Geoderma 155 (2010) 36–45

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

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

G.R. Hancock [a,*], D. Murphy [b], K.G. Evans [a,c]

[a] School of Environmental and Life Sciences, Geology Building, The University of Newcastle, Callaghan, New South Wales, 2308, Australia
[b] School of Earth and Geographical Sciences, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia
[c] Hydrological and Geomorphic Processes Program, Environmental Research Institute of the Supervising Scientist, Darwin, Northern Territory, Australia

ARTICLE INFO

Article history:
Received 12 December 2008
Received in revised form 16 November 2009
Accepted 18 November 2009

Keywords:
Soil carbon
Soil erosion
Catchment modelling
Hillslope hydrology
Wetness index
Digital elevation model

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.

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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

* Corresponding author.
E-mail address: Greg.Hancock@newcastle.edu.au (G.R. Hancock).

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doi:10.1016/j.geoderma.2009.11.021

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).

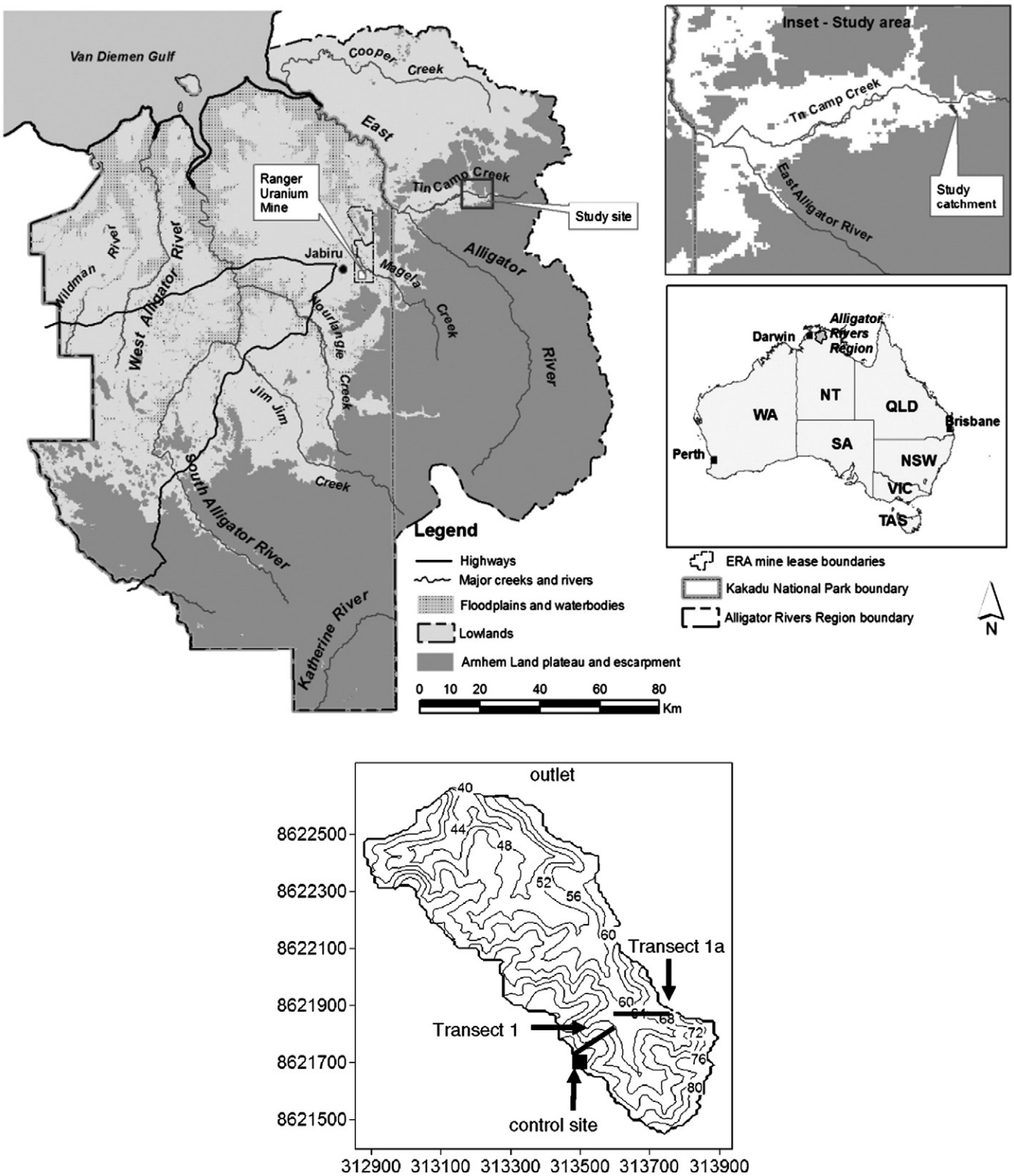

Fig. 1. Location of Tin Camp Creek (TCC) study site (top) and contour map of the study catchment (bottom) (dimensions in metres) showing the location of the hillslope transects and the control site. The boundaries in the top figure represent Kakadu National Park.

Consequently this approach was used to examine SC at Tin Camp Creek. In this study a number of soil cores were collected for analysis both at the hillslope and catchment scale over a 3 year period (2002, 2004 and 2005). The soil cores were analysed for SC as well as the fallout radionuclide ^{137}Cs and compared to hillslope geomorphology derived from surveying of the study site.

