Simulating a century of soil erosion for agricultural catchment management

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Abstract

Agricultural land management requires strategies to reduce impacts on soil and water resources while maintaining food production. Models that capture the effects of agricultural and conservation practices on soil erosion and sediment delivery can help to address this challenge. Historic records of climatic variability and agricultural change over the last century also offer valuable information for establishing extended baselines against which to evaluate management scenarios. Here, we present an approach that combines centennial-scale reconstructions of climate and agricultural land cover with modelling across four lake catchments in the UK where radiometric dating provides a record of lake sedimentation. We compare simulations using MMF-TWI, a catchment-scale model developed for humid agricultural landscapes that incorporates representation of seasonal variability in vegetation cover, soil water balance, runoff and sediment contributing areas. MMF-TWI produced mean annual sediment exports within 9-20% of sediment core-based records without calibration and using guide parameter values to represent vegetation cover. Simulations of land management scenarios compare upland afforestation and lowland field-scale conservation measures to reconstructed historic baselines. Oak woodland versus conifer afforestation showed similar reductions in mean annual surface runoff (8-16%) compared to current moorland vegetation but a larger reduction in sediment exports (26-46 vs. 4-30%). Riparian woodland buffers reduced upland sediment yields by 15-41%, depending on understorey cover levels, but had only minor effect on surface runoff. Planting of winter cover crops in the lowland arable catchment halved historic sediment exports. Permanent grass margins applied to sets of arable fields across 15% or more of the catchment led to further significant reduction in exports. Our findings show the potential for reducing sediment delivery at the catchment scale with land management interventions. We also demonstrate how MMF-TWI can support hydrologically-informed decision making to better target conservation measures in humid agricultural environments.

1. Introduction

Changes in agricultural land use and management over the last century produced significant environmental impacts. Agricultural intensification, particularly since the 1940s, occurred across Europe with demand for higher food production and was associated with large increases in arable farming, machinery use, livestock numbers and chemical applications (Stoate et al, 2001; Robinson & Sutherland, 2002). Impacts include losses of biodiversity and habitat heterogeneity (Benton et al, 2003), with notable declines in populations of butterflies, birds and plants over the past 40 years in Britain linked to habitat degradation (Thomas et al, 2004). Agricultural intensification also increased soil erosion, excess fine sediment and nutrient inputs to streams and rivers (Evans, 2010), with adverse consequences for aquatic habitats, fish breeding and clean water supply (Owens et al, 2005). For example, lake sediment studies show post-1950s increases in sedimentation rates in agricultural landscapes across Britain (Foster et al, 2011) and Europe (Rose et al, 2011).

Biodiversity losses may primarily reflect reduced habitat heterogeneity in agricultural landscapes (Benton et al, 2003). This relates to changes in the pattern and extent of various land covers (e.g. woodlands, pasture and cropped land) and landscape features (e.g. riparian woodlands, grass field margins, hedgerows, ponds). These factors also affect surface runoff, soil erosion and sediment transport from hillslopes to streams. Higher soil losses tend to occur on cultivated land than pasture or woodland (Cerdan et al, 2010) and increases in the extent of cultivated land at the catchment-scale may lead to higher sediment yields (Foster & Lees, 1999; Smith et al, 2014). The spatial pattern of different land uses also influences runoff and soil erosion rates and levels of hydro-sedimentary connection between eroding areas and the stream network (Van Oost et al, 2000; Moussa et al, 2002; Zhang et al, 2017). Landscape features can trap and store water and sediment (Boardman & Vandaele, 2016), thereby reducing sedimentation and associated impacts on downstream aquatic environments. Hence, changes in landscape structure and heterogeneity have impacts on both terrestrial biodiversity and hydro-sedimentological processes, which in turn affect aquatic ecosystem health.

In response, many policy and management initiatives aim to reduce soil erosion and associated water quality impacts from agriculture. For example in the UK, these presently include the Water Framework Directive, the Catchment Sensitive Farming and Environmental Stewardship schemes, and Cross Compliance rules designed to achieve Good Agricultural and Environmental Condition (GAEC) as part of the requirements for farm subsidy payments under the Common Agricultural Policy (CAP). However, there remains a lack of detailed, longer-term baseline information extending beyond the instrumental record against which to measure the success or otherwise of management interventions.

Instrumental records of catchment soil erosion and sediment delivery to streams are limited and rarely exceed a decade in duration (Boardman, 2006). As such, results may be highly dependent on the specific environmental conditions that prevail during these short measurement periods (Burt, 1994; Wilby et al, 1997). Establishing longer-term paired catchment experiments in agricultural landscapes presents a significant challenge for the implementation of treatments and for maintaining a control, given individual variations in farm-level agricultural practices and decision-making (Riley et al, 2018). This can hinder investigation of management initiatives designed to reduce soil erosion because of difficulties in evaluating the effectiveness of such changes at the catchment-scale across multiple farms and for a range of hydro-climatic conditions.

There is an urgent need for longer-term information on soil erosion and catchment sediment yields against which to assess management changes and support planning to mitigate impacts on aquatic ecosystems and water resources. To address this problem, we present an integrated approach that combines reconstructions of a century of climate variability and agricultural change with modelling in lake catchments where radiometric dating provides a record of lake sedimentation. The centennial timescale captures a larger range in past land use change and climatic variability than shorter-term studies based on direct measurements of soil erosion and catchment sediment yields. The last century also represents a period for which more relevant climate and land cover data is available than for any period preceding it. Focusing on this period is a compromise between length of record to capture a wider range of hydro-climatic conditions and levels of data available for model parameterisation.

We couple the reconstructions with a new catchment-scale soil erosion model, MMF-TWI, which is designed for use in humid agricultural environments (Peñuela et al, 2017). MMF-TWI is based on the Morgan-Morgan-Finney model (Morgan & Duzant, 2008), but incorporates new processes to capture sub-annual variability in hydrology, vegetation cover and land management practices (Peñuela et al, 2017). MMF-TWI represents a compromise between process-based models with higher parameter and computing demands and empirical models based on observations from certain regions (Prosser et al, 2001; Merritt et al, 2003). As a conceptual model, MMF-TWI provides a general description of runoff and erosion process while keeping computation and data requirements low (Peñuela et al, 2017). This makes MMF-TWI well suited for simulating past runoff, erosion and catchment sediment exports over centennial timescales using available historic datasets. In the present study, we aim to demonstrate (1) MMF-TWI performance against centennial-scale lake sediment records and (2) the effect of land management scenarios on catchment sediment exports compared to reconstructed historic baselines across four catchments in the UK.

2. Environmental reconstructions

2.1. Lake catchments

The four lake catchments span upland and lowland environments (Fig 1). Loweswater and Brotherswater are located in the Lake District, an upland region in northwest England, Loch of the Lowes in the Southern Uplands of Scotland, and Loch of Skene in Aberdeenshire in northeast Scotland. The catchments were chosen to represent different agricultural land uses and, within the set of upland catchments, to span a range in size and relief (Table 1). The three upland catchments are characterized by smaller catchment areas (8.8-27 km^2), higher precipitation (1502-2144 mm y^{-1}) and steeper mean slopes (12-24°), compared to the lowland Loch of Skene catchment (area 49 km^2, precipitation 773 mm y^{-1}, mean slope 3.8°). Soils in the upland catchments are typically brown podzolic soils and brown earths with peaty soils on upper slopes, while soils are mostly humus-iron podzols in the Loch of Skene catchment (Table 1). Land cover is predominantly moorland in the upland catchments and agricultural activities are limited mostly to sheep grazing. In contrast, improved pasture and arable land is widespread in the Loch of Skene catchment where the main crop is spring barley and livestock include both sheep and cattle. All catchments contain areas of woodland.

Insert figure 1 here

Insert table 1 here

2.2. Climate reconstruction

Daily precipitation was reconstructed for each lake catchment using records available from the British Atmospheric Data Centre (BADC). Composite records were quality controlled, cross-correlated, gap filled, and high magnitude totals checked against the Met Office's British Rainfall reports. The procedure involved selecting a reference station (Table 1) with >30 year record based on proximity and comparability in average annual precipitation between the station and the catchment using the Met Office 1 km gridded precipitation map for 1961-1990. The selected reference station records range 41-118 years in length. Station selection for gap filling was based on the significance ($p < 0.05$) of correlation coefficients and 95% confidence intervals produced by bootstrap sampling ($n = 1000$) of paired records. The resulting gap-filled composite series comprise 3-5 individual records, including reference stations, and span 97-126 years in length (Table 1).

We require mean daily temperature data for simulating crop growth and evaporation. Mean daily temperature records were obtained from stations near the catchments (Table 1) and correlated with the mean daily Hadley Centre Central England Temperature (HadCET) series (Parker et al, 1992). We employ a Cumulative Distribution Function (CDF) matching technique (Panofsky and Brier, 1968; Thrasher et al, 2012) between HadCET and the selected local record using monthly data. The CDFs are fitted to gamma distributions and the corresponding cumulative probability is found for each HadCET value, which is used to select local observations to replace the HadCET data. This transfer function is applied to the HadCET record to derive a composite daily temperature series for the same period as the composite precipitation record. The dry adiabatic lapse rate (0.0098 °C m^{-1}) is used to correct the composite temperature series for the difference between median catchment elevations and the elevation of the local measurement stations.

Subhourly precipitation data are required for simulating erosive rainfall. However, these data are unavailable for the length of daily precipitation records. We accessed records from stations that range 8-13 years in duration and 2.5-17 km from the lakes. We use these records to calculate the mean of the maximum monthly 30-minute rainfall intensity (I_{30}, mm h^{-1}) for storm events discretized using the Rainfall Intensity Summarization Tool (RIST) (USDA, 2014) and to compute direct throughfall energy in MMF-TWI on a mean monthly basis (Peñuela et al, 2017). Storms were considered discrete events when separated by a 6-hour period with precipitation of less than 0.05 inches (1.27 mm) (Renard et al, 1997). Snowfall periods were excluded from rainfall energy-intensity calculations by assuming intensity is zero when the mean daily temperature is below -1°C. Previous work has shown that varying the rain-snow temperature threshold by ±2°C around 0°C had negligible effect on rainfall energy-intensity calculations (Lee & Olsen, 2000).

