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Soil erosion and tolerable soil loss: Insights into erosion rates for a well-managed grassland catchment

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ABSTRACT

Soil erosion and its spatial and temporal variabilities are rarely placed in the context of soil production and soil depth. This study examines the question of sustainable soil erosion and soil loss in a conservatively managed grassland catchment in South East Australia in what at first appears to be a catchment with a tolerable soil loss. Catchment erosion rates are determined using the environmental tracer ^{137}Cs. A thorough examination of the accuracy and reliability of this method is conducted across a number of spatial scales and years providing confidence in the method and results. Soil depth is measured across the study catchment providing the first bedrock map of a basalt derived soil catchment. Both soil erosion and soil depth are topographically assessed using a high resolution digital elevation model. Results show that soil depth was strongly correlated with elevation and also wetness indices indicating a strong relationship with soil moisture in soil production. Interestingly bedrock topography was decoupled from surface topography. Erosion rates using the ^{137}Cs method and calibrated against independent field data produced a maximum erosion rate of between 0.8 and 2.9 t ha^{-1} yr^{-1} using two different modelling approaches. Even though the erosion rates are low, given a mean soil depth of 0.44 m for the catchment this suggests that soil is being lost at rates greater than production. This highlights the significance of assessing erosion loss in the context of overall soil depth and production rates and that even in areas with what appears to be low soil loss rates, the loss can be higher than production. The findings provide a rationale to examine soil erosion in the context of whole catchment processes, not simply soil loss in isolation to other hillslope and catchment data.

1. Introduction

Soil erosion can be a serious issue when soil erosion is greater than soil production resulting in the long-term loss of soil depth therefore reducing water holding capacity, nutrient storage and overall soil productivity (Li et al., 2009; Mandal et al., 2006; Phillips, 2010). In many grassland environments, both in Australia and globally, soil is being lost at a greater rate than its production yet there is surprisingly little data to quantify this issue (Di Stefano et al., 2005; Edwards, 1987; Fifield et al., 2010; Heimsath et al, 2000, 2002, 2009; Li et al., 2009; Phillips, 2010; Pillans, 1997; Porto and Walling, 2012; Porto et al., 2013; Wilkinson and McElroy, 2007; Wilkinson et al, 2005; Williams, 1978). Few soil erosion studies quantitatively examine this issue in terms of soil production rates and a sustainable or tolerable soil loss (Li et al., 2009; Mandal et al., 2006; Montgomery, 2007b).

The reason for this is that determining soil erosion rates, while theoretically easy, is anything but simple (Boix-Fayos et al., 2006; Merritt et al., 2003; Parsons and Foster, 2011; Porto et al., 2009; Tucker and Hancock, 2010). Determining soil production rates is even more difficult. In practice determining an erosion rate is fraught with difficulties due to spatial and temporal practicalities. Methodologies range from very inexpensive devices such as erosion pins used at the smallest (point) scale, with multiple pins used for hillslope scale analysis (i.e. Hancock and Evans, 2010), through integrated catchment assessments employing flumes where total sediment load is collected (i.e. Boix-Fayos et al., 2006; Hancock et al., 2000). In all cases many years of data collection are required so that a sufficient number of representative events are likely to occur and are sampled. Rainfall simulators and other devices such as laboratory flumes on the other hand can provide quick and repeatable data but have the issue of scale and choice of rainfall event to contend with (Loughran et al., 2002, 2004; Porto et al., 2001; Zapata et al., 2002). Environmental tracers such as ^{137}Cs offer the ability to quantify decadal scale erosion rates but tracer methods require extensive soil sampling, expensive analysis equipment and complex analysis procedures (Parsons and Foster, 2011). Nevertheless, environmental tracer analysis is a reliable and proven method by which decadal scale (10–50 yrs) erosion assessments can be determined despite the many limitations (Parsons and Foster, 2011).

While the determination of soil erosion patterns and rates is a non-trivial task, quantification of soil production rates is much more difficult. Soil production rates are impacted by many environmental factors and

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determining the influence of each through time is difficult (Cohen et al., 2009). Field assessments at sites where there are well structured paleao-sequences of soil can provide relative ages and production rates using methods such as Uranium/Thorium data (Pillans, 1997). Soil production rates for unconsolidated parent materials can be determined from chronosequence of sedimentary origin and cosmogenic techniques used for materials with high quartz content but determining soil development rates on consolidated parent materials is much more difficult to achieve (Pillans, 1997). The above methods provide average or long-term production rate data yet provide little insight into the likely non-linear production rates as influenced by long-term climate fluctuations and associated biotic response.

The difference between soil erosion and soil production at any point on a hillslope is soil depth. Soil depth varies down a hillslope and across a catchment and according to the catena concept it is shallow at the hillslope crest and deepest at the footslope. Soil depth is a notoriously difficult hillslope feature to quantify. Quantification of these patterns can only be achieved by physical depth measurement using probes or alternatively remote sensing methods such as ground penetrating radar (GPR) (Frances and Lubczynski, 2011; Simeoni et al., 2009). Physical measurement is accurate and reliable yet time consuming if large areas require data (Boer et al., 1996; Nicotina et al., 2011; Tesfa et al., 2009; Vanwalleghem et al., 2010), while GPR is more rapid and easily done over large areas however interpretation of the return signal is problematic as the soil matrix, conductivity and water content changes. Due to these difficulties there is a global paucity of catchment scale soil depth data.

