

1 **Modelling soil erosion responses to climate change in three catchments of Great Britain**

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14 **Abstract**

15 Simulations of 21st century climate change for Great Britain predict increased seasonal precipitation
16 that may lead to widespread soil loss by increasing surface runoff. Land use and different vegetation
17 cover can respond differently to this scenario, mitigating or enhancing soil erosion. Here, by means of
18 a sensitivity analysis of the PESERA soil erosion model, we test the potential for climate and vegetation
19 to impact soil loss by surface-runoff mechanisms to three differentiated British catchments. First, to
20 understand general behaviours, we modelled soil erosion adopting regular increments for rainfall and
21 temperature from the baseline values (1961-1990). Then, we tested future climate change scenarios
22 adopting projections from UKCP09 (UK Climate Projections) under the IPCC (Intergovernmental
23 Panel on Climate Change) on a defined medium CO₂ emissions scenario, SRES A1B (Special Report
24 on Emissions Scenarios, SRES: IPCC, 2000), at the horizons 2010-39, 2040-69 and 2070-99. Our
25 results indicate that the model reacts to the changes of the climatic parameters and the three catchments
26 respond differently depending on their land use arrangement. Increases in rainfall produce a rise in soil
27 erosion while higher temperatures tend to lower the process because of the mitigating action of the

28 vegetation. Even under a significantly wetter climate, warmer air temperatures can limit soil erosion
29 across areas with permanent vegetation cover by enhancing primary productivity and in turn improving
30 leaf interception, soil infiltration-capacity, and the erosive resistance of soil. Consequently, under a
31 global balance and for specific land uses, the increase in air temperature associated with climate change
32 can modify the rainfall thresholds required to generate soil loss, and rates of soil erosion could decline
33 by up to about 30% from 2070-2099.

34 We deduce that enhanced primary productivity due to climate change can introduce a negative-feedback
35 mechanism limiting soil loss by surface runoff as vegetation-induced impacts on soil hydrology and
36 erodibility offset the effects of increased precipitation. The expansion of permanent vegetation cover
37 could provide an adaptation strategy to reduce climate-driven soil loss.

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40 **Keywords**

41 Soil erosion, Pesera model, sensitivity analysis, climate change, vegetation productivity

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45 **1. Introduction**

46 Intensifying seasonal precipitation predicted to result from climate change (Kharin et al., 2007;
47 O’Gorman and Schneider, 2009) will increase surface runoff and possibly rates of soil erosion
48 (Nearing et al., 2004; Lal, 2004; Boardman, 2013; Galy et al., 2015, Burt et al., 2016), thereby
49 increasing economic costs associated with soil loss, which was as high £177m (\$207m USD, 2019) in
50 England and Wales alone (UK Environment Agency, 2019).

51 Surface runoff occurs as result of a number of natural mechanisms, including infiltration-excess
52 overland flow, return flow, and direct precipitation onto saturated soil. These mechanisms may
53 generate soil erosion by detaching and entraining soil particles over widespread areas (Hairsine and
54 Rose, 1992; Whiting et al., 2001).

55 Vegetation can limit this process and may decrease the likelihood of surface runoff by reducing the
56 intensity of rainfall through leaf interception as well as the moisture content of soil through
57 transpiration (Zuazo et al., 2008). Nevertheless, its role in controlling surface runoff for assessing the
58 potential climate-driven soil erosion by water remains uncertain (IPCC, 2019; Rogers et al. 2017).

59 Anthropogenic increases in atmospheric CO₂ concentrations may increase the water-use efficiency of
60 plants by lowering transpiration rates, which could promote the generation of surface runoff by
61 enhancing the moisture content of soil (Cramer et al., 2001; Gedney et al., 2006, Keenan et al., 2013).
62 However, increased atmospheric CO₂ may also enhance plant productivity by acting as a fertilizer
63 (Melillo et al., 1993), which could increase both plant water-usage and the infiltration capacity of soil
64 through the addition of soil organic matter, thereby reducing the likelihood of surface runoff during
65 precipitation events. Experimental results support predictions of increased plant productivity in
66 response to elevated air temperatures and precipitation amounts (Piao et al., 2007; Walker et al.,
67 2006), both of which are expected to increase in future climate scenarios (Boardman and Favis-
68 Mortlock, 1993; Kharin et al., 2007; O’Gorman and Schneider, 2009).

69 The research of the climatic impact on soil erosion (Xiong et al., 2019) is typically based on erosion
70 modelling techniques, of which extensive reviews are reported in Li and Fang (2016) and Pandey et
71 al. (2016). Process-based models have been widely used in assessments of climate-driven impacts on
72 soil erosion (e.g., Favis-Mortlock and Boardman, 1995; Luetzenburg et al., 2019; Mullan, 2012; 2013;

73 Nunes et al., 2013; Pastor et al., 2019, Routschek et al., 2014, 2015; Serpa et al., 2015), including
74 impacts on vegetation and on agricultural practices in different climates (e.g., Garbrecht et al., 2015;
75 Nearing et al., 2005; O’Neal et al., 2005; Pruski and Nearing, 2002a; Scholz et al., 2008; Zhang et al.,
76 2005, 2012). Despite of the large number of approaches existing for modelling erosion, process-based
77 models are frequently uniquely suited for explicitly considering specific soil transport mechanisms
78 and the impacts of climatic factors on soil hydrology (Guo et al., 2019).

79 In this research, using a model sensitivity analysis, we aimed to investigate the potential role of
80 climate change and plant productivity on soil erosion by surface runoff in a context of predicted
81 increases of precipitation and temperature. For that, we opted to a process-based model
82 implementable at spatial scales relevant to catchment-wide assessments of soil loss, in which
83 catchments can be greater than 100 km² in size and be comprised of the full range of plant functional
84 types. The Pan European Soil Erosion Risk Assessment (PESERA) model was specifically designed
85 to accomplish such task (Kirkby et al., 2008).

86 PESERA calculates soil erosion via infiltration-excess overland flow by explicitly considering a range
87 of physical processes controlling soil hydrology and has been successfully employed across many
88 natural settings (e.g., Baggaley et al., 2010, De Vente et al., 2008; Esteves et al., 2012; Karamesouti et
89 al., Licciardello et al., 2009; Meusburger et al., 2010; Pásztor et al., 2010; Tsara et al., 2005).

