catchment outlet. The catchment is ungauged, and discharge data were not available, so goodness of fit was determined by visual comparison of time-to-peak between river level and calibrated-model responses to measured rainfall (Figure 3).

2.7 | Land Cover Scenarios

A number of agroforestry and general woodland scenarios were tested using the model, in order to consider how a range of placement strategies for trees and hedgerows influence the hydrological response of the catchment, compared with the land-use baseline. All scenarios tested correspond to planting within the livestock farm boundary only.

2.7.1 | Current Land Use

The first group of scenarios examines whether the introduction of hedgerows and trees at a scale similar to that currently planted at the farm (Figure 4a) and typical of lowland agroforestry schemes has a meaningful effect on downstream flood management, and how an equivalent area (1 ha) of several realistic interventions—hedgerow, copse, cross-slope tree rows, down-slope tree rows, shelterbelt and riparian woodland—compares in terms of potential to attenuate flood peak following a significant storm event. Planting 1 ha of each agroforestry type corresponds to 2.5% of the livestock farm area and 0.6% of the whole catchment, and is also currently the minimum woodland planting area to qualify for financial support under the England Woodland Creation Offer (Forestry Commission 2025). A hypothetical 'endmember' scenario, in which the whole farm area is planted with continuous woodland (25% of catchment), is included to determine a theoretical limit to NFM benefit of tree planting at the study site against which other agroforestry options can be compared (Figure 4b). The purpose of testing agroforestry scenarios mirroring current land use is to consider whether minimal intervention commensurate with normal farm operations can contribute to NFM, which planting type has the greatest impact, and how the influence of current planting strategies compares with an endmember scenario.

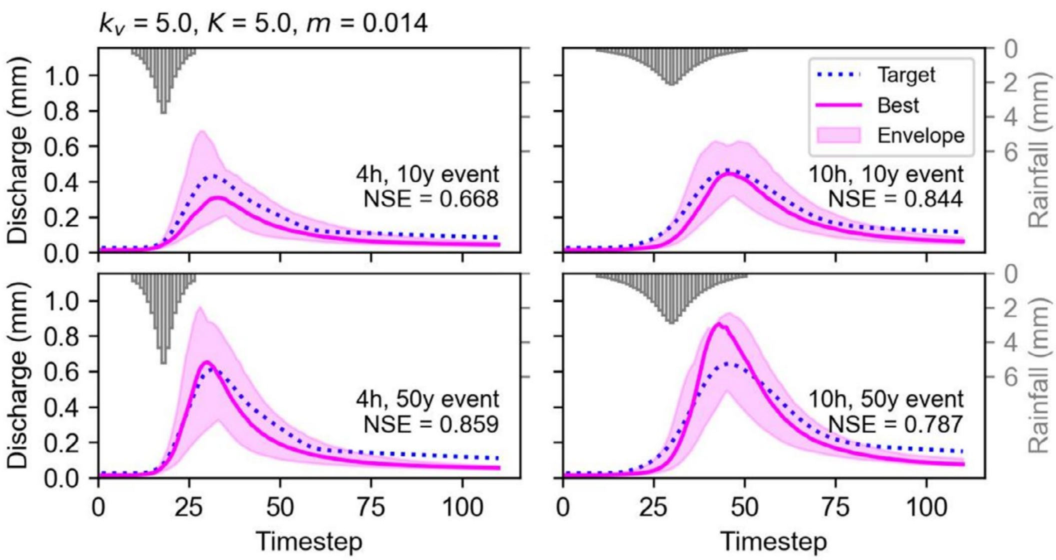

FIGURE 2 | Calibration results for the study catchment. Grey bars represent study catchment synthetic rainfall events estimated from the Revitalised Flood Handbook (ReFH) for four storm events. Blue dotted line represents estimated ReFH hydrograph. Pink line shows SD-TOPMODEL estimated hydrograph using selected parameter values for K, k_v and m. Pink shaded area indicates hydrograph bounds for parameter sets with NSE in highest 20% of tested values.

TABLE 4 | Measured storm events used for validating calibrated model.

Validation storm no.	Storm duration (h)	Total rainfall (mm)	Mean rainfall intensity (mm h^{-1})	Maximum rainfall intensity (mm h^{-1})
1	10	17.80	1.78	6.26
2	18	35.82	1.99	6.22
3	23	30.23	1.31	4.74

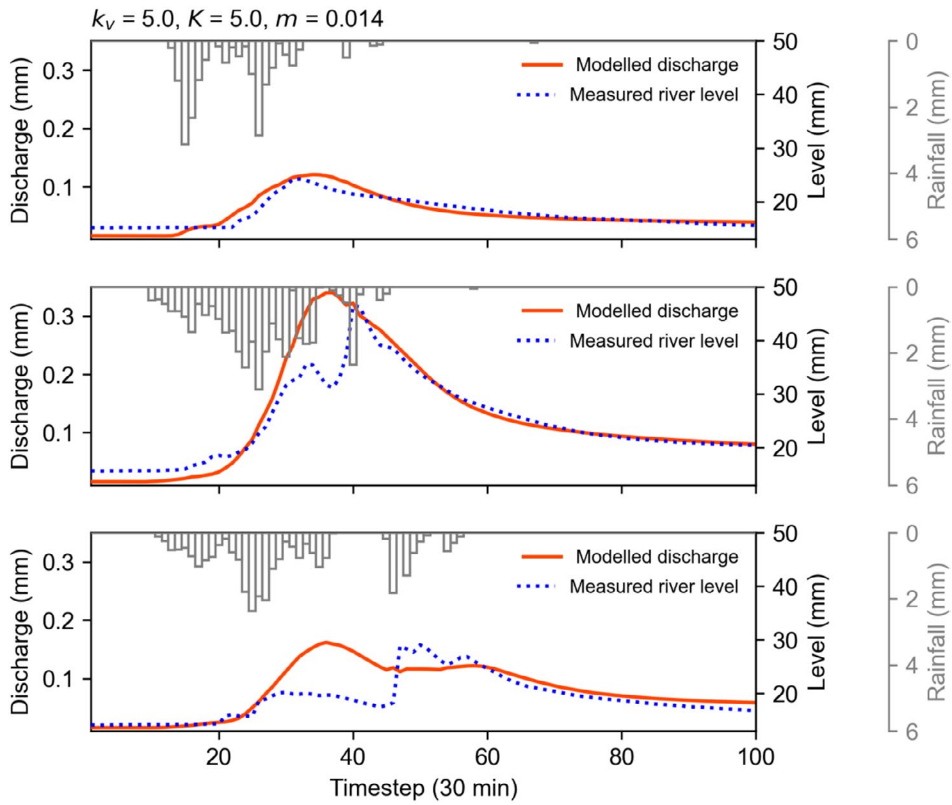

FIGURE 3 | Validation results for the study catchment, for three storm events of (a) 10, (b) 18 and (c) 23 h in length. Grey bars represent rainfall recorded Spen Farm (4 km away). Blue dotted line (right black axis) indicates river level recorded at the catchment outlet. Orange line represents SD-TOPMODEL estimated hydrograph for recorded rainfall, using parameter values for K, k_v and m selected at the calibration stage. With only river level data, curves are not intended to match, rather the purpose of validation is matching peak timing between measured river level and modelled runoff.