3.1. Hillslope transects and soil sampling

Two hillslope transects (named Transect 1 and Transect 1a) were selected that ran from the hillslope divide to the main drainage line (Fig. 1). These transects were opposite each other and field examination demonstrated that hillslope morphology (the majority

of hillslopes in the catchment have a convex profile), soil and vegetation were representative of the overall catchment. Soil samples were collected in May 2002, and again in September 2004 and September 2005 along the same two transects, but sample points were placed approximately 1 m away from each other to avoid soils disturbed by sampling in previous years. In 2005 a further series of samples were collected on 100 m by 100 m grid over the catchment to assess SC at the catchment scale. This sampling resulted in an additional 21 cores being collected in 2005.

The length of each hillslope was measured and sampling sites selected so that samples were collected at approximately equal intervals down the slope, thus ensuring that the entire toposequence was sampled. This resulted in 16 samples being collected at 9 m intervals for the 130 m long Transect 1, and 17 samples at 6 m intervals for 96 m long Transect 1a. The samples were collected within 200 mm long steel cores. In 2002 cores with an internal diameter of 86 mm were used while in 2004 and 2005 cores with a 65 mm internal diameter were used. Prior to sampling, the cylinder was fitted with a dolly that protected the rim from being distorted and enabled the corer to be driven easily into the ground with a sledge hammer until it was flush with the soil surface.

A reference or control site for ^{137}Cs analysis was selected on the catchment divide where there was no evidence of disturbance or run-on or runoff of sediment (Fig. 1). The site, located high in the catchment was well away from large hills, and probably not unduly affected by any rainshadow from surrounding topography or large trees. Samples were collected by scraper plate at 20 mm increments within a frame 195 × 500 mm to a depth of 160 mm (Campbell et al., 1988). At the base of the scraper plate excavation two cores were inserted to full depth (200 mm) at either end of the excavation providing a total depth of sampling of 360 mm. These samples were individually analysed. The relatively large surface area (97,500 mm^2) of the device averages out some of ^{137}Cs variability brought about by uneven labelling or micro-topographical effects (Loughran, 1989).

Core samples were collected on a 3 m by 3 m grid (nine samples) surrounding the reference site using the 300 mm long steel cylinder, and a further two cores were collected on the summits of ridges, making 11 bulk core reference samples in all. These samples provided a measure of ^{137}Cs variability at the site.

In addition to the scraper plate, cores were collected at the hillslope divide, midslope and the toe of the slope from both transects using the 65 mm diameter core down to a depth of 280 mm in both 2004 and 2005. These cores were sectioned at 40 mm increments to assess SC down the hillslope profile with samples dried and analysed as for the other samples. There was insufficient sample for ^{137}Cs analysis.

3.2. Laboratory analysis for soil C

Soil samples were removed from the steel collection cores and were air dried in an oven at 40 °C for 2–3 days. The dried samples were gently disaggregated and mixed with a mortar and pestle. The sample was then passed through a 2 mm sieve and the coarse fraction (>2 mm) separated. The <2 mm fraction was further disaggregated with a mortar and pestle, mixed and weighed. The <2 mm soil fraction was then ground in a mill to a fine powder and soil C concentration measured by a LECO 2000 analyser at the University of Western Australia.

3.3. Laboratory analysis for soil caesium-137

For the ^{137}Cs analysis the core samples (<2 mm sample) with a mass between 400 g and 1000 g were placed in a Marinelli beaker on a hyperpure germanium detector at the University of Newcastle. The detector was calibrated using a standard soil of known ^{137}Cs concentration (IAEA Soil-6). Samples were counted for ^{137}Cs for a minimum of 24 h and converted to areal activity using methods described in Loughran et al. (2002).

3.4. Catchment topography

Digital elevation models (DEMs) provide a rapid and sophisticated means of assessing hillslope and catchment geomorphology. A high quality regular 10 m grid DEM created specifically for the site using digital photogrammetry has been used extensively in past studies (Hancock et al., 2002; Hancock, 2003, 2005). Hancock (2005) has demonstrated that a 10 m digital elevation model grid size is a suitable size to capture the catchment hillslope properties at Tin Camp Creek.

Transects 1 and 1a were also surveyed using a total station to provide an accurate hillslope profile. Measurements were taken at each point where a soil core was collected as well as multiple points in between ensuring all surface features were captured. This provided two further representations of the study hillslopes in addition to the DEM data.

3.5. Independent measures of soil erosion and vegetation

To independently assess erosion, in September 2004 erosion pins were installed down both transects at each sample point. The erosion pins were 300 mm long, 5 mm diameter galvanised steel rods which were inserted into the ground at each sample point leaving approximately 50 mm exposed. The exposed tip was measured by digital vernier calliper to the nearest 0.1 mm and again in 2005. This provided 1 year of data.

Plant litter is the major contributor to SC with microbial residues providing secondary material. To assess the role of vegetation in contributing to SC concentrations, in September 2005 above ground biomass (AGB) was collected down each transect at each sample point as well as at each hectare grid sampling point. All standing and on-ground biomass was collected from within a 0.5 m by 0.5 m quadrat. As the catchment had been burnt in 2004 this standing and on-ground biomass is representative of 1 year of vegetative growth. This biomass was placed in plastic bags, weighed, then dried in an oven at 40 degrees for 5 days and then reweighed. In total there were 54 AGB samples.

4. Results

4.1. Soil carbon and soil depth

Average SC for Transects 1 and 1a was not significantly different between 2002 and 2005 (Table 1). On average, SC for Transect 1 is less than Transect 1a. Nevertheless there is no significant difference between transects or years. SC concentrations from the 21 soil cores collected on a 1 hectare grid in 2005, while having a higher mean and a larger range are statistically similar to that of the transect data. This suggests that the two transects are representative of the overall catchment SC concentrations.