90 PESERA only considers soil transfer by sheet wash and rilling during infiltration-excess overland
91 flow, but both are widespread and pervasive mechanisms of soil transfer that can be simply and
92 explicitly linked to land cover and climate, making it particularly useful for assessing the ability of
93 vegetation to mitigate climate impacts on widespread soil loss. PESERA has also been used as base-
94 platform to prepare similar models that implement procedures simulating other soil surface processes.
95 These include PESERA-L (Borselli et al., 2011), which integrates sediment yield due to shallow mass
96 movement, PESERA-DESMICE (Fleskens et al., 2016), which extends its functionalities to evaluate
97 the agricultural financial viability of the measures to mitigate land degradation, and PESERA-PEAT
98 (Li et al., 2016), where the model was modified to include blanket peat erosion processes. Some
99 specific sensitivity analyses of PESERA also exist, such as that by Cheviron et al. (2010; 2011) who

100 clarified the influence of the major model parameters, and Baggaley et al. (2017) who tested the effect
101 of topography and soil erodibility characteristics.

102 We applied PESERA to three characteristic catchments comprised of the major land-cover types of
103 Great Britain, similar to those in environments of temperate climates across the globe (Prentice et al.,
104 1992). The Conwy (Wales), Ehen (England), and Dee (Scotland) catchments (Figure 1) are
105 characterized by significant intra- and inter-catchment differences in topography, climate, soil and
106 land use (Table 1), allowing us to describe the sensitivity of land-cover specific soil erosion to these
107 variables. Further, the catchments have been recognized as important habitats for the endangered
108 freshwater pearl mussel (*Margaritifera margaritifera*) (Cooksley et al., 2012; Joint Nature
109 Conservation Committee, 2007), whose life cycles are negatively affected by fine-grained particulates
110 derived from upland erosion (Geist and Auerswald, 2007).

111 Climatic responses to increased emissions of greenhouse gases are predicted to similarly affect each
112 of the catchments. For example, under the IPCC-defined medium-emissions scenario SRES A1B
113 (IPCC, 2000), UK Met Office Climate Predictions (Jenkins et al., 2010) indicate that, for the time
114 period 2070-2099, average monthly rainfall within each catchment could increase by more than 20%
115 relative to modern conditions, with much of this increase occurring during winter months. With the
116 aim to inspect the impact of rainfall and air temperature on soil erosion over the current century, first,
117 to understand the general behaviour, we adopted regular increments for rainfall (from -25 to +100%)
118 and temperature (from +0 to +8°) from the baseline values (1961-1990), then, we assessed erosion
119 rates for the periods 2010-39, 2040-69 and 2070-99 using specific future climate scenarios adopting
120 projections from UKCP09 (UKCP09 - UK Climate Projections, 2017a, 2017b) under the IPCC
121 (Intergovernmental Panel on Climate Change) on a defined medium CO₂ emissions scenario, SRES
122 A1B (Special Report on Emissions Scenarios, SRES: IPCC, 2000).

123

124 **2. Materials and Methods**

125 **2.1 Summary of the modelling approach**

126 PESERA is a spatially distributed, physically-based, continuous model created to quantify soil erosion

127 over wide areas with different land-use types, soils, and landscape features. In PESERA, soil
128 erodibility is a specific property that defines a soil's potential to be eroded and transported by water
129 processes. However, the model does not differentiate between rill and interrill processes. Soil
130 erodibility and soil crusting are associated to characteristic soil surface properties (e.g., texture,
131 vegetation cover, and organic carbon) through the application of pedotranfer functions (Kirkby et al.,
132 2003a; Le Bissonnais et al., 2002, 2005).

133

134 PESERA uses topography, climate, and soil characteristics to determine when rainfall intensity
135 exceeds infiltration capacity generating runoff. Vegetation directly affects this threshold by limiting
136 rainfall intensity through interception and increasing infiltration capacity through soil organic matter.
137 Vegetation also functions to protect soil particles from being detached, thus reducing soil erodibility.
138 Gross primary productivity is determined as a function of actual evapotranspiration based on
139 empirical data (Lieth, 1975), with net primary productivity determined as the difference between
140 gross primary productivity and temperature-driven respiration (Kirkby et al., 2008). Forests are
141 comprised of a composite of conifers and deciduous trees, where the timing of leaf senescence is
142 driven by changes in air temperature (Kirkby et al., 2008). The PESERA estimate of plant
143 productivity can be seen as a maximum because the impacts of the limited availability of nutrients are
144 not considered. Any enhancement in primary productivity could result in an exhaustion of nutrients
145 within the rooting zone, thereby limiting vegetation growth in the long-term (Reich et al., 2014).

146 In its implementation, PESERA iterates model runs integrating vegetation-growth dynamics and a
147 soil-water balance until a temporally stable output between rainfall, soil, and vegetation growth is
148 generated. The implementation also assumes that daily rainfall amounts follow a gamma distribution,
149 which is defined using empirical data described below and a probability density function based on
150 input precipitation values to calculate daily rainfall, runoff, and erosion for all possible storm events.

151

152 We note that, in PESERA, rainfall characterization may underestimate the role of short-duration,
153 high-intensity precipitation events in fostering surface runoff. However, the model has been calibrated
154 against field measurements (Pan-European Soil Erosion Risk Assessment map, Kirkby et al., 2003a)

155 that show non-linear increases in surface runoff and soil erosion with intensifying precipitation. This
156 non-linear relationship is consistent with process-based models involving hourly rainfall rates
157 (Nearing et al., 2005; Pruski and Nearing, 2002b). Most important to our analysis, the characterization
158 of rainfall at daily timescales allows PESERA simulations to be directly integrated with UKCP09
159 predictions.

