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Spatial variability of fluvial blanket peat erosion rates for the 21st Century modelled using PESERA-PEAT

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Abstract

Many peatlands across the world suffer from degradation. Blanket peatlands are found mainly in high latitude oceanic areas and subpolar islands. Exacerbated erosion of blanket peatlands is common particularly where they have been disturbed by human influence or where climate has become more marginal for their functioning. A recently developed fluvial blanket peat erosion model, PESERA-PEAT was applied across 845 km^2 of blanket peatlands in the North Pennines of northern England. The aim was to evaluate the spatial and temporal variability of erosion rates under climate change and land management scenarios. Climate change data to the end of the 21st Century, derived from UKCP09 median emission projections aligned to the UK Met Office's historical meteorological dataset, were downscaled to 100 m cells. Land management scenarios were developed which included intensified and extensified grazing, artificial drainage and prescribed burning. The modelling results showed that under current management, 21st Century climate change would slightly increase the overall fluvial erosion rates for the study region from the climatic baseline (2.2 t ha^{-1} yr^{-1}) to the 2080s (2.3 t ha^{-1} yr^{-1}). However, the predicted response to climate change was spatially very variable. Predicted erosion rates decreased at locations that are currently wet and cold while they increased in some warmer and drier locations by more than 50%. Summer desiccation was found to become more important for the study region under climate change. Thus, predicted autumn sediment yields became the biggest component of the annual budget by the 2080s. Less intensive management was shown to reduce blanket peat erosion but potentially enhance wildfire severity. The results demonstrated that land management change will be useful in mitigating the impact of 21st Century climate change on the amount and spatial pattern of blanket peat erosion. The results of our study can be used within blanket peatland regions to inform spatially-targeted management strategies.

Keywords: Erosion modelling, peatlands, freeze-thaw, desiccation, climate change, land management

1 Introduction

Peatlands are important global carbon stores (Yu, 2012). Peat can be the dominant soil type in some large regions including, for example, high latitudes of North America and Eurasia, eastern Siberia, tropical regions such as the Congo, Southeast Asia, and parts of the Amazon basin (Parish et al., 2008). Blanket peatlands, are a type of bog (rainwater-fed peatland) which can occur on flat or sloping terrain if there is sufficient rainfall and impeded subsurface drainage. Blanket peatlands can be susceptible to rapid erosion following disturbance of vegetation (Evans et al, 2006; Shuttleworth et al., 2015) because overland flow is common in these environments (Holden and Burt, 2003; Evans and Warburton, 2007). Bog erosion has been reported particularly in many parts of the UK and Ireland (Evans and Warburton, 2005), but also local areas in Newfoundland (Glaser and Jansens, 1986), the Falkland Islands (Wilson et al., 1993), and Sweden (Foster et al., 1988). In the UK, blanket peat covers 17% of the landscape (Baird et al., 2009) and in some areas the erosion rate has been noted to be extreme in a global context (Evans and Warburton, 2007).

Peat erosion leads to a series of ecological and economic problems, which includes disturbed terrestrial and aquatic habitats (Ramchunder et al., 2009), reduction of reservoir capacity (Labadz et al., 1991), discoloration of water (Pattinson et al., 1994), heavy metal pollution of river flow (Rothwell et al., 2005; 2007) and release of carbon (Evans et al., 2012; Grayson et al., 2012; Pawson et al., 2012). Recently there has therefore been a large amount of investment aimed at reducing erosion losses from blanket peatlands (Parry et al., 2014).

Freshly exposed blanket peat surfaces are quite resistant to erosion given their strongly fibrous nature (Carling et al., 1997; Mulqueen et al., 2006). A period of weathering is therefore needed to break intact peat surfaces into loose materials which can be easily entrained and transported by erosive agents such as saturation-excess overland flow, winds and mass movement (Warburton, 2003; Foulds and Warburton, 2007a; b). Freeze-thaw and desiccation are dominant weathering mechanisms for sediment production in blanket peatlands (Francis, 1990; Labadz, 1991). Freeze-thaw is characterized by the formation of needle ice, which is supported by a strong thermal gradient between the cold surface and warmer peat at depth (Evans and Warburton, 2007). The removal of vegetation may increase the thermal gradient during cold conditions (Brown et al., 2015) and thus make the soil surface susceptible to freeze-thaw action in winter. Desiccation results from warm conditions and a lack of precipitation over several days and may be enhanced by sparse vegetation cover which encourages significant warming and drying of the peat surface in summer (Francis, 1990; Brown et al., 2015). Hence, sediment production from blanket peatlands is closely related to temperature and soil moisture conditions (Evans and Warburton, 2007; Francis, 1990). Climate change may play an important role in driving changes in fluvial peat erosion rates as both temperature and precipitation patterns will drive peat weathering and transport rates. In addition, during some very dry periods, wildfire could have severe sediment production consequences since the size and severity of the fire may become more intense (McMorrow et al. 2009; Rothwell et al., 2007; Esteves et al. 2012). Wildfire can lead to a destruction of the seed stock, loss of vegetation cover (Maltby, 1990) and subsequent generation of erodible peat surfaces with rapid connectivity (e.g. gullies, sheet erosion) to stream networks (Bower 1961; Stevenson et al. 1990; Rothwell et al. 2007).

Bioclimatic modelling results have suggested that many areas where there are currently blanket peatlands may no longer be under a climate suitable for active peat growth as the climate shifts over the 21st century (Clark et al., 2010; Gallego-Sala et al., 2010; Gallego-Sala and Prentice, 2012). These bioclimatic modelling exercises have not examined peatland erosion directly. However, there is a possibility that where peatlands shift out of a suitable bioclimatic envelope for peat formation, they may be at a greater risk of degradation and erosion if the peat surface conditions are conducive. For example, under drier climate, desiccation could be enhanced to increase the erodible peat which can then be transported to stream channels during runoff events. In addition, peatland wildfire risk may also be enhanced under future climate change (McMorrow et al., 2009; Rothwell et al., 2007; Alberston et al., 2010), increasing potential erosion within blanket peatlands. However, in some areas it is equally plausible that, as climate changes, blanket peat erosion remains stable or is reduced. For example, under warmer conditions freeze-thaw weathering could be significantly weakened which may therefore reduce the supply of sediment available for subsequent transport.