2.3. Agricultural reconstruction

Changes in agricultural land cover and livestock numbers over the last century were reconstructed from a combination of records. These include annual parish-level agricultural statistics, aerial imagery, and farmer interviews. Annual data on parish livestock numbers and areas of agricultural land use were obtained from the Agricultural statistics of England and Wales: Parish summaries, 1866-1988 (MAF68) and the Scotland Agricultural Census: Parish Summaries, 1912-1994 (AF40). Historic aerial photographs (1940-1990s) were obtained from collections held by English Heritage and the National Collection of Aerial Photography in Scotland. Further information on land cover was available from the UK Land Cover Maps (LCM) for 1990, 2000 and 2007 (Moreton et al, 2011) and Google Earth imagery (2000-2010s).

Livestock numbers were reconstructed from parish data covering the catchments. Data was obtained from the parish with the largest area intersecting each catchment, which equated to 85, 88 and 100% of Loch of the Lowes, Loweswater, and Brotherswater catchments, respectively. In these parishes, the total annual number of sheep and cattle were recorded and reported as livestock numbers per unit parish area. For the larger Loch of Skene catchment, five parishes were used and individually cover 12-40% of the catchment area to give a combined catchment coverage of 98.6% (Fig. 2a). For Skene, livestock numbers were determined by the sum of sheep or cattle per unit parish area weighted by the proportion of each parish intersecting with the catchment.

Insert figure 2 here

The reconstruction of agricultural land cover focused on Loch of Skene because this is the only catchment to contain a significant area of arable land. The annual extent of cropped land (excluding non-permanent grass) was determined from five parishes (Fig. 2a). The annual catchment fractional crop area (Fig. 2b) was calculated from the sum of parish fractional crop areas (area under crop/parish area) weighted by the area of each parish intersecting with the catchment for the period between 1912 and 1992 (end of available record). This data was combined with crop areas obtained by digitising catchment land cover from aerial imagery to produce a composite record of agricultural land cover change for the catchment (Fig. 2b).

2.4. Lake sedimentation

Radiometric dating of sediment cores was used to estimate centennial-scale lake sedimentation. Sediment cores were collected from each lake during the period 2010-2012. For Loweswater and Loch of Skene, five cores each were taken from around the lake centre to provide a measure of variability in sedimentation rate. These two lakes are characterized by lower catchment-to-lake area ratios (14-44) and lower mean catchment slopes (3.8-12°) than Brotherswater and Loch of the Lowes (72-73 ratio and 14-24° mean slope). Therefore, lake-centre cores were considered to provide a reasonable approximation of mean lake sedimentation in the absence of pronounced inflow deltas. In contrast, sediment cores (n = 3 each for dating) were retrieved from delta-proximal to more distal locations in Brotherswater and Loch of the Lowes, where there is a clear gradient in sedimentation rates away from the inflow delta (Schillereff et al, 2016).

Sediment cores were sub-sampled at 1-2 cm intervals for radiometric dating. ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am were measured by gamma spectrometry using Ortec HPGe GWL series coaxial low background detectors (Appleby et al, 1986). Core chronologies were determined using the CRS model (Appleby & Oldfield, 1978) and compared to ^{137}Cs activity peaks associated with fallout from Chernobyl (1986) and the 1963 peak in atmospheric nuclear weapons testing. The calculated sedimentation rates were corrected for organic content by loss on ignition. For Loweswater and Loch of Skene, the mean mineral sediment flux to the lakes (t y^{-1}) was determined by taking an average based on annual linear interpolation of each core for the period of overlapping records.

The distinct gradient in sediment accumulation across Brotherswater and Loch of the Lowes required a different approach for estimating lake sediment flux. For these two lakes, the linear-interpolated mineral sediment accumulation rates were combined by taking an average weighted according to the lake area apportioned into sedimentation zones. For Brotherswater, sedimentation zones were characterised by drawing on an additional nine cores that encompass lake-wide variation in sedimentation rates (Schillereff et al, 2016) to apportion a delta-proximal higher-rate zone (25% of lake area) versus a lower-rate zone spanning the remaining lake area. Additional cores were unavailable for Loch of the Lowes. In this lake, the three cores formed a delta-proximal to distal transect along which sedimentation zones were defined by core locations that formed the mid-point of each zone.

3. Model simulations

3.1. Model description

MMF-TWI is a conceptual catchment-scale soil erosion model (Peñuela et al, 2017) that builds on the Morgan-Morgan-Finney (MMF) set of models (Morgan et al., 1984; Morgan, 2001; Morgan & Duzant, 2008). The modelling approach adopts a simplified representation of surface runoff and erosion processes while avoiding the greater parameter and computational demands of more physically-based models. This allows simulations of larger areas at high spatial resolutions and over longer timescales (decades to centuries) than could otherwise be achieved, while preserving reasonable model run times. MMF-TWI predicts soil loss, deposition and sediment delivery for clay, silt and sand-size particles on a monthly timestep. This captures the effects of sub-annual variability in climate, soil moisture and vegetation cover, in contrast to the annual outputs of MMF. MMF-TWI also addresses several important limitations in the modified version of the MMF model (Morgan & Duzant, 2008), which include poor performance in runoff prediction and a disconnection between the modelled processes of overland flow generation and sediment delivery (Peñuela et al, 2017).

MMF-TWI incorporates new representation of crop growth, soil moisture, and delineates surface runoff and sediment contributing areas (Peñuela et al, 2017). Crop growth simulation employs the SWAT model approach (Neitsch et al, 2011) to generate canopy cover and plant interception parameters. This captures changes in canopy cover related to crop type, planting time, growth rates, and harvesting. Seasonal variations in deciduous woodland canopy cover (Neitsch et al, 2002) and in woodland understorey, moorland and pasture covers (Hough & Jones, 1997) are also represented. Plant growth parameters for the different vegetation types are summarised in table 4 (Appendix).

Soil moisture is computed using a saturation-excess sub-model comprising net precipitation (i.e. less interception), actual evaporation, deep percolation, and saturation-excess runoff (for details see Peñuela et al, 2017). Soil data for the catchments in England was supplied by the National Soil Resources Institute (NSRI, 2014) and by the James Hutton Institute for the catchments in Scotland (James Hutton Institute, 2014b). Soil hydraulic parameters were estimated using pedotransfer functions based on soil texture (Hollis et al, 2015). The soil parameters used in MMF-TWI are summarised for each catchment in table 5 (Appendix).

MMF-TWI employs the topographic wetness index (TWI, Beven & Kirkby, 1979; Ambroise et al, 1996) to represent the distribution of saturated and overland flow prone areas according to a saturation threshold. MMF-TWI should therefore be applied in humid environments where saturation excess is considered the characteristic mechanism for runoff generation (Dunne et al, 1975; Walter et al, 2000). Monthly overland flow equates to monthly effective rainfall over saturated areas from which simulated soil loss is routed until it reaches a deposition area or a surface water body.

3.2. Historic simulations

Reconstructions of lowland agricultural change based on annual parish records in the Loch of Skene catchment do not provide information on land cover spatial arrangement. This information is only available for those years with aerial imagery, approximately one year per decade. Crop rotation produces a changing mosaic of crop and pasture fields that could influence patterns of soil erosion and sediment delivery to streams. Therefore, for those years without spatial data, we account for uncertainty in crop spatial arrangement by applying a Monte Carlo procedure to generate sets of catchment maps representing randomised spatial arrangements of crop and pasture fields. This procedure involves (1) producing a catchment map from aerial imagery that excludes non-arable land (Fig. 2c), (2) defining time intervals based on periods of change and stability in crop cover characterised by a maximum and minimum crop fraction (Fig. 2d), and (3) randomly assigning crops to individual fields until the proportion of catchment area covered by crop fell within the range of crop cover for each defined interval. In the absence of parish data after 1992, the estimated range in Skene fractional crop area between 1993 and 2010 was based on mapped cover from aerial imagery and the preceding parish data. Farmer interviews also indicated that crop growing had changed little in recent decades. For those years with aerial imagery, the mapped land cover is used. For periods without aerial imagery, we generate 50 annual synthetic combinations of maps for the period between 1912 and 2009.

Land cover change in the three upland catchments was limited in the absence of significant arable farming. Aerial imagery from the 1940s shows woodland extent is comparable to the present with the exception of the Loch of the Lowes. In this catchment, conifer plantations were established in the 1970s and cover 10% of the catchment. The recently established plantations (no canopy, but roads, ditches and fence lines visible) are evident in aerial photographs from 1976, whereas canopy closure is near complete by the 1989 imagery. To capture the effect of this land cover change, we assume a planting year of 1973 (Leaf Area Index, LAI = 0, height= 0.2 m) and linear growth until canopy closure by 1993 (*LAI* = 5 and height = 8 m, approximating height at which leaf drips reach terminal velocity; Satterlund & Adams, 1992), after which canopy cover and height are considered constant. This timeframe is consistent with the timing of peak plantation planting in Scotland (Stott & Mount, 2004) and a period of ~20 years until canopy closure for conifer plantations in upland Britain (Robinson, 1998). Our simulation represents the effect of plantation canopy interception and leaf drainage on soil erosion, but does not capture the short-duration (~3-5 years) impact on erosion from plantation establishment (Stott & Mount, 2004).

Insert table 2 here

Livestock grazing and trampling can reduce ground-level vegetation and ground cover and increase soil erosion, particularly in intensively managed grasslands (Bilotta et al, 2007). We use the mean stocking density, observed differences in ground cover, and the absence of cattle in moorland areas as the basis for setting cover guide values for moorland and improved pasture (Table 2). We are unable to simulate time-varying grazing effects on soil erosion due to a lack of empirical relationships between grazing intensity and ground cover. Moreover, parish-level stocking data does not equate to field-scale stock densities because livestock are not evenly distributed across the parish and are excluded from grazing some areas. Hence, we do not capture the effect of changes in stock numbers on erosion, but do reflect relative differences between catchments. The original guide values for cover parameters are given in Morgan & Duzant (2008, Table III). Cattle consume larger quantities of vegetation and exert greater treading force than sheep (Bilotta et al, 2007). Therefore, the limited areas of sheep-grazed improved pasture in upland catchments are represented by higher ground cover (GC) values than given by Morgan & Duzant (2008) for pasture grazed by cattle. In contrast, cattle dominate in Loch of Skene catchment (Table 2) so we use unchanged guide values to represent this lowland grass cover.