It is generally recognised that SC is largely concentrated in the top 200–300 mm of soil (Lorenz and Lal, 2005). In this study the scraper plate data (Fig. 2, top) provides an integrated measure of SC over a

Table 1
Soil carbon (%) for Transects 1 and 1a and hectare grid data.

	Transect 1				Transect 1a			
	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
2002	0.59	0.18	0.42	1.14	0.70	0.30	0.55	1.58
2004	0.70	0.16	0.60	1.18	0.98	0.47	0.15	2.11
2005	0.73	0.14	0.56	1.12	0.95	0.29	0.61	1.55
2005 hectare	1.08	0.44	0.40	2.07	–	–	–	–

1000 cm^2 area. The 0–20 mm surface data was not analysed as it was largely a gravel lag with little soil. The 20–40 mm layer also had a high rock content and had a SC concentration lower than the 40–60 mm layer which had the highest SC concentration of all depths. SC concentration declined to 160 mm. The core samples collected at the base of the excavation represent a 200 mm depth of soil and have very similar concentrations but are the lowest of all the samples.

An assessment of SC concentration with depth down the hillslope profile (Fig. 2, middle and bottom) shows that the majority of SC is located close to the soil surface. All SC concentrations decline exponentially with depth. SC concentration in the cores from the downslope end of the transect was greater than in the cores from the upslope end of the transect. It also shows that the 200 mm deep cores used for the hillslope and catchment wide assessment are capturing the majority of SC with little below 200 mm.

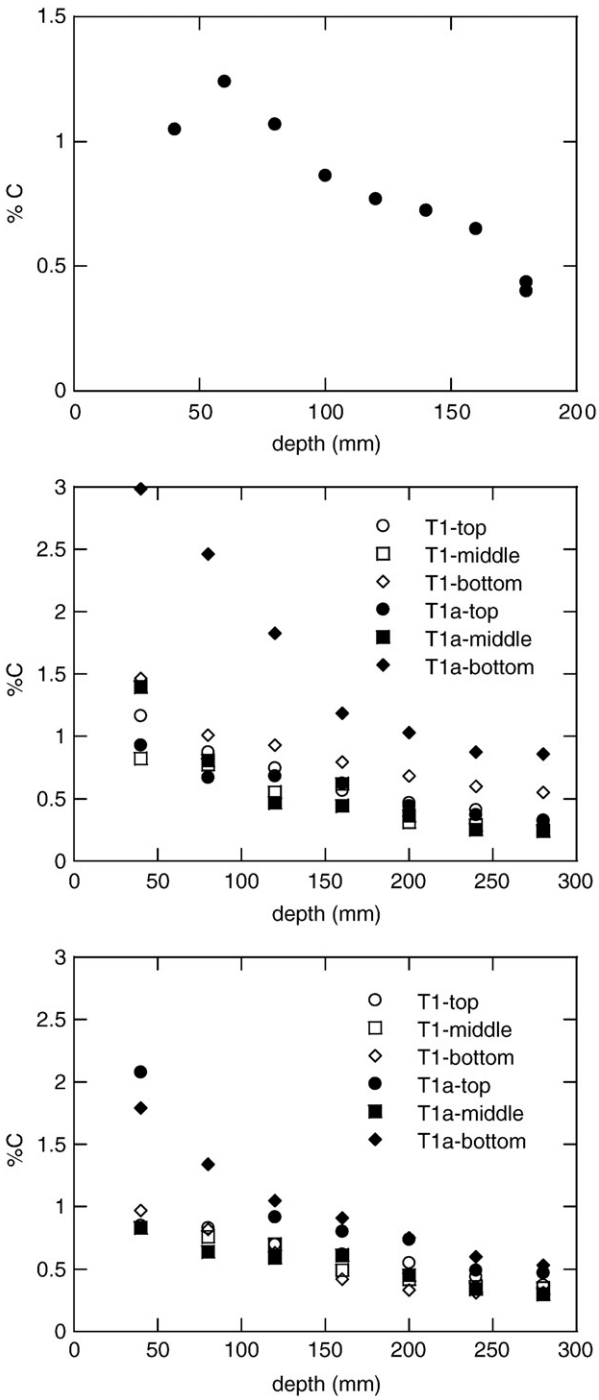

Fig. 2. Soil carbon (%) at depth from the scraper plate control site in 2002 (top), and from soil cores at the top, midslope and bottom of Transects 1 and 1a for 2004 (middle) and 2005 (bottom).

4.2. Soil carbon and geomorphology

The hillslope profiles of T1 and T1a are concave while the SC concentration follows a convex pattern opposite to that of the hillslope profile (Fig. 3) and is consistent across all years. SC is lower at the top of the hillslope (catchment divide) and then increases moving downslope suggesting that SC concentration is related to position on the hillslope. Strong and significant non-linear relationships were found when comparing SC with distance down the hillslope profile, slope and relative elevation for both individual transects and also when data for both transects were combined when the topographic data was derived from the surveyed hillslope profiles (Table 2). No strong statistical relationship was found between upslope area and slope determined from the DEM for any of the data sets. Nevertheless, a strong and significant relationship exists between SC and elevation determined from both the survey elevations and the DEM (Table 2).

Poor and insignificant relationships between SC, slope and upslope area determined from the DEM were found both for the hectare grid samples collected in 2005 as well as when combined with the hillslope transect data from 2005. Nevertheless a weak yet significant ($r = 0.44$, $d.f. = 52$, $p = 0.001$) relationship existed between SC and elevation when both transect and grid data for 2005 were combined.