Land management practices including artificial drainage, grazing and prescribed burning for grouse and gun-sport management affect blanket peat erosion mainly through altering the balance between the forces of erosion (e.g. frost, desiccation, wind and runoff) and the retention of surface peat by vegetation. Artificial drainage alters hydrological properties of blanket peat and incision of ditch sides often results in more bare peat and thereafter erosion (Holden et al., 2004; 2007a; 2011; Wallage and Holden, 2011). Both rotational burning and grazing reduce vegetation cover, potentially enhancing the occurrence and spread of blanket peat erosion (Holden et al., 2007b). Additionally, there may also be interaction effects between wildfires and land management since surface vegetation fuel load may be greater without other active land management strategies (McMorrow et al., 2009; Worrall et al., 2010; McMorrow, 2011) making the potential impact of a wildfire on peatland erosion worse.

To date it is not clear how important future climate change may be in terms of driving changes in peat erosion and its spatial variability compared with the importance of potential changes in UK land management practices. Previous studies have suggested two major end-member, but plausible, directions of change in land management practices in UK uplands from the current ‘Business-As-Usual (BAU)’. They are i) managing the land for wildlife and carbon or ii) food security management (Reed et al., 2013). In the former, there would be a partial ‘rewilding’ of blanket peatlands including damming of existing drainage ditches, a reduction in stocking densities and the cessation of prescribed burning so that carbon can be enhanced. In terms of food security, this would require more land to put under production, and managing the land that is already used more intensively (Reed et al., 2013). In the case of UK blanket peatlands, often located in the uplands, it is more likely that those areas already drained, used for grazing or with prescribed burning would be used more intensively, rather than there being a widespread increase in the area of blanket peat under less intensive production. This is because, in marginal rural environments, stripped of subsidies under a more open food production market, intensive practices are likely to be the only profitable practices (Foresight Land Use Futures Project, 2010). Thus under a food security scenario there could be an increased intensity of drainage, grazing and prescribed burning on UK blanket peatlands in areas where these practices already take place. Of course, it is also possible that a larger area of blanket peat could come under intensive use but in order to constrain the range of scenarios that we examined in our study below we have focused on intensification of areas already drained, grazed and burned. It is important to understand how such management change may impact peatland erosion rates in comparison with BAU land management and climate change. Given the impact of wildfire on peat erosion and its relationship with environmental conditions, it is also important to understand the interactions between possible future land management, climate change and wildfires, so that land managers can better understand the implications of management options and future climate.

In order to understand the relative roles of climate change and land management in overall regional and spatial patterns of peat erosion it is advisable to model the effects and test different scenarios of future change against one another. A recently developed fluvial erosion model for blanket peatlands, PESERA-PEAT (Li et al., 2016a; b) offers an opportunity to fulfill the above needs. PESERA-PEAT was developed through modifying an existing fluvial erosion model, PESERA-GRID (Kirkby et al., 2008), to explicitly account for freeze-thaw and desiccation processes and also for typical land management practices in blanket peatlands. The advantage of PESERA-PEAT compared to other existing erosion models such as USLE and CAESAR

(Wischmeier and Simth, 1978; Coulthard et al., 2002) is that it considers, for the first time, freeze-thaw and desiccation as dominant sediment production mechanisms in peatlands. PESERA-PEAT also has the potential to incorporate the occurrence of wildfires and their influences on erosion processes as the original PESERA model had already been successfully adapted to do so (Esteves et al., 2012).

PESERA-PEAT was previously applied on particular points across Great Britain to predict the response of blanket peat erosion to environmental change (Li et al., 2016a). In that study blanket peatlands in different regions of Great Britain were represented by individual points, and the spatial variability of environmental conditions and peat erosion rates within each region represented by that point was not considered. There have been no studies that have examined the spatial variability of blanket peat erosion under environmental change within an individual region. Such an assessment may be useful for planning purposes so that more spatially-targeted conservation and peat protection measures (e.g. dams and revegetation) can be implemented by land managers to ensure efficient use of limited resources to protect peatlands.

Here we used PESERA-PEAT to investigate fluvial erosion rates and wildfire severity in 845 km^2 of blanket peatlands in northern England. We used downscaled, spatially-distributed climate change forecasts and spatially-distributed land-management scenarios to investigate spatial patterns of erosion rates and wildfire severity across the region to determine whether there were any distinct spatial patterns driven by these future scenarios. Erosion rates and wildfire severity were compared to those predicted under baseline climate and BAU land management to understand the relative roles of the different drivers of change.

2 Study site

The North Pennines (Figure 1) form the northernmost section of the Pennine range of hills which runs north-south through northern England, covering an area of approximately 2,000 km^2. Blanket peatlands (with an organic content > 45 % and depth > 40 cm) cover 43% of the North Pennines, equating to 845 km^2 (shaded areas shown in Figure 1a, b and c). The altitude of the blanket peat in the North Pennines ranges between 80 and 891 m (Figure 1c). Mean annual precipitation and temperature between 1961 and 1990 was 1568 mm and 5.6 °C. The majority (around 95%) of the blanket peatlands are covered by what is classified by the UK Landcover Map (2000) as grassland and scrub (Figure 1a). Managed burning, grazing (light grazing / overgrazing) and artificial drainage are widespread (Figure 1b). Severe peat erosion in the Pennines has been a feature of the last 70 years (e.g. Bower, 1961; Longden, 2009). Wildfires occur in the North Pennines during dry periods (McMorrow, 2011), triggering or exacerbating the rate and extent of blanket peat erosion. There have been numerous previous studies conducted on the erosion rates and mechanisms in the North Pennines blanket peatlands (e.g. Holden and Burt, 2002; Warburton, 2003; Evans and Warburton, 2005; Evans et al., 2006; Grayson et al., 2012). Most of these studies focused on small catchments rather than the whole of the North Pennines and there have been no studies predicting blanket peat erosion under future environmental change.