Livestock may contribute to increased streambank erosion where access is unrestricted (Trimble & Mendel, 1995). The extent of access varied between the catchments and was greatest in the uplands where sheep grazing dominated. Sheep have less trampling impact on streambanks than cattle (Evans, 1998), which, combined with unenclosed grazing on open moorlands where sheep are less concentrated than in fields, suggests that impacts on streambank erosion may be comparatively minor. In the lowland Loch of Skene catchment livestock access to streams was more widely restricted and field observations suggested that streambank erosion was limited. Inspection of historic aerial imagery indicated little change in channel positions supporting our view that streambank erosion is unlikely to be a significant source of fine-grained sediment delivered to the lakes during the study period.

3.3. Scenario simulations

We examine three contemporary land cover change scenarios using the reconstructed climate records to compare with historic baseline simulations. The first scenario examines the effect of complete afforestation on surface runoff and sediment exports versus the current moorland cover for the three upland catchments. We compare deciduous oak woodland and evergreen conifer plantation. Both forest types are simulated with a maximum canopy cover equating to *LAI* = 5 and seasonal changes in understorey and deciduous woodland canopy covers. We use a maximum *LAI* for deciduous woodland understorey of 2.5, which lies within the reported range for an oak woodland understorey in England (Pitman & Broadmeadow, 2001), and 1.25 for the conifer understorey. The difference in *LAI* reflects the lower understorey typically observed under conifer plantations due to reduced light transmittance (Barsoum & Henderson, 2016), although GC remains high due to the accumulation of needles on the soil surface (Table 2). We assume sufficient light transmittance below the conifer canopy to sustain some understorey vegetation. This reflects a trend towards continuous cover forestry in the UK, which seeks to balance understorey light requirements for biodiversity and regeneration while maintaining canopy cover and avoiding the need for clearfelling (Hale et al, 2009).

The oak woodland envisages a hypothetical 'rewilding' scenario that involves the restoration of a semi-natural woodland habitat and some of the associated ecosystem functions (Brown et al, 2011). In contrast, the conifer plantation scenario represents commercial afforestation but within the context of continuous cover forestry, which represents a 'multi-purpose' approach that combines non-commercial objectives such as environmental and aesthetic concerns with timber production (Mason et al, 1999). We do not aim to capture the specific impacts of plantation management operations (e.g. thinning), but instead compare how the two different forest covers could affect surface runoff and sediment exports based on simulations spanning a century of historic climatic variability.

The second scenario involves simulating a 10 m deciduous riparian woodland buffer strip planted either side of the stream network in the upland catchments (Fig.

1). We test the effect of three hypothetical riparian buffer understorey covers corresponding to high (*LAI* = 3.75, *NV* = 300), moderate (*LAI* = 2.5, *NV* = 200) and low (*LAI* = 1.25, *NV* = 100) cover values. This envisages a conservation focused scenario aimed at restoring riparian woodland for multiple potential benefits, including terrestrial habitat, stream shading, channel stability, and reduced sediment supply to improve water quality (Broadmeadow & Nisbet, 2004; Thomas et al, 2016). Riparian woodland spanning the full length of the stream network represents the maximum possible effect this scenario could have in reducing sediment exports.

The third scenario addresses lowland agricultural land management. We examine the effect of planting permanent grass margins around arable fields in the Loch of Skene catchment. Arable grass field margins can provide habitat to improve farmland biodiversity and promote sediment deposition to reduce off-field impacts (Vickery et al, 2002; Marshall & Moonen, 2002). According to the Scottish Government, field margins must be adjacent to arable land and between 1 and 20 m wide to meet the requirements of Ecological Focus Areas as part of the EU Common Agricultural Policy (Scottish Government, 2017). Here, we are interested in quantifying the effect of grass field margins for reducing sediment exports at the catchment scale. We applied the maximum allowable margin width of 20 m around cropped fields where the crop area spans 30% of the catchment, which equates to the centennial-scale average. We simulate a spring barley crop followed by a winter cover crop and selected the randomly-generated crop spatial arrangement (from n = 50) that was found to produce the maximum catchment sediment export (i.e. worst case scenario in terms of field arrangement). We then randomly assigned grass margins to cropped fields to cover 0, 25, 50, 75, and 100% of arable fields. For 25-75% of arable fields with grass margins, we simulate 10 spatial replicates to capture the effect of spatial variability in field margin placement.

4. Results and Discussion

4.1 Centennial-scale simulations

We compare the period of overlap between reconstructed climate records used for MMF-TWI simulations and sediment core records (Table 3). Model simulations of mean annual catchment sediment flux to the lakes show reasonable agreement with core-based estimates (Fig. 3). The absolute difference between modelled and core records equates to 9.4-20% with the largest difference observed for the larger lake catchments, namely Loch of the Lowes and Loch of Skene, where modelled values are under-estimated compared to lake cores. Statistical comparison (Mann-Whitney U test) of modelled versus lake core records shows Brotherswater (p = 0.111) was not significantly different, in contrast to Loweswater (p < 0.001), Loch of the Lowes (p < 0.001) and Loch of Skene (p = 0.002). Nonetheless, the performance is noteworthy given that the model was not calibrated and relied on guide cover parameter values that were, where appropriate, adjusted to reflect local catchment conditions (Table 2). The results demonstrate that our modelling approach can reproduce sediment yields reasonably well on a centennial-scale mean annual basis using historic records.

Insert table 3 here

We also compare modelled mean annual sediment yields with reported literature values based on UK lake measurements of inorganic sedimentation rates during the last century. The range in modelled mean sediment yields for the upland catchments of 0.08-0.12 t ha^{-1} y^{-1} is consistent with the lower-end of the reported range for moorland catchments of 0.09-0.46 t ha^{-1} y^{-1} spanning periods of 46-85 years (McManus & Duck, 1985; Duck & McManus, 1994; Foster & Lees, 1999; Holliday et al, 2008). In contrast, the mean modelled sediment yield for the Loch of Skene catchment of 0.05 t ha^{-1} y^{-1} is lower than the reported range of 0.07-0.46 t ha^{-1} y^{-1} for post-1953 sediment yields in lowland agricultural catchments in England and Scotland (Foster & Lees, 1999). This may reflect differences in the extent of arable land, which averaged 28% of the Loch of Skene catchment since the 1950s versus 25-92% for the mixed arable catchments investigated by Foster & Lees (1999). Moreover, soil loss in the Loch of Skene catchment is highly localised at the field and sub-field scale. Hence, catchment average sediment yields appear low when locally rates can be considerably higher.

Insert figure 3 here

Insert figure 4 here

The spatial patterns of centennial-scale mean annual net soil loss are shown in Fig. 4. Soil loss was concentrated in convergent flow areas prone to saturation. The highest mean soil loss occurred in Loch of the Lowes followed closely by Brotherswater, which are characterized by steeper slopes (14-24°), higher mean precipitation (1571-2144 mm y^{-1}), and higher mean sheep densities (2.39-2.49 sheep ha^{-1}) than Loweswater (note the difference in the soil loss intensity scale in Fig. 4a, d versus Fig. 4b, c). Despite the presence of arable land (mean 30%, range 25-39%; 1912-2012) in the lowland Loch of Skene catchment, mean soil loss was lower than in the upland catchments. This probably relates to the lower mean slope (3.8°) and precipitation (773 ± 123 mm y^{-1}) producing lower overland flow soil detachment and transport capacities in the absence of clear differences in soil infiltration rates between upland and lowland catchments (Table 5). The Loch of Skene catchment soil loss map captures the mean of the 50 randomized arrangements of crop cover used to address uncertainty in the spatial arrangement of cropped fields for years without aerial imagery. Hence, erosion hotspots in Fig. 4d reflect areas most prone to erosion, particularly on arable land, rather than the effect of a single arrangement of crop cover.

4.2 Historic agricultural and climate variability

Model simulations are temporally less consistent with annual-interpolated core-based sediment yields. Model outputs comprise monthly-averaged surface runoff and sediment contributing areas used to compute erosion and sediment delivery to the lakes on an annual basis for comparison with lake records. Peaks and troughs in the 10 y moving average sediment yield tend not to align between model and core-based records (Fig. 5). For the three upland catchments, the decadal trends in modelled sediment yield reflect precipitation variability. However, this variability is not readily apparent in the sediment core records. The Loweswater core-record indicates an increasing trend in annual sediment load over the last century ($p < 0.001$, non-parametric Mann-Kendall test), whereas Brotherswater and Loch of the Lowes do not show a trend ($p > 0.05$). In contrast, the core-based sediment yield in the Loch of Skene catchment exhibits a significant decreasing trend ($p < 0.001$). Here, we examine variability in both modelled and core-based sediment fluxes with reference to agricultural and climate reconstructions.

4.2.1 Upland catchments

Analysis of aerial imagery indicates negligible land cover change in the Brotherswater and Loweswater catchments. The aerial imagery suggests that limited cultivation within Loweswater catchment may have occurred during the 1940s. Parish records for Loweswater show cultivated land accounted for a mean 5.3 ± 2.7% (1894-1971) of the parish area, which declined to negligible levels after the Second World War (Bennion & Winchester, 2010). However, the Loweswater parish is over four times the size of the catchment and includes downstream low-slope valley floor areas suitable for cultivation. Sheep stocking densities for the parishes covering Brotherswater and Loweswater show significant increasing trends ($p \leq 0.001$) from the mid 1940s and 1910s, respectively (Fig. 5a, b). This trend was reported to accelerate in Loweswater during the 1980s (Bennion & Winchester, 2010) and is consistent with the increase in the core-based sediment yield (Fig 5a). In contrast, parish sheep numbers decrease ($p < 0.001$) throughout much of the 20th Century for the Loch of the Lowes catchment (Fig. 5c). As noted, the only land cover change in the Loch of the Lowes catchment involved establishment of conifer plantations across 10% of the catchment during the 1970s. There is no relationship between parish livestock densities and lake sediment yields for Brotherswater and Loch of the Lowes, despite both being covered by parishes reporting higher mean sheep densities than Loweswater (Table 2).