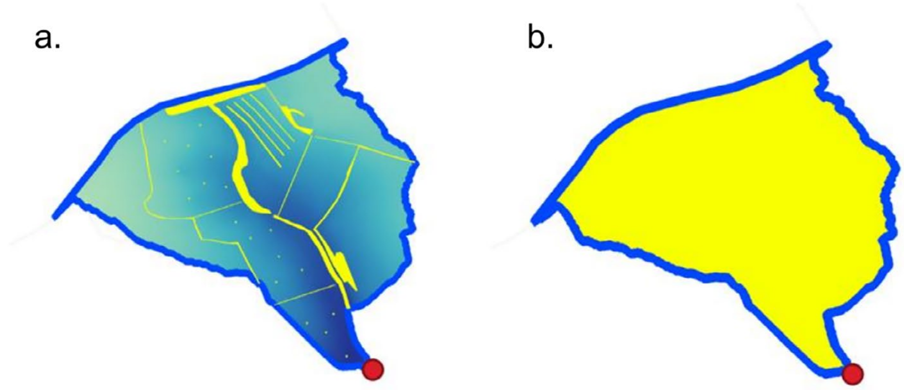

FIGURE 4 | Within-farm scenarios examining (a) combined agroforestry as planted (current land use) and (b) a theoretical endmember scenario with the whole farmed area under woodland. Combined agroforestry is also subdivided into separate scenarios for each vegetation type (shelterbelt, riparian woodland, cross-slope tree rows, hedgerow, copse) with each normalised to a 1 ha area, illustrated in the Supporting Information. Outlet point shown in red.

2.7.2 | Equal Area Scenarios

The second group of scenarios, mirroring the approach of Gao et al. (2016), examines systematic approaches to tree planting based on catchment topographic characteristics. Equal areas of woodland are placed within the farm boundary in the following areas: areas of steepest gradient, areas of shallowest gradient, the riparian zone and woodland copses dispersed at random.

The areas compared correspond to 10% tree cover of the livestock-farmed area (Figure 5a–d)—equivalent to the amended Universal Action for Tree Planting in Wales as part of the Sustainable Farming Scheme (Welsh Government 2024)—and 20% tree cover of the livestock-farmed area (Figure 5e–h). The purpose is to consider which coverage of trees delivers greatest NFM benefit, and how benefit increases with cover.

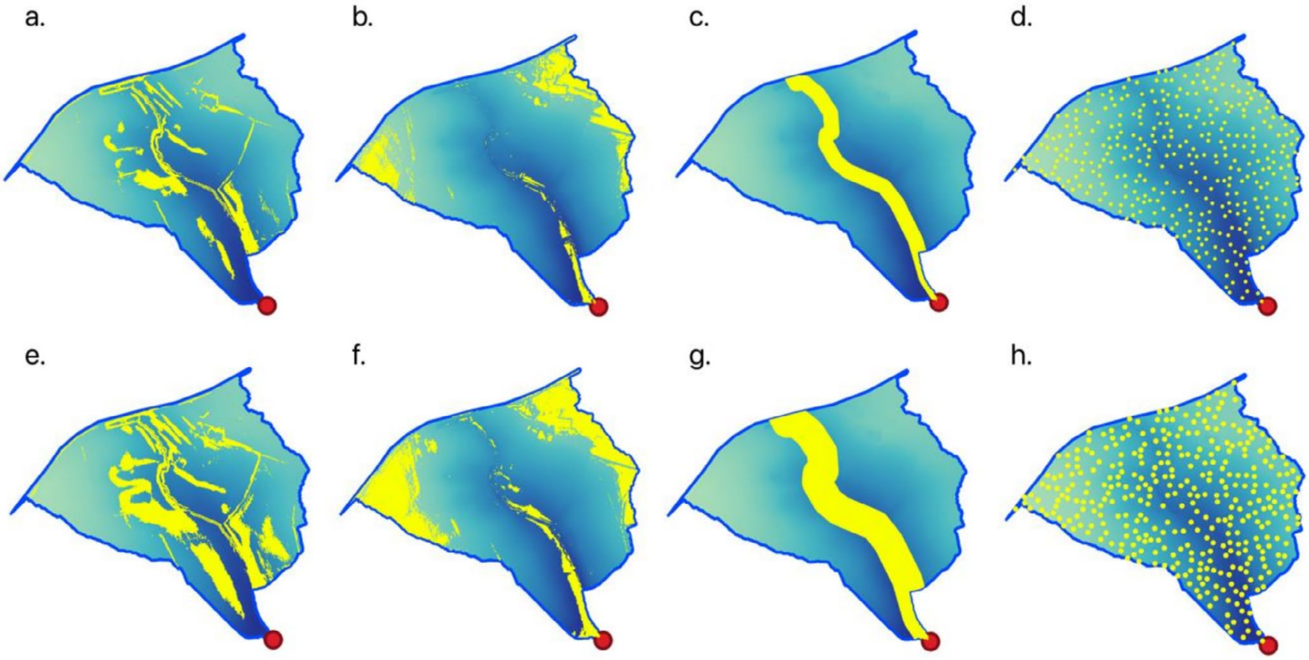

FIGURE 5 | Equal area agroforestry scenarios within the farm boundary. Scenarios (a–d) illustrate 10% woodland cover of (a) steepest gradient, (b) shallowest gradient, (c) riparian zone and (d) randomly distributed copses. Scenarios (e–h) illustrate 20% cover of the same planting strategies. Catchment outlet where stream level was recorded shown in red.

2.8 | Analysis Methods

For each planting scenario, as in other studies, two metrics—size of peak and time to peak—were used to evaluate differences in runoff characteristics compared with UKCEH baseline land use for the catchment (Kingsbury-Smith et al. 2023; Gao et al. 2016; Bond et al. 2022). Response hydrographs were smoothed using an interpolating B-spline function, removing artefacts whereby peaks may be located between two points of similar discharge value, and allowing us to compare small differences between peak size and time to peak without compromising the shape or meaning of observed or modelled time series (Oh et al. 2020; Unser et al. 1993). For this, we used the *make_interp_*spline algorithm from the *SciPy* package within *Python* (Virtanen et al. 2020). Hydrograph differences between scenarios are illustrated in the Supporting Information (SFig X). We compare scenario responses for storms of the same two return periods and durations used in model calibration to understand response dynamics of tree planting scenarios under different flow intensities.

2.9 | Limitations and Uncertainty

As others have noted (Gao et al. 2016; Kingsbury-Smith et al. 2023), parameter selection represents the largest source of uncertainty in the model, particularly as estimates of parameter values corresponding to land cover types can vary so considerably between studies and contexts. However, the possibility of multiple behavioural parameter sets is a well-known limitation of hydrological modelling more generally (Cameron et al. 1999; Gao et al. 2015), and is overcome here and elsewhere by systematic scanning of the parameter space informed by prior studies using TOPMODEL (K. Beven 1997; Gao et al. 2015; Kingsbury-Smith et al. 2023) and across storm types to determine best-fit values. We also note considerations with using ReFH data for calibration: the ReFH model is based on catchment descriptors alone and does not account for complex and asynchronous flood generation patterns (Rogger et al. 2017; Faulkner and Barber 2009). This introduces uncertainty to flow estimates and is only intended to provide an estimated range of peak flow values in the absence of recorded discharge data. For this reason, we include empirical river level data as a check on calibrated values, and good peak timing fit between the calibrated model and measured river level data indicate that the model is capable of generating sufficiently realistic response hydrographs for the purpose of comparing outcomes from land-use scenarios. The purpose of the study is not to determine absolute values for flood peak sizes and arrival times for the catchment, but to consider relative differences between scenarios and baseline land use. Methodological consistency between scenarios, in combination with robust calibration and validation, ensure that parameter and modelling uncertainty are minimised.