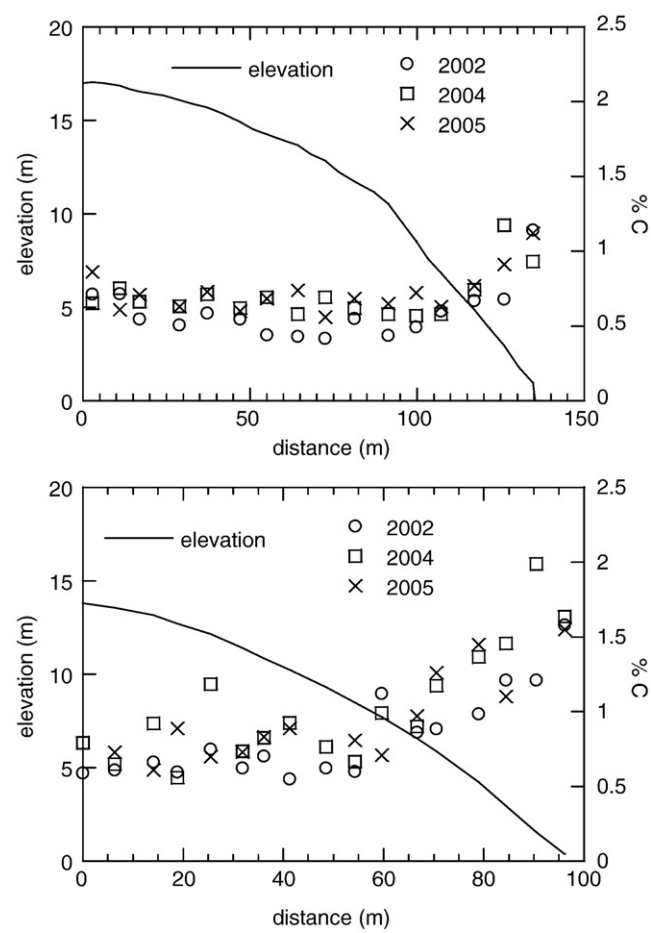

Fig. 3. Hillslope profile and soil carbon for Transects 1 (top) and 1a (bottom).

Table 2
Correlations (r, p) between soil carbon and distance, slope and elevation determined from the surveyed hillslope profile for both individual transects and both transects combined. Note that $p<0.001$ for all data except where $^{+}$ represents $p<0.05$, $^{++}$ represents $p<0.02$ and $^{+++}p<0.01$.

	Transect 1 ($n=16$ for each year)			Transect 1a ($n=17$ for each year)			Combined data ($n=33$ for each year)		
	2002	2004	2005	2002	2004	2005	2002	2004	2005
Distance	0.87	0.7^{+++}	0.81	0.92	0.87	0.88	0.71	0.32^{++}	0.35^{++}
Slope	0.50^{+}	0.88	0.64^{+++}	0.92	0.88	0.88	0.81	0.84	0.80
Elevation (survey)	0.92	0.79	0.87	0.93	0.75	0.88	0.89	0.83	0.87
Elevation (DEM)	0.93	0.75	0.86	0.87	0.89	0.88	0.89	0.83	0.88

4.3. Soil carbon and soil erosion

Results from the reference site show that ^{137}Cs is concentrated in the surface layers, with ^{137}Cs present to a depth of 160 mm (Table 3). Below this depth no ^{137}Cs was detected. The pedon contains the greatest quantities of ^{137}Cs in the uppermost 20–40 mm with the inventory generally decreasing with depth. The results indicate that the shape of the ^{137}Cs profile is consistent with that typically found at undisturbed sites, with ^{137}Cs inventories decreasing exponentially with depth. The total ^{137}Cs inventory at the scraper plate reference site was 216.7 ± 17.5 Bq m^{-2}. The results from the 11 bulk core samples at the reference site show variability in ^{137}Cs inventories, with an average ^{137}Cs inventory of 168.6 Bq m^{-2} and standard error of the mean of 20.07 Bq m^{-2} (Table 4).

A total of 98 soil samples were collected and analysed for Transects 1 and 1a in 2002, 2004 and 2005, respectively. An additional 21 cores were collected and analysed from the hectare grid samples. Of the transect data, eight contained no detectable ^{137}Cs: two from Transect 1 and six from Transect 1a (Table 5). The highest ^{137}Cs content was at two sample points on Transect 1a (2004), 481 ± 63 and 413 ± 58 Bq m^{-2}. The highest values on Transect 1 were 330 ± 40 and 290 ± 70 Bq m^{-2}. Conversely, Transect 1a had the greater number of samples with less than 100 Bq m^{-2} of ^{137}Cs, 15, compared with five on Transect 1.

The hectare grid data contained 3 cores with no detectable ^{137}Cs. The highest concentration was 218 Bq m^{-2} with 3 cores containing less than 100 Bq m^{-2} of ^{137}Cs. The ^{137}Cs concentrations were therefore within the range found for Transects T1 and T1a suggesting that the samples were representative of the catchment.

Overall the ^{137}Cs distribution along the transects was highly variable, with no apparent relationships observed between ^{137}Cs inventories and hillslope position. No obvious pattern of ^{137}Cs distribution was observed from the hectare grid samples.

Table 3
Caesium-137 depth profile at Tin Camp Creek reference site.
McFarlane et al., 1992.

