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SOIL RESEARCH

Using environmental tracers to understand soil organic carbon and soil erosion on a steep slope hillslope in south-east Australia

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ABSTRACT

Context. It is well recognised that soil organic carbon (SOC) can be transported and deposited along the same pathways as those of soil erosion and deposition. **Aims.** To examine the viability of environmental tracers ^{137}Cs and unsupported ^{210}Pb (^{210}Pb$_{ex}$) as tools to inform soil erosion and deposition patterns as well as that of the distribution of SOC. **Methods.** Multiple soil cores were collected along two transects of similar length and aspect in a steep-slope soil mantled environment in south-east Australia. **Key results.** Average SOC concentration was high for both transects (~6% and 4%). SOC decreased moving downslope suggesting loss of SOC by erosion. There were strong and significant positive relationships of SOC with ^{137}Cs and ^{210}Pb$_{ex}$ (both $r > 0.77$, $P < 0.0001$). At this site, SOC concentration appears related to erosion and deposition patterns. **Conclusion.** The hillslope distribution of ^{137}Cs and ^{210}Pb$_{ex}$ were very similar, indicating that both tracers were viable in this environment ($r = 0.9$, $P < 0.0001$). The different origins and half-lives of ^{137}Cs and ^{210}Pb$_{ex}$ also demonstrate that the patterns of erosion and deposition are consistent at decadal time scales. **Implications.** The use of ^{210}Pb$_{ex}$ provides an alternative method for understanding erosion and deposition patterns as well as that of SOC, given that the viability of ^{137}Cs (half-life of 30.1 years) is now questionable due to no new replenishment.

Keywords: ^{137}Cs, ^{210}Pb, ^{210}Pb$_{ex}$, carbon sequestration, lead-210, sediment transport, SOC, soil erosion.

Introduction

Understanding the movement and fate of soil organic carbon (SOC) is essential for improved management of the soil–landscape system as well as C sequestration (Murphy 2015; Minasny *et al.* 2017; Lal 2019). The location and movement of SOC has been shown to be related to soil erosion and deposition. Therefore, quantifying SOC soil redistribution requires an understanding of erosion and deposition processes at multiple spatial and temporal scales (Moore *et al.* 1993; Knighton 1998; Lal 2001, 2003, 2004; Berhe *et al.* 2007; Hancock *et al.* 2010; Quinton *et al.* 2010; Ruiz Sinoga *et al.* 2012; Gaspar and Navas 2013; Berhe *et al.* 2014; Kirkels *et al.* 2014; Murphy 2015; Doetterl *et al.* 2016; Hoyle *et al.* 2016).

Here, environmental tracers (^{137}Cs and unsupported ^{210}Pb also known as ^{210}Pb$_{ex}$) are used to provide insights to sediment transport and SOC. Environmental tracers, particularly ^{137}Cs are well understood and well used to understanding erosion and deposition patterns and erosion rates (Ritchie and McHenry 1975; Longmore *et al.* 1983; McFarlane *et al.* 1992; Loughran 1994; Loughran *et al.* 2002, 2004; Zapata *et al.* 2002; Walling *et al.* 2003; Zapata 2003; Li *et al.* 2006; Zhang *et al.* 2006; Fukuyama *et al.* 2008; Olley *et al.* 2013; Özden *et al.* 2013; Teramage *et al.* 2013; Mabit *et al.* 2014; Fissore *et al.* 2017).

Using both ^{137}Cs and ^{210}Pb$_{ex}$ provides information over different time periods (He and Walling 1997; He *et al.* 2002; Li *et al.* 2003; Fukuyama *et al.* 2008; Mabit *et al.* 2009, 2014; Kato *et al.* 2010; Teramage *et al.* 2013). While ^{137}Cs has been extensively used to determine soil erosion and deposition patterns, ^{210}Pb$_{ex}$ has been less commonly used (Lewis 1977; Walling *et al.* 2003; Walling *et al.* 2011). Further, it was shown that ^{137}Cs and ^{210}Pb$_{ex}$ can be bound to soil organic and inorganic materials and be used as tracers (Lewis 1977; Dorr 1995). Teramage *et al.* (2013) found a stronger affinity between SOC and ^{210}Pb$_{ex}$ than for SOC and ^{137}Cs. Few studies have examined the relationship between these tracers and SOC, particularly $^{210}Pb_{ex}$ in the Australian environment.

As the last atmospheric nuclear test was 1972, ^{137}Cs provides information on erosion and deposition patterns over an approximate 50-year period. In contrast, ^{210}Pb is derived from naturally occurring ^{222}Rn (Bunzl *et al*. 1995) and provides information over an approximate 100–200 year period (Walling and He 1999; Zapata *et al*. 2002; Walling *et al*. 2003; Zapata 2003; Zhang *et al*. 2006; Mabit *et al*. 2014). Both tracers therefore provide information at two different temporal scales (Wallbrink *et al*. 1994; Walling and He 2001; Li *et al*. 2003; Walling *et al*. 2003; Kato *et al*. 2010).