3 | Results

3.1 | Equal Area: 1 ha Agroforestry Scenarios

For shorter, 4-h storm durations, the majority of 1 ha agroforestry scenarios produced small differences in flood peak timing, with the exception of riparian woodland which reduced peak size by 2.6% and delayed flood peak arrival by 6.6% (19 min) for a 10-year return period storm event (Table 5, Figure 6). These figures were −2.4% and +4.2%, respectively,

TABLE 5 | Peak runoff and time to peak values for all scenarios tested for a 4-h storm duration with 10- and 50-year return periods.

4 h duration	10-year return period				50-year return period			
Scenario	Peak runoff ($mm\,h^{-1}$)	Diff. cf. baseline (%)	Time to peak (h)	Diff. cf. baseline (%)	Peak runoff ($mm\,h^{-1}$)	Diff. cf. baseline (%)	Time to peak (h)	Diff. cf. baseline (%)
UKCEH baseline	*1.118*	—	*4.93*	—	*2.313*	—	*4.57*	—
All current planting	1.104	−1.3	5.20	+5.5	2.258	−2.4	4.76	+4.2
All woodland	1.071	−4.2	5.50	+11.6	2.118	−8.4	4.93	+7.8
Copse (1 ha)	1.111	−0.7	4.93	—	2.298	−0.6	4.57	—
Riparian (1 ha)	1.090	−2.6	5.26	+6.6	2.258	−2.4	4.76	+4.2
Shelterbelt (1 ha)	1.112	−0.6	4.98	+1.1	2.285	−1.2	4.60	+0.6
Hedge (1 ha)	1.121	+0.3	4.96	+0.6	2.296	−0.7	4.55	−0.6
Cross-slope (1 ha)	1.116	−0.2	4.90	−0.6	2.297	−0.7	4.57	—
Down-slope (1 ha)	1.117	−0.1	4.90	−0.6	2.295	−0.8	4.60	+0.6
Steepest (10%)	1.115	−0.3	5.01	+1.7	2.287	−1.1	4.66	+1.8
Shallowest (10%)	1.108	−0.9	5.04	+2.2	2.273	−1.7	4.66	+1.8
Riparian (10%)	1.092	−2.4	5.34	+8.3	2.249	−2.8	4.82	+5.4
Copse (10%)	1.115	−0.3	4.98	+1.1	2.288	−1.1	4.57	—
Steepest (20%)	1.113	−0.5	4.96	+0.6	2.269	−1.9	4.63	+1.2
Shallowest (20%)	1.102	−1.5	5.09	+3.3	2.249	−2.8	4.68	+2.4
Riparian (20%)	1.093	−2.3	5.28	+7.2	2.239	−3.2	4.82	+5.4
Copse (20%)	1.112	−0.6	5.01	+1.7	2.279	−1.5	4.63	+1.2

Note: Differences are given relative to UKCEH baseline values. Dashes (—) denote no change. Baseline values are given in italics.

for a 50-year return period event (Table 5). Shelterbelt planting produced a small effect on peak size (10-year: −0.6%, 50-year: −1.2%) as did copse planting (10-year: −0.7%, 50-year: −0.6%), whereas hedgerows, cross-slope and downslope tree rows all produced very small or opposing differences; the 1 ha hedgerow scenario produced a very small increase in peak runoff (+0.3%). For all 1 ha agroforestry systems (or tree planting schemes), a longer return period of 50 years led to a larger absolute difference in peak runoff compared with baseline land use, with riparian planting still producing the largest difference; and smaller absolute differences in time-to-peak for most 1 ha scenarios.

For longer, 10-h storm durations (Table 6), the change in peak runoff compared with baseline land use was smaller and more similar between scenarios, particularly for higher flow (Table 6). None of the 1 ha scenarios produced a peak size difference exceeding 1% in a 10-h event (Table 6, Figure 6), contrasting with the larger peak size differences observed for a 4 h event. Differences in time-to-peak flow compared with the baseline tended to be smaller in percentage terms for longer storms, but similar in absolute terms. Riparian woodland delayed peak arrival by 18 min (+3.6%) for a 10-year, 10-h event, whereas all other 1 ha scenarios caused only very small differences in peak timing following longer storms.

Across both storm durations and return periods, riparian woodland consistently produced the largest changes to flood peak size and time-to-peak when compared with a 1 ha area of other tree planting types, with the effect particularly pronounced for shorter, 4-h events. Only in high-flow (50-year) and longer (10-h) storms were differences between 1 ha scenarios less evident. Moreover, the flood hydrograph corresponding to 1 ha of riparian woodland most closely resembled the hydrograph for all combined agroforestry types (riparian woodland, cross-slope alleys, hedges, shelterbelt and copse) implying that catchment response characteristics between the two scenarios were similar. Finally, it should be noted that