160

161 We first assessed the sensitivity of erosion to changes in rainfall and air temperature, ensuring that the
162 ranges of rainfall and temperature changes encompassed the expected variations reported in the
163 UKCP09 projections. We defined baseline conditions for each catchment using the UKCP09 defined
164 baseline period, 1961-1990, with values of monthly average temperature, monthly average rainfall,
165 and daily total rainfall derived and interpolated from available weather station data. The sensitivity
166 analysis then involved increasing mean-monthly air temperature from 1 to 8 °C above the 1961-1990
167 equivalent baseline values. Mean-monthly rainfall was adjusted by a fixed percentage from -25 to
168 +100% of the corresponding baseline values (Figure 4).

169

170 In our modelling framework, we held the spatial distribution of land cover unchanged, allowing us to
171 directly consider specific UKCP09 projections for the SRES A1B emissions scenario during the
172 following defined time periods: 2010-2039, 2040-2069, and 2070-2099 (Figure 2). UKCP09 climate
173 simulations indicate probable changes in future air temperature and precipitation, and we utilised the
174 10th, 50th, and 90th percentiles of the outputs for each period. We used two-tailed t-tests and
175 Kruskal-Wallis (KW) tests to quantify the significance of differences in the populations of our
176 measurements. Kolmogorov-Smirnov (KS) tests were applied to assess the distinctiveness of
177 measurement distributions.

178

179 **2.2 Description of PESERA**

180 Details of the modelling framework and data requirements of PESERA have been previously reported
181 (Kirkby et al., 2003a; 2003b; 2008), but we offer a description of the modelling framework here. An

182 initial assumption of the model is that, during overland flow, sediment is transported at a rate equal to
183 the flow's transport capacity per unit of flow width (T), which can be stated as the following based on
184 the formulation by Kirkby et al. (2008):

185

$$186 \quad T = k_v q^2 \Lambda, \quad (1)$$

187

188 where T is measured in units of $\text{kg m}^{-1} \text{day}^{-1}$, k_v is soil erodibility of a vegetated surface with units of
189 kg m day L^{-2} , q is overland flow discharge per unit of flow width with units of $\text{L m}^{-1} \text{day}^{-1}$, and Λ is
190 the local slope gradient. To account for the upslope contribution to overland flow, Eq. (1) can be
191 restated as:

192

$$193 \quad T = k_v (rx)^2 \Lambda, \quad (2)$$

194

195 where r is the infiltration-excess runoff in units of $\text{L m}^{-2} \text{day}^{-1}$ for each storm and x is the distance
196 from the drainage divide in units of meters. The cumulative value of T that results from the frequency
197 distribution of storm events that occur in a month can then be written as:

198

$$199 \quad \sum T = k_v x^2 \Lambda \sum r^2. \quad (3)$$

200

201 Eq. (3) is used in a relation that allows for estimates of the hillslope-length averaged Sediment Yield
202 (Y) to the slope base, or:

203

$$204 \quad Y = \frac{\sum C_b}{x_b} = k_v x_b \Lambda_b \sum r^2 \quad (4)$$

205

206 where the unit of Y is $\text{kg m}^{-2} \text{day}^{-1}$ and the subscript b denotes an evaluation at the hillslope base.

207 Eq. (4) does not consider fractions of sediment stored within the hillside during soil transfer, and

208 PESERA does not model soil transfer through the catchment network. Moreover, the equation also

209 does not consider the range of grain sizes that can be mobilized across the hillside, effectively treating
210 all grain sizes as equally mobile. PESERA solves Eq. (4) within a raster model of the landscape that
211 requires spatially distributed values of k_s , estimates of local relief derived from a digital elevation
212 model, and spatially distributed estimates of r derived from a biophysical model.

213 The calculation of r is based on a bucket model that states:

214

$$215 \quad r = p(R - h), \quad (5)$$

216

217 where R is the total daily rainfall that reaches the soil surface and h is the runoff threshold or the
218 maximum rainfall amount that can infiltrate into the soil, having unit m , and p is the proportion of
219 rainfall above the runoff threshold. The value of h is determined from soil classification data and
220 estimates of the hydrological conditions within the near surface, including surface roughness (e.g., the
221 storage capacity of furrows), the soil water holding capacity, and soil crusting. For the hydrological
222 conditions of the near surface, PESERA constructs a water balance for each storm event, estimating
223 amounts of interception loss due to vegetation cover, evapotranspiration loss due to vegetation cover
224 and climate conditions, and the loss due to the subsurface flow of infiltrated water modelled using
225 TopModel (Beven and Kirkby, 1979).

226

227 Vegetation is explicitly modelled by PESERA, which considers both natural and crop cover, and
228 exerts three important controls on the likelihood of soil erosion during storm events. First, the
229 presence of vegetation cover limits the amount of rainfall that reaches the surface through
230 interception, so that $R = R0(1 - pI)$ where $R0$ (m) is the rainfall above the canopy and pI is the
231 proportion of rainfall that is intercepted. PESERA determines pI using the following:

232

$$233 \quad pI = 1 - \exp\left(-\frac{V}{5}\right), \quad (6)$$

234

235 where V is aboveground plant biomass in units of kg ha^{-1} , which dynamically evolves as a function of
236 climatic conditions. Second, vegetation increases the organic content of soil, which increases the
237 soil's water-holding capacity and thus the runoff threshold, h . PESERA accounts for this in its
238 calculation of h , using the following:

239

$$240 \quad h = bh_m + VI + \lambda O, \quad (7)$$

241

242 where b is the proportion of bare soil, h_m is water storage within the mineral components of the soil, I
243 is the canopy storage of intercepted water per unit of biomass, λ is water storage within the organic
244 components of the soil per unit of mass of organic soil, having unit m , and O (kg ha^{-1}) is the mass of
245 organic soil. And third, the presence of vegetation decreases soil erodibility, limiting rates of soil loss
246 during a storm, and the soil erodibility of a vegetated surface (k_v) is calculated as:

247

$$248 \quad k_v = k_0 \exp\left(-\frac{\theta}{pr_0\varepsilon}\right), \quad (8)$$

249

250 where k_0 is the soil erodibility of the bare surface derived from soil classification data (kg m day L^{-2}),
251 θ is a flow-threshold for sediment entrainment ($\text{L m}^{-1} \text{ day}^{-1}$), r_0 is the mean rainfall amount per rain
252 day ($\text{L m}^{-2} \text{ day}^{-1}$) and ε , with unit m , is the product of slope length and \mathcal{A} . The variable k_0 is primarily
253 a function of grain-size characteristics, with the highest values for sandy and silty soils with low clay
254 content (Kirkby et al., 2008). The variable θ reflects the partitioning of shear stress exerted by
255 overland flow onto both the soil surface and vegetation. The less vegetation that is present, the greater
256 the amount of shear stress exerted onto the soil surface and the lower the value of θ .

