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Addressing key limitations associated with modelling soil erosion under the impacts of future climate change

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ABSTRACT

Future climate change is expected to impact the extent, frequency, and magnitude of soil erosion in a variety of ways. The most direct of these impacts refers to the projected increase in the erosive power of rainfall, whilst other more indirect impacts include changes in plant biomass and shifts in land use to accommodate the new climatic regime. Given the potential for climate change to increase soil erosion and its associated adverse impacts, modelling future rates of erosion is a crucial step in its assessment as a potential future environmental problem, and as a basis to help advise future conservation strategies. Despite the wide range of previous modelling studies, in the majority of cases limitations are apparent with respect to their treatment of the direct impacts (changed climate data), and their failure to factor in the indirect impacts (changing land use and management). In this study, these limitations are addressed in association with the modelling of future soil erosion rates for a case study hillslope in Northern Ireland using the Water Erosion Prediction Project (WEPP) model. The direct impacts are handled using statistical downscaling methods, enabling the generation of site-specific, daily resolution future climate change scenarios, and a simple sensitivity analysis approach is employed to investigate the previously unstudied impacts of sub-daily rainfall intensity changes. Finally, the frequently neglected indirect impacts are examined using a scenarios-based approach. Results indicate a mix of soil erosion increases and decreases, depending on which scenarios are considered. Downscaled climate change projections in isolation generally result in erosion decreases, whereas large increases are projected when land use is changed from the current cover of grass to a row crop which requires annual tillage, and/or where large changes in sub-daily rainfall intensity are applied. The overall findings illustrate the potential for increased soil erosion under future climate change, and illuminate the need to address key limitations in previous studies with respect to the treatment of future climate change projections, and crucially, the factoring in of future land use and management.

1. Introduction

Soil erosion is a major environmental threat to the sustainability and productive capacity of agriculture (Yang et al., 2003; Feng et al., 2010). It is estimated that around 10 million hectares of cropland are lost to erosion annually (Yang et al., 2003; Pimentel, 2006). With world population projected to increase by 47% from the start to the mid-point of the 21st century (UN, 2005), global food demand is increasing at a time when per capita food productivity is beginning to decline. This reduction in soil productivity and fertility, which represents the most significant of the 'on-site impacts' of soil erosion, is most prevalent in the tropical and subtropical agroecosystems of Asia, Africa and South America, where soil loss averages 30–40 t/ha/year (Taddese, 2001). In temperate regions, meanwhile, it is the 'off-site impacts' of soil erosion that tend to present a greater problem. The term 'muddy flood' perhaps best encapsulates the off-site impacts of erosion, describing the flow of water and sediment out of agricultural fields, resulting in downslope damage to properties, roads and watercourses (Boardman, 2010). Studies from around Europe have estimated the costs of muddy floods, resulting from damage to private householders and public infrastructure, revealing costs of €957,000 following a single event in Brighton, England in 1987 (Robinson and Blackman, 1990), €118 ha^{-1} $year^{-1}$ in Soucy, France over a ten year period, and a mean annual cost of around €14–140 million $year^{-1}$ in Belgium (Evrard et al., 2007). Erosion has also been recognised as a major non-point pollution source that adversely affects ecosystem water quality (Cochrane and Flanagan, 1999). In Ireland, for example, the generally low permeability of soils, coupled with gentle stream courses, mean runoff rates are among the highest in

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Western Europe (Wilcock, 1997). This results in the off-site transport of agricultural pollutants in runoff, with nitrate and phosphate from agricultural fertilisers considerably degrading water quality in major Irish lakes such as Lough Neagh and Lower Lough Erne (e.g. Anderson, 1997; Watson et al., 2000; Watson and Foy, 2001).

The incidence of these adverse impacts of soil erosion may become a more significant problem, since future climate change is expected to impact the extent, frequency, and magnitude of soil erosion in a variety of ways (Pruski and Nearing, 2002a). The most direct of the impacts of climate change on soil erosion is the change in the erosive power of rainfall (Favis-Mortlock and Savabi, 1996; Williams et al., 1996; Favis-Mortlock and Guerra, 1999; Nearing, 2001; Pruski and Nearing, 2002a). Increases in global temperature lead to increases in the moisture-holding capacity of the atmosphere at a rate of about 7% per 1 °C. This results in increased water vapour in the atmosphere, and ultimately a more vigorous hydrological cycle (Nearing et al., 2005), promoting a trend towards more intense precipitation events (Trenberth et al., 2003). Climate models are projecting a continued increase in intense precipitation events during the 21st century (IPCC, 2007). Another potential consequence of climate change upon soil erosion relates to changes in plant biomass, with complex changes that can both increase erosion rates through faster residue decomposition from increased microbial activity (Nearing et al., 2005), and decrease erosion rates through an increase in soil surface canopy cover and biological ground cover (Rosenzweig and Hillel, 1998). A more indirect potential impact of climate change on soil erosion refers to shifting agricultural practice and hence land use to accommodate the new climatic regime (Williams et al., 1996). Reacting to changes in climate could range from changing planting dates to the implementation of new crops or complete land use changes, which have the potential to significantly alter soil erosion rates and patterns (Nearing et al., 2005). For example, the introduction of new crops suited to warmer conditions, such as maize and sunflowers, increase risk of erosion as both take a significant amount of time to provide adequate crop cover in early summer (Boardman and Favis-Mortlock, 1993).