3 Materials and methodology

3.1 Model description

The first fluvial erosion model for blanket peatlands (PESERA-PEAT) has recently been developed (Li et al., 2016a; b), offering an opportunity to undertake investigations of how climate change might drive changes in fluvial blanket peat erosion. PESERA-PEAT is based upon the grid version of the Pan-European Soil Erosion Risk Assessment model (PESERA-GRID) (Kirkby et al., 2008), for which substantial modifications were made to ensure its suitability for the blanket peatland case.

PESERA-GRID is a physically-based, spatially distributed model, estimating soil erosion on a monthly time step. It has three modules: hydrology, vegetation growth and erosion. The hydrological part of the model is centered on a water balance, with precipitation divided into overland flow, evapotranspiration and soil water storage. It is suitable for modelling runoff production in blanket peatlands as the core of the hydrological part is TOPMODEL, which works well for saturation-excess overland flow dominated soil systems (Beven et al., 1984). The vegetation growth model is based on a biomass carbon balance to update the vegetation cover, vegetation biomass and soil organic matter on a monthly basis. Total sediment yield is estimated as the transporting capacity of runoff flow, driven by erodibility, overland flow and local relief, weighted for fractional vegetation cover, assuming erodible materials are always ample for runoff wash. The sediment yield is interpreted as the erodible materials produced on hillslopes and delivered to the base of each hillslope.

In PESERA-PEAT, the hydrology and vegetation growth modules are the same as those of PESERA-GRID. However, the sediment yield in PESERA-PEAT is dependent upon both sediment production and transport. Sediment production is a result of weathering processes (freeze-thaw and desiccation), which are linked with climatic (i.e. temperature) and soil moisture conditions through a novel sediment supply index (Li et al., 2016b). The transporting capacity is estimated in the same way as in PESERA-GRID. Both sediment supply and transport are considered to be impacted by vegetation cover. A storage component is also defined to indicate surplus erodible materials when erodible materials exceed transporting capacity. The soil erodibility in PESERA-PEAT refers to the sensitivity of weathered peat to erosion.

Reduced vegetation and changed soil moisture condition resulting from land management interventions interact with the hydrology, vegetation growth, sediment production and transport processes. A more detailed description of PESERA-PEAT including parameterizations and equations can be found in Li et al. (2016b).

PESERA-PEAT can be implemented in two modes: equilibrium and time-series (Li et al., 2016a; b). In equilibrium mode, the model iterates sufficient times to determine the equilibrium status of hydrology and erosion. Average monthly climate data over the study period are used as input values. Therefore, modelling outputs are also average monthly data. In time-series mode, the model runs only once through the whole time period. Climatic conditions for each month are required over the whole study period. The outputs from the time-series model are continuous monthly data for the study period. The applicability of PESERA-PEAT (equilibrium and time-series modes) for blanket peat erosion has previously been demonstrated with long-term measured sediment flux data from several UK blanket peat-covered catchments, which were subject to varying erosion conditions and management intensities, and sensitivity analysis based on conditions of a typical blanket peat-covered catchment (i.e. Trout Beck catchment) in the North Pennines (Li et al., 2016b). In this paper, we used the equilibrium version of PESERA-PEAT to examine the spatial variability of fluvial blanket peat erosion across the study region, given that, compared to the time-series model, the equilibrium model is easier to apply over a large spatial area at high resolution and for long-term periods because of its smaller data requirements.

In order to estimate the monthly wildfire severity, in this paper simplified versions of fire algorithms (Equation 1) developed and tested independently by Venevsky et al. (2002) were incorporated into PESERA-PEAT. We did not model fire likelihood (occurrence of wildfire), so the wildfire severity here indicated the *potential* severity of wildfire (PFS) once the fire started.

$$\mathrm{PFS} = \mathrm{VEGTN}\ (1 + 5\left(1 - \sqrt{{}^{\mathrm{AET}}/_{\mathrm{PET}}}\right)) \qquad \text{Equation 1}$$

where, VEGTN represents the vegetation biomass in kg m^{-2}; AET and PET are actual and potential evapotranspiration in mm.

3.2 Preparation of input data for PESERA-PEAT

PESERA-PEAT requires climate, local relief, soil properties, land use and management information to operate. In this study, local relief, soil properties and land use were considered stable, while climate and land management changed in the future. Four time periods of climate data were chosen to characterize future climate shifts in the North Pennines. They are ‘climatic baseline’, ‘2020s’, ‘2050s’ and ‘2080s’, covering 30-year periods of 1961-

1990, 2010-2039, 2040-2069 and 2070-2099 respectively. Climatic baseline data were provided by the UK Met Office Integrated Data Archive System (MIDAS), while future climate projections (2020s, 2050s and 2080s) were derived from the outputs of UKCP09 (Jenkins et al., 2009). The chosen periods and their names are consistent with those employed in future climate projections of UKCP09, ensuring climate projection data could be readily used in this study. Possible land management shifts in the future were established through quantifying the narrative scenarios proposed by Reed et al. (2013).

3.2.1 Climate

Baseline climate

The equilibrium version of PESERA-PEAT requires six climate inputs: monthly total precipitation (P); mean precipitation per precipitation day (P_{day}); coefficient of variation of precipitation per precipitation day (CV_{pday}); monthly temperature range (T_{range}); monthly temperature (T); and monthly potential evapotranspiration (PET). There were thirty two MIDAS stations with precipitation records between 1961 and 1990. All of these stations (Figure 1d) were chosen to produce a gridded surface of precipitation during the climatic baseline period. Twenty seven of them were selected for P and P_{pday} interpolation while the other five stations, were used for validation of the interpolated results. Stations used for the interpolation and validation were distributed as evenly as possible across the region rather than being concentrated in one part of the region. P and P_{pday} were interpolated through linear regressions based on precipitation variables, elevation and coordinates. The CV_{pday} was interpolated with the Inverse Distance Weighted (IDW) method because no good relationship could be found between CV_{pday}, elevation and coordinates during winter months of both climatic baseline and future periods. For T and T_{range}, there were only eight stations with records (Figure 1d). All eight stations were used to interpolate the spatial baseline temperature data through a relationship between temperature variables, elevation and coordinates as elevation and coordinates were proved to be the dominant factors. Some example equations used for the interpolation of the climate variables during the climatic baseline period are given in Table 1. Potential evapotranspiration (PET) was derived from a temperature-based model originally proposed by Oudin et al. (2005). The model was modified to include wind speed and vegetation height, as used in the PET estimation by Clark (2005). Validation of the interpolated results demonstrated that the R^2 was generally over 0.75 and RMSE/Average was no more than 0.18 (Table 2). The R^2 of CV_{pday} was 0.46 and lower than those of other parameters. However, a low RMSE/Average (0.1) indicated that the overall difference in the value of the interpolated and actual CV_{pday} was small. Overall, the interpolated results of the climate parameters were considered robust.