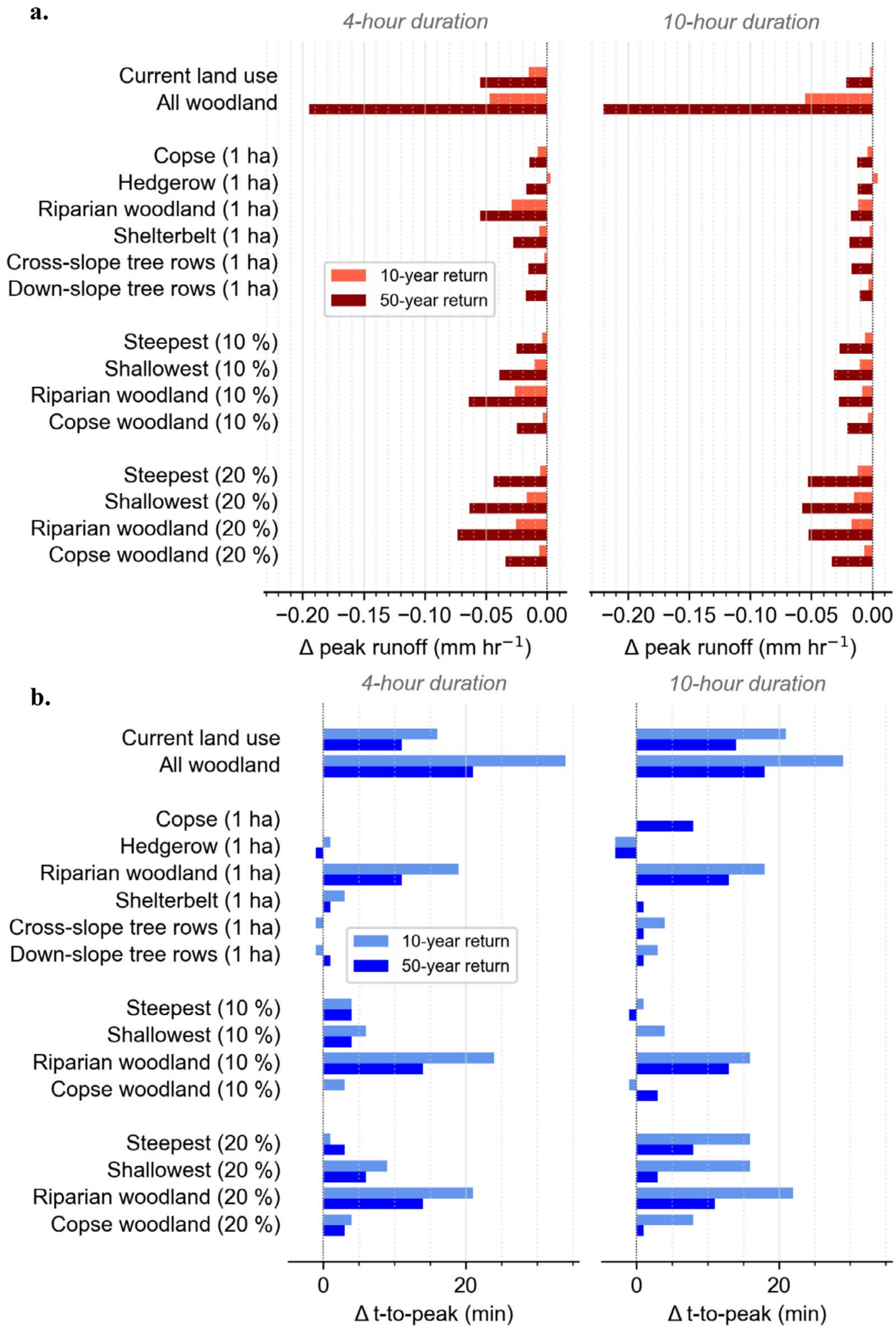

FIGURE 6 | Absolute changes in (a) peak runoff and (b) time-to-peak values compared with UKCEH baseline land use for all scenarios, for both 4-h and 10-h duration storms and 10- and 50-year return periods. 'All woodland' is a scenario in which the whole farmed area is converted to woodland. 'Steepest' and 'Shallowest' refer to the steepest and shallowest gradients within the farmed area, respectively. Percentage values in brackets indicate proportion of the farmed area converted to each land cover type. Proportional differences in time-to-peak and peak runoff are illustrated in the Supporting Information.

the difference in peak size between the whole-farm-under-woodland scenario and 1 ha riparian woodland was only a factor of 1.6 for shorter storms/lower flow, rising to 13 fold for longer/higher flow while the all-woodland scenario required a 40-fold larger area of woodland (Figure 6a). Across all storm types, the all-woodland scenario produced at most a 1.9-fold longer peak time delay than the 1 ha riparian woodland scenario (Figure 6b).

TABLE 6 | Peak runoff and time to peak values for all scenarios tested for a 10-h storm duration with 10- and 50-year return periods.

10 h duration	10-year return period				50-year return period			
Scenario	Peak runoff ($mm\,h^{-1}$)	Diff. cf. baseline (%)	Time to peak (h)	Diff. cf. baseline (%)	Peak runoff ($mm\,h^{-1}$)	Diff. cf. baseline (%)	Time to peak (h)	Diff. cf. baseline (%)
UKCEH baseline	*1.434*	—	*8.34*	—	*2.763*	—	*8.04*	—
All current planting	1.432	−0.1	8.69	+4.3	2.741	−0.8	8.28	+3.1
All woodland	1.379	−3.9	8.83	+5.9	2.542	−8	8.34	+3.7
Copse (1 ha)	1.430	−0.3	8.34	—	2.750	−0.4	8.17	+1.7
Riparian (1 ha)	1.423	−0.8	8.64	+3.6	2.745	−0.6	8.26	+2.7
Shelterbelt (1 ha)	1.432	−0.2	8.34	—	2.744	−0.7	8.07	+0.3
Hedge (1 ha)	1.439	0.3	8.28	−0.7	2.750	−0.4	7.98	−0.7
Cross-slope (1 ha)	1.433	−0.1	8.42	+1.0	2.745	−0.6	8.07	+0.3
Down-slope (1 ha)	1.431	−0.2	8.39	+0.7	2.752	−0.4	8.07	+0.3
Steepest (10%)	1.428	−0.4	8.37	+0.3	2.736	−1	8.01	−0.3
Shallowest (10%)	1.424	−0.7	8.42	+1.0	2.731	−1.1	8.04	—
Riparian (10%)	1.426	−0.6	8.61	+3.3	2.735	−1	8.26	+2.7
Copse (10%)	1.431	−0.2	8.31	−0.3	2.742	−0.7	8.09	+0.7
Steepest (20%)	1.422	−0.8	8.61	+3.3	2.710	−1.9	8.17	+1.7
Shallowest (20%)	1.419	−1.1	8.61	+3.3	2.705	−2.1	8.09	+0.7
Riparian (20%)	1.417	−1.2	8.72	+4.6	2.710	−1.9	8.23	+2.4
Copse (20%)	1.428	−0.4	8.47	+1.6	2.729	−1.2	8.07	+0.3

Note: Differences are given relative to UKCEH baseline values. Dashes (—) denote no change. Baseline values are given in italics.

3.2 | Equal-Area: 10% and 20% Tree Cover Scenarios

In general, flood peak size was more sensitive to planting scenario for shorter duration storms, but more sensitive to area coverage for longer storms (Figure 6a). Among scenarios with 10% tree cover, riparian woodland produced the largest change in peak size and time-to-peak compared with baseline land use for 4-h storm events (Figure 6, Table 5). Peak runoff was reduced by 2.4% (0.026 $mm\,h^{-1}$) and 2.8% (0.064 $mm\,h^{-1}$) for 10- and 50-year events, respectively (Figure 6a). Tree planting on the shallowest gradients on the farm produced a smaller change (10-year: −0.9%, 50-year: −1.7%), followed by steepest gradient planting (10-year: −0.3%, 50-year: −1.1%) and copse planting (10-year: −0.3%, 50-year: +1.1%).

The effect of each tree planting scenario on time-to-peak broadly followed the same pattern, with the largest difference observed for riparian woodland (10-year: +7.4%, 50-year: +5.7%), followed by trees on shallowest gradients (10-year: +1.6%, 50-year: +2.3%), copse (10-year: +1.1%, 50-year: +0.6%) and trees on steepest gradients (10-year: +0.5%, 50-year: +0.6%). Increasing tree area from 10% to 20% had only a small effect on time-to-peak for most of the tree planting scenarios.

At 20% tree cover, differences in peak runoff for most scenarios following 4-h storms only marginally increased and not commensurately with tree area. For example, peak runoff reduced by 3.2% (0.073 $mm\,h^{-1}$) under 20% riparian woodland cover for a 50-year event, compared with 2.8% (0.064 $mm\,h^{-1}$) under 10% cover. However, for longer 10-h storms, doubling tree area led to a doubling of peak size reduction for almost all scenarios, including riparian woodland (10% cover: −0.027 $mm\,h^{-1}$, 20% cover: −0.052 $mm\,h^{-1}$), shallowest-gradient (10%: −0.031 $mm\,h^{-1}$, 20%: −0.057 $mm\,h^{-1}$) and steepest-gradient planting (10%: −0.027 $mm\,h^{-1}$, 20%: −0.053 $mm\,h^{-1}$, all examples for 50-year return).

3.3 | Endmember Scenario

Absolute differences in flood peak size and timing between the baseline and whole-farm-under-woodland scenario were sensitive to storm intensity but not storm duration. For a 4-h storm duration, the all-woodland scenario altered flood peak size by $-0.042\,\mathrm{mm\,h^{-1}}$ (−4.2%) for a 10-year event, and $-0.195\,\mathrm{mm\,h^{-1}}$ (−8.4%) for a 50-year event. These figures were $-0.055\,\mathrm{mm\,h^{-1}}$ (−3.9%) and $-0.220\,\mathrm{mm\,h^{-1}}$ (−8.0%), respectively, for a 10-h storm. Flood peak in a 4-h storm was delayed by 36 min (11.6%) compared with baseline land use for a 10-year event, and 21 min (7.8%) for a 50-year event. These differences were similar for a longer, 10-h storm. Differences in peak size between the all-woodland scenario and agroforestry scenarios were an order of magnitude smaller (1.6-fold) for shorter, lower intensity storms, rising to 13-fold for longer, more intense events. For flood peak timing, all-woodland produced at most a 1.9-fold longer delay than the best agroforestry scenarios across all storm types.