Given the potential for climate change to increase soil erosion and its associated adverse impacts, modelling future rates of erosion is a crucial step in its assessment as a potential future environmental problem. Prediction models have become increasingly important tools in the assessment of soil erosion and are the only practicable means of assessing the response of soil erosion to future climate change (Lal, 1998; Toy et al., 2002). In particular, the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995) has been widely used in the prediction of future erosion rates under climate change (e.g. Favis-Mortlock and Boardman, 1995; Favis-Mortlock and Guerra, 1999, 2000; Pruski and Nearing, 2002a,b; Zhang et al., 2004, 2009; O'Neal et al., 2005; Zhang, 2005, 2007; Zhang and Liu, 2005; Zhang and Nearing, 2005; Klik and Eitzinger, 2010). The WEPP model is a physically-based, continuous simulation model that simulates hydrology, water balance, plant growth, soil, and erosion at field, hillslope, and small watershed scales. In this study, WEPP is used to model soil erosion under the impacts of future climate change for a hillslope in Northern Ireland. In association with this, the case study aims to illuminate some of the key issues associated with modelling soil erosion under future climate change, by reviewing and critiquing the methodologies used in previous studies, and then outlining approaches to address them.

2. Previous studies and their limitations

A number of modelling studies have investigated the impact of future climate change on soil erosion (Table 1). Three fundamental

Table 1
Previous studies of soil erosion under future climate change, including treatment of future climate change and consideration of future land use.

Year	Author(s)	Country/region	Erosion model	Representation of climate change			Representation of land use/management
				Approach	Spatial scale	Temporal scale	
1990	Boardman et al.	Southern England	EPIC	Sensitivity analysis based upon qualitative data	Regional	Monthly – disaggregated to daily	Only discussed
1993	Phillips et al.	Conterminous USA	USLE	Climate change scenarios from four GCMs	Regional	Annual	Only discussed
1995	Favis-Mortlock and Boardman	UK South Downs	EPIC	Change factor downscaling	Site-specific	Monthly – disaggregated to daily	Only discussed
1996	Lee et al.	US Corn belt	EPIC	Sensitivity analysis	Regional	Monthly – disaggregated to daily	Not considered
1999	Favis-Mortlock and Guerra	Mato Grosso, Brazil	WEPP	Change factor downscaling	Site-specific	Monthly – disaggregated to daily	Only discussed
2000	Favis-Mortlock and Guerra	Mato Grosso, Brazil	WEPP	Change factor downscaling	Site-specific	Monthly – disaggregated to daily	Only discussed
2002a 2002b	Pruski and Nearing	USA	WEPP	Change factor downscaling	Site-specific	Monthly – disaggregated to daily	Only discussed
2004	Zhang et al.	Oklahoma, USA	WEPP	Change factor downscaling	Site-specific	Monthly – disaggregated to daily	Planting dates changed using analogues
2005	O'Neal et al.	Midwest USA	WEPP	Change factor downscaling	Site-specific	Monthly – disaggregated to daily	Changes in crops and planting dates modelled
2005	Zhang	Oklahoma, USA	WEPP	Statistical downscaling	Site-specific	Monthly – disaggregated to daily	Planting dates changed using analogues
2005	Zhang and Liu	Southern Loess Plateau, China	WEPP	Statistical downscaling	Site-specific		
2007	Zhang	Southern Loess Plateau, China	WEPP	Statistical downscaling	Site-specific	Monthly – disaggregated to daily	Planting dates changed using analogues
2009	Zhang et al.	Southern Loess Plateau, China	WEPP	Statistical downscaling	Site-specific	Monthly – disaggregated to daily	Planting dates changed using analogues
2010	Klik and Eitzinger	Austria	WEPP	Change factor downscaling	Site-specific	Daily	Various scenarios