Reconstructed precipitation series show limited agreement with sediment core records, in contrast to model results which follow the decadal trend in annual precipitation (Fig. 5). None of the precipitation records exhibit a significant trend (p = 0.126-0.944) for the complete period of overlap with sediment core records. Loweswater and Brotherswater display peaks in modelled sediment yield in the early 1950s during which two of the three largest annual sediment loads occurred (1951, 1954) in both catchments (simulations end in 2010). Our reconstructed precipitation records show the late 1940s and early 1950s was a wet period and precipitation in 1951 and 1954 was 40-50% above the long-term mean. Newspaper reports in September and November 1951 noted large rises in Lake Windermere in the Lake District (Meteorological Office, 1951). Moreover, a reconstructed precipitation record for the Lake District shows a general increase in annual precipitation from around 1910 to mid-century (Barker et al, 2004), which is also evident in our records for Loweswater (Fig. 5a) and Brotherswater (Fig. 5b). Conversely, the years with the lowest precipitation and modelled sediment yield (e.g. 1889, 1973 and 1996) for these two catchments coincide with reported drought periods (Marsh et al, 2007). These observations demonstrate the consistency of our reconstructed precipitation records with wider historic evidence.

Insert figure 5 here

The general lack of agreement between the reconstructed precipitation series and core-based sediment records suggests lake sedimentation rates determined by ^{210}Pb dating may be insensitive to decadal variability in annual precipitation in these catchments. This could reflect the use of lake-centre cores in Loweswater that are less responsive to variable inflows. However, sediment records from Brotherswater and Loch of the Lowes included delta-proximal cores that capture the effects of greater inflow variability in these catchments. Nonetheless, neither lake sediment record shows consistent agreement with precipitation variability. For example, the modelled and core-based sediment yields and precipitation exhibit a distinct trough during the mid 1970s in Loch of the Lowes, reflecting widespread drought conditions during this time (Marsh et al, 2007), but precipitation and sediment core records are out-of-phase during the 1920s-30s (Fig. 5c). We observe similar non-synchronous behaviour between the precipitation and sediment core records for Brotherswater (Fig. 5b).

The lack of correspondence between precipitation and sediment core records may reflect uncertainties in ^{210}Pb dating where errors of ±2-15 y could produce out-of-phase records at the decadal timescale. Uncertainties in ^{210}Pb dating of lake sediments have long been recognized and increase with age (Binford, 1990). ^{210}Pb dating of sediment cores may provide a reasonable basis for estimating mean rates and trends in century-scale lake sedimentation when combined with ^{137}Cs and ^{241}Am date markers for validation (Appleby, 2008). However, dating uncertainties present a challenge when seeking temporal agreement between instrumental records and variable lake sedimentation with annual-to-decadal resolutions.

4.2.2 Lowland arable catchment

The sediment core record for the lowland Loch of Skene catchment exhibits a significant decreasing trend ($p < 0.001$) punctuated by a short-lived increase in sediment flux (Fig. 5d). Agricultural records for the parishes covering the catchment reveal marked trends ($p < 0.001$) in livestock numbers. Cattle increased between 1940 to a peak in 1975 while sheep numbers peaked in the early 1930s and only returned to these levels in the early 1990s near the end of the parish record. The reconstructed fractional crop area shows a brief peak (max. 39% crop cover) in 1942-43 in response to increased food demand during the Second World War. Subsequently, there is a declining trend ($p < 0.001$) that plateaued between 25-30% annual crop cover from the mid 1970s based on the parish records and mapping from aerial imagery. Notably, the early 1940s peak in crop cover is not synchronous with the 1958 peak in the core-based sediment yield. Either this reflects uncertainty in dating or the sediment peak is unrelated to the increased crop cover, but alternative explanations for this brief rise in lake sedimentation remain unclear. The declining trend in the core-based sediment yield in the second half of the 20th Century occurred despite the highest annual precipitation occurring after the 1980s and increasing livestock numbers, particularly cattle, which are known to impact on soil erosion (Bilotta et al, 2007). These observations suggest that other aspects of agricultural land management beyond climate or the extent of cropping and livestock numbers are influencing sediment flux to the lake.

Winter cover crops are grown for their benefits in reducing nitrate leaching and to add organic matter to soils (Skinner et al, 1997; Baggs et al, 2000). In terms of erosion, cover crops protect soils from rain-drop impact and increase vegetative roughness thus slowing overland flow, both effects captured by MMF-TWI (Peñuela et al, 2017). Game cover crops may also be grown as a food source for farmland birds over winter (Parish & Sotherton, 2004). Spring barley is the dominant cereal crop in the region around Loch of Skene, so the planting of cover crops provides protective cover during the winter to early spring period of increased precipitation, runoff and erosion. Prior to the 1970s many fields in the region with spring-sown cereals were left bare over winter (Watson & Evans, 2007). However, in more recent decades there has been increasing promotion and planting of cover crops, which qualify as an Ecological Focus Area as part of the rural payments system in Scotland.

In the absence of specific records on the extent of winter cover crops, we hypothesise that increased planting of cover crops may account for the reduction in the Loch of Skene catchment sediment exports over recent decades. To approximate this trend, we assume no cover crops were planted prior to 1980 after which we linearly increase the area planted with cover crops (simulated as rye grass) until it reaches 100% of cropped fields in 2000. The modelled sediment yield based on the hypothesised 1980-2000 cover crop transitional period is consistent with the core-based record (Fig 6a). This figure also shows the uncertainty resulting from the unknown crop spatial arrangement represented by the randomized placement of cropped fields (n = 50 maps per year). The mean range (± std. dev.) between annual maximum and minimum sediment yields associated with different crop arrangements equates to 21 ± 7% of the mean annual sediment yield. We also simulate the effect of planting spring barley followed by a winter cover crop versus spring barley without cover crop over the full historic record to compare the effect on sediment flux to Loch of Skene (Fig. 6b). These results clearly demonstrate the large effect of cover crops where the ‘no cover crop’ scenario produces more than double the mean annual sediment export to the lake (0.056 vs. 0.025 t ha^{-1} y^{-1}).

Our Monte Carlo approach for simulating crop spatial arrangement captures spatial uncertainty that is frequently overlooked in model simulations of historic land cover change. Moreover, it provides an approach to effectively utilize longer-term agricultural records in the absence of spatial data. This is particularly useful because most spatial land cover data, whether based on satellite imagery or aerial photographs, is restricted to the last 30-70 years, and represents only a snapshot in time. For historic aerial photographs, this equates to one image capture per decade at best with the earliest photographs taken during the 1940s. Parish records of agricultural production offer a valuable source of information for catchment modelling over extended historic timescales. Our approach provides a robust basis for incorporating this time-series data within a framework for representing uncertainty in land cover spatial arrangement.

Insert figure 6 here

4.3 Catchment management scenarios

We found that deciduous oak woodland covering the three upland catchments resulted in a mean 8.0-15% and 26-46% reduction in annual surface runoff and sediment exports to the lakes compared to the current moorland cover, respectively (Fig. 7a, b). In comparison, the conifer plantation produced a comparable mean 8.4-16% reduction in annual surface runoff but a smaller reduction of 4-30% in sediment exports compared to the moorland cover. The difference in surface runoff between the afforestation scenarios was not statistically significant for Loweswater and Brotherswater ($p > 0.05$, Mann-Whitney U test), but was significant for Loch of the Lowes ($p = 0.001$). Notably, the simulated reduction in surface runoff for both forest types is proportionally consistent with measurements of a 1-2% reduction in total water yield with every 10% of upland catchment covered by mature conifer forest (Calder & Newson, 1979; Nisbet, 2005).

The comparable reduction in modelled surface runoff between the deciduous woodland and conifer plantation scenarios reflects contrasting canopy and understorey interception. We model the seasonal variation in canopy cover and interception, but not species-dependent differences in transpiration rates. This is justified by previous work which has shown that (1) canopy interception losses greatly exceed transpiration in UK uplands (Calder & Newson, 1979), (2) winter interception is the most important factor explaining differences in total evapotranspiration between evergreen trees and other vegetation types (Dunn & Mackay, 1995), and (3) annual forest transpiration rates for deciduous and evergreen species in the UK tend to be similar (Roberts, 1983).

Insert figure 7 here

Woodland understorey can make a significant contribution to total interception, varying between 10-50% of net precipitation, i.e. throughfall (Gerrits & Savenije, 2011). This is important because we apply a higher understorey cover fraction in deciduous (seasonal *LAI* range: 1-2.5) versus evergreen (range: 0.25-1.25) woodland to reflect contrasting levels of understorey shrubs and grasses typically observed under deciduous woodlands that allow greater light transmission to the understorey than conifer plantations (Barsoum & Henderson, 2016). As a result, the higher understorey interception largely offsets lower winter canopy interception for deciduous woodland compared to the evergreen plantation, thereby producing only a small difference in predicted surface runoff between the forest types. The understorey vegetation in the deciduous woodland also plays an important role in reducing sediment exports compared to the evergreen plantation. The higher deciduous woodland understorey intercepts more canopy throughfall and further reduces the kinetic energy of rain drops or canopy leaf drainage. It also provides greater vegetative roughness at ground-level (dependent on the number of stems per unit area) than the plantation understorey to reduce overland flow velocities and increase deposition.

Upland afforestation has been a focus in debates over natural flood management (Wynne-Jones, 2016). MMF-TWI captures changes in surface runoff volumes linked to afforestation on a monthly to annual timescale but not changes in the magnitude or timing of flow event peaks. Nonetheless, by simulating surface runoff, which directly contributes to stormflows, we show that afforestation may provide some benefit in reducing flood flows at the scale of the catchments investigated. However, how this effect might propagate downstream is highly dependent on the wider landscape response and flow contributions from other tributaries. Evidence suggests that such localised land cover changes are unlikely to have a significant effect on downstream flood risk, particularly for the largest events (Dadson et al, 2017; Stratford et al, 2017).