257

258 The model keeps track of three important values associated with vegetation. The outline of this
259 portion of the model is presented here; for details and supporting references, interested readers should
260 see Kirkby et al. (2008). The change in foliar cover (c) is determined as:

261

262 $\Delta c = (c_0 - c)e^{-0.2V},$ (9)

263

264 where c_0 , the equilibrium cover, is calculated as the ratio between the actual evapotranspiration and
265 the potential evapotranspiration. At each time-step, V is determined by adding the net primary
266 productivity (NPP) to the previous time-step's biomass. The NPP , in turn, is calculated as:

267

268 $NPP = GPP - \Sigma - \Omega,$ (10)

269

270 where GPP is gross primary productivity, Σ is respiration, and Ω is leaf and root fall. GPP is
271 determined as a linear function of plant water use based on available empirical data (Lieth et al.,
272 1975); note, however, that these data are for NPP and, thus, the model will conservatively
273 underestimate the amount of biomass generation. The variable Σ is determined as a function of
274 temperature, and Ω contribute organic matter to the soil at a rate that is dependent on biomass; the soil
275 organic matter, in turn, decays at an exponential rate dependent on temperature.

276

277 **2.3 The Study Sites**

278 The 55-km long River Conwy drains 627 km² of north Wales into the Irish Sea at the Conwy Estuary.
279 The Conwy uplands extend into the Meignant Moor of Snowdonia National Park, a Special Area of
280 Conservation designated under the European Union Habitats Directive and characterized by steep
281 slopes and flashy discharge. The average annual discharge of the River Conwy is 19 m³ s⁻¹, with a
282 95% exceedance discharge of 1.4 m³ s⁻¹ and a 5% exceedance discharge of 46 m³ s⁻¹ at the
283 Cwmlanerch gauging station (EA No. 66011) for the period 1964-2011. Climate data for the period
284 1961-1990 indicate an increase in rainfall from the coast to the upland borders of the catchment, from
285 400 to nearly 2000 mm annually. The climate data also indicate that precipitation events are most
286 frequent during autumn (September to November) and winter months (December to February). Mean
287 winter and summer temperatures (at sea level) are 4.9 and 15.0 °C. UK Met Office Climate
288 Predictions (UKCP09, Jenkins et al., 2010) indicate that, for the period between 2070 and 2099,
289 summer and winter temperatures across Wales will increase on average by 3.3 and 2.9 °C, with

290 precipitation decreasing by 18.2% during summer months and increasing by 11.3% during winter
291 months relative to 1961-1990 averages. Ordovician, Silurian and Cambrian igneous and sedimentary
292 rocks underlie much of the Conwy catchment, which generally weather into brown podzolic soils,
293 peats and gleys. Overall, the Conwy catchment is rural, with urban areas making up only 1.2% of the
294 region. The dominant land use is pasture and grassland, accounting for 64% of the catchment and
295 supporting the primary contributor to the economy, cattle and sheep farming. Over 28% of the
296 remaining land area is managed or natural forest (Fuller et al., 2002).

297

298 The 27-km long River Ehen drains 225 km² of England's west coast into the Irish Sea, with
299 headwaters in the Ennerdale Water, a deep glacial lake that also serves as a reservoir for several urban
300 areas in the region. The average annual discharge of the river is 5.2 m³ s⁻¹, with a 95% exceedance
301 discharge of 0.94 m³ s⁻¹ and a 5% exceedance discharge of 11.9 m³ s⁻¹ at the Braystones gauging
302 station (EA No. 74005) for the period 1974-2011. Average annual precipitation is between 158 and
303 1250 mm across the catchment with much of the precipitation occurring during autumn and winter
304 months. The mean seasonal summer to winter temperature range is approximately 10.7 oC, with a
305 winter mean temperature of 3.8 °C and a summer mean temperature of 14.5 °C. Predictions (UKCP09,
306 Jenkins et al., 2010) indicate that, for the period between 2070 and 2099, summer and winter
307 temperatures across the region will increase on average by 3.4 and 2.6 °C, with precipitation
308 decreasing by 15.7% during summer months and increasing by 20.2% during winter months relative
309 to 1961-1990 averages. Impervious Borrowdale volcanics underlie the upper portions of the
310 catchment, and Ordovician sedimentary rocks are found in the lower portions, forming podzolic soils,
311 peats and gleys in the uplands and brown soils in the lowlands. Most of the catchment is comprised of
312 pasture and grassland (55%), with arable and forested lands being equally represented, each
313 comprising 20% of the catchment (Fuller et al., 2002). Conservation efforts have led to the end of
314 managed forestry, thought to be a major instigator of soil erosion within the uplands of the catchment
315 (Killeen, 2009).

316

317 The 140-km long River Dee drains 2100 km² of eastern Scotland into the North Sea at the Dee
318 Estuary (Baggaley et al., 2009). The headwaters are found in the Cairngorm massif in north-eastern
319 Scotland, which forms part of the Cairngorm National Park. The average annual discharge of the Dee
320 is 47.1 m³ s⁻¹, with a 95% exceedance discharge of 8.75 m³ s⁻¹ and a 5% exceedance discharge of 95.4
321 m³ s⁻¹ at the Park gauging station (SEPA No. 12002) for the period 1972-2011. The catchment
322 receives approximately 810 to 2100 mm of precipitation annually, most of which falls in the winter
323 months, 30% of it as snow. The mean seasonal summer-winter temperature range is 10.8°C, with a
324 mean winter temperature of 3.4 °C and a mean summer temperature of 14.2 °C (at sea level).
325 Predictions (UKCP09, Jenkins et al., 2010) indicate that, for the period between 2070 and 2099,
326 summer and winter temperatures across eastern Scotland will increase on average by 3.4 and 2.3 °C,
327 with precipitation decreasing by 10.7% during summer months and increasing by 7.4% during winter
328 months relative to 1961-1990 averages. Heavily metamorphosed Precambrian sedimentary rocks
329 flanked by igneous intrusive rocks of the Caledonian orogeny underlie the catchment, forming humic-
330 iron podzolic soils in the lowlands and expansive areas of poorly drained blanket peat bogs and
331 podzolic soils in the uplands. Most of the catchment is comprised of forest and moorland (71.2%),
332 with pasture and grassland comprising 17.5% and arable land comprising 7.9% (Fuller et al., 2002).
333 The uplands have been identified as being particularly susceptible to erosion due to the prevalence of
334 peaty soils (Towers et al., 2006).

