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Hillslope and catchment scale soil organic carbon concentration: An assessment of the role of geomorphology and soil erosion in an undisturbed environment

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ABSTRACT

The role of geomorphology in relation to the spatial and temporal distribution of soil carbon is of considerable interest in terms of landscape management and carbon sequestration. Soil carbon plays an important role in soil water holding capacity, soil structure and overall soil health. Soil is also a significant store of terrestrial carbon. This study examines total soil carbon (SC) concentration at the hillslope and catchment scale in the Tin Camp Creek catchment, Arnhem Land, Northern Territory, Australia. The catchment is largely undisturbed by European agriculture or management practices and is located in the monsoonal tropics. Results show that SC concentration along hillslope transects has remained consistent over a number of years and it is strongly related to hillslope position and topographic factors derived from precision surveying and provides a baseline assessment. Poor relationships were found when using a good quality medium resolution digital elevation model to derive topographic factors. This finding demonstrates the need for high resolution survey data for the prediction of total C at the hillslope and catchment scale. There was little difference in SC concentration between years and overall, SC down the hillslope profile varies little temporally suggesting that concentrations are relatively stable in this environment. An assessment of the relationship between SC and soil erosion using ^{137}Cs and erosion pins demonstrates that sediment transport and deposition play little role in the distribution of SC in this environment. Vegetative biomass appears to be the major contributor to SC concentration with vegetative biomass being strongly controlled by topographic factors. While the SC concentration is constant over the study period further sampling is required to assess decadal trends.

1. Introduction

Catchment soil carbon (SC) dynamics are linked to nutrient cycling and sediment transport and therefore should show temporal and spatial variability (Palis et al., 1997; Starr et al., 2000; Page et al., 2004; Polyakov and Lal, 2004; Schiettecatte et al., 2008). The availability of nutrients has a large impact on the breakdown of organic matter because soil bacteria require nitrogen for the breakdown of plant litter and soil temperature impacts on the rate of soil biological activity (Jobbagy and Jackson, 2000; Lorenz and Lal, 2005). Nutrients such as phosphorus can be attached to sediment and transported through and out of the catchment by fluvial processes. Living plant matter and leaf litter will also impact on sediment transport by providing a protective cover from rainfall and wash processes (Polyakov and Lal, 2004). Consequently to understand SC it is essential to understand both the spatial and temporal variation in SC and soil erosion and deposition dynamics (Ritchie and McCarty, 2003; Van Oost et al., 2005).

Position and terrain attributes in the landscape relative to hillslope curvature or slope segment is also considered an important factor in SC variability (Moore et al., 1993; Pennock et al., 1994; Thompson et al., 1997; Arrouays et al., 1998; Gregorich et al., 1998; Gessler et al., 2000; Chaplot et al., 2001; Polyakov and Lal, 2004; Tsui et al., 2004; Yimer et al., 2006; Yoo et al., 2006; Huang et al., 2007; Li et al., 2007). Hillslope position affects soil moisture content (Beven and Kirkby, 1979; Ticehurst et al., 2007), soil temperature and whether the soil experiences net erosion or deposition. Position also affects plant growth type and consequently biomass amount (Gessler et al., 1995). Hillslope soil erosion is also likely to affect SC content (Lorenz and Lal, 2005). Consequently hillslope position and soil toposequence is likely to influence SC and its cycling.

There is much to learn how land management and erosion processes affect carbon sequestration and redistribution in many environments (Van Oost et al., 2005; Dai and Huang, 2006; Li et al., 2006, 2007). Of the hydrological and SC studies undertaken many have concentrated on forested tropical and subtropical regions or in

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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; Welsch et al., 2001; VandenBygaart, 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) or incomplete (Ritchie et al., 2004). Field experiments and flume studies also provide the capacity for solid insights under controlled conditions and demonstrate how much more work is needed to understand field processes (Kuhn, 2007; Schiettecatte et al., 2008).

Several studies have examined the relationship between SC 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. The environmental tracer ^{137}Cs has been used in the past to assess the relationship between soil erosion and SC (DeJong et al., 1983; Pennock et al., 1994; Mabit and Bernard, 1998; Pennock, 2000; Ritchie and Rasmussen, 2000; VandenBygaart, 2001; Ritchie and McCarty, 2003; Van Oost et al., 2005; Li et al., 2006, 2007; Mabit et al., 2008) as the movement of SC is believed to be linked to the movement of the mineral fraction of soil. ^{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 fine soil 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 SC concentration and erosion and deposition.