Here, both ^{137}Cs and $^{210}Pb_{ex}$ are used to understand SOC and soil erosion and deposition patterns on a relatively steep slope (~30%) in south-east Australia. This study forms part of a long-term investigation of hillslope geomorphology in the south-east region of Australia (Rüdiger *et al*. 2007; Martinez *et al*. 2009, 2010; Hancock *et al*. 2010, 2015; Wells *et al*. 2012; Wells and Hancock 2014; Chen *et al*. 2015; Kunkel *et al*. 2016, 2019; Hancock and Wells 2021). There appears to be few studies where the two tracers have been directly used and compared in this way.

The aims are (1) to report and understand the patterns of the environmental tracers (^{137}Cs and $^{210}Pb_{ex}$) and SOC in a relatively high rainfall steep-slope environment and (2) assess the viability of the environmental tracers as tools to provide insights concerning soil erosion and deposition patterns as well as hillslope SOC concentration.

Study site

The study site (Springhills) is located in the headwaters of the Krui River catchment (~562 km^2), New South Wales (NSW), Australia (Fig. 1), a tributary of the Goulburn River which joins the Hunter River and discharges at Newcastle. The site is underlain with Tertiary basalt of the Liverpool Range beds and forms part of the Merriwa Plateau. The basaltic soils are highly fertile. The study site is located on the property 'Springhills' and has undulating to steep topography typical of the local headwaters with relief at the site of approximately 500 m.

Original vegetation has been mostly cleared over the past 150 years and replaced with improved and natural pasture. While steep, landuse is well suited to cattle and sheep and cattle grazing (Story *et al*. 1963; Kovac and Lawrie 1991). Vegetation species include *Austrostipa aristiglumis* (plains grass) and various *Poa* (tussock) species (Fig. 2).

Climate is classified as temperate dominated by continental influence (Kovac and Lawrie 1991). Annual average rainfall is approximately 1000 mm. Mean monthly minimum and maximum air temperatures are 3°C (winter) and 16°C (summer), and 17°C (winter) and 30°C (summer), respectively (www.bom.gov.au).

Here two sites with approximately the same easterly aspect, relief, slope and slope lengths and management (pasture and grazing) but at two different elevations were examined (Figs 2, 3). A transect-based sampling methodology was

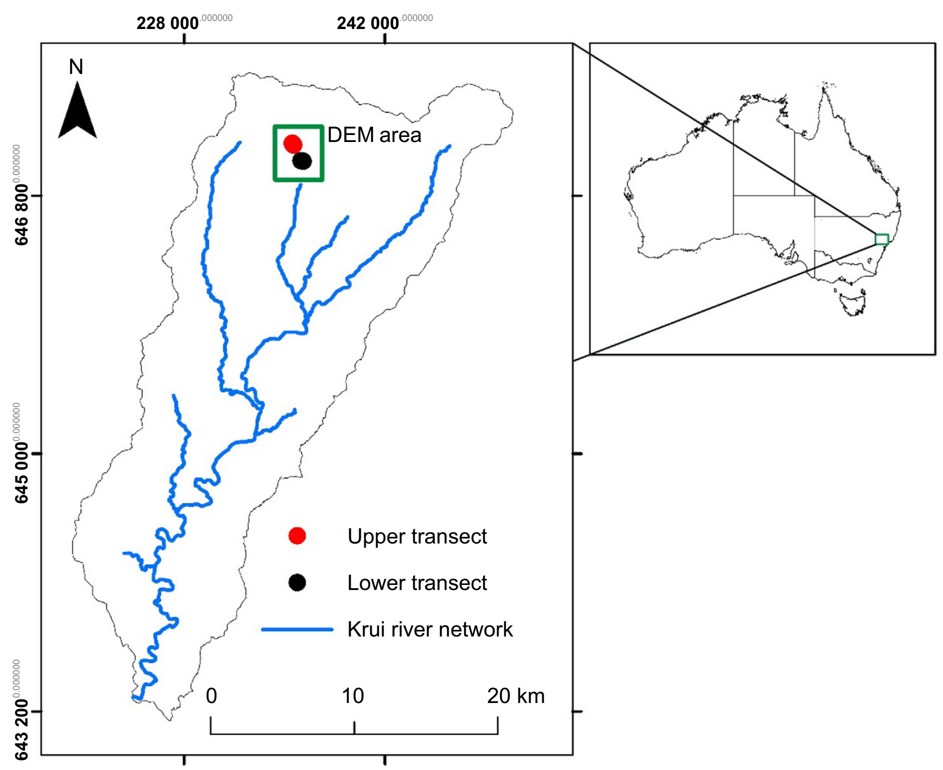

Fig. 1. Location of the Springhills study site.