335

336 **2.4 Terrain data**

337 Topographic information for each catchment was derived from the Landmap Digital Terrain Model,
338 which provides photogrammetrically derived elevation-data at 5-m resolution resampled, which we
339 resampled to 100-m to fit an affordable resolution for modelling. Data for soil characteristics of the
340 Conwy and Ehen catchments were obtained under license from the UK National Soil Research
341 Institute (NATMAP1000, National Soil Map of England and Wales, 2013), and of the Dee from the
342 James Hutton Research Institute (Soil Information for Scottish Soils, SIFSS). The soil data were used
343 to give field capacity and saturated water capacity for each dominant soil series. At a resolution of
344 100-m with soils data of a lower resolution (1-km) than used in PESERA, crusting and erodibility

345 were obtained through a conversion from soil texture (percentage of sand, silt and clay) (Baggaley et
346 al., 2010, 2011).

347

348 Land cover data were obtained from the UK Centre for Ecology and Hydrology under the Land Cover
349 Map 2000 (LCM2000) based on Landsat image data. Most of each of the catchments is covered by
350 forest or grassland, providing a permanent cover of the soil surface throughout the year. Agricultural
351 crops consist of vegetables, forage, and other minor cultures such as root crops and oilseeds. These
352 cultures have a harvesting cycle mainly between March and August, and specific calendars for
353 planting and harvesting have been obtained from UK Agri-Environment Offices (Table 1).

354

355 **2.5 Climate**

356 In our assessment of potential climate-change impacts, we defined the period 1961-1990 as the
357 baseline following the UKCP09 – Observed UK climate data (1961-1990) (UKCP09, 2017a). For
358 each catchment, precipitation data were processed for PESERA by computing monthly rainfall
359 metrics at each rain gauge site as follows: mean monthly rainfall, mean rain per rain day, and the
360 coefficient of variation of mean rain per rain day. Linear regressions of gauge elevation and rainfall
361 were used to interpolate the station data between gauge sites, forming a contiguous grid across all
362 three catchments. Rainfall gauges were grouped according to elevation (0-10 m; 10-100 m; 100-200
363 m; 200-300 m; 300-400 m & 400-500 m), and monthly and daily rainfall data were averaged across
364 all gauges within each elevation group. These mean values for monthly and daily rainfall were then
365 plotted against the upper value of each elevation groups (i.e. 10 m; 100 m, 200 m, 300 m; 400 m &
366 500 m) from which a linear regression was fitted, giving an equation linking rainfall metric (monthly
367 or daily) to elevation. To calculate the coefficient of variation of mean rain per rain day across the
368 whole catchment, the monthly coefficient of variation of mean rain per rain day data were first
369 grouped into seasons (December to February – winter; March to May – spring; June to August –
370 summer; September to November – Autumn) before being averaged across all gauges within each
371 elevation group and plotted, as described previously. Finally, we converted gridded elevation data into
372 monthly rainfall metrics using the regression equations described above. Mean daily temperature and

373 the daily temperature range were calculated from the weather stations in each catchment and then
374 standardised by recalculating them at sea level using a lapse rate of 6°C per 1000 m. Where
375 catchments had more than one temperature gauge, the catchments were divided into equally spaced
376 parcels with temperature values derived from the nearest weather station.

377

378 Climate predictions of future changes were interpolated from weather station data provided by the UK
379 Met Office and proportionally modified for the future scenarios using UKCP09 projections under the
380 medium-emissions scenario SRES 1AB, projections are based on the UK Met Office Hadley Centre
381 climate model HadCM3. Estimates of potential evapotranspiration across each catchment were
382 obtained from the UK Met Office Rainfall and Evaporation Calculation System (MORECS, Hough et
383 al., 1997).

384

385 Precipitation and temperature data for the periods 2010-2039, 2040-2069, and 2070-2099 were
386 obtained from the 25 km-grid UK Climate Predictions (UKCP) User Interface (UK Climate
387 Predictions 2012, Figure 2) for each calendar month under the SRES A1B emissions scenario. In
388 particular, data were downloaded for each calendar month under the low, medium and high emissions
389 scenarios and at the 10%, 50% and 90% probability levels. Probabilistic climate projection are
390 measures of strength of evidence in different future climate change outcomes. These measures are
391 based on the current available evidence, encapsulating some of the uncertainty associated with
392 projecting future climate and conventionally concerning the probability of change being less than
393 given thresholds. (Murphy et al., 2010). The resolution of UKCP predictions are 40 km², and so each
394 100-m² grid square of each catchment was attributed to the correct UKCP grid number using the
395 extract value to points tool in ArcGIS. The nearest land predictions were used for parcels of land
396 within UKCP09 grid squares that were predominantly ocean. Temperature data were standardised
397 using a lapse rate of 6°C per 1000 m. The absolute change values from the UKCP-09 data were then
398 added to the baseline values for precipitation and temperature. No change was made to the coefficient
399 of rainfall per rain day values since the monthly and daily rainfall values had all been manipulated by
400 exactly the same amount the degree of change remained constant. Temperature range was adjusted

401 using the absolute change values for minimum and maximum daily temperatures.