Future climate scenarios and their downscaling

Future climate change was derived from 100 model realizations of medium-emission climate projections produced by the UKCP09 weather generator, which can produce daily climate projections over the 21st Century with a spatial resolution of 5 km (Jenkins et al., 2009). Climatic variables were derived from values of central estimates (50% probability level) from UKCP09 for each month to ensure we chose moderate rather than extreme conditions for each variable (Jenkins et al., 2009). Such a scenario establishment captured the likely change of each variable with time at a monthly scale and was suited to extrapolation onto gridded surfaces.

Twelve points (Figure 1d) distributed over the North Pennines were selected to create gridded surfaces of future climate projections derived from the UKCP09 weather generator. Interpolation methods were the same as those used for the MIDAS climatic baseline datasets. However, future UKCP09 climate projections used the Met Office's historical (1961-1990) gridded datasets as a baseline climate (Perry and Hollis, 2005), which are not the same as the above climatic baseline gridded datasets we produced based on MIDAS records since interpolation methods are different (Perry and Hollis, 2005; Jenkins et al., 2009). In order to ensure future climate projections were consistent with the MIDAS climatic baseline data we used, interpolated UKCP09 climate projections were transferred to MIDAS climatic baseline gridded datasets using Equation 2:

$$UKCP_m = BASE_m + (UKCP - BASE_u) \qquad \text{Equation 2}$$

where, $UKCP_m$ is the climate projections based on MIDAS climatic baseline gridded datasets ($BASE_m$); UKCP is the gridded datasets of UKCP09 climate projections; $BASE_u$ Met Office's historical (1961-1990) gridded datasets.

The resolution of the UKCP09 data used was 5 km (Jenkins et al., 2009) which was too coarse to show the spatial pattern of climate (and drive spatially variable erosion) across the North Pennine landscape. Hence the transferred UKCP09 data was downscaled from 5 km to 100 m, which was considered a sufficiently fine resolution to show spatial variability across the landscape. The transferred temperature gridded datasets were downscaled with the assumption that temperature decreased with elevation at the standard lapse rate (i.e. 6.5 °C per 1 km) (Brunt, 1933). Downscaling of transferred precipitation variables (i.e. P, P_{pday} and CV_{pday}) and temperature range (i.e. T_{range}) from 5 km to 100 m were conducted using the method proposed by Cooper et al. (2010). It was assumed that the ratio of each 100 m square value to 5 km square value remained stable from the climatic baseline to future periods. Regression equations resulting from MIDAS climatic baseline data were applied to produce gridded surfaces with resolutions of 100 m and 5 km respectively (except for CV_{pday} which was interpolated by IDW). The resulting gridded surfaces were then employed to identify the ratios of 100 m and 5 km square values.

During data transfer and downscaling, it was not possible to transfer CV_{pday}, P_{pday} and PET directly with Met Office climatic baseline values based on Equation 2, as these three variables were not available in the Met Office UKCP09 climatic baseline gridded dataset (Jenkins et al., 2009). For baseline CV_{pday}, the average value was taken on the selected 12 points derived from 100 model realizations of the UKCP09 weather generator. These values were then interpolated into a gridded surface with IDW. Climatic baseline P_{pday} was calculated as Met Office gridded monthly precipitation divided by precipitation days per month. Precipitation days per month was the average of values derived from 100 model realizations of the UKCP09 weather generator, and interpolated into a gridded surface based on its relationship with elevation and coordinates. The 100 m PET was directly calculated using the downscaled temperature gridded surface (100 m), wind speed and vegetation height with the temperature-based model employed for the climatic baseline PET (Clark, 2005; Oudin et al., 2005), without undergoing transfer and downscaling processes separately.

3.2.2 Topography, soil, land use and management

Local relief was calculated based on the 100-m DEM downloaded from Digimap (Digimap, 2012). Soil parameters were set according to Kirkby et al. (2008) and the PESERA manual (Irvine and Kosmas, 2003). The soil erodibility in PESERA-PEAT refers to the sensitivity of soil to erosive agents after weathering processes, which has been demonstrated to be 2-3 times greater than of intact peat (Mulqueen et al., 2006). The erodibility of intact peat was estimated to be 1.16 mm through the pedo-transfer function presented in the PESERA manual (Irvine and Kosmas, 2003). Land-use types (Figure 1a) were derived from Land Cover Map 2000 (LCM2000) (Fuller et al., 2002). The corresponding parameters for each land-use type were set in terms of the PESERA manual (Irvine and Kosmas, 2003). The distribution of ditches in the North Pennines was provided by the North Pennines AONB Peatland Partnership. ArcGIS 10 was employed to calculate the current drainage density based on the distribution of ditches. Maps provided by Natural England gave the exact extent of burning and overgrazing (Longden, 2009). All areas other than where there was overgrazing were considered to receive light grazing. The combination of current land management practices is displayed in Figure 1b.