Australia has received much less attention in this area and consequently there is a pressing need for accurate carbon accounting. Consequently, with the paucity of data upon which to develop carbon budgets, many fundamental questions concerning the fluxes and distribution of carbon, nutrients and sediment remain unanswered. This study examines SC over a number of years along hillslope transects in an undisturbed environment. The variation of SC with topographic attributes and elements of soil-landcape models (i.e. Gessler et al., 1995; Thompson et al., 1997; Arrouays et al., 1998; Gessler et al., 2000; Chaplot et al., 2001) related to erosion and deposition and vegetation biomass are assessed together with the role of hillslope and catchment scale sediment transport. The aim is to better understand the most important factors behind the spatial distribution of SC at the hillslope and catchment scale and provide baseline data to assess change at 5 years to decadal time scales.

2. Study site

Tin Camp Creek is in Arnhem Land, Northern Territory, Australia (Fig. 1). The catchment has a geology very similar to the Energy Resources Australia Ranger uranium mine (ERARM) and is thought to be an analogue for the long-term rehabilitated post-mining landscape. Subsequently the catchment has undergone extensive research in recent years to aid mine rehabilitation (Riley and Williams, 1991; Glindeman, 1992; Riley et al., 1997; Moliere et al., 2002; Hancock et al., 2002; Willgoose et al., 2003; Hancock, 2003, 2005; Hancock and Evans, 2006). This study investigating SC provides a further background assessment which will enhance knowledge of the natural processes and environment as an aid in the rehabilitation of uranium mines in the area.

The site is located in the seasonally wet/dry tropical environment of northern Australia, with an annual average rainfall of approximately 1400 mm, mostly falling in the wet season months from October to April. Short, high intensity storms are common and consequently fluvial erosion is the primary erosion process (Saynor et al., 2004).

The area is presently tectonically inactive (Needham, 1988). The Tin Camp Creek catchment is part of the Ararat Land System (Story et al., 1976) developed in the late Cainozoic by the retreat of the Arnhem Land escarpment, resulting in a landscape dissected by active gully erosion. In this study, a smaller geologically uniform 50 hectare sub-catchment was selected for study (Fig. 1) similar to many others in the area. The catchment consists of closely dissected short and steep slopes 10–100 m long and gradients generally between 15 and 50%. The soils are part of the Zamu family and are red loamy earths and shallow gravely loam with some micaceous silty yellow earths and minor solodic soils on alluvial flats (Aldrick, 1976; Riley and Williams, 1991). Specifically on the study transects the soils are classified as Red Rough-Ped Earth (Gn4.11) according to the Factual Key (Northcote et al., 1975; Glindemann, 1993).

The native vegetation is open dry-sclerophyll forests and although composed of a mixture of species, is dominated by *Eucalyptus* and *Acacia* species (Story et al., 1976). *Melaleuca* spp. and *Pandanus spiralus* are also found in the low-lying riparian areas with an understorey dominated by *Heteropogon contortus* and *Sorghum* spp. There is vigorous growth of annual grasses during the early stages of the wet season. These grasses often fall over during the wet season, providing a thick mulch which causes large reductions in erosion rates of bare soil. Cover afforded by vegetation is often reduced by fire during the dry season, which enhances the potential for fluvial erosion at the wet seasons' onset (Saynor et al., 2004). In recent years the study catchment has been burnt in alternate years.

Erosion and denudation rates have been established for the catchment using a variety of different methods. An assessment using the fallout environmental radioisotope caesium-137 (^{137}Cs) as an indicator of soil erosion status for two transects in the catchment produced net soil redistribution rates between 2 and 13 t ha^{-1} year^{-1} (0.013–0.86 mm year^{-1} denudation rate) (Hancock et al., 2008). Erosion pins located at the base of hillslopes in the catchment produced rates of 14 t ha^{-1} year^{-1} (~1 mm year^{-1} denudation rate) over a 2 year period. Estimated rates using the Revised Universal Soil Loss Equation (RUSLE) produced erosion rates of 10t ha^{-1} year^{-1} (0.67 mm year^{-1}). The RUSLE input parameter values were derived from field data collected from the area for that specific purpose.

Differences in erosion rates exist as a result of different methods being employed for their determination, that is field and modelling approaches. The measured erosion rates, using ^{137}Cs, for the upper slopes of the study area compare favourably with that of overall denudation rates for the area (0.01 to 0.04 mm year^{-1}) determined using stream sediment data from a range of catchments of different sizes in the general region (Cull et al., 1992; Erskine and Saynor, 2000). The variation between measured rates above and denudation rates derived using stream sediment data may result from (i) the value of the bulk density of surface material applied when converting mass to volume to derive a denudation rate, and (ii) the application of a sedimentary delivery ratio to the hillslope measurements to derive as catchment output.

3. Methods

Recent studies have demonstrated the importance of landscape position in relationship to the flow of water and sediment and SC down a hillslope profile and at the catchment scale using elements of a soil-landscape approach (Moore et al., 1993; Pennock et al., 1994; Gessler et al., 1995; Thompson et al., 1997; Gregorich et al., 1998; Arrouays et al., 1998; Gessler et al., 2000; Chaplot et al., 2001).