Planting a 10 m deciduous woodland riparian buffer either side of the stream network reduced sediment exports in the three upland catchments (Fig. 7c). The simulated low, moderate and high understorey cover scenarios led to reductions in mean sediment exports compared to historic baselines of 15-30, 22-36 and 27-41%, respectively. These reductions represent the maximum achievable given treatment of the entire stream network with riparian woodland. The riparian woodland buffers had only a minor effect in reducing mean annual surface runoff by 0.8-2.1%. This indicates that modelled reductions in sediment exports are due largely to reduced particle detachment associated with changes in raindrop kinetic energy rather than runoff. A small decrease in transport capacities within buffer areas associated with higher ground contact cover (GC) and lower runoff than in moorland areas also increased sediment deposition.

The riparian woodland buffer accounts for 78-91% of the reduction in sediment exports achieved with complete afforestation by deciduous woodland with the same level of understorey cover. This shows the importance of buffer placement as near-stream areas are more prone to saturation and runoff generation than locations further upslope, and form sediment source areas connected to the stream network (Fig. 4). Our results emphasise the significance of understorey vegetation comprising grasses and shrubs for maintaining the effectiveness of riparian woodland buffers. Similar findings were reported for eucalyptus forest buffers where low surface cover meant that the buffer acted as a sediment source on several occasions (McKergow et al, 2006). To maximize buffer effectiveness, land managers should seek to maintain the highest understorey cover that can be supported by light levels below the canopy.

Hence, the exclusion or limiting of livestock access is likely to be necessary to prevent loss of understorey cover with excessive grazing and trampling.

The riparian and catchment afforestation scenarios do not involve changes to soil hydraulic parameters. Research has shown that soils under long undisturbed broadleaf woodland (180 and 500 years-old) have higher saturated hydraulic conductivities and macroporosity than more recently established woodland (45 years-old) or improved pasture, where no difference was observed (Archer et al, 2013). Other studies have noted this contrast between old forests versus those established in recent decades (Hümann et al, 2011; Archer et al, 2016), although in some instances trees may negatively influence soil infiltration (Chandler & Chappell, 2008). Reported increases in soil hydraulic conductivity also occurred in areas recently planted with trees and excluding livestock relative to grazed improved pasture (e.g. Marshall et al, 2014; Chandler et al, 2018). We suggest that this comparison may produce larger contrasts in infiltration due to greater trampling and compaction effects with higher stocking densities in enclosed improved pasture fields relative to open moorland areas.

In the three upland catchments moorland is the dominant land cover. The predicted saturated hydraulic conductivities (K_{sat}) based on pedotransfer functions (Hollis et al, 2015) range 33-235 mm h^{-1} with the highest K_{sat} values in the Brotherswater and Loch of the Lowes catchments that contain the largest area of moorland. Notably, the range in K_{sat} in the Loch of the Lowes catchment (66-202 mm h^{-1}) is consistent with the reported range in mean K_{sat} (56-224 mm h^{-1}) for similar soils under woodland in the same region (Archer et al, 2013). This suggests that the relative effect of afforestation on soil hydraulic properties may be less in open moorland areas than improved pasture fields, while forest age is probably an important factor influencing the extent of soil structural changes that lead to higher infiltration rates. Our scenarios aim to capture the effect of afforestation measures on surface runoff and sediment exports under variability associated with a century of historic climate. We are not seeking to simulate the longer-term evolution of soil properties nor to compare the effect of older forests (>100 years) which lie outside the scope of contemporary change in upland land management.

The use of grass field margins in the Loch of Skene catchment produced mean reductions in sediment exports compared to the no-margin simulation of between 5-22% when margins were randomly applied to 25-100% of cropped fields. The application of grass margins to 25% of cropped fields had no significant effect on sediment exports (p = 0.114, Mann-Whitney U test), whereas applying margins to ≥50% of cropped fields equated to a significant (p < 0.01) mean reduction (≥11%) in exports. In this scenario, we applied a spring barley crop followed by a winter cover crop to arable fields covering 30% of the catchment for the full simulation period. Notably, the reduction in sediment exports are larger when no cover crops is planted (e.g. reduction of 16 vs. 11% where 50% of fields have grass margins). Uncertainty associated with the random spatial combinations of cropped fields treated with grass margins was small. The range between maximum and minimum sediment exports for the 25-75% field margin scenarios equated to only 2.7-3.5% of the mean annual sediment export based on 10 spatial replicates of margin placement.

Our results show that a statistically significant reduction in catchment sediment exports is detectable when grass margins are applied randomly to cropped fields covering at least 15% or more of the catchment area. The largest effect is achieved where grass margins are located around cropped fields within stream-connected runoff and sediment generating areas. For example, when 50% of fields have grass margins applied but these fields are located only within the stream-connected contributing area the reduction in sediment export increases from 11 to 18%. This is equivalent to treating 75% of arable fields located randomly across the catchment with grass margins. MMF-TWI simulates the spatial and seasonal variation in surface runoff. This allows identification of saturated areas based on topographic and vegetation controls of soil moisture that intersect with periods of low crop cover and high rainfall to produce the largest soil losses. An advantage of the MMF-TWI modelling approach is that it provides a quantitative basis for addressing the combined effect of field spatial organization (Boardman & Vandaele, 2016) and the 'window of opportunity' for erosion during low crop cover periods (Boardman & Favis-Mortlock, 2014) on catchment-scale sediment delivery in humid agricultural environments. Hence, the model offers a hydrological basis for supporting decisions over field selection for planting of grass margins where the aim is to reduce sediment supply to the stream network.

5. Conclusion

We demonstrate the performance of a new catchment-scale model, MMF-TWI, for simulating soil erosion and sediment delivery in humid agricultural landscapes. The model was applied to four lake catchments in the UK with a century of reconstructed climate, land cover, and dated lake sedimentation data. Over a centennial timescale, MMF-TWI performed well. The model produced mean annual sediment exports within

9-20% of sediment core-based records without calibration and using guide parameter values to represent vegetation cover. Variability in modelled sediment exports reflects reconstructed precipitation. In contrast, lake sediment records were not consistent with decadal variability in annual precipitation, probably reflecting uncertainty in ^{210}Pb dating leading to asynchronous records over decadal timescales.

Land management simulations examined the effects of upland afforestation and lowland field-scale conservation scenarios compared to reconstructed historic baselines. Simulations of semi-natural oak woodland versus conifer afforestation showed similar reductions in mean annual surface runoff compared to current moorland vegetation. The deciduous woodland understorey largely offset higher rainfall interception by the conifer canopy. In contrast, conifer plantations produced 1.3 times more sediment than oak woodland due to lower understorey protection from raindrop impact. Riparian woodland buffers along stream networks account for 78-91% of the reduction in sediment exports achieved with catchment afforestation by deciduous woodland. Buffers had only minor effect on runoff but reduced rainfall detachment in connected near-stream locations prone to saturation and runoff generation. Sediment exports were sensitive to levels of riparian woodland understorey, highlighting the importance of active management to maintain ground-level vegetation cover in woodlands.

Field-scale conservation measures had a large effect on erosion and sediment delivery in the lowland arable catchment. We found the declining trend in sediment flux observed in lake-core records for recent decades could be explained by increased planting of winter cover crops. Historic simulation without cover crops doubled the mean annual sediment yield compared to with cover crops. We applied a Monte Carlo approach that randomly assigned crops to arable fields to represent the unknown crop spatial arrangement for periods without aerial imagery. This showed that variability in crop arrangement amounted to 21% of the historic mean annual sediment yield. Nonetheless, use of cover crops had greater effect on catchment sediment exports than annual variation in either crop extent or spatial arrangement over the last century. Further reductions in sediment yield were achieved by applying permanent grass margins around crops in randomly selected sets of arable fields. This led to a statistically significant decline in sediment exports when margins were applied to 15% or more of the catchment area (i.e. ≥50% of cropped fields).

Agricultural land management requires strategies to mitigate impacts on soil and water resources while maintaining food production. Models that capture the effects of spatial and temporal variation in agricultural and conservation practices on soil erosion and sediment delivery can help to address this challenge. Our findings demonstrate the effect of woodland, cover crops and grass field margins in reducing catchment sediment yields compared to centennial-scale historic baselines. MMF-TWI balances data availability with parameterization and computational needs while representing variability in hydrology, land cover and conservation practices. It can support hydrologically-informed decision making to better target conservation measures to reduce soil erosion and sediment delivery in humid agricultural environments.

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Table 1 Lake catchment characteristics and climate records.

	Loweswater	Brotherswater	Loch of the Lowes	Loch of Skene
Catchment area (km^2)	8.8	13	27	49
Lake area (km^2)	0.61	0.19	0.37	1.1
Catchment/lake ratio (-)	14	72	73	44
Elevation range (relief) (m)	119-543 (424)	157-821 (664)	246-614 (368)	83-417 (334)
Mean catchment slope (°)	12.1	23.5	14.2	3.8
Catchment geology	Glacial diamicton, Ordovician mudstones & siltstones	Glacial diamicton, Ordovician volcanics	Glacial diamicton, Silurian sand/silt/mud-stones	Glacial diamicton, Silurian granodiorite
Catchment soils	Fine loamy brown podzolic soils and brown earths.	Brown podzolic soils. Stony loams with peaty soils on upper slopes.	Peaty podzols, brown earths, blanket peat on upper slopes.	Humus-iron podzols, alluvial soils, basin peat.
Recent land cover (2007-2012)	Moorland (56%), improved pasture (28%), woodland (8%)	Moorland (91%), improved pasture (2.4%), woodland (4.9%)	Moorland (87%), plantation (10%)	Pasture and cropland (75%), woodland (22%)
Mean precipitation (mm y^{-1}) ± std. dev. (composite record)	1502 ± 230 (1888-2014)	2144 ± 347 (1888-2014)	1571 ± 235 (1915-2014)	773 ± 123 (1912-2009)
Daily precipitation reference station ID and name (MIDAS database) &	12874 Cornhow S Wks	12953 Grisedale Bridge	1023 Eskdalemuir	14983 Dunecht House
Subhourly precipitation station ID and name (MIDAS database)	12802 Seathwaite; 12874 Cornhow S Wks	12802 Seathwaite; 12874 Cornhow S Wks	1023 Eskdalemuir	18976 Westhill
Mean temperature (°C d^{-1}) ± std. dev.	8.4 ± 4.8	5.9 ± 4.8	5.6 ± 4.9	7.8 ± 4.7
Mean daily temperature reference station ID and name (MIDAS database)	1060 Keswick	1060 Keswick	1023 Eskdalemuir	161 Dyce

Table 2 Land cover parameters used for simulations in each lake catchment with historic parish-level mean sheep and cattle densities.