3.3 Construction of environmental scenarios

Twelve environmental scenarios, including interactions between climate change and land management shifts, were set up (Table 3). The current land management conditions were employed as the baseline land management scenario, and termed Business-As-Usual (BAU) (Figure 1b). In the BAU scenario, artificial drainage, light grazing and overgrazing were represented in PESERA-PEAT by the current artificial drainage density, 15% and 30%

vegetation removal (Li et al., 2016b). Typical prescribed burning frequencies for upland environments in the UK are between once in every 7 and once in every 25 years (Holden et al., 2007b). In the BAU scenario, we used a 10-year burning frequency in the model to account for the vegetation removed by managed burning (Li et al., 2016b). A carbon storage scenario and a food security scenario previously described for future UK upland management (Reed et al., 2013) are represented as ‘Carbon’ and ‘Food’ in Table 3. As discussed in the introduction, the carbon storage scenario was represented by completely removing grazing, drainage and prescribed burning as a partial rewilding process to secure carbon storage. The food security scenario we modelled utilised more intensive use of land that is already under active management. For the food security scenario, burning frequency was increased from once in 10 years to once in 5 years in the areas where there is currently burning and drainage density was doubled in the areas where there is currently drainage. The intensity of grazing in currently overgrazed areas would be unlikely to increase further given its high impact on vegetation cover and biomass, but other areas that are currently grazed (i.e. 15% vegetation removal) were moved to ‘overgrazed’ (i.e. 30% vegetation removal) in the food security scenario.

3.4 Model implementation

During model implementation, the land cover category ‘artificial lands’ (covering less than 1 km^2 of the total area) was masked out given that no blanket peat erosion was considered to occur in these areas. The vegetation growth model calculated the vegetation cover on ‘Grassland or pasture’, ‘Scrub’ and ‘Degraded natural land’. Vegetation biomass and soil organic matter were calculated by the vegetation growth model for all land-use types other than ‘Bareland’, where they were kept as zero. Land management practices were considered to only occur on ‘Pasture or grassland’, ‘Scrub’ and ‘Degraded natural land’, which covered about 95% of the blanket peatlands in the North Pennines to impact soil moisture and vegetation conditions. In areas with multiple management practices, total vegetation cover and biomass removal was the sum of vegetation cover and biomass reduced by separate management practices.

3.5 Analysis of modelling results

Modelling results were compared with outputs based on the ‘Baseline_BAU’ scenario (i.e. baseline climate and current land management) to examine the response of the blanket peat ecosystem to environmental change. The impact of climate change was investigated with climate conditions for the 2020s, 2050s and 2080s under the BAU land management scenario. Both Carbon and Food scenarios were applied with climate conditions at climatic baseline and for future climate in order to assess the impact of land management alone and also the interaction effects between land management shifts and climate change.

The highest monthly potential wildfire severity during the summer half year (April-September) was used to represent the potential wildfire severity for a year (annual potential wildfire severity). This is because higher temperatures and evapotranspiration in the summer half year facilitate the occurrence of wildfires (McMorrow et al., 2009; McMorrow, 2011, Esteves et al., 2012). Annual potential wildfire severity was employed to investigate the impacts of climate change, land management and their interactions on wildfires in the North Pennines.

4 Results

4.1 Climate change

Using the downscaled climate projections, on average, from climatic baseline to 2020s, 2050s and 2080s mean annual temperature would increase by 1.5, 2.4 and 3.2 °C respectively (Figure 2a), while mean annual precipitation would increase by 216.3, 204.8 and 220.2 mm respectively (Figure 2c). However, mean annual precipitation was projected to experience a slight decrease (i.e. 11.5 mm) between the 2020s and 2050s, and then an increase of 15.4 mm between the 2050s and 2080s. Projections of mean monthly temperature suggested a 1.0 to 3.8 °C of increase from the climatic baseline to the three future periods (2020s, 2050s and 2080s) (Figure 2b). Mean monthly precipitation in winter months (December - February) was found to increase by 23.7 to 62.5 mm between the climatic baseline and the three future periods

(Figure 2d). In the summer months (June - August), mean monthly precipitation, compared to that of the climatic baseline period, would increase by up to 4.1 mm in the 2020s and decrease by 2.2 to 17.7 mm in subsequent time periods (2050s and 2080s) (Figure 2d). Overall, the North Pennines blanket peatlands were projected to experience warmer, wetter winters and warmer, drier summers in the future in terms of central estimates from UKCP09.

Climatic baseline precipitation peaked in high-altitude areas and decreased in lower lying areas (Figure 3). Between the climatic baseline and the three future periods the increase of precipitation was projected to be greatest in the western and central part of the North Pennines where mean annual precipitation increased by over 400 mm (Figure 4a). In the central areas and some of the northern parts of the North Pennines mean annual precipitation would decrease from the climatic baseline to future time periods and the decrease of mean annual precipitation could be more than 200 mm in some places (Figure 4a). Changes in temperature over time formed a simpler pattern. Mean annual temperature increased more quickly in the southern part than in northern part of the North Pennines (Figure 4b). For the 2080s, most areas of the North Pennines were projected to be subject to a warmer mean annual temperature by over 3°C (Figure 4b).

4.2 Erosion

Under climate change with BAU management (BAU scenarios), modelling results showed that mean annual sediment yield over the North Pennines blanket peatlands would slightly increase (< 5%) (Figure 5a). Mean sediment yield for the study region was predicted to decrease by up to 14.6% in winter and increase by up to 14.3% in other seasons (Figure 5b). For land management change scenarios excluding climate change, mean sediment yield for the region, compared to that of the 'Baseline_BAU' scenario, was predicted to decline by > 50% under carbon management scenarios (Baseline_Carbon) and increase by > 40% under food security scenarios (Baseline_Food) at both seasonal and annual scales (Figure 5a and b). Mean annual and seasonal sediment yield under interaction scenarios were predicted to follow a similar pattern to that of sediment yield under management scenarios.

Under climate change with BAU management (BAU scenarios), the contribution of winter erosion was predicted to decline from 35.3% in the baseline period to 28.8% in the 2080s while spring, summer and autumn erosion was shown to contribute proportionally more to the annual sediment yield. Autumn erosion was demonstrated to become the biggest part (> 32%) of the annual soil loss in the 2050s and 2080s, while during the climatic baseline period and 2020s, winter erosion was predicted to contribute the largest proportion of the annual budget (> 33%) (Figure 6). Land management change was shown to alter the seasonal distribution of annual sediment yield but less so than climate change. For each time period, the contribution of spring and autumn erosion to the annual sediment yield was predicted to remain stable while the contribution of summer erosion was predicted to decline and winter erosion was shown to rise with intensity of management practices (Figure 6).