4 | Discussion

Tree cover at densities sufficiently low for normal farm activity was shown to have a considerable and beneficial influence on flood peak size and timing. The capacity for trees on farms to attenuate flood peak aligns with the majority of work comparing woodland with other land-use types, in which increased interception, infiltration and water holding capacity in afforested soils contribute to smaller and delayed flood peaks (Dadson et al. 2017; Archer et al. 2013; McCulloch and Robinson 1993; Monger et al. 2024). However, the extent of this influence was strongly determined by both storm intensity and spatial layout of tree planting, with important considerations for farm management and policy support for agroforestry and other types of farmland afforestation. Results demonstrate that even a very small area of trees on farms, correctly sited, can positively influence flood discharge in a small catchment.

4.1 | Tree Placement

For nearly all planting densities, storm return periods and durations, riparian woodland delivered the largest downstream flood risk reduction for a fixed area of planting. With just 1 ha (2.5% of farmed area, 0.6% of study catchment) converted to riparian woodland, flood peak size reduced by 2.6% and arrived 19 min (6.6%) later for a typical storm event with a 10-year return period. With a 50-year return period, these figures were 2.4% and 4.2%, respectively. Studies elsewhere have found this to be the case for very different catchment scales and vegetation types. For example, Gao et al. (2016) determined that flood peak attenuation in blanket peatland basins was most sensitive to vegetation cover on the peat surface in the vicinity of streams. Although the reverse effect has been found—that rougher surfaces at higher elevation produce a later flood peak than rougher surfaces nearer the stream (Huang and Lee 2009; Maske and Jain 2013)—Gao et al. (2016) suggest this discrepancy may be caused by differences in catchment gradients. Nonetheless, they demonstrate the same riparian area sensitivity even with a flattened DEM. Furthermore, they found, as we did, that trees on shallower slopes were more effective in attenuating flood peak than trees on steeper slopes, for an equivalent area of woodland. Mean slope in our study catchment is 4.9%, intermediate between Gao et al. (2016) (> 9%) and Maske and Jain (2013) (1%–3%). Monger et al. (2024), also found riparian woodland to be effective in attenuating flood peak in a steeper, upland catchment of similar scale (~$2\,\mathrm{km^2}$), albeit not as effective as cross-slope placement. However, our study is the first demonstration of flood peak sensitivity to riparian planting in the context of lowland agroforestry.

Riparian zone planting carries high potential for multiple ecosystem benefits in addition to flood risk reduction. Restoration of riparian areas creates marginal habitat and can host watercourse restoration where streams have been modified for historic farmland reclamation. In-stream ecological heterogeneity is increased, leading to increased habitat potential and riparian plant species diversity (Rohde et al. 2005; Randhir and Ekness 2013). Riparian woodland can foster climate resilience by lowering spring and summer in-stream temperatures, with biological significance for aquatic organisms (Bowler et al. 2012; Justice et al. 2017). Where woodland is fenced, watercourses are better protected from livestock interference, reducing sediment, pathogen and nutrient loading to streams, along with denitrification benefits of trees (Campbell and Allen-Diaz 1997; Hutchins 2012; Scott et al. 2023). Finally, whereas in-field trees such as copses, cross- or downslope tree rows can generate a trade-off through interference with the use of farm equipment, riparian buffers are typically set aside from cultivated areas, potentially limiting impact on agricultural management and productivity.

The influence of linear row of tree or hedgerow placement strategies on flood peak was limited, and in some cases, isolated measures caused flood peaks to arrive earlier or be larger than for baseline land use, with either negligible or inconclusive findings. Moreover, comparison between hydrograph responses for combined current NFM planting and riparian planting alone suggests that the latter had the most significant influence on peak flow reduction. The complexity of distributed, linear features for catchment hydrology has been noted elsewhere. For example, Fiener et al. (2011) note that hydraulic functioning of linear woody vegetation is rarely modelled, and that depending on placement features can either increase or decrease hydraulic connectivity within catchments. Given the growing promotion of agroforestry, such as tree and hedgerow planting (Biffi et al. 2023; Rolo et al. 2023), the need to understand these effects in temperate catchments is urgent if agricultural landscapes are to contribute to flood risk reduction while mitigating and adapting to climate change.

4.2 | Woodland Area

Although the 'all woodland' scenario had the largest positive effect on discharge across storm events, our results illustrate that increasing the area of on-farm woodland to cover the whole farm does not produce a commensurate increase in flood peak attenuation compared with other agroforestry scenarios (Figure 6). The importance of tree area coverage over placement for NFM increases for longer, more intense storms, and at 10%–20% coverage, tree area aligns more closely with peak size reduction in very intense events. However, this is not the case for a much higher rate of tree coverage (all-woodland), and a diminishing return is generally observed between increasing woodland cover and discharge response for both peak size and timing. This diminishing return is considerably stronger in the case of flood peak timing, with only a marginally increasing delay with increasing tree area.

The above findings imply that the trade-off between land lost to NFM and flood risk reduction is manageable, and especially so for shorter, more frequently-encountered extreme rainfall events. Monger et al. (2024) estimated a 3.3% increase in flood peak attenuation for each 10% area increase in riparian woodland up to 30% of their catchment, although the difference between each 10% step was highly nonlinear. Increasing from 0% to 10% riparian cover in their scenario decreased flood peak size by 2.6%, whereas moving from 10% to 20% in their scenario led to a further 5.7% drop, followed by an additional 1.6% drop from 20% to 30%. Depending on storm duration and return frequency, we observe a 0.6%–2.8% drop for 10% riparian cover, increasing to 1.2%–3.2% for 20% cover within the farm boundary alone. Buechel et al. (2022) estimated a 1.4% ± 0.6% reduction in the top 1% of flows for each 10% increase in woodland cover for large UK catchments (500–10 000 km^2), although they found weaker correlation between increasing tree area and decreasing flow in the case of high flows. We found woodland planting over the whole farm area (25% of the catchment) decreased flow peak by just 1.6 times more (4.2%) than 1 ha of riparian woodland (2.6%) at lower flow, rising to 13 times more at the highest flows, while requiring 40 times more catchment area taken out of production. As Monger et al. (2024) note, the effect of riparian woodland on flood peak magnitude and timing may also be underestimated because of in-stream debris further attenuating flow (Cooper et al. 2021; Thomas and Nisbet 2012), which present modelling does not account for. These findings are significant in demonstrating the importance of tree siting considerations for optimal NFM benefit at lower area coverage and for shorter storm durations, as opposed to a focus on maximising woodland area alone. Furthermore, spatially distributed hydrological modelling should be used to support the design of future agroforestry schemes in order to maximise potential for flood risk reduction.

4.3 | Scaling Findings

As demonstrated here and elsewhere, planting for NFM in a small catchment can have positive local effects on flood peak magnitude and timing (Marshall et al. 2014; Dadson et al. 2017). Although our findings show that small amounts of farm woodland can substantially influence catchment hydrology, these results are for a small catchment (175 ha) in which tree planting at a single farm representing 25% of catchment area has a significant impact on whole-catchment hydrological functioning. Over a wider area, catchment hydrology will depend on a larger and more complex network of sub-catchments and land holdings, and understanding of spatial connectivity of flow processes across networks such as these remains poor (Rogger et al. 2017).