Depth (mm)	^{137}Cs inventory (Bq m^{-2})
0–19	27.6 ± 3.9
20–39	46.3 ± 5.6
40–59	37.9 ± 6.1
60–79	41.0 ± 7.0
80–99	25.1 ± 6.8
100–119	14.2 ± 6.4
120–139	14.3 ± 5.9
140–159	10.4 ± 7.3
160–260	ND
Total ^{137}Cs	216.7 ± 17.5

ND = ^{137}Cs not detected in sample.
Inventory includes adjustment for estimated ^{137}Cs on gravel.

Table 4
Statistical parameters of the core samples at the reference site.

Statistical parameters	
Mean (Bq m^{-2})	168.6
Standard deviation (Bq m^{-2})	66.6
Standard error mean (Bq m^{-2})	20.1
Reference range (Bq m^{-2})	128.5–208.7

^{137}Cs concentration was compared with SC concentration for both the individual transects on a yearly basis as well as the hectare grid data (Fig. 4). No relationship was found for either the individual transect data or when all transect data was combined. No relationship was found between the ^{137}Cs and SC from the hectare grid samples.

Soil redistribution in units of mass can be quantified using models that relate ^{137}Cs loss or gain to soil erosion and deposition rates, respectively. Both Empirical (Australian Empirical Model, AEM) (Campbell et al., 1986; Loughran, 1989; Elliott et al., 1990; Loughran and Elliott, 1996) and Theoretical models (Profile Distribution Model, PDM) (Walling and He, 1999; Walling et al., 2002) have been used at the site (Hancock et al., 2008). No relationship was found between erosion and deposition patterns and SC concentration.

4.4. Erosion pins and vegetation

The erosion pin measurements obtained from one full season provided an average erosion rate of 5.7 mm ($\sigma=4.3$ mm) and 1.2 mm ($\sigma=7.5$ mm) for Transects 1 and 1a respectively. Both transects had areas of both erosion and deposition. The data showed no apparent relationships observed between erosion and deposition pattern and hillslope position. For all data there was no relationship between erosion and deposition determined from the pin data and SC in 2005. No relationship was found for either the individual transect data or when all transect data was combined. There was no correlation between erosion pin data and ^{137}Cs concentration.

The above ground biomass (AGB) data provided a full season of vegetation growth as the catchment had been burnt in September 2004 just prior to the sampling campaign therefore the 2005 data was all growth for a full season with no residual biomass from the previous season. Average biomass was 3 t/ha ($\sigma=1.8$ t/ha), 3.8 t/ha ($\sigma=1.9$ t/ha) and 3.7 t/ha ($\sigma=2.1$ t/ha) for Transects 1, 1a and the hectare grid samples respectively. Significant relationships existed between AGB

Table 5
Caesium-137 (Bq m^{-2}) inventories for sampling points on Transects 1 and 1a for 2002 and 2004; (all values decayed to May 2002).

Sample point	T1	T1	T1	T1a	T1a	T1a
	2002	2004	2005	2002	2004	2005
1 (top of slope)	111	34	155	52	246	169
2	195	98	63	167	ND	ND
3	115	213	145	20	177	120
4	29	330	227	40	103	136
5	48	267	184	42	178	124
6	266	184	127	269	257	176
7	266	269	188	235	88	60
8	218	201	130	96	213	144
9	290	219	152	109	200	133
10	265	249	173	225	413	261
11	167	219	140	30	162	101
12	174	233	162	144	12	ND
13	207	274	186	94	161	108
14	132	No sample	ND	162	ND	ND
15	245	101	67	23	139	93
16	ND	131	80	8	481	284
17 (base of slope)	–	–	–	62	ND	ND

ND: no ^{137}Cs detected in sample.