Lake catchment	Parish mean sheep (/ha)	Parish mean cattle (/ha)	Land cover parameter	Moorland[a]	Improved pasture[a]	Arable crop (spring barley)	Cover crop (rye grass)	Deciduous woodland	Conifer plantation
Loweswater	1.97 ± 0.21	0.20 ± 0.04	LAI_m	5	5	n/a	n/a	Canopy: LAI_m=5 PH=8 NV=1.2 D=1.5 Understorey: LAI_m=2.5 GC=1 PH=0.2 NV=200 D=0.01	Canopy: LAI_m=5 PH=8, NV=1.2 D=1.5 Understorey: LAI_m=1.25 GC=1 PH=0.2 NV=100 D=0.01
			GC	0.9[b]	0.9[c]				
			PH	0.2	0.1				
			NV	400	200				
			D	0.01	0.01				
Brotherswater	2.39 ± 0.25	0.07 ± 0.02	LAI_m	5	5	n/a	n/a		
			GC	0.9[b]	0.9[c]				
			PH	0.2	0.1				
			NV	400	200				
			D	0.01	0.01				
Loch of the Lowes	2.49 ± 0.24	0.04 ± 0.02	LAI_m	5	n/a	n/a	n/a		
			GC	0.8					
			PH	0.2					
			NV	400					
			D	0.01					
Loch of Skene	0.43 ± 0.2	0.65 ± 0.2	LAI_m	n/a	5	4	4		
			GC		0.6	0.3	0.3		
			PH		0.1	1.2	0.2		
			NV		200	200	200		
			D		0.01	0.04	0.01		

[a]Moorland and improved pasture correspond to 'Moorland rough grazing (sheep)' and 'Lowland grass (cattle)', respectively, in Morgan & Duzant (2008, Table III), where GC is ground cover, PH is maximum plant height, NV is the number of stems per unit area, and D is plant diameter.
[b]GC for Loweswater and Brotherswater was increased from 0.8 to 0.9 to reflect higher vegetation cover and lower stocking levels compared to Loch of the Lowes.
[c]GC representing improved pasture for Loweswater and Brotherswater was increased from 0.6 to 0.9 to reflect the absence or historically very low numbers of cattle present in these upland catchments.
[d]LAI_m is the maximum leaf area index. LAI varies seasonally for crops, deciduous woodland, woodland understories, moorland and improved pasture (Neitsch et al, 2002; Hough & Jones, 1997).

Table 3 Comparison of lake sediment flux from core-based records versus model simulation results for each lake catchment.

Lake catchment	Period of record overlap	Mean sediment flux ± std. dev. (t y^{-1}) [mean sediment yield, t ha^{-1} y^{-1}]		
		Sediment core	Model simulation	Absolute difference (%)
Loweswater	1907-1997	77 ± 15 [0.09]	66 ± 18 [0.08]	15
Brotherswater	1888-2010	140 ± 24 [0.11]	154 ± 48 [0.12]	9.4
Loch of the Lowes	1915-2003	398 ± 56 [0.15]	318 ± 81 [0.12]	20
Loch of Skene	1917-2009	289 ± 101 [0.06]	242 ± 87 [0.05]	16

Appendix: Plant growth and soil parameters

Table 4 Plant growth parameters used in MMF-TWI in the four lake catchments. For further description of model functions and parameters see Peñuela et al (2017) and Neitsch et al (2011).

Cover type	Planting julian date	Maturity or harvesting julian date	PHU[a]	T_{base}[b] (°C)	$h_{c,max}$[c] (m)	LAI_{max}[d]	L_1[e]	L_2[e]	$F_{PHU,sen}$[f]	k[g]
Moorland	n/a	n/a	n/a	n/a	0.2	5	n/a	n/a	n/a	0.35
Improved pasture	n/a	n/a	n/a	n/a	0.1	5	n/a	n/a	n/a	0.35
Arable crop (spring barley)	51	221	1570	0	1.2	4	5.92	21.47	0.6	0.45
Cover crop (rye grass)	222	50	1400	5	0.2	4	1.45	11.55	0.5	0.35
Deciduous woodland (oak)	n/a	n/a	n/a	10	8	5	n/a	n/a	n/a	0.65
Oak understorey	n/a	n/a	n/a	n/a	0.2	2.5	n/a	n/a	n/a	0.35
Conifer plantation	n/a	n/a	n/a	n/a	8	5	n/a	n/a	n/a	0.65
Conifer understorey	n/a	n/a	n/a	n/a	0.2	1.25	n/a	n/a	n/a	0.35

[a]PHU: Total heat units required for a plant to reach maturity, [b] T_{base}: minimum temperature for plant growth, [c]$h_{c,max}$: maximum canopy height, [d]LAI_{max}: maximum leaf area index, [e]L1 and L2 are shape coefficients used in calculating the daily increase in LAI (Neitsch et al, 2011), [f]$F_{PHU,sen}$: period of leaf senescence, [g]k: light extinction coefficient.

Table 5 Soil parameters used in MMF-TWI simulations in the four lake catchments. Data for catchments in England (Loweswater and Brotherswater) and Scotland (Loch of the Lowes and Loch of Skene) supplied by NSRI (2014) and the James Hutton Institute (2014b), respectively. For further description of model functions and parameters see Peñuela et al (2017).

Lake catchment	Soil series name	d_s[a] (mm)	silt (%)	clay (%)	sand (%)	θ_{sat}[b]	θ_{fc}[c]	θ_{wp}[d]	S_{fc}[e] (mm)	S_{wp}[f] (mm)	K_{sat}[g] (mm day^{-1})	T_0[h] (m^2 day^{-1})	ST[i]
Loweswater	Hafren	150	47	29	24	0.64	0.55	0.26	82	39	1073	0.04	0.20
	Manod	250	43	27	30	0.52	0.44	0.24	110	60	797	0.04	0.20
	Denbigh	250	43	28	29	0.52	0.45	0.25	112	61	797	0.04	0.10
Brotherswater	Malvern	250	41	14	45	0.60	0.52	0.20	131	51	5646	0.32	0.25
	Bangor	250	26	17	57	0.71	0.62	0.30	155	75	2548	0.17	0.50
	Enborne	200	34	27	39	0.50	0.43	0.23	85	47	797	0.03	0.05
	Wilcocks	250	52	23	25	0.72	0.63	0.30	157	76	2469	0.16	0.50
Loch of the Lowes	Blanket Peat	150	15	30	55	0.80	0.64	0.39	96	58	2804	0.12	0.05
	Linhope	150	32	33	35	0.58	0.47	0.25	71	37	1578	0.05	0.05
	Dod	200	35	31	34	0.74	0.55	0.24	109	48	4857	0.27	0.05
	Dochroyle	250	32	21	47	0.80	0.64	0.37	161	93	2836	0.21	0.05
Loch of Skene	Alluvial	200	16	25	59	0.44	0.34	0.18	68	36	1066	0.03	0.05
	Basin Peat	150	15	30	55	0.80	0.64	0.39	96	59	2804	0.12	0.05
	Countesswells	150	12	22	66	0.60	0.42	0.18	63	27	3745	0.13	0.05
	Terryvale	200	16	20	64	0.54	0.38	0.17	76	34	2683	0.11	0.05
	Charr	200	18	15	67	0.83	0.65	0.38	130	76	3469	0.21	0.05

[a]d_s: Soil A horizon depth, [b]θ_{sat}: saturated soil water content (m^3 m^{-3}), [c]θ_{fc}: soil water content at field capacity (m^3 m^{-3}), [d]θ_{wp}: soil water content at wilting point (m^3 m^{-3}), [e]S_{fc}: volume at water in the soil at field capacity, [f]S_{wp}: volume of water in the soil at wilting point, [g]K_{sat}: saturated hydraulic conductivity, [h]T_0: local transmissivity at saturation, [i]ST: stone or bedrock cover.

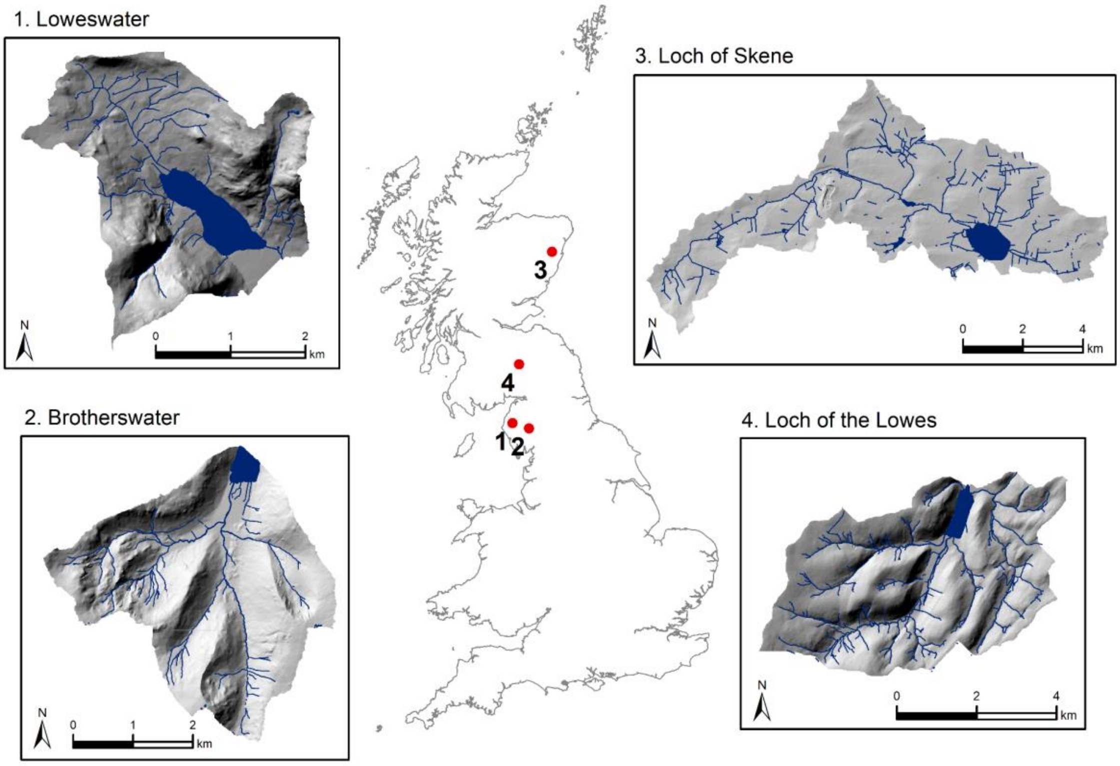


Figure 1 Location of the four lake catchments within the UK and catchment hillshades based on the DEMs (5 m grid size) used in model simulations.