Studies have attempted to address this empirically, such as at Pontbren in Wales where extensive sampling and instrumentation over a ~10 km^2 catchment were used to examine changes in overland flow generation and infiltration under woodland and intensively grazed pasture (Wheater et al. 2012; Marshall et al. 2014). Overland flow generation in the vicinity of woodland was reduced by as much as two thirds at Pontbren, mirroring the local effect of trees in our own modelling. Similarly, in the Coalburn catchment, an empirical, long-term study by Bathurst et al. (2018) showed a 24% annual reduction in runoff under forest cover compared with grassland, although single event comparisons with this study were complicated by the presence of ditching in their woodland treatment. However, verifying effects such as these for different scales and landscape features is complicated by the logistical challenge of undertaking large empirical studies, along with complications in transferring results between differing catchment geographies. As we show, this is likely to be the case for linear features such as hedgerows or rows of trees; two common types of agroforestry system.

Modelling at larger scales is therefore needed to verify whether a flood peak reduction within a smaller catchment delivers downstream flood peak reduction at scale, or conversely whether the delayed peak from the small catchment results in flood peak synchronicity (and peak increase) in downstream, larger river channels. Additionally, modelling studies considering wider catchment processes and longer-term responses beyond single storm events would be welcome. Anecdotal evidence exists for positive wider-scale benefits of NFM interventions (e.g., Nisbet 2017), yet little is known about underlying mechanisms or complex interactions of summing local effects over whole landscapes. Nonetheless, if our findings hold for small catchments elsewhere, we believe it is likely that flood benefits can be realised at larger scales.

5 | Conclusions

Using SD-TOPMODEL, we analysed changes to rainfall-runoff characteristics following various agroforestry planting scenarios in a 1.75 km^2 lowland catchment in Yorkshire, UK. We have shown that using very small areas of agricultural land for tree planting can have substantial benefit for flood peaks, providing woodland is appropriately sited. Riparian woodland covering just 2.5% of farmed area, or 0.6% of the catchment, was capable of attenuating flood peak by 2.6% and delaying its arrival by 6.6%, or 19 min. The effect of an equivalent area of shelterbelt or in-field copse planting was much more modest, and linear features such as in-field tree rows or hedges had a negligible or opposing effect on flood peak size and timing, reflecting the complexity of their hydrological characteristics. More work is needed to understand these effects considering the growing promotion of in-field agroforestry schemes and trees on farms (Woodland Trust 2022; Defra 2025; CCC 2020; IPCC 2014a). Increasing the area of trees produced a diminishing return in terms of changes to the flood peak, and hypothetical woodland cover over the whole farmed area (25% of the catchment) produced only 1.6 times the peak size reduction as 0.6% riparian cover in low flow scenarios, rising to 13 times at the highest flows, despite requiring 40 times more land taken out of production.

We therefore conclude that if sited on shallow gradients or in the riparian zone, agroforestry can significantly contribute to NFM without substantially impacting land available for productive agriculture. Integrated policy support that connects agroforestry to hydrological benefits would be welcome in the future and broader benefits could also be studied (such as reduced soil erosion and transport) so that policy incentives consider the full range of 'stacked' environmental benefits. These findings are significant in demonstrating the greater importance of tree siting considerations over coverage rates in lowland NFM, and the capacity of agroforestry to deliver multiple landscape benefits.

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Data Availability Statement

Model outputs associated with this paper are available from the University of Leeds at https://doi.org/10.5518/1859.

References

Araujo, A., L. Leite, B. De Freitas Iwata, M. De Andrade Lira, G. R. Xavier, and M. V. B. Figueiredo. 2012. "Microbiological Process in Agroforestry Systems. A Review." *Agronomy for Sustainable Development* 32, no. 1: 215–226.

Archer, N. A. L., M. Bonell, N. Coles, A. M. MacDonald, C. A. Auton, and R. Stevenson. 2013. "Soil Characteristics and Landcover Relationships on Soil Hydraulic Conductivity at a Hillslope Scale: A View Towards Local Flood Management." *Journal of Hydrology* 497: 208–222.

Ashwood, F., K. Watts, K. Park, E. Fuentes-Montemayor, S. Benham, and E. I. Vanguelova. 2019. "Woodland Restoration on Agricultural Land: Long-Term Impacts on Soil Quality." *Restoration Ecology* 27, no. 6: 1381–1392.

Bathurst, J., S. Birkinshaw, H. Johnson, et al. 2018. "Runoff, Flood Peaks and Proportional Response in a Combined Nested and Paired Forest Plantation/Peat Grassland Catchment." *Journal of Hydrology* 564: 916–927.

Beven, K. 1997. "TOPMODEL: A Critique." *Hydrological Processes* 11, no. 9: 1069–1085.

Beven, K. J. 2012. *Rainfall-Runoff Modelling: The Primer*. John Wiley & Sons.

Beven, K. J., and M. J. Kirkby. 1979. "A Physically Based, Variable Contributing Area Model of Basin Hydrology/Un Modèle à Base Physique de Zone D'appel Variable de L'hydrologie du Bassin Versant." *Hydrological Sciences Bulletin* 24, no. 1: 43–69.

Beven, K. J., M. J. Kirkby, J. E. Freer, and R. Lamb. 2021. "A History of TOPMODEL." *Hydrology and Earth System Sciences* 25, no. 2: 527–549.

BGS. 2013. "BGS Geology 10K [Geospatial Data]." https://www.bgs.ac.uk/datasets/bgs-geology-10k/.

Biffi, S., P. J. Chapman, R. P. Grayson, and G. Ziv. 2023. "Planting Hedgerows: Biomass Carbon Sequestration and Contribution Towards Net-Zero Targets." *Science of the Total Environment* 892: 164482.

Blyth, E. M., A. Martinez-de la Torre, and E. L. Robinson. 2019. "Trends in Evapotranspiration and Its Drivers in Great Britain: 1961 to 2015." *Progress in Physical Geography: Earth and Environment* 43, no. 5: 666–693.

Bond, S., T. Willis, J. Johnston, et al. 2022. "The Influence of Land Management and Seasonal Changes in Surface Vegetation on Flood Mitigation in Two UK Upland Catchments." *Hydrological Processes* 36: e14766.

Bond, S. G. 2022. *The Hydrological Function of Organo-Mineral Soil Grasslands in UK Uplands*. University of Leeds.

Bowler, D. E., R. Mant, H. Orr, D. M. Hannah, and A. S. Pullin. 2012. "What Are the Effects of Wooded Riparian Zones on Stream Temperature?" *Environmental Evidence* 1: 3.

Buechel, M., L. Slater, and S. Dadson. 2022. "Hydrological Impact of Widespread Afforestation in Great Britain Using a Large Ensemble of Modelled Scenarios." *Communications Earth & Environment* 3: 6.

Burgess, P. 1999. "Effects of Agroforestry on Farm Biodiversity in the UK." *Scottish Forestry* 53, no. 1: 24–27.

Butler, D., S. Ward, C. Sweetapple, et al. 2017. "Reliable, Resilient and Sustainable Water Management: The Safe & SuRe Approach." *Global Challenges* 1: 63–77.

Cameron, D., K. Beven, J. Tawn, S. Blazkova, and P. Naden. 1999. "Flood Frequency Estimation by Continuous Simulation for a Gauged Upland Catchment (With Uncertainty)." *Journal of Hydrology* 219, no. 3–4: 169–187.