Under the ‘Baseline_BAU’ condition, locations with overgrazing had the highest predicted sediment yield of > 3.0 t ha^{-1} yr^{-1}, while the lowest predicted sediment yield of < 1.0 t ha^{-1} yr^{-1} occurred on areas without management (Figure 1b, Figure 7a). Higher-altitude areas tended to have less erosion than lower-elevation regions. The southern and northeastern parts of the North Pennines tended to have low predicted sediment yields of < 1.5 t ha^{-1} yr^{-1}.

Modelled blanket peat erosion change for the study area from the ‘Baseline_BAU’ condition was spatially highly variable (Figure 7b-l). Under climate change with BAU management (BAU scenarios) an increasing area of blanket peatlands was predicted to experience more severe erosion by the end of 21st Century (Figure 7b-d). Most of these areas were at relatively low-elevations (i.e. 500 m or less) (Figure 1c, Figure 3). The greatest predicted rate of erosion increase occurred in the south and northeast, where mean annual erosion was predicted to increase by over 1.5-fold from the climatic baseline period. The total area over which erosion was predicted to decline in the 2020s, 2050s and 2080s was 678, 431 and 366 km^2 respectively, and these areas retreated to higher altitudes through time (Figure 1c, Figure 7b-d).

Under management and interaction scenarios, in areas with land management shifts, sediment yield was predicted to decrease when land was managed for carbon storage and increase when land was managed for food security, regardless of the impacts of climate change (Figure 7e-l). Under carbon storage scenarios, the greatest relative reductions in predicted erosion rates (> 70%) occurred in areas that were overgrazed under BAU scenarios (Figure 7e-h, Figure 1b). Under food security scenarios, the greatest relative increases of predicted erosion rates (> 110%) were mainly found in the southern and northeastern parts of the North Pennines which, in BAU scenarios, were managed with artificial drainage and light grazing, light grazing and managed burning or artificial drainage, light grazing and managed burning (Figure 7j-l, Figure 1b). In addition, there were areas with increased predicted erosion rates in ‘2020s_carbon’, ‘2050s_carbon’ and ‘2080s_carbon’ scenarios (Figure 7f-h), and decreased modelled erosion rates in ‘2020s_food’, ‘2050s_food’ and ‘2080s_food’ scenarios (Figure 7j-l). These areas were mainly restricted to those without management options and so here blanket peat erosion change was driven by climate alone (Figure 1b).

Under ‘Baseline_BAU’ condition, approximately half of the blanket peatland area in the North Pennines was predicted to produce an annual sediment yield of 2.0 to 2.5 t ha^{-1} and areas with a higher (> 2.5 t ha^{-1}) and lower (< 2.0 t ha^{-1}) annual sediment yield were demonstrated to become smaller (Table 4). The distribution of blanket peatlands with different amounts of erosion under ‘Baseline_BAU’ scenario was predicted to be similar to the distribution under future climates with BAU management (Table 4a). However, under carbon storage and food security scenarios the predicted spatial distribution was very different from that of the ‘Baseline-BAU’ condition, with > 98% of the area subject to an erosion rate of < 1.5 t ha^{-1} yr^{-1} for carbon storage scenarios or >67% of the area subject to an erosion rate of > 3.0 t ha^{-1} yr^{-1} for food security scenarios (Table 4b and c).

4.3 Potential wildfire severity

Under BAU scenarios an increasing area was predicted to move from a low PFS category (< 0.3) to a medium PFS category (0.3-0.5) (Table 5a), resulting in a predicted mean annual PFS increase from the climatic baseline to future time periods of between 4.5% and 13.0% (Figure 8). Over 95% of the area was predicted to have a low PFS (< 0.3) under carbon storage scenarios and a high PFS (> 0.5) under food security scenarios (Table 5b and c). As a result, mean annual PFS was predicted to increase by up to 181.7% under the carbon storage scenarios and decrease by up to 26.1% under the food security scenarios. Variations of mean annual values and spatial patterns of the PFS with the management scenarios were predicted to be much bigger than with climate change (Figure 8, Table 5).

5 Discussion

5.1 The impacts of climate change

Based on central estimates of UKCP09, the North Pennines will experience a warming climate with a spatially variable precipitation change (some drier and some wetter areas) to the end of the 21st Century (Figures 2-4). In average terms, the North Pennines is expected to have warmer, drier summers and warmer, wetter winters (Figure 2). Such patterns are consistent with the general climate change for the whole of the UK estimated by UKCP09, although the magnitude of climate change varies for different regions (Jenkins et al., 2009).

At an annual scale, our results suggested that climate change over the 21st Century may lead to a slight increase (< 5%, Figure 5a) of mean fluvial erosion across blanket peatlands in the North Pennines compared to that of the climatic baseline period. This is consistent with the point modelling results of Li et al., (2016a), in which the relative erosion change for the North Pennines was lower than for other sites studied across Great Britain, possibly because the North Pennines tend to have a higher altitude than the other sites, and therefore maintain cool, wet conditions conducive to active peat growth. The mean PFS of the North Pennines blanket peatlands was predicted to increase under 21st Century climate change. Meanwhile, the likelihood (occurrence) of wildfires in summer was also deemed to increase in the future (McMorrow et al., 2009; Albertson et al., 2010; McMorrow, 2011). Wildfire can lead to a destruction of the seed stock, loss of vegetation cover (Maltby, 1990) and subsequent generation of erodible peat surfaces with rapid connectivity (e.g. gullies, sheet erosion) to stream networks (Bower 1961; Stevenson et al. 1990; Rothwell et al. 2007). It is therefore implied that the erosion forecast by PESERA-PEAT may be an underestimate since wildfire-induced erosion may lead to more enhanced erosion than predicted.