402

403 **2.6 Sensibility Analysis implementation**

404 Temperature and rainfall increments were examined using an experimental framework, combining
405 temperatures ranging from 0 to 8 °C and rainfall variations from -25 to +100% compared to the
406 baseline values (i.e., averages of 1961/1990 dataset). It should be noted that this combination attempts
407 to represent and explore how the PESERA models react to a systematic change of these two variables
408 and is not used for climatic modelling of the area (Figure 4). Within the charts, dots indicate the
409 points related to the effective rainfall temperature combination of the three climatic scenarios derived
410 from UKCP09 SRES A1B simulations. The procedure is useful to observe the reaction of the model,
411 explore values other than those from real simulated scenarios, and to test different feedbacks in the
412 context of climate and vegetation type.

413

414 **3. Results and Discussion**

415 **3.1 Retrospective**

416 The assessment of soil erosion by modelling remains a complex exercise due to uncertainty of the
417 outputs, result validation (Alewell et al., 2019; Batista et al., 2019; Boardman, 2018; Evans & Brazier,
418 2005; Evans et al., 2016; Nearing, 2011), and the models behaviour in simulating hydrological fluxes
419 (Baartman et al., 2020; Eekhout & De Vente, 2019). In addition to inspecting PESERA's capabilities
420 under the climate change constraints, some reflections should be directed to the previous soil erosion
421 observations, when possible, in areas close to the catchments we modelled. The intention is to provide
422 support, even if marginal, as an ideal validation of our results.

423

424 The main concern is scarcity of specific observations within the studied catchments as well as the
425 availability of direct monitoring at the basin scale. Nevertheless, Great Britain presents consistent
426 literature on soil erosion and a rich dataset of soil erosion observations, which has been collected
427 since the 1960s using a wide range of methodologies on various spatial and temporal scales
428 (Boardman, 2006, 2013; Boardman et al., 1990; Boardman & Evans, 2006, 2019; Brazier, 2004;

429 Evans, 1995, 2005; Evans et al., 2016, 2017). In situ observations over long periods have been
430 performed in several programs. For instance, studies, such as the regional Soil Survey of England and
431 Wales (SSEW, 1982-1986), Soil Survey and Land Research Centre (SSLRC, 1996-1998) on the
432 location of the National Soil Inventory (NSI), and Agricultural Development and Advisory Service
433 (ADAS, 1989-1994), have constituted some of the largest efforts in quantifying soil erosion
434 nationwide until now (Boardman, 2002; Evans, 2005).

435

436 Recent works inventoried Great Britain erosion data to improve the understanding of the
437 phenomenon. Benaud et al. (2020) realised a web-based, open-access, interactive geodatabase from
438 previous records of soil erosion, which is at now available and integrable by users (i.e.,
439 <https://piabenaud.shinyapps.io/SoilErosionMap>), that undoubtedly provides excellent support to
440 collect past and future data as support for modelling validations. For a general reference of the
441 phenomenon, a total of 1566 individual records across Great Britain have reported soil loss averages
442 of 1.27 and 0.72 t ha⁻¹ y⁻¹ for arable and grassland, respectively. In addition, Graves et al. (2015)
443 grouped erosion values from the available national datasets for the principal soils of Great
444 Britain and determined erosion averages of 1.0 to 22.4, 0.05 to 0.75, and 0.01 to 0.5 t ha⁻¹ y⁻¹ in
445 different soil textures of arable land, grasslands, and forestry, respectively. Similar values were
446 summarized by Rickson et al. (2014) based on reports of Brazier (2004) and Brazier et al. (2012),
447 providing rates of erosion from hillslope to the large catchment scale from various soil/land use
448 combinations. Erosion data generally have a wide distribution of values (by one order of magnitude),
449 and significant temporal trends have not been clearly identified by the numerous field observations
450 over the country. Nevertheless, an increase in flooding due to land use changes have been recorded,
451 such as in the case of observations of S-E England (South Downs) collected over 25 years
452 (Boardman, 1976-2000; Boardman, 2003; Evans & Boardman, 2003). In general, even if the erosion
453 is supposed to increase in the future because of increased rainfall (Burt et al., 2016) due to climate
454 change (Boardman & Favis-Mortlock, 2001; Mullan et al., 2012), there are a multitude of other
455 factors that make it difficult to understand this phenomenon such as changes in land use and crops
456 that increase erosive cultures meant to increase soil loss (Boardman et al., 2009; Evans, 2002),

457 conversion to more intensive livestock rearing (Evans, 2006b) or changes in the timing of crop
458 planting from spring to autumn. A report of state-of-the-art observations as support for erosion
459 modelling activities is given by Evans et al. (2016).

460

461 To the best of our knowledge, there have been a few observations close to our study sites. For
462 instance, in Cumbria County (Ehen catchment), Brazier (2004), from previous studies done by the
463 Agricultural Development and Advisory Service in collaboration with the Soil Survey of England and
464 Wales (1982-86), founded averages of about 0.22 t ha⁻¹ y⁻¹ in medium and light sandy loams, while
465 Skinner and Chambers (1996), and similarly Evans (1993, 2013), reported rates of 1.5 m³ ha⁻¹ for a
466 four-year record in the same catchment.

467 The available information for Northern Wales (Conwy catchment) is, for the most part, referred to as
468 the extensive grassland of the region. For instance, James et al. (1998) estimated annual soil loss
469 ranging 0-2.7 t ha⁻¹ y⁻¹ from grassland in Clwydian Hill using plot simulations. McHug et al. (2002,
470 2007) observed general increases in highlands of Wales and England fields and no changes in erosion
471 for sites of northern Wales based on with data collected from 1997-1999 and 2001-2002.

472 Much of what we know about erosion rates on agricultural land in Eastern Scotland (Dee catchment)
473 comes from individual studies (Davidson et al., 2001). Watson and Evans (2008) obtained large
474 distribution values with a median of about 2.5 m³ ha⁻¹ from field observations in agricultural lowlands.
475 Rickson et al. (2019) utilized Scottish Environment Protection Agency (SEPA) surveys on 10 selected
476 catchments and summarized previous datasets to estimate erosion rates of 0.01-23.0 t ha⁻¹ yr⁻¹ in
477 arable areas of Scotland in addition to soil losses of 0.13-0.33, 0.07-0.12, and 0.04-0.07 mm yr⁻¹ for
478 arable land, rough grassland, and forests, respectively.