Placing erosion rates in the context of soil production and resultant soil depth is important for understanding and quantifying soil loss tolerance for long-term environmental and agricultural sustainability (Li et al., 2009; Mandal et al., 2006; Verheijen et al., 2009). Li et al. (2009) provide a review of soil loss tolerance definitions with the generally accepted concept being one where a high level of productivity and fertility be maintained over long time periods. This requires accurate spatial data for both soil loss and soil depth (Verheijen et al., 2009) however it has been recognised that soil loss and soil production rates and ultimately a soil loss tolerance value will vary both spatially and temporally (Mandal et al., 2006; Verheijen et al., 2009).

This paper is part of a long-term programme by the authors to quantify landscape evolution, soil erosion rates and paedogenesis over annual, decadal and millennial time scales using both field and modelling approaches (Cohen et al., 2009; Hancock et al., 2008, 2010, 2011; Martinez et al., 2009). In this study we determine erosion rates for a catchment in SE Australia across a range of spatial scales using an environmental tracer (^{137}Cs) and place the results in context of both reliability and accuracy. Soil depth patterns are also determined and the erosion and soil depth data are placed in the context of soil production. Finally, the results are discussed within the concept of tolerable soil loss and landscape management.

2. Study site

This study is based within the 150 ha Stanley catchment in the Upper Hunter region of New South Wales, Australia. The Stanley catchment (150°07′00″E and 32°05′32″S) is a tributary of the 562 km^2 Krui River catchment (Fig. 1). The Stanley catchment is an organic beef cattle grazing property. Portions of the catchment were once cropped (along the lower flats of the catchment), but are now covered with native pastures for cattle grazing. Currently, cell grazing and time-controlled grazing activities are practised on the property whereby cattle are routinely moved around from paddock to paddock restricting grazing pressure to small controlled areas for short time periods. This management practice is typical for the area and is believed to be more agriculturally productive as well as providing the additional benefits of controlling weeds, maintaining vegetation cover and minimising soil erosion.

The study site is located in the temperate zone of eastern Australia. The average annual rainfall for the area is 624 mm with distribution evenly spread across all months (www.bom.gov.au). The risk of erosion is greatest in summer months due to an increased occurrence of high intensity storms (Kovac and Lawrie, 1991) with fluvial erosion being the dominant process. Runoff production and erosion have occurred very infrequently since the commencement of field data collection (2003). In 2007 the catchment received record levels of storm rainfall and this produced severe erosion in the study catchment and surrounds. Modelling suggests that it is infrequent storms that produce the majority of morphological change (Hancock and Coulthard, 2012). Further, the landowners of 20 yrs have only seen runoff from the catchment during and shortly after storm events. Therefore the major runoff production process is infiltration excess overland flow with saturation excess flow only on rare occasions. Rills and gullies were observed by the authors after the 2007 storm suggesting that fluvial erosion is the dominant process. However, given the dense and consistent grass cover, surface wash may have occurred for other events but this has not been observed.

The geology of the area is predominantly tertiary basalt (Galloway, 1963), a product of Cainozoic volcanism which took place throughout much of eastern Australia (Branagan and Packham, 2000). The extent of the basalt however has been reduced largely as a result of erosive processes (Galloway, 1963). The Stanley catchment is underlain by Tertiary Basalt of the Liverpool Range beds and forms part of the Merriwa Plateau. Soils in the catchment consist of black dermosols on the ridge line, red dermosols on the hillslopes and vertosols (Isbell, 2002) on the creek flat.

The study catchment has 7 permanent monitoring stations installed which measure soil moisture and soil temperature (at depths of 0–50 mm, 0–300 mm, 300–600 mm, and 600–900 mm), one of which, S2, doubles as a weather station. Sites S2–S4 and S5–S7 are positioned on south–west and north–west facing hillslopes respectively, while S1 is located towards the catchment outlet on relatively flat terrain which lies alongside the main drainage line (see Rüdiger et al., 2007 for site details). The catchment contains the 8.83 ha first order stream catchment ("Stanley Jr") (Martinez et al., 2009) (Fig. 1) which is located on the southern side of the catchment and is a focus of this study.

The catchment flora is dominated by native grasses with scattered eucalypt species. Kovac and Lawrie (1991) classify the region's vegetation as eucalypt tree savannah, with sparse tree cover (Fig. 2). Since the field site was established in 2003 (Rüdiger et al., 2007) vegetation cover in the form of native and introduced species has been consistently maintained. To evaluate vegetation cover density at Stanley a field (samples were collected at 100 m spacings using a 0.5 m by 0.5 m quadrat in November 2005) and remote sensing assessment (using MODIS and Landsat data (2005–2007), Martinez, 2010) showed that while vegetation cover varied seasonally and annually this variation was consistent across the catchment. While it is not possible to assess vegetation variability prior to 2003, it is believed that the current landowners have consistently managed the vegetation since the property was acquired over the previous 20 yrs.

3. Methods

The aim of this paper is to better understand the relationship between soil erosion and soil depth at the catchment scale. This requires sampling of soil for a physical assessment of soil properties, an erosion assessment using fallout radionuclides along a series of transects and also at the catchment scale. Soil depth was also measured at the catchment scale. For the purposes of this paper we define soil as the entire soil profile down to bedrock. The data was spatially analysed using a digital elevation model (DEM). The field data collection, laboratory analysis and DEM data are described below.