The spatial pattern of erosion change under future climate was complicated but can be interpreted based on underlying driving mechanisms. The areas where there was a predicted decline in erosion rates retreated towards higher elevations over time under the BAU condition. At higher elevations such as the western part of the North Pennines, there is usually more precipitation and lower temperatures (Figures 3-4), which encourages frost action to dominate sediment production (Labadz et al., 1991; Charman, 2002; Evans and Warburton, 2007). Therefore, reduced blanket peat erosion is accounted for by weakened frost action induced by warmer climate. The decreased erosion under climate change demonstrates the resilience of blanket peatlands to climate change. It may therefore be that the shrinkage of areas suitable for active peat growth induced by future climate change (Clark et al., 2010; Gallego-Sala et al., 2010; Gallego-Sala and Prentice, 2012) does not necessarily entail the loss of peat through fluvial erosion. At lower elevations such as southern and northeastern parts of the North Pennines, desiccation processes become more important due to a relatively warm and dry climate (Francis, 1990; Charman 2002; Evans and Warburton, 2007). A warmer future climate would enhance desiccation in these regions, resulting in more peat loss via fluvial processes. Southern and northeastern parts of the study region are also subject to low local relief (Figure 1c), which means that weathered peat produced by freeze-thaw and desiccation are more likely to be stored rather than transported to river channels. However, a wetter climate in the 2020s, 2050s and 2080s (Figure 4) together with higher vegetation removal under intensified management conditions were demonstrated to significantly encourage sediment transport and enhance sediment yield at these locations (Figure 1b, Table 3).

At a seasonal scale, mean sediment yield of the North Pennine blanket peatlands was forecast to peak in winter during the climatic baseline and 2020s (Figure 6). For the 2050s and 2080s, increased temperature in winter months was predicted to weaken the impact of freeze-thaw (Labadz et al., 1991; Charman, 2002; Evans and Warburton, 2007), so that sediment yield in winter was predicted to decline despite a higher transport capacity resulting from wetter climate (Figure 2c and d). Elevated temperature and lower precipitation (Figure 2b, d) may aggravate desiccation in summer months (Francis, 1990; Charman 2002; Evans and Warburton, 2007). Therefore, more weathered surface peat is likely to be generated which can be washed away by subsequent storms (Figure 5b). As a result, the sediment flux was predicted to peak during autumn in the 2050s and 2080s (Figure 6).

5.2 The impact of land management

Modelling results showed that blanket peat erosion in areas with management options (i.e. artificial drainage, prescribed burning and grazing) were predicted to increase under carbon storage scenarios and decrease under food security scenarios (Figure 5 and Figure 7e-l). Artificial drainage lowers the water table (mainly downslope) within blanket peatlands (Holden et al., 2004; 2006; 2011; Wallage and Holden, 2011), and vertical incision creates ditch sides which often result in more bare peat and thereafter erosion (Holden et al., 2007a; Evans and Warburton, 2007). Prescribed burning (Brown et al., 2015; Holden, 2008; Holden et al., 2007b; 2014; 2015) and grazing (Holden et al., 2007b; Holden, 2008; Meyles et al., 2006) are also known to impact peat surface conditions (e.g. removal of vegetation) and soil properties (e.g. infiltration rate). In PESERA-PEAT all management options are linked to changes in vegetation cover and biomass while the impact of artificial drainage on soil moisture condition is also accounted for using empirical data available from the literature (Li et al., 2016b). Hence, the carbon storage scenario was associated with a decline in final sediment yield while the food security scenario was associated with increased final sediment yield.

PFS responded to shifts in land management in the opposite way to erosion (Figure 5 and Figure 8) because as biomass increases, erosion declines but the fuel load increases (McMorrow et al., 2009; Worrall et al., 2010; McMorrow, 2011; Esteves et al., 2012). Intensified land management (i.e. food security scenarios), results in reduced vegetation biomass and therefore fuel load, but creates more bare areas which lead to increased peat erosion. Further work is therefore required to understand the interactions between land management and wildfire (fire probability and severity) and their interacting effects on blanket peat erosion.

5.3 Interactions of climate and management shifts and their implications for peatland management

Modelling results showed that management shifts employed in this paper were likely to be more influential than 21st Century climate change in altering both the rates and the spatial pattern of blanket peat erosion and PFS across the North Pennines (Figures 5, 7 and 8, Tables 4 and 5). It is acknowledged that our study only examined two opposing prescribed land management changes in comparison to a BAU scenario and there are many other land management possibilities in between. However, our modelling results strongly suggest that careful land management could be a key factor in reducing blanket peat erosion risk and that particular types of management change could largely mitigate the effects of climate change on fluvial peat erosion and PFS in the 21st Century for the North Pennines. This assertion is supported by empirical studies that have shown the importance of blocking ditches and increased vegetation cover in reducing blanket peat erosion (e.g. Holden 2007b; Evans et al., 2006; Grayson et al., 2010; Parry et al., 2014; Shuttleworth et al., 2015; Brown et al., 2015).

The predicted spatial pattern of fluvial erosion change for the North Pennines blanket peatlands was quantitatively assessed (Figure 7b-l). This provides land managers with a spatially-distributed indicator of potential erosion risk or erosion mitigation potential through management decisions. PFS assessments are also helpful when evaluating the potential impact of wildfires enhanced by management strategies (Worrall et al., 2010; McMorrow, 2011). Using PESERA-PEAT outputs, land managers will be able to develop spatially-targeted peatland conservation and protection strategies, enabling limited funds and resources to be preferentially allocated to locations where management interventions might have the greatest impact under future climate change. Such a spatially-targeted strategy will also reduce impacts associated with peat erosion including heavy metal pollution (Rothwell et al., 2005; 2007), disturbed river ecology (Ramchunder et al., 2009) and loss of carbon (Evans et al., 2012; Grayson et al., 2012; Pawson et al., 2012).

5.4 Implications for future work

Our work showed how a spatially distributed erosion model can be applied to large study regions in the context of climate change. Future work could test a number of different spatial configurations of management change or different types of management interventions so that new erosion mitigation strategies can be developed. The model will also be able to incorporate future advances in process understanding of the influence of management practices on peatland processes (e.g. if prescribed burning is shown to impact peatland water tables as well as vegetation cover; Holden et al., 2011; 2015; Worrall et al., 2007), improving its capability in predicting the potential consequences of policies.