479

480 **3.2 Modelling results**

481 Our modelling results, under baseline conditions, determined average soil erosion rates of 0.24 and
482 0.28 t ha⁻¹yr⁻¹ for Conwy and Ehen catchments, respectively (Figure 3, Table 2). The Dee catchment
483 experienced higher rates of soil loss, with a catchment-wide average soil erosion rate equal to 0.65 t
484 ha⁻¹yr⁻¹ due to the prevalence of highly erodible soils within steep catchment margins. Model results

485 under baseline conditions also reveal the importance of land cover in soil loss. In all cases, average
486 soil erosion rates for forests and grasslands were significantly less than those for arable lands (t-tests:
487 $\alpha=0.05$; KW: $\alpha=0.05$). KS tests further confirm that the distribution of soil erosion rates for arable
488 lands differs from forests and grasslands ($\alpha<0.05$) in all catchments.

489 On average, PESERA predicts that forests, grasslands, and arable lands yield 0.36, 0.26, and 1.09
490 t ha⁻¹yr⁻¹ of soil during baseline conditions (Table 2). Values obtained for soils of forests, grassland,
491 and arable land in Conwy, Ehen, and Dee catchments were determined to be 0.20, 0.22, 1.17; 0.25,
492 0.23, 0.48; and 0.62, 0.32, 1.62 t ha⁻¹yr⁻¹, respectively.

493

494 In climatic projections for 2010-2039, 2040-2069, and 2070-2099 (Figure 4, Table 2), all the
495 catchments show, at the 10th and 50th percentiles, values lower or slightly lower than the baseline
496 (from 0.17 to 0.21, 0.22 to 0.28 and 0.44 to 0.66, t ha⁻¹yr⁻¹, for the Conwy, Ehen and Dee,
497 respectively). At the 90th percentile, the Conwy catchment still holds values close to the baseline (0.23
498 to 0.25 t ha⁻¹ yr⁻¹), while Ehen and Dee are higher than the reference (0.34 to 0.45 and 0.90 to 0.95 t
499 ha⁻¹yr⁻¹, respectively).

500 Sensitivity analyses of testing temperature changes from 0 to 8 °C and rainfall variations from -25%
501 to +100% reveal specific erosion trends, proportional to rainfall and inversely proportional to
502 temperature risings (Figure 4). Globally, the values span from a minimum of 0.02 in Conwy to a
503 maximum of 3.26 t ha⁻¹y⁻¹ in Dee (Figure 5a) with variations from the baseline ranging from -90% to
504 +402.9% (Figure 5b).

505

506 **3.3 General considerations**

507 The sensitivity analysis reveals that the three catchments have similar responses to the variations of
508 climatic parameters (Figures 4 and 5): 1) The erosion rate displays a growing trend proportional to
509 increasing rainfall, which is less evident in the Conwy and more pronounced in the Ehen and Dee, 2)
510 A reduction effect of temperature on soil loss is observed in the Conway and Ehen catchments most
511 likely due to vegetation production, but less evident in Dee as detailed below.

512 Regarding impacts of incremental increases in rainfall on soil erosion but at baseline temperature (i.e.,
513 temperature increment = 0) (Figure 5b), we note a minor effect across the Conwy catchment (from 0
514 to 213.5%), an average response across the Ehen (from -24.1 to 315.1%), and a maximum influence
515 across the Dee (from -24.5 to 379.5%), which appears to result from the integrative effects of
516 different land uses. Forest and grassland, the most mitigating surfaces, are dominant (92%) in the
517 Conwy, where there are also limited crops (1.8%), and thus can contribute to reduced erosion. In
518 contrast, crops can enhance the effect across the Dee as they comprise 7.2% of the land surface.
519 Temperature also has a contribution in reducing erosion. At baseline rainfall values (Figure 5b) (i.e.,
520 rainfall increment = 0), increases in temperature can reduce erosion to -45.5, -36.8, and -24.2% for the
521 Conwy, Ehen, and Dee, respectively.

522 When erosion reduction is calculated respect to the baseline temperature within each relative rainfall
523 increment (Figure 5c), it is still the greatest in the Conwy (from -90% at -25% rainfall to -28.5% at
524 +100% rainfall), has an average effect in the Ehen (from -32.7% at -25% rainfall to -18.9% at +100%
525 rainfall), and exerts a more constraining effect in the Dee (from -30% at -25% rainfall to 2.8% at
526 +100% rainfall). This influence is more evident in the Conwy and Ehen due to the vegetation
527 productivity of forest and grassland, which respectively comprise a total of 92% and 94% of the
528 surface compared to 88% in the Dee catchment.

529 Based on our results, temperature growth can compensate for the increased erosion that would have
530 otherwise been generated through increases in rainfall. As shown in Figure 5b, a reversal point is
531 detected at 25% rainfall between 4-6 °C in the Conwy, at +5% rainfall between 0-1°C in the Ehen,
532 and at +5% rainfall between 2-4°C in the Dee. The difference is still due to the effect of the higher
533 percent of forest and grassland in the Conwy and Ehen than in the Dee.

534 Generally, the sensitivity analysis reveals the potential role of vegetation in limiting rates of soil loss
535 caused by increased rainfall. Each catchment is capable of experiencing reduced rates of soil loss
536 relative to baseline conditions when the increased rainfall is associated with higher air temperatures.
537 If primary productivity is not limited by nutrient availability or soil moisture, then sustained increases
538 in air temperature should lead to greater vegetation cover, requiring more rainfall to accelerate soil
539 loss. Temperature-driven increases in aboveground biomass decrease the likelihood of infiltration-

540 excess runoff because of the associated increases in both rainfall interception and the soil's water-
541 holding capacity (Routschek et al., 2014).