Campbell, C. G., and B. Allen-Diaz. 1997. "Livestock Grazing and Riparian Habitat Water Quality: An Examination of the Oak Woodland Springs in the Sierra Foothills of California." In *Proceedings of a Symposium on Oak Woodlands: Ecology, Management, and Urban Interface Issues*, edited by N. H. Pillsbury, J. Verner, and W. D. Tietje, 339–346. USDA Forest Service.

CCC. 2020. *Land Use: Policies for a Net Zero UK*. Committee on Climate Change. https://www.theccc.org.uk/publication/land-use-policies-for-a-net-zero-uk/%0Ahttps://www.theccc.org.uk/2020/01/23/major-shift-in-uk-land-use-needed-to-deliver-net-zero-emissions/.

Chow, V. T., D. R. Maidment, and L. W. Mays. 1988. *Applied Hydrology*. McGraw-Hill Inc.

Christidis, N., M. McCarthy, D. Cotterill, and P. A. Stott. 2021. "Record-Breaking Daily Rainfall in the United Kingdom and the Role of Anthropogenic Forcings." *Atmospheric Science Letters* 22: e1033.

Cooper, M. M. D., S. D. Patil, T. R. Nisbet, H. Thomas, A. R. Smith, and M. A. McDonald. 2021. "Role of Forested Land for Natural Flood Management in the UK: A Review." *Wiley Interdisciplinary Reviews: Water* 8: e1541.

Cotterill, D., P. Stott, N. Christidis, and E. Kendon. 2021. "Increase in the Frequency of Extreme Daily Precipitation in the United Kingdom in Autumn." *Weather and Climate Extremes* 33: 100340.

Cranfield University. 2022. *The Soils Guide*. Cranfield University.

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: 20160706.

Defra. 2025. *Funding and Grants for Agroforestry*. Department for Food, Environment and Rural Affairs. https://www.gov.uk/government/publications/funding-and-grants-for-agroforestry/funding-and-grants-for-agroforestry.

Dolman, A. 1987. "Summer and Winter Rainfall Interception in an Oak Forest. Predictions With an Analytical and a Numerical Simulation Model." *Journal of Hydrology* 90: 1–9.

EDINA Aerial Digimap Service. 2022. "High Resolution (25cm) Vertical Aerial Imagery [JPG Geospatial Data], Scale 1:500, Tiles: sx9088,sx8988, 1:500." Getmapping.

Farley, K. A., E. G. Jobbágy, and R. B. Jackson. 2005. "Effects of Afforestation on Water Yield: A Global Synthesis With Implications for Policy." *Global Change Biology* 11, no. 10: 1565–1576.

Faulkner, D. S., and S. Barber. 2009. "Performance of the Revitalised Flood Hydrograph Method." *Journal of Flood Risk Management* 2, no. 4: 254–261.

Ferguson, C., and R. Fenner. 2020. "Evaluating the Effectiveness of Catchment-Scale Approaches in Mitigating Urban Surface Water Flooding." *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences* 378: 20190203.

Fiener, P., K. Auerswald, and K. Van Oost. 2011. "Spatio-Temporal Patterns in Land Use and Management Affecting Surface Runoff Response of Agricultural Catchments—A Review." *Earth-Science Reviews* 106, no. 1–2: 92–104.

Forestry Commission. 2025. *Tree and Woodland Grants and Incentives Overview*. Forestry Commission. https://www.gov.uk/government/publications/woodland-grants-and-incentives-overview-table/woodland-grants-and-incentives-overview-table.

Gao, J., J. Holden, and M. Kirkby. 2015. "A Distributed TOPMODEL for Modelling Impacts of Land-Cover Change on River Flow in Upland Peatland Catchments." *Hydrological Processes* 29, no. 13: 2867–2879.

Gao, J., J. Holden, and M. Kirkby. 2016. "The Impact of Land-Cover Change on Flood Peaks in Peatland Basins." *Water Resources Research* 52, no. 5: 3477–3492.

Geris, J., D. Tetzlaff, J. McDonnell, and C. Soulsby. 2014. "The Relative Role of Soil Type and Tree Cover on Water Storage and Transmission in Northern Headwater Catchments." *Hydrological Processes* 29, no. 7: 1844–1860.

Hartmann, T., L. Slavíková, and S. McCarthy. 2019. "Nature-Based Solutions in Flood Risk Management." In *Nature-Based Flood Risk Management on Private Land: Disciplinary Perspectives on a Multidisciplinary Challenge*, edited by T. Hartmann, L. Slavíková, and S. McCarthy, 3–8. Springer Nature Switzerland AG.

Herbst, M., P. T. W. Rosier, D. D. McNeil, R. J. Harding, and D. J. Gowing. 2008. "Seasonal Variability of Interception Evaporation From the Canopy of a Mixed Deciduous Forest." *Agricultural and Forest Meteorology* 148, no. 11: 1655–1667.

Hirabayashi, Y., R. Mahendran, S. Koirala, et al. 2013. "Global Flood Risk Under Climate Change." *Nature Climate Change* 3, no. 9: 816–821.

Holden, J., R. P. Grayson, D. Berdeni, et al. 2019. "The Role of Hedgerows in Soil Functioning Within Agricultural Landscapes." *Agriculture, Ecosystems and Environment* 273: 1–12.

Hrachowitz, M., C. Soulsby, D. Tetzlaff, J. J. C. Dawson, and I. A. Malcolm. 2009. "Regionalization of Transit Time Estimates in Montane Catchments by Integrating Landscape Controls." *Water Resources Research* 45: W05421.

Huang, J.-K., and K. T. Lee. 2009. "Influences of Spatially Heterogeneous Roughness on Flow Hydrographs." *Advances in Water Resources* 32, no. 11: 1580–1587.

Hutchins, M. G. 2012. "What Impact Might Mitigation of Diffuse Nitrate Pollution Have on River Water Quality in a Rural Catchment?" *Journal of Environmental Management* 109: 19–26.

IPCC. 2014a. *Agriculture, Forestry and Other Land Use (AFOLU)*, edited by O. Edenhofer, R. Pichs-Madruga, Y. Sokona, et al., 811–922. Cambridge University Press.

IPCC. 2014b. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects*. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar5/wg2/.

Jefferson, R., S. Smith, and E. MacKintosh. 2014. *Lowland Grasslands*. Joint Nature Conservation Committee. http://jncc.defra.gov.uk/page-2303.

Judson, J. B., J. Holden, P. Chapman, and M. V. Galdos. 2023. "Trees, Hedges, Agroforestry and Microbial Diversity." In *Encyclopaedia of Soils in the Environment*, edited by M. J. Goss and M. Oliver, 2nd ed., 469–479. Elsevier.

Justice, C., S. M. White, D. A. McCullough, D. S. Graves, and M. R. Blanchard. 2017. "Can Stream and Riparian Restoration Offset Climate Change Impacts to Salmon Populations?" *Journal of Environmental Management* 188: 212–227.

Kingsbury-Smith, L., T. Willis, M. Smith, et al. 2023. "Evaluating the Effectiveness of Land Use Management as a Natural Flood Management Intervention in Reducing the Impact of Flooding for an Upland Catchment." *Hydrological Processes* 37: e14863.

Kjeldsen, T. R. 2007. *The Revitalised FSR/FEH Rainfall-Runoff Method*. Centre for Ecology and Hydrology.

Lane, S. N. 2017. "Natural Flood Management." *WIREs Water* 4, no. 3: 1–14.

