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Soil properties and environmental tracers: A DEM based assessment in an Australian Mediterranean environment

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ABSTRACT

Terrain properties vary at the hillslope and catchment scale and play a significant role in the distribution of water and sediment. Of particular interest in recent years has been the role of hillslope and catchment properties in the spatial and temporal distribution of soil organic carbon (SOC) and the ability to predict SOC from DEM terrain analysis. SOC plays a significant role in soil health and productivity as well as providing a significant store of terrestrial carbon. This study examined SOC concentration along representative pasture transects in a catchment located in southern Western Australia with a Mediterranean climate. Results demonstrate that the majority of SOC (%) is located in the near-surface (300 mm) and is concentrated in the top 0.2 m. There was no relationship found between SOC (or microbial biomass) and topography or topographic derivatives such as wetness and terrain indices from DEMs. Significant relationships were however found between SOC and environmental tracers (^{137}Cs and ^{210}Pb$_{ex}$) down the soil profile. Weak, yet significant, relationships were found between SOC and the environmental tracers along the hillslope transects, suggesting that organic carbon moves along the same pathways as clay particles in soil. An erosion assessment using ^{137}Cs and also a numerical soil erosion and landscape evolution model found low and comparable erosion rates at the site. The results demonstrate that SOC concentration is relatively uniform across the study site and that a transect scale assessment can provide a measure of hillslope and catchment scale SOC in this environment.

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1. Introduction

Soil organic carbon (SOC) is central to soil aggregate formation, provides a buffer for nutrients and cation exchange capacity (especially in soils dominated by sand) and is the energy source for microbial activity and as such it is highly relevant to agricultural productivity. In recent years SOC has also become of interest for its carbon sequestration potential. Considerable research has been done to understand and predict the spatial and temporal distribution of SOC in relation to topography and vegetation together with erosion and deposition patterns (Pennock et al., 1994; Gregorich et al., 1998; Eatherall et al., 2000; Starr et al., 2000; Chaplot et al., 2001; Li and Lindstrom, 2001; VandenBygaart, 2001; Welsch et al., 2001; Ritchie and McCarty, 2003; Page et al., 2004; Thompson and Kolka, 2005; Van Oost et al., 2005; Yoo et al., 2006; Li et al., 2006, 2007; Huang et al., 2007; Gili et al., 2010). However, the ability to predict the spatial and temporal patterns of SOC is yet to be achieved for all environments. In particular, Australian environments have received much less attention (Young et al., 2005, 2009; Chan et al., 2010, 2011; Dalal et al., 2011).

Terrain attributes such as slope and hillslope curvature are considered important factors in SOC variability (Moore et al., 1993; Odeh et al., 1994; Pennock et al., 1994; Gregorich et al., 1998; Gessler et al., 2000; Chaplot et al., 2001; Tsui et al., 2004; Thompson and Kolka, 2005; Yimer et al., 2006; Yoo et al., 2006; Li et al., 2007). Geomorphology affects soil moisture content (Beven and Kirkby, 1979; Ticehurst et al., 2007), soil temperature and whether the soil experiences net erosion or deposition. This also affects plant growth type, and consequently, biomass amount (Gessler et al., 1995; Cookson et al., 2008). Hillslope soil erosion is also likely to affect SOC content (Lorenz and Lal, 2005). Consequently, hillslope position and soil toposequence will influence SOC and its cycling (Kirkby et al., 2011).

Microorganisms also have an important role in controlling the amount of SOC and its decomposition (Cookson et al., 2005; Hoyle and Murphy, 2007; Cookson et al., 2008). The physical location of microorganisms within the soil matrix, and also position within the catchment can also alter the supply of carbon and nutrients via soil solution (Hoyle and

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Murphy, 2007; Cookson et al., 2008). While a relatively small component of the overall SOC content, microbial biomass is understood to be the most dynamic fraction of overall soil organic carbon concentration.

Of the hydrological and SOC studies undertaken many have concentrated on forested tropical and subtropical regions or in cool temperate landscapes in Europe, North America and Asia where there is a strong anthropogenic influence (Pennock et al., 1994; Gregorich et al., 1998; Eatherall et al., 2000; Starr et al., 2000; VandenBygaart, 2001; Welsch et al., 2001; Ritchie and McCarty, 2003; Page et al., 2004; Van Oost et al., 2005; Yoo et al., 2006; Li et al., 2006, 2007; Huang et al., 2007). Investigations of non-tilled agricultural areas or undisturbed hillslopes are few (Yoo et al., 2006; Hancock et al., 2010; Martinez et al., 2010) or incomplete (Ritchie et al., 2004).

Several studies have examined the relationship between SOC and soil erosion (Pennock et al., 1994; Palis et al., 1997; Mabit and Bernard, 1998; Pennock, 2000; VandenBygaart, 2001; Ritchie and McCarty, 2003; Polyakov and Lal, 2004; Shukla and Lal, 2005; Van Oost et al., 2005; Li et al., 2006, 2007; Mabit et al., 2008) using both field and modelling approaches. In particular, the environmental tracer ^{137}Cs has been used in the past to assess the relationship between soil erosion and SOC (Pennock et al., 1994; Mabit and Bernard, 1998; Pennock, 2000; Li and Lindstrom, 2001; VandenBygaart, 2001; Ritchie and McCarty, 2003; Van Oost et al., 2005; Li et al., 2006, 2007; Mabit et al., 2008) as the movement of SOC is thought to be linked to the movement of the mineral fraction of soil. Few studies have examined the use of both ^{137}Cs and ^{210}Pb to quantify the movement of soil and SOC and assessed their viability as environmental tracers.