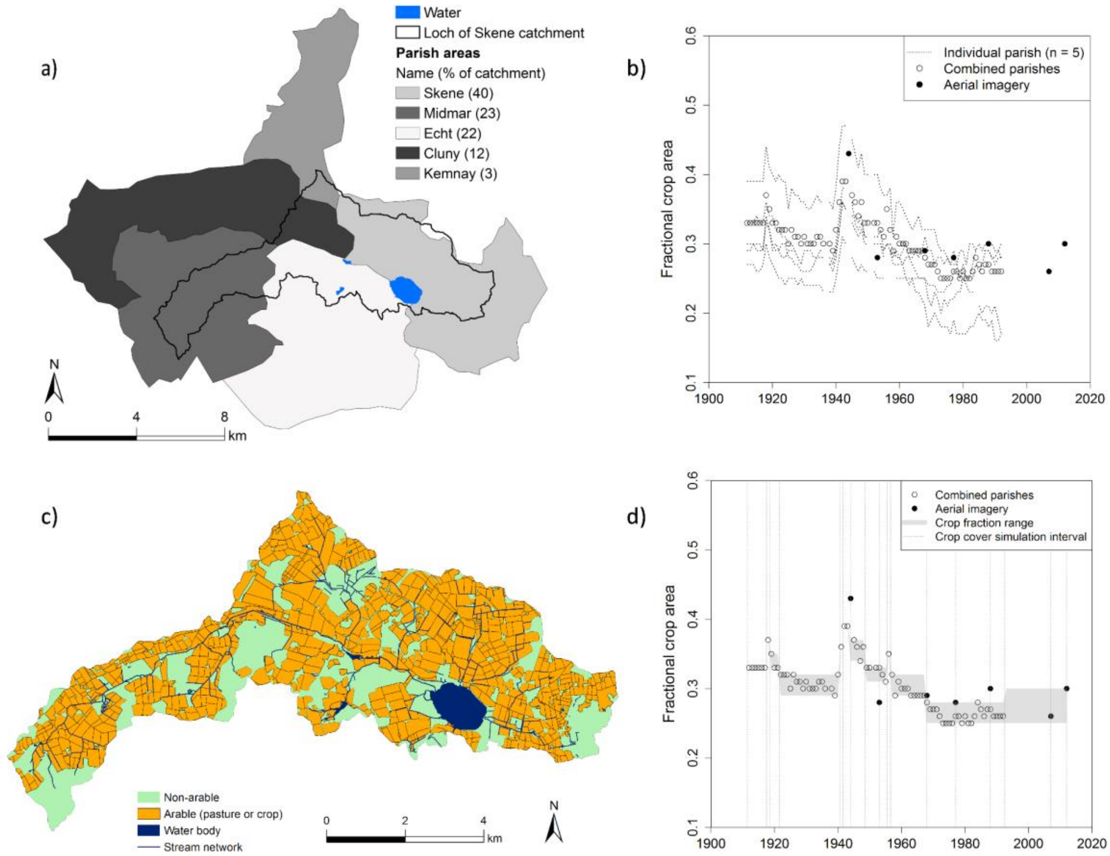


Figure 2 Loch of Skene land cover reconstruction showing (a) parish coverage of the catchment, (b) the annual change in fractional crop area reconstructed from parish agricultural records and aerial imagery, (c) map of arable fields, and (d) time intervals that define the range in fractional crop covers (grey shading) for use in the randomised classification of fields into crop and pasture to represent uncertainty in the historic spatial arrangement of agricultural land cover (see section 3.2). For those years with aerial imagery, only the mapped land cover is used. The arable versus non-arable areas in Fig 2c are derived from LCM 2007 (Moreton et al, 2011) in combination with the Land Capability for Agriculture Assessment (James Hutton Institute, 2014a) to exclude areas of less productive land.

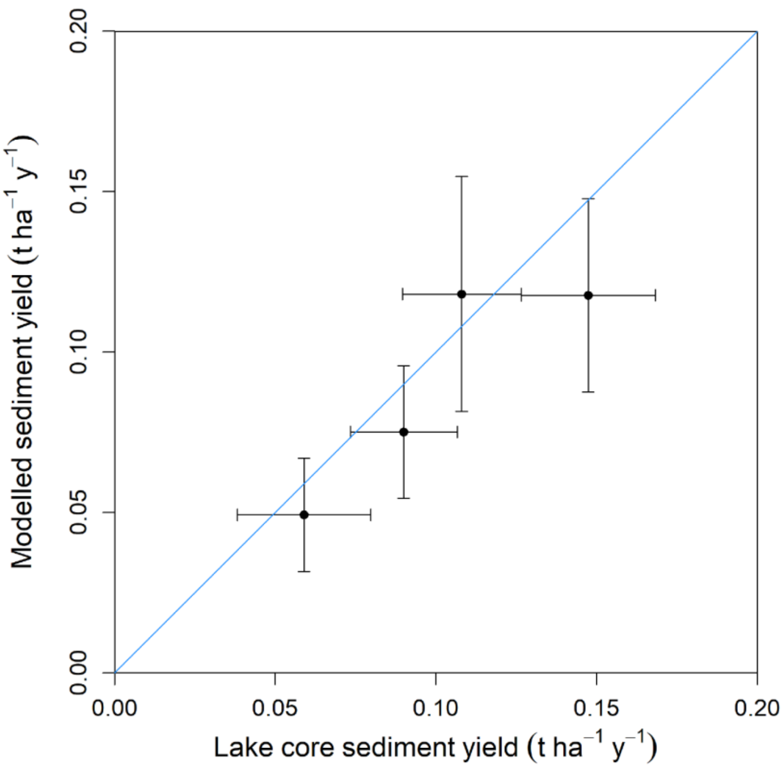


Figure 3 Mean annual lake core versus modelled sediment yields (± std. dev.) for the four lake catchments plotted with the 1:1 line.

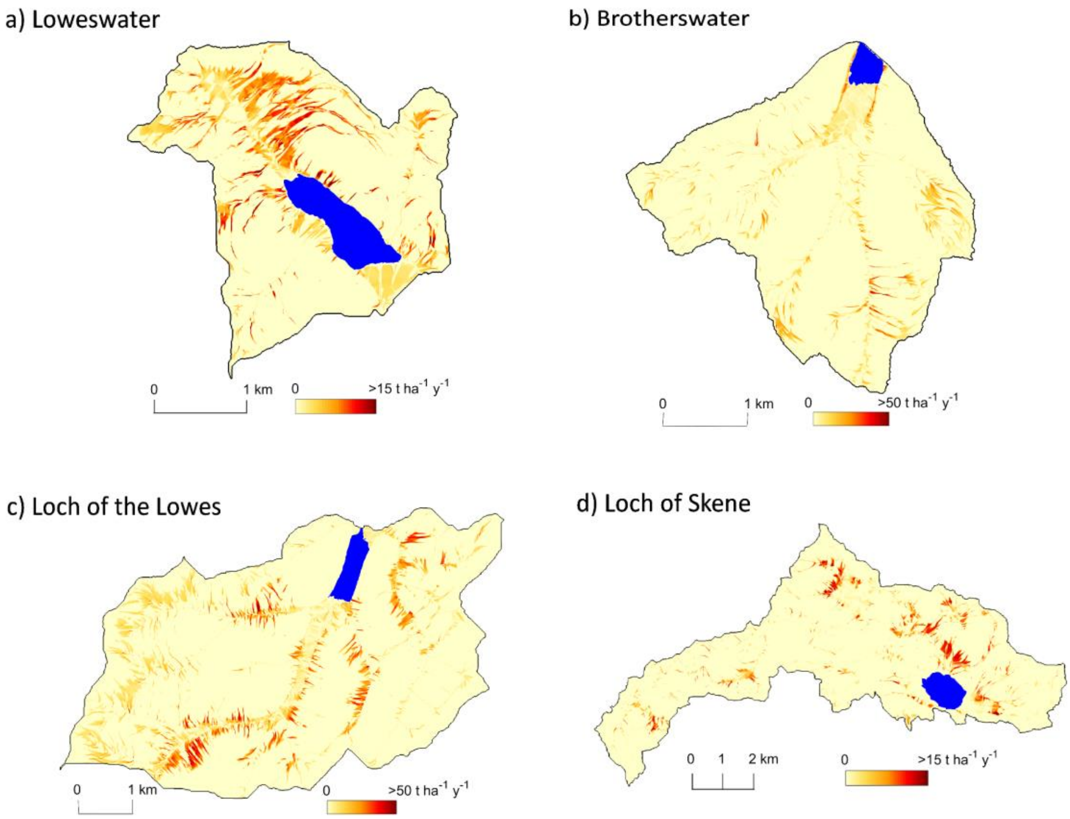


Figure 4 Mean annual soil loss maps based on modelled processes comprising within-cell soil detachment and immediate deposition and down-slope sediment transport and deposition for (a) Loweswater, (b) Brotherswater, (c) Loch of the Lowes, and (d) Loch of Skene for the historic simulation periods. Cells with net deposition are shown as zero erosion. Note the difference in maximum soil loss rates between catchments.