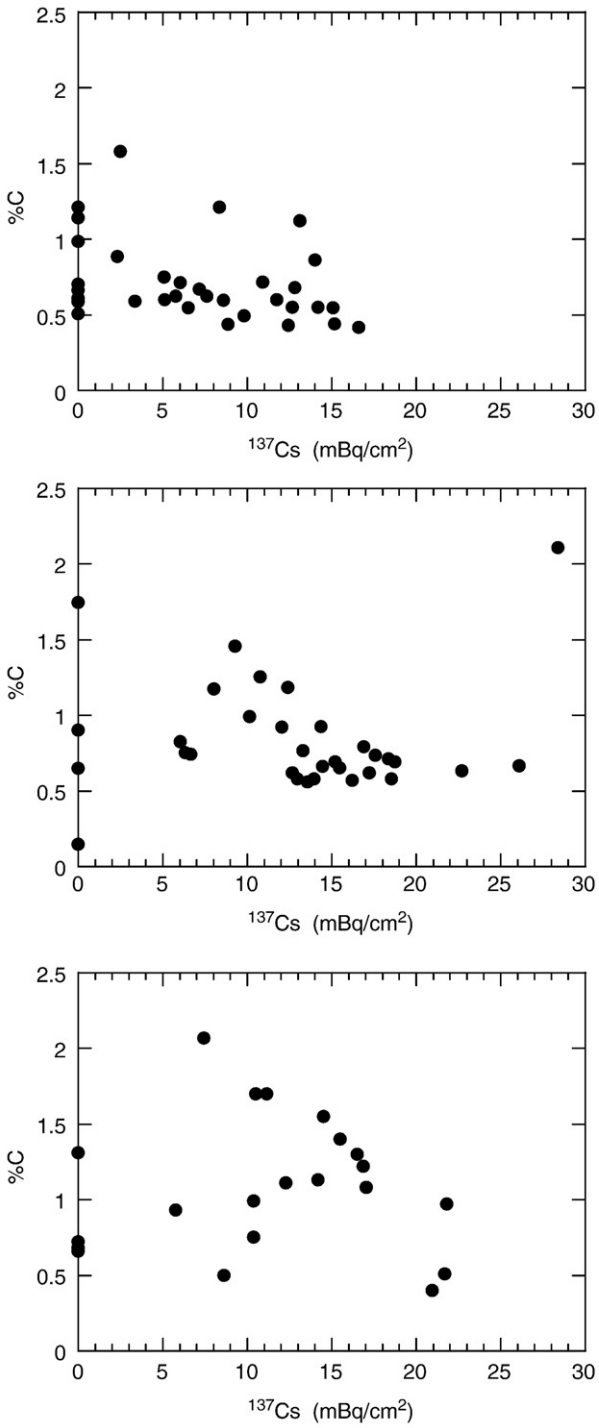

Fig. 4. Relationship between ^{137}Cs and soil carbon concentration for both Transects 1 and 1a for 2002 (top), 2004 (middle) and 2005 for the hectare grid data (bottom).

and SC for Transect 1 ($r=0.68$, $d.f.=14$, $p<0.01$), Transect 1a ($r=0.79$, $d.f.=15$, $p<0.001$), hectare grid samples ($r=0.69$, $d.f.=19$, $p<0.001$) and also when all data points were combined ($r=0.62$, $d.f.=52$, $p<0.001$) (Fig. 5). There was no relationship between AGB and the erosion pin data or AGB and ^{137}Cs.

Strong and significant relationships existed between AGB and distance down the hillslope for T1 ($r=0.72$, $d.f.=14$, $p<0.01$) and T1a ($r=0.61$, $d.f.=15$, $p<0.01$) and also when both transect data were combined ($r=0.61$, $d.f.=31$, $p<0.001$) (Fig. 6). Similar strong and significant relationships existed between AGB and slope determined from the surveying for T1 ($r=0.74$, $d.f.=14$, $p<0.001$) and T1a ($r=0.61$, $d.f.=15$, $p<0.01$) and also when both transect data was combined ($r=0.7$, $d.f.=31$, $p<0.001$). There was no significant relationship between AGB and slope or upslope contributing area derived from the DEM.

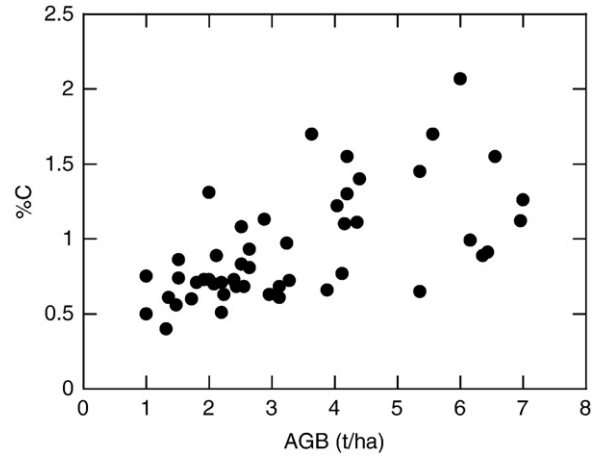

Fig. 5. Above ground biomass (AGB) in relation to soil carbon concentration for the Tin Camp Creek catchment in 2005.

Strong and significant relationships existed between AGB and surveyed elevation for T1 ($r=0.80$, $d.f.=14$, $p<0.001$) and T1a ($r=0.67$, $d.f.=15$, $p<0.01$) and also when both transect data were combined ($r=0.72$, $d.f.=31$, $p<0.001$). DEM elevation and AGB also had strong and significant relationships for T1a ($r=0.78$, $d.f.=14$, $p<0.001$) and T1a ($r=0.66$, $d.f.=15$, $p<0.01$) and also when both transect data were combined ($r=0.70$, $d.f.=31$, $p<0.001$). The relationship between elevation and the 21 hectare grid samples was not significant at the 5% level ($r=0.41$ $d.f.=19$, $0.1>p>0.05$). The relationship between AGB and DEM elevation for all data (T1, T1a and the hectare grid samples) provided a low yet significant relationship ($r=0.32$ $d.f.=52$, $p<0.05$).

5. Discussion

The role of geomorphology in relation to the spatial and temporal distribution of SC is of considerable interest in terms of landscape management and carbon sequestration. While the findings here are for a particular area of the global land surface, the monsoonal tropics comprise large areas of both Australia and the globe so the findings here provide insight into an under-researched region.

5.1. Soil carbon in relationship to topography

Despite the differences in rainfall and fire occurrence the results show that on average SC concentration is higher for Transect 1a than for Transect 1 but the transects are not significantly different. There is little difference between years and overall, SC down the hillslope profile varies little temporally. While the SC concentration data is for a short period found by others it suggests that concentrations are relatively stable in this environment.