^{137}Cs (half-life of 30.1 years) is a product of the atmospheric testing of nuclear weapons which commenced in the 1950s (Loughran, 1994). During these atmospheric tests, ^{137}Cs was injected into the stratosphere and circulated globally. ^{137}Cs reaches the Earth's surface through both wet and dry deposition, with the majority of ^{137}Cs fallout through wet deposition (Walling and Quine, 1992). Upon reaching the soil surface, ^{137}Cs is rapidly and strongly adsorbed to clay particles (Ritchie, 1998) and remains virtually irreversibly attached to the soil particle. The subsequent movement of ^{137}Cs following adsorption is therefore a result of the physical movement of the soil particle itself (Ritchie and McHenry, 1975). This characteristic, along with its relatively long half-life, ease of measurement and the known timing of its introduction and distribution in the environment, make it an ideal tracer of soil movement. Many of the above studies have demonstrated strong relationships between SOC concentration and erosion and/or deposition (Mabit and Bernard, 1998; Li et al., 2006, 2007; Mabit et al., 2008).

Lead-210 (^{210}Pb) is a naturally occurring radionuclide from the ^{238}U decay series. It is derived from the decay of gaseous ^{222}Rn. Some ^{222}Rn in soil diffuses into the atmosphere and decays to ^{210}Pb and subsequent fallout of ^{210}Pb to the landscape surface provides an input that is not in equilibrium (but in excess) with its parent ^{226}Ra (Zapata, 2003). Fallout ^{210}Pb is commonly termed unsupported or excess ^{210}Pb (^{210}Pb$_{ex}$) when incorporated into soils or sediments in order to distinguish it from the ^{210}Pb produced *in situ* by the decay of ^{226}Ra. The use of environmental radionuclides overcomes many of the limitations associated with the traditional approaches for soil erosion measurement (i.e. erosion plots, erosion pins, stream sediment budgets) and has been shown as an effective way of studying erosion and deposition within the landscape (Zapata, 2003).

The key benefit of using ^{137}Cs and ^{210}Pb$_{ex}$ techniques is that they can provide retrospective information on medium-term (~50 year span) and long-term (~150 year span) redistribution patterns of soils within landscapes, without the need for long-term monitoring programs (He et al., 2002). When these isotopes reach the soil surface they are strongly adsorbed to the clay fraction of soil with biological and chemical processes removing little and with the physical processes of wind and water transporting ^{137}Cs and ^{210}Pb$_{ex}$ labelled soil both laterally and horizontally through the soil landscape. As environmental tracers, the chemistry of ^{137}Cs and ^{210}Pb$_{ex}$ is well understood (Zapata et al., 2002).

Numerical models of soil erosion also offer insights into soil redistribution patterns. Soil erosion models are used as tools for understanding erosion processes and their interactions and for the assessment of the environmental impacts of erosion, including loss of organic matter and nutrients, reduction of landscape productivity and a reduction in downstream water quality. More recently, and possibly aligned with ever increasing computer processing power, landscape evolution and soil erosion models have been developed that use digital elevation models (DEMs) to represent the land surface (Coulthard, 2001; Tucker and Hancock, 2010). These models have considerable advantages over traditional modelling approaches, as they remove the need to manually determine slope length and angle. Such models can also determine both erosion and deposition and dynamically adjust the landscape to erosion and deposition, producing a better representation of slope and angle over the duration of the simulation.

This study examines SOC and hillslope- and catchment-scale sediment transport along several hillslope transects in a Mediterranean-type climate of southern Western Australia subject to cattle grazing. The soils of Western Australia are characterised by low organic matter (typically <2%), low clay (typically <10%) and silt contents and therefore have generally low SOC accumulation. The variation of SOC with topographic attributes (derived from a DEM) is assessed together with the role of hillslope and catchment scale sediment transport both from field data and numerical models. While it is suggested that soils be sampled to at least 1 m or to bedrock if possible (McKenzie et al., 2000), this study focuses on the more biologically active near-surface layer (top 300 mm) where SOC is most concentrated and the environmental tracers ^{137}Cs and ^{210}Pb$_{ex}$ are present. The aim of this study is to better understand the factors regulating the spatial distribution of SOC at the hillslope and catchment scale in this little studied environment.

2. Study Site

The study catchment, located on Young River Station, drains into Stokes Inlet on the South coast of Western Australia, 75 km west of Esperance (Fig. 1). The area is dominated by agriculture with wheat, barley, canola and other crops grown together with the grazing of cattle and sheep. The property was one of the first in the area to be cleared in the 1950s as the area opened up for agriculture. There is no record of the study area being tilled since clearing and has been conservatively stocked with fertiliser applied every year to second year.

The site has a Mediterranean-type climate with an annual average rainfall of approximately 510 mm (1957–1999) (range of 291–748 mm), mostly falling in the winter months. Temperatures range from a mean maximum of between 27–29 degrees Celsius in summer to average winter lows of between 8–9 degrees Celsius (www.bom.gov.au). Evaporation in the summer months is high, with a January average of 240 mm (8 mm a day). The monthly evaporation decreases to 66 mm in June (2 mm a day). Daily evaporation can vary significantly from over 15 mm on a hot windy summer day to almost negligible on a cold wet winter day.

The area is presently tectonically inactive with basement rock of Achaean granites and gneisses emplaced during the Pre-Cambrian. During the tertiary, marine sediments were deposited over the basement rocks, creating the Werillup sedimentary formation. During the Quaternary, sands and limestone have been deposited and the Young River has eroded the sediments to expose bedrock at many places in the drainage lines (Bowyer, 2001).

The study catchment is representative of many in the local area and consists of a series of subcatchments which have long, linear hillslope profiles (Fig. 2). Hillslope length varies with subcatchment size. The study catchment size is approximately 470 ha and elevation ranges from 13 to 63 metres.

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