Marapara, T. R., B. M. Jackson, S. Hartley, and D. Maxwell. 2020. "Disentangling the Factors That Vary the Impact of Trees on Flooding (a Review)." *Water and Environment Journal* 35, no. 2: 514–529.

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.

Maske, S. P., and M. K. Jain. 2013. "Study on Effect of Surface Roughness on Overland Flow From Different Geometric Surfaces Through Numerical Simulation." *Hydrological Processes* 28, no. 4: 2595–2616.

McCulloch, J. S. G., and M. Robinson. 1993. "History of Forest Hydrology." *Journal of Hydrology* 150: 189–216.

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: e14567.

Monger, F., D. V. Spracklen, M. Kirkby, and L. Schofield. 2022. "The Impact of Semi-Natural Broadleaf Woodland and Pasture on Soil Properties and Flood Discharge." *Hydrological Processes* 36: e14453.

Monger, F., D. V. Spracklen, M. J. Kirkby, and T. Willis. 2024. "Investigating the Impact of Woodland Placement and Percentage Cover on Flood Peaks in an Upland Catchment Using Spatially Distributed TOPMODEL." *Journal of Flood Risk Management* 17: e12977.

Morton, R. D., C. G. Marston, A. W. O'Neil, and C. S. Rowland. 2023. *Land Cover Map 2023 (Land Parcels, GB), 1:250000*. UK Centre for Ecology and Hydrology.

Munich Re. 2024. "Flood Risks on the Rise—Greater Loss Prevention Is Needed." Munich Re. https://www.munichre.com/en/risks/natural-disasters/floods.html.

Nair, P. K. R. 2005. "Agroforestry." In *Encyclopedia of Soils in the Environment*, edited by D. Hillel, 1st ed., 35–44. Elsevier.

Nisbet, T. 2017. *Slowing the Flow at Pickering*. Forest Research.

Oh, C., S. Han, and J. Jeong. 2020. "Time-Series Data Augmentation Based on Interpolation." *Procedia Computer Science* 175: 64–71.

Randhir, T. O., and P. Ekness. 2013. "Water Quality Change and Habitat Potential in Riparian Ecosystems." *Ecohydrology & Hydrobiology* 13, no. 3: 192–200.

Ritter, A., and R. Muñoz-Carpena. 2013. "Performance Evaluation of Hydrological Models: Statistical Significance for Reducing Subjectivity in Goodness-Of-Fit Assessments." *Journal of Hydrology* 480: 33–45.

Rodgers, P., C. Soulsby, and S. Waldron. 2005. "Stable Isotope Tracers as Diagnostic Tools in Upscaling Flow Path Understanding and Residence Time Estimates in a Mountainous Mesoscale Catchment." *Hydrological Processes* 19, no. 11: 2291–2307.

Rogger, M., M. Agnoletti, A. Alaoui, et al. 2017. "Land Use Change Impacts on Floods at the Catchment Scale: Challenges and Opportunities for Future Research." *Water Resources Research* 53: 5209–5219.

Rohde, S., M. Schütz, F. Kienast, and P. Englmaier. 2005. "River Widening: An Approach to Restoring Riparian Habitats and Plant Species." *River Research and Applications* 21, no. 10: 1075–1094.

Rolo, V., D. Rivest, É. Maillard, and G. Moreno. 2023. "Agroforestry Potential for Adaptation to Climate Change: A Soil-Based Perspective." *Soil Use and Management* 39, no. 3: 1006–1032.

Sayers, P., M. Horritt, S. Carr, et al. 2021. *Third UK Climate Change Risk Assessment (CCRA3): Future Flood Risk*. Committee on Climate Change.

Scott, A., R. Cassidy, J. Arnscheidt, D. Rogers, and P. Jordan. 2023. "Quantifying Nutrient and Sediment Erosion at Riverbank Cattle Access Points Using Fine-Scale Geo-Spatial Data." *Ecological Indicators* 155: 111067.

Soulsby, C., and D. Tetzlaff. 2008. "Towards Simple Approaches for Mean Residence Time Estimation in Ungauged Basins Using Tracers and Soil Distributions." *Journal of Hydrology* 363, no. 1–4: 60–74.

Thomas, H., and T. Nisbet. 2012. "Modelling the Hydraulic Impact of Reintroducing Large Woody Debris Into Watercourses." *Journal of Flood Risk Management* 5, no. 2: 164–174.

Thorne, C. 2014. "Geographies of UK Flooding in 2013/4." *Geographical Journal* 180, no. 4: 297–309.

Torralba, M., N. Fagerholm, P. J. Burgess, G. Moreno, and T. Plieninger. 2016. "Do European Agroforestry Systems Enhance Biodiversity and Ecosystem Services? A Meta-Analysis." *Agriculture, Ecosystems and Environment* 230: 150–161.

Unser, M., A. Aldroubi, and M. Eden. 1993. "B-Spline Signal Processing. I. Theory." *IEEE Transactions on Signal Processing* 41, no. 2: 821–833.

Virtanen, P., R. Gommers, T. E. Oliphant, et al. 2020. "SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python." *Nature Methods* 17: 261–272.

Welsh Government. 2024. "Sustainable Farming Scheme: Proposed Scheme Outline (2024)." https://www.gov.wales/sustainable-farming-scheme-proposed-scheme-outline-2024-html.

Wheater, H., C. Ballard, N. Bulygina, N. Mcintyre, and B. Jackson. 2012. "Modelling Environmental Change: Quantification of Impacts of Land Use and Land Management Change on UK Flood Risk." In *System Identification, Environmental Modelling, and Control System Design*, edited by L. Wang and H. Garnier, 449–481. Springer-Verlag.

Woodland Trust. 2022. *Farming for the Future: How Agroforestry Can Deliver for Nature and Climate*. Woodland Trust. https://www.woodlandtrust.org.uk/media/51622/farming-for-the-future-how-agroforestry-can-deliver-for-nature-climate.pdf.

Zhu, Q., M. Klaar, T. Willis, and J. Holden. 2024. "A Quantitative Review of Natural Flood Management Research." *WIREs Water* 12: e1765.

Zhu, Q., M. Klaar, T. Willis, and J. Holden. 2025. "Use of Spatially Distributed TOPMODEL to Assess the Effectiveness of Diverse Natural Flood Management Techniques in a UK Catchment." *Hydrological Processes* 39: e70122.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Within-farm scenarios based on current planting for agroforestry, in which each scenario is adjusted to an equivalent 1 ha area. Agroforestry scenarios include (a) copse planting, (b) hedgerows, (c) riparian woodland, (d) shelterbelt, (e) cross-slope tree rows and (f) down-slope tree rows. **Figure S2:** Percentage changes in (a) peak runoff and (b) time-to-peak values compared with UKCEH baseline land use for all scenarios, for both 4-h and 10-h duration storms and 10- and 50-year return periods. 'All woodland' is a scenario in which the whole farmed area is converted to woodland. 'Steepest' and 'Shallowest' refer to the steepest and shallowest gradients within the farmed area, respectively. Percentage values in brackets indicate proportion of the farmed area converted to each land cover type. See main text (Figure 6) for absolute differences. **Figure S3:** Hydrograph response for all agroforestry scenarios, storm durations and return periods. Scenario hydrograph shown as solid lines, with UKCEH baseline (black dotted) and all current agroforestry (blue dotted) hydrographs illustrated for comparison. Inset area corresponds to grey box on left plot for each storm. All insets shown to same scale.