The results demonstrate that there is a strong relationship with hillslope morphology and topography as (Moore et al., 1993; Gessler et al., 1995, 2000; Tsui et al., 2004). For both transects the highest SC concentration was at the foot of the slope while the lowest concentration was midslope for T1 and top of the hillslope for T1a and is a similar pattern to that found by others who have examined landscapes containing both concave and convex hillslopes (Polyakov and Lal, 2004; Yoo et al., 2006; Li et al., 2006, 2007). There was a statistically strong relationship between SC and distance from the

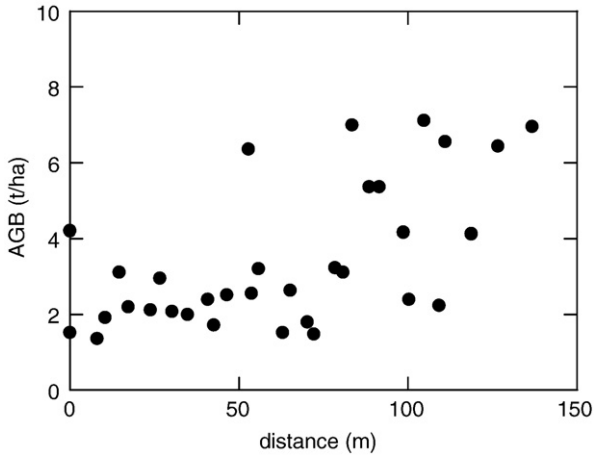

Fig. 6. Hillslope distance from the divide in relation to above ground biomass (AGB) for Transects 1 and 1a for the Tin Camp Creek catchment in 2005.

catchment divide, elevation and slope (Table 2) despite other studies finding no relationship with slope or elevation (Yoo et al., 2006). This demonstrates the potential to determine SC concentrations from topographic data (Moore et al., 1993; Gessler et al., 1995, 2000; Tsui et al., 2004). Nevertheless, poor relationships were found when topographic data such as slope and upslope contributing area were extracted from the DEM. Further analysis of SC against the Compound Topographic Index (CTI) of Moore et al. (1993) and the TopModel Index of Beven and Kirkby (1979) also showed no relationships. Regridding the DEM to a higher resolution (i.e. 5 m grid spacing) as examined by others (i.e. Gessler et al., 2000) did not improve the relationship with the CTI and TWI.

The strong relationship between downslope distance, slope and elevation both for the individual transects and when both transect data are combined (Table 2) suggest that similar topography-related processes are occurring along both transects (Gessler et al., 2000). Therefore for the data set examined SC concentration can be modelled from topographic data. Nevertheless, the finding that there is a weaker correlation between elevation and SC for the hectare grid samples indicates that the hillslope process affecting SC concentration may be catchment location specific (Moore et al., 1993). This is an area for considerable further research with site specific data likely to be required for catchment and regional scale modelling and prediction (Gessler et al., 1995; Thompson et al., 1997; Arrouays et al., 1998; Gessler et al., 2000; Chaplot et al., 2001).

Despite the poor relationship with slope and area derived from the DEM, strong correlations were found between SC and elevation for both the hillslope profile as well as the DEM as found by others (Yimer et al., 2006; Huang et al., 2007). Some studies have found no relationship between SC and elevation (Yoo et al., 2006) while others have found a link between related factors such as elevation and soil moisture (Famiglietti et al., 1998; Western et al., 1999; Dai and Huang, 2006; Martinez et al., 2007; Ticehurst et al., 2007). In addition Polyakov and Lal (2004) suggest that SC concentration is likely to be related to soil moisture. At this site it appears that elevation can be used as a proxy for the spatial distribution of SC concentration with confidence at the hillslope and transect scale.

As suggested by others (i.e. Gessler et al., 2000), detailed hillslope and catchment characterisation is needed for the characterisation of soil C. While elevation appears to be a proxy for soil C and provides a preliminary assessment for understanding soil-landscape functionality in terms of soil C in this environment, it provides spatial information only with little ability to make assessment as to how a landscape will respond to external drivers such as climatic variability. As soil C appears to be at a steady state in this environment the geomorphic drivers are yet to be determined at 5 years to decadal time scales.

5.2. SC in relationship to soil erosion

Previous assessments of ^{137}Cs redistribution have used either transect or grid sampling. In this study we have used both methods providing both good coverage over the catchment as well as intense sampling down the transects. The data from the two transects and hectare grid samples shows that there is no relationship between SC and ^{137}Cs content as opposed to the findings of others (Mabit and Bernard, 1998; Pennock, 2000; VandenBygaart, 2001; Ritchie and McCarty, 2003; Ritchie et al., 2004; Van Oost et al., 2005; Li et al., 2006, 2007; Mabit et al., 2008). While the labelling of ^{137}Cs with the clay fraction has been shown to be variable (Campbell et al., 1988; Loughran, 1994), according to the findings of other researchers, it is reasonable to expect that a mean trend would result given the number of samples collected over the study period. This study calls into question the relationship between soil erosion/deposition and SC in the study catchment using the ^{137}Cs method. The results show that ^{137}Cs cannot be used as a predictor of SC concentration nor is there direct field evidence of a link between ^{137}Cs and soil erosion as suggested by Li et al. (2006, 2007) in this environment.

Nevertheless this study site is different to all others where a statistical relationship between SC concentration and ^{137}Cs content has been found. Firstly, the ^{137}Cs content is low compared to the Northern Hemisphere where the majority of studies have been conducted. Secondly, the majority of studies that have found a relationship between SC and ^{137}Cs content have been conducted in agricultural fields that have been subject to tillage leading to a likely mixing of both SC and ^{137}Cs throughout the profile whereas this study catchment is undisturbed. Other researchers have suggested that tillage redistributes soil at far greater rates than that of non-tilled hillslopes with a net loss of soil from convex slopes and an increase in soil at footslopes (Van Oost et al., 2005). Thirdly, the two transects have convex profiles like the majority of hillslopes in the catchment and there have been few studies examining SC for such topography (Yoo et al., 2006).