542

543 **3.4 Land use influence**

544 In conjunction with a decrease in soil erodibility caused by the enriched biomass, these effects can
545 lead to a potential negative-feedback mechanism that can limit climate-driven soil loss, but only
546 where vegetation cover persists throughout the year. Forests and grasslands, which comprise a greater
547 proportion of the land surface of all catchments, appear relatively resilient to increased rainfall, where
548 any associated increases in air temperature generally reduce changes in erosion (Figure 4, a and b).
549 Conversely, large surfaces of arable lands can be more reactive to rainfall changes with a lower
550 response to increases in temperature (Figure 4c). These behaviours are well observed in charts for
551 different land uses, as shown in Figure 6, where the threshold line is shifted to the right in grassland
552 and forest (towards high rainfall - high temperatures), with no substantial effect from high
553 temperatures on arable lands.

554 The negative feedback provided by forests and grasslands should be limited during winter months,
555 when aboveground biomass is reduced and rainfall is more intense. Seasonal patterns in soil loss
556 across arable lands are more sensitive to agricultural cycles associated with particular crops, which
557 will define the time periods when arable lands are fallow. Arable lands will thus require mitigation
558 strategies to minimize soil loss during fallow periods when vegetation cover is minimal or absent.

559

560 **3.5 Climatic scenarios effect**

561 Mapping the UKCP09 projections for the IPCC medium-emissions scenario SRES A1B onto the
562 results of the sensitivity analysis (Figures 4 and 6) reveals perhaps the most important implication of
563 our findings. UKCP09 projections indicate that future climate changes may involve consistent
564 changes in average-monthly rainfall and average-annual air temperatures. Consequently, moving
565 through the 2010-39, 2040-69, and 2070-99 projections, we observe some differences between the
566 erosion response of the catchments (Figure 4, Table 2). For the Conwy, we report a decrease of
567 erosion rate at all the percentile levels (from 4.2 to -33%), which is more consistent at the 10th

568 percentile. In the Ehen, a slight decrease in erosion (from 0 to -28.6%) is detected at the lower
569 percentiles (10th and 50th), while an increase is observed from 21.4 to 60.7% at the 90th percentile. The
570 Dee catchment has a similar behaviour, but with a more consistent decrease for the 10th and 50th
571 percentiles (from 1.5 to -35.8%) and higher erosion rates for the 90th percentile (from 31.1 to 46.2%).
572 Over the statistical framework of the climatic scenario projections, it is reasonable to say that,
573 considering the 90th percentile as the more “inclusive” of the climatic predictions, a generalised future
574 decrease of the erosion rates is verified in the Conwy catchment, while an increase is identified for the
575 Ehen and Dee.

576 Critical to our findings is that patterns of land use is the principal variable determining the varying
577 responses to climate change between the catchments. Forest and grassland are responsible for a
578 decreasing or stationary change in erosion rates, more pronounced for the Conwy and less marked in
579 the Ehen and Dee. In the Dee, more erodible soils due to topography cause a slightly different
580 response, but the effect of arable lands associated with increased erosion are present in almost all
581 projections, especially in the Ehen and Dee catchments starting from 50th and 90th percentiles.

582 Although the manner by which vegetation will respond to climate change remains unclear (Arneth,
583 2015, Davies-Barnard et al., 2015), including a possible expansion of arable lands (Adams et al., 1990;
584 Nelson et al., 2014), our findings indicate the potential of climate change to reduce soil loss by
585 enhancing primary productivity. Our results, illustrating the potential impacts of climate change on
586 vegetation growth, are comparable to previous assessments (Bull, 1991; Melillo et al., 1993; Acosta et
587 al., 2015). Moreover, the negative-feedback mechanism that we observed may be pervasive
588 throughout permanently vegetated environments, given that soil erosion can occur due to a range of
589 processes that can be limited by enhanced primary productivity (e.g., rain splash, debris flow).

590

591 **4. Conclusions**

592 The objective of this research was to verify the impact of climate change and vegetation on soil
593 erosion in three catchments by the way of a sensitivity analysis as modelled by the Pesera. For that,
594 with adopted a systematic implementation of changes of temperature and rainfall to acknowledge
595 general behaviour of the model, then, we assessed the impact on erosion using the climatic projection

596 from UKCP09 at the horizons 2010-39, 2040-69 and 2070-99. The results of the modelling suggest
597 that an increasing in rainfall has a direct and positive effect on erosion, while temperature rise can
598 mitigate runoff and erosion. Current evidence suggests that climate change is increasing net primary
599 productivity (Nemani et al., 2003; Buermann et al., 2016; Ballantyne et al., 2017) with the potential
600 for increased water usage (Frank et al., 2015; Berg et al., 2016) and vegetation cover on a global scale
601 (Betts et al., 1997). Based on our findings, the presented modelling work is in line with these
602 observations and highlights the potential impacts of climate change on soil erosion due to overland
603 flow.

604

605 In areas with permanent vegetation cover, climate change could reduce the likelihood of overland
606 flow by increasing interception losses and infiltration rates. Increases in below-ground biomass would
607 also reduce soil erodibility. This effect is evident when arable lands and forest/grassland are
608 compared: forest and grasslands are highly affected by primary vegetation productivity, mitigating the
609 impact of climatic change (i.e., increased rainfall and temperature) on soil erosion; while arable lands
610 are less influenced by the vegetation productivity effect due to their annual agricultural cycle. That
611 said, there are three important issues should be further addressed regarding our findings.

612

613 First, plant growth in our modelling approach is driven primarily by air temperature and does not
614 consider increases in atmospheric CO₂, which may end up improving plant water-use efficiency (Van
615 der Sleen et al., 2015). Second, our use of daily rainfall in assessing precipitation may be too coarse to
616 adequately document the impacts of short-lived, high-intensity events. Although predictions of hourly
617 and sub-hourly rainfall resulting from climate change may be speculative, advances in modelling
618 performance provide an opportunity to assess the impacts of rainfall extremes (Kendon et al., 2014).

619 And finally, our approach does not consider sustained shifts in land cover that may result directly
620 (Eigenbrod et al., 2015) or indirectly (Nelson et al., 2014) from climate change. Nevertheless, our
621 results confirm the potentially negative feedback of the function of plants in the environment as
622 implemented in the model. Indeed, the results verify the importance of both conserving and expanding

623 vegetation cover to improve the landscapes' ability to withstand the impacts of climate change on
624 widespread soil loss.

625

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638

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