5.5 Limitations of climate projections and modelling approaches

Climate scenarios in this study were established based on central estimates of UKCP09 projections which inevitably reduced the variability of climate variables given they only cover one possibility (50% probability level) of future climate conditions. Therefore, climate change derived from other possible future climate projections such as IPCC AR5 (Christensen et al., 2013) also needs to be assessed in the future. As climate change is likely to be different across the UK (Jenkins et al., 2009), and the current climate conditions are not the same across all UK blanket peatlands, the response of blanket peat erosion to climate change may vary across the UK (Li et al., 2016a) as well as across other global blanket peatland regions. Further work is therefore required to examine the response of blanket peat erosion to climate change and land management shifts at a national and international scale.

PESERA-PEAT was developed based on field data collected from catchment outlets, implying that the erosion estimated by PESERA-PEAT is lumped hillslope and channel erosion (thereby inherently incorporating features such as gullies). This was a compromise because of a lack of long-term hillslope erosion records in blanket peatlands, and forms a limitation of the model. However, the suitability of such a simplification is supported by previous erosion studies on hillslope processes in blanket peatlands and stream bank processes in other soil systems (e.g. Evans and Warburton, 2007; Wynn et al., 2008). Wind erosion, which may be important at some blanket peat-covered locations (Warburton, 2003; Foulds and Warburton 2007a; b), is currently not accounted for in PESERA-PEAT. The incorporation of more erosion processes into PESERA-PEAT is thus desirable in the future.

There was a lack of a sufficiently fine-resolution DEM across the study region to support automated mapping of gullies using methods developed in previous studies such as Evans and Lindsay (2010). Gullies, which can be parameterized in PESERA-PEAT using the ‘ditch level’ function (but with deeper and wider values), were not separately considered in the modelling work here. It may be that the erosion estimates provided in this paper are underestimates for areas of severe gullying. However, PESERA-PEAT is capable of directly considering gullies and so spatially distributed blanket peat erosion modelling that incorporates gully landforms can be conducted in the future for the North Pennines or other regions if gully maps and fine-resolution DEMs are available.

6 Conclusions

The first fluvial erosion model developed for blanket peatlands, PESERA-PEAT, was applied across the North Pennines to predict the response of blanket peat erosion to environmental change. Modelling results showed that the reaction of blanket peat erosion to climate change was likely to be spatially highly variable. Increasing rates of blanket peat erosion with climate change within an individual large region are likely to be smaller in wetter and colder places. Summer desiccation may become a more important sediment source for blanket peat erosion in places under a warmer and drier future climate, leading to more sediment erosion released from blanket peatlands during subsequent rainstorms. Land management was found to have stronger impacts than climate change on blanket peat erosion. Conservation land management practices can therefore potentially act as a useful tool in mitigating the impacts of climate change on blanket peat erosion. However, when blanket peatlands are managed to protect them from soil erosion through ensuring a thriving vegetation biomass cover, wildfire-awareness and precautionary fire measures would be required as the wildfire risk increased substantially with climate change and may also increase with some land management strategies. This study, for the first time, demonstrated how a spatially-distributed model (PESERA-PEAT) could be used to evaluate blanket peat erosion under environmental change at a regional scale. The model could be used for blanket peatlands in other regions of the world to assess fluvial erosion rates and to help land managers determine spatially-targeted land management and protection strategies. The model would also be potentially suitable for a range of organo-mineral soils that are located in regions where freeze-thaw or desiccation commonly drives surface sediment production.

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Figure Captions

Figure 1 Maps of the study site (North Pennines), including land cover for blanket peatlands (a); management combinations within blanket peatlands (b), each code represents a management option: 1 = artificial drainage; 2 = light grazing; 3 = overgrazing; 4 = managed burning; local relief (c); points selected for climate interpolation (d).

Figure 2 Change of mean annual and monthly temperature (a and b) and precipitation (c and d) for the North Pennines blanket peatlands evaluated based on the MIDAS baseline (1961-1990) climate records and future (2020s, 2050s and 2080s) climate projections derived from MIDAS baseline data and UKCP09 projections. Error bars show the range of mean annual temperature and precipitation. Month 1-12 corresponds to January - December.

Figure 3 Mean annual precipitation temperature derived from the MIDAS baseline (1961-1990) records and elevation of North Pennines blanket peatlands.

Figure 4 Spatial patterns of changes in mean annual precipitation (a) and temperature (b) for the North Pennines blanket based on the MIDAS baseline (1961-1990) climate records and future (2020s, 2050s and 2080s) climate projections derived from MIDAS baseline data and UKCP09 projections.

Figure 5 Predicted response of mean annual (a) and seasonal (b) sediment yield for the

North Pennines blanket peatlands. ‘Baseline’, ‘2020s’, ‘2050s’ and ‘2080s’ represent the climate condition of 1961-1990, 2010-2039, 2040-2069 and 2070-2099, while ‘BAU’, ‘Carbon’ and ‘Food’ represent land management conditions of Business-As-Usual, carbon storage and food security.

Figure 6 Predicted seasonal distribution of erosion averaged over the whole blanket peat-covered area of the North Pennines. ‘Baseline’, ‘2020s’, ‘2050s’ and ‘2080s’ represent the climate condition of 1961-1990, 2010-2039, 2040-2069 and 2070-2099, while ‘BAU’, ‘Carbon’ and ‘Food’ represent land management conditions of Business-As-Usual, carbon storage and food security.

Figure 7 Predicted mean annual erosion under the ‘Baseline_BAU’ scenario (a) and changes of mean annual erosion from the ‘Baseline_BAU’ scenario for other scenarios (b-l). ‘Baseline’, ‘2020s’, ‘2050s’ and ‘2080s’ represent the climate condition of 1961-1990, 2010-2039, 2040-2069 and 2070-2099, while ‘BAU’, ‘Carbon’ and ‘Food’ represent management conditions of Business-As-Usual, carbon storage and food security.

Figure 8 Predicted response of mean annual potential wildfire severity in blanket peatlands of the North Pennines to environmental change. ‘Baseline’, ‘2020s’, ‘2050s’ and ‘2080s’ represent the climate condition of 1961-1990, 2010-2039, 2040-2069 and 2070-2099, while ‘BAU’, ‘Carbon’ and ‘Food’ represent land management conditions of Business-As-Usual, carbon storage and food security