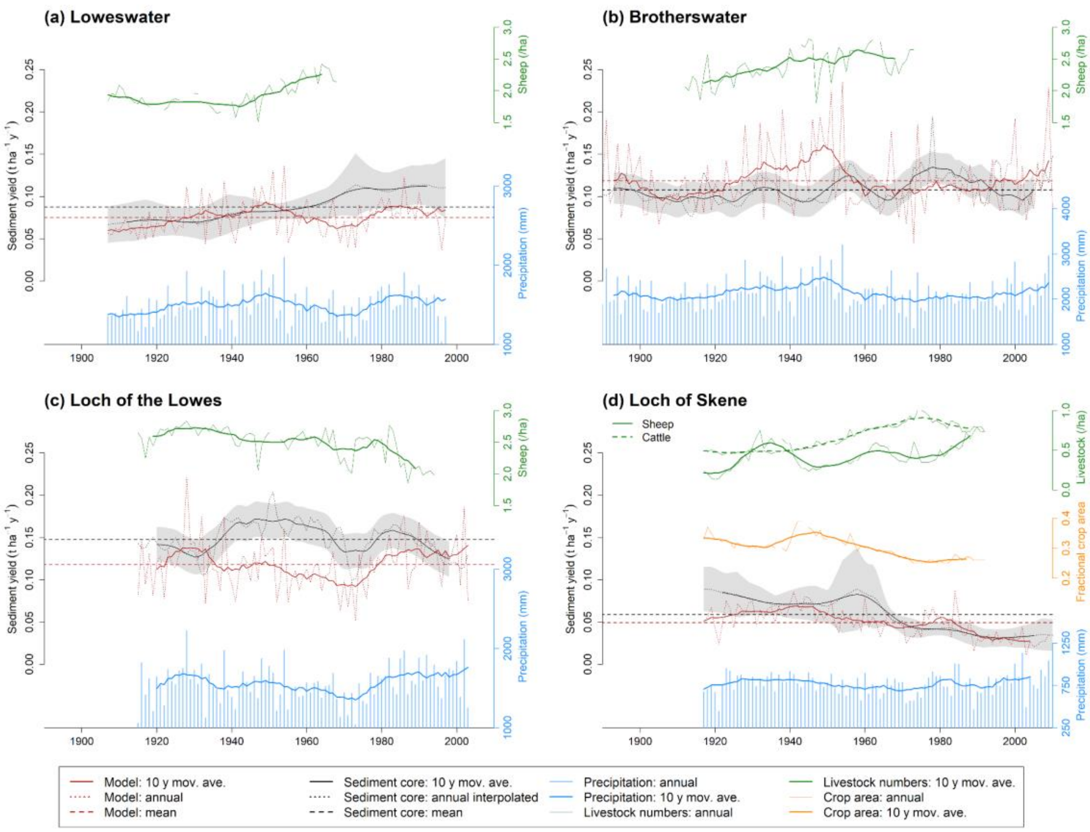
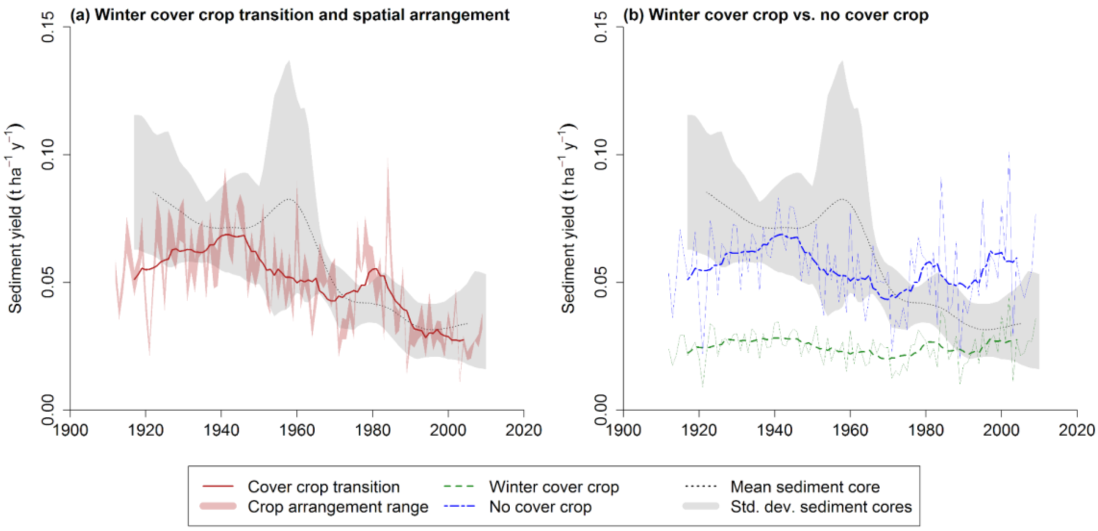


Figure 5 Catchment sediment flux estimated from lake sediment records (black line 10 y moving average, grey shade is standard deviation) and model simulations (red line is 10 y moving average and dashed line is annualized model output based on monthly simulation) with reconstructed annual precipitation, livestock numbers and fractional crop area (Skene only) for (a) Loweswater, (b) Brotherswater, (c) Loch of the Lowes, and (d) Loch of Skene.



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1160 **Figure 6** Loch of Skene simulations of catchment sediment exports (with 10 y moving
1161 average and annualized output based on monthly simulation) showing (a) transition to
1162 winter cover crop (1980-2000) in combination with the range in model outputs
1163 associated with 50 replicates of randomized crop spatial arrangement and (b) winter
1164 cover crop versus no cover crop simulations. The catchment sediment flux estimated
1165 from lake sediment records is also shown (black line 10 y moving average, grey shade
1166 is standard deviation of multiple core records).

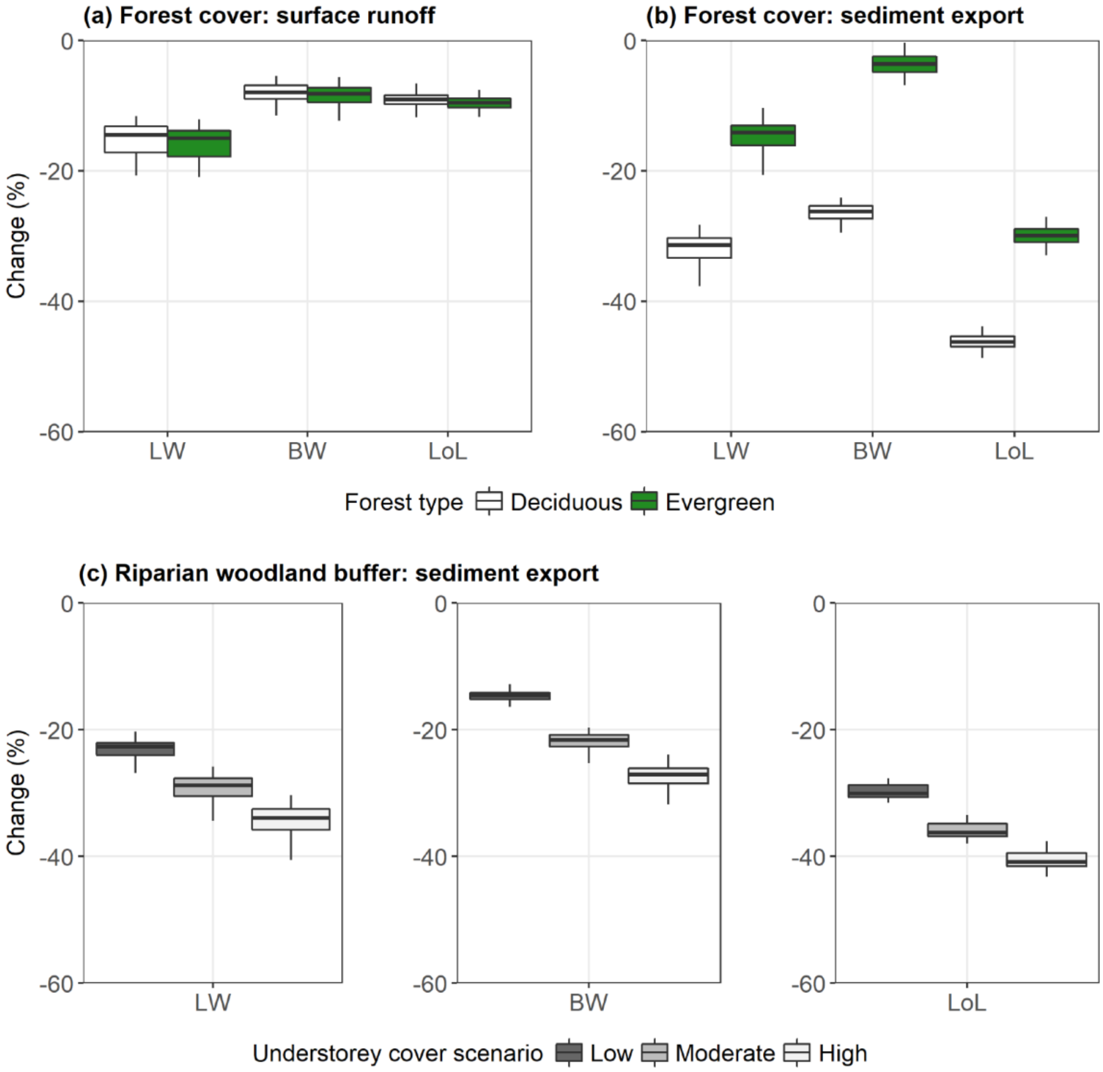

Figure 7 Upland catchment land cover scenario simulations based on historic climate reconstructions. Boxplots show the percent relative change in (a) surface runoff and (b) sediment exports for deciduous oak woodland and evergreen conifer plantation for Loweswater (LW), Brotherswater (BW), and Loch of the Lowes (LoL) catchments. The percent change in sediment exports (c) with planting of a 10 m deciduous woodland riparian buffer either side of the stream network is shown for the low, moderate and high understorey cover scenarios. All changes are relative to the historic baseline simulations. Boxplots show the median, 25th and 75th percentiles and whiskers extend to 1.5 x Interquartile Range.