Yoo et al. (2006) examined the spatial patterns of SC at two sites which contained both concave and convex hillslopes and found soil thickness to be the key control. Fig. 2 suggests that soil thickness at this site has no impact as SC asymptotes to approximately the same values despite the difference in hillslope position. They also found no or little relationship between topography and vegetation and SC, again opposite to our findings.

It is hypothesised here that SC concentration in the catchment are at a maximum or equilibrium level considering the undisturbed nature of the study area. This is opposed to most other sites examined by other researchers which have been subjected to agricultural practices involving soil disturbance. In these agricultural environments SC is well recognised to be reduced when compared to natural or undisturbed areas and soil erosion is recognised to be higher (Pennock et al., 1994; Mabit and Bernard, 1998; Shukla and Lal, 2005). Therefore SC and ^{137}Cs in terms of both horizontal and vertical (soil profile) spatial distribution has the potential to be different to that of undisturbed areas.

Further, the relationship between SC and ^{137}Cs is based on the premise that SC moves along the same pathways and by the same processes as soil (Ritchie and McCarty, 2003; Shukla and Lal, 2005; Li et al., 2006, 2007). It may be that in this environment that the movement of SC is not related to erosion processes because SC concentration is a peak or equilibrium concentration that is more related to hillslope position and carbon inputs both from upslope and the immediate area. Therefore SC concentration may be a direct product of mineralisation rates rather than being more strongly related to the material deposited and eroded at a point due to

enhanced erosion processes on disturbed hillslopes (Li et al., 2007). The relationship between SC and AGB suggests that this may be an explanation.

Further, in a laboratory flume study examining the interrill erosion on two soils, Kuhn (2007) concluded that enrichment of organic matter is dominated by the erosion process and that different soils generate unique environments for the erosion of SC. It could be argued that the tropical monsoonal climate with high intensity rainfall, high temperatures and undisturbed soil surface is different to that of other sites as others have suggested that the intensity of the erosion process may be an important factor in SC transport and deposition (Schiettecatte et al., 2008). We do not believe this to be the case as the depth distribution of ^{137}Cs and SC is similar to other sites and the erosion rates for the study catchment are not extreme (see Section 2).

The erosion pins provided an independent assessment of erosion at each point yet no significant relationship was found between SC concentration and topographic variables. A possible reason for this lack of correlation is that 1 year is a settling down period as the insertion of the pins disturbs the immediate surrounds and any relationship with SC being a result of multi-season erosion and depositional processes. A pin also provides data for a very small area and may not be representative of the local sample collection area. Nevertheless, the finding that erosion rates from either a simple method such as erosion pins or a more complex analytical method such as ^{137}Cs are not correlated with SC concentration provides evidence that SC concentration is independent of erosion and deposition processes in this environment. This issue is an area for further investigation.

Data on relationships between vegetation and SC is scant for most areas and non-existent for many undisturbed areas of the world (Jobbagy and Jackson, 2000; Lorenz and Lal, 2005) but global interpolated databases do exist together with national studies (Paustian et al., 1997; Barrett, 2001; Dai and Huang, 2006; Zhang et al., 2008; Batjes, 2008). While the AGB data are for one season only, the findings here indicate that significant relationships exist with hillslope geomorphology and soil-landscape type models can provide insight. Further, both SC and AGB can be predicted from high quality topographic data and topographic derivatives. While plant litter decomposition rates will be higher due to higher temperatures and much vegetation is removed due to the biannual fire regime, the results indicate that vegetation is a major contributor to SC concentration. These findings auger well for vegetation remote sensing techniques to predict SC in this environment and is an area for further research.

6. Conclusion

The results of this study demonstrate that there is little change in SC concentration on the hillslope transects over the study period suggesting that concentration and spatial distribution is constant. The steady state concentrations found over the study period suggest that SC may be at a maximum given current land use. Therefore the ability of this area to sequester greater amounts of SC may be limited. Strong relationships were found between hillslope position and SC suggesting that hillslope and catchment scale geomorphology and hydrology have a strong control on SC. The finding that SC concentration was significantly correlated with above ground biomass suggests that vegetation has a strong control and remote sensing of vegetation may be able to be used to predict SC concentration. This is an area of further research.

Poor relationships were found between SC and hillslope and catchment geomorphology when data were derived from what is considered to be a good quality medium resolution DEM of the catchment. Significant results were found when precision survey hillslope transect data were used. Consequently, high resolution and high accuracy DEM data appears necessary for modelling using topographic data. The results of this study show that further work is required to better understand SC at the hillslope scale. This information is needed if we intend to not only better understand hillslope SC but also SC distribution at the catchment scale. This knowledge is especially important if we are to numerically model landscape response to different inputs and resultant impact on SC. Nevertheless it is recognised that longer term data is needed to assess change in response to climate and geomorphic drivers of SC variability.

Acknowledgments

The traditional owners of the land where the study site is located, The Northern Land Council and Supervising Scientist Group staff, especially Bryan Smith and Gary Fox are thanked for their cooperation and assistance. The technical support in sample preparation (Peter Loughran) and ^{137}Cs analysis (Chris Dever) and hospitality offered by AFMECO Mining and Exploration Pty Ltd (John Fabray) and Cameco Australia Pty Ltd (Ted O'Connor, Jennifer Parks and Gavin Otto) at Myra Camp are also gratefully acknowledged. This research was supported by the Australian Research Council Discovery Grant (DP 0556941: "Carbon, nutrient and sediment dynamics in a semi-arid catchment"). The comments of three anonymous reviewers greatly strengthened this paper.

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