Fig. 2. View from the Upper transect looking south down the Krui valley (top) and looking upslope (bottom). The white tape is the location of the sampling.

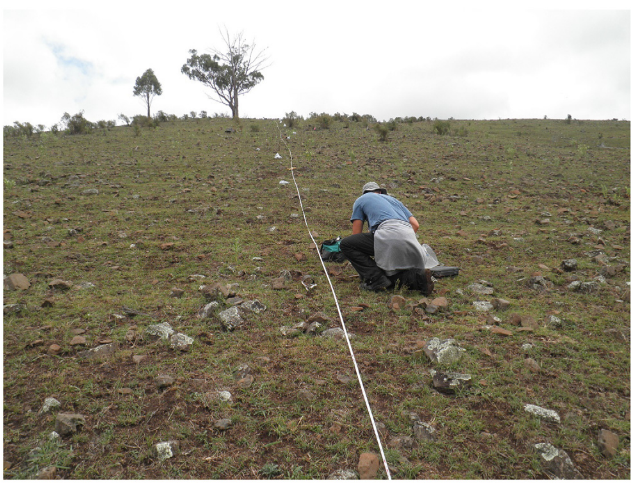

Fig. 3. Lower transect looking upslope. The white tape displays the transect position with soil samples (in bags) indicating the sample positions.

Table 1. Upper and Lower transect topographic and sampling data.

	Length (m)	Min. elevation (m)	Max. elevation (m)	Relief (m)	Tan slope
Upper	152	785.3	829.9	44.7	0.32
Lower	153	535.3	581.7	46.4	0.30

employed. The two transects were named 'Upper' and 'Lower' transects (Table 1). The Upper transect at an elevation of 830 m was 150 m long and ran a ridgeline to a zero-order drainage line at its base (Fig. 2; Table 1). The 160-m-long Lower transect (highest elevation approximately 535 m) ran from ridgeline to a creek flat (Fig. 3). Both sites had similar vegetation cover (native and improved pasture), uniform soil type and consistent landuse (grazing).

Methods

Sampling and laboratory methodology

Soil samples were collected at regular intervals using a transect approach ensuring that the whole toposequence was sampled (Pennock and Appleby 2002). Steel cores were used for sampling (95 mm internal diameter and length 210 mm). For insertion of the core, a cap or 'dolly' was placed on top of the steel core and a hammer manually used to insert the core to the core maximum depth or point of refusal. Cores were extracted using vice-grips to twist the core and lift it from the ground. Each soil sample was double-bagged and labelled for transport.

Soil samples were processed at the University of Newcastle Soils Laboratory. Soil samples were first weighed and dried in a 40°C oven for at least 7 days. Each sample was disaggregated mechanically by hand using a mortar and pestle and passed through a 2 mm sieve to separate fine and coarse fractions and mass was recorded. Sand, silt and clay contents of the <2 mm fraction were determined by the hydrometer method (Smith and Atkinson 1975). Rock fraction here is defined as the >2 mm size fraction. Subsamples for total C assessment were sent to the Environmental Analysis Laboratory at Southern Cross University, Lismore, NSW (LECO dry combustion method).

Environmental tracers

Environmental radionuclides such as ^{137}Cs and $^{210}Pb_{ex}$ are useful for providing details on erosion and deposition across multiple spatial and temporal scales (Olley *et al.* 2013). The ^{137}Cs can be used to understand medium-term (~50 year old) soil erosion and deposition patterns (Ritchie and McHenry 1975; Longmore *et al.* 1983; Campbell *et al.* 1988; McFarlane *et al.* 1992; Loughran 1994; Loughran *et al.* 2002, 2004; Krause *et al.* 2003; Zapata 2003; Martinez *et al.* 2009;

Gaspar and Navas 2013; Hancock *et al.* 2015). ^{137}Cs in soil was supplied as fallout from atmospheric testing of nuclear weapons and nuclear accidents (Teramage *et al.* 2013, 2015) and is adsorbed to clay after atmospheric fallout. There has been no input of ^{137}Cs to the Australian environment since atmospheric testing of nuclear weapons stopped in the early 1970s. The half-life of ^{137}Cs is relatively short (30.1 years); however, it is still detectable in many parts of Australia (including this site). Several studies have used this approach in the general study area (Martinez *et al.* 2009; Hancock *et al.* 2015; Hancock and Wells 2021).

Derived from the decay of gaseous ^{222}Rn, $^{210}Pb_{ex}$ is a naturally occurring radionuclide from the ^{238}U decay series. 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 (excess) with its parent ^{226}Ra (Walling *et al.* 2003; Zapata 2003; Gaspar *et al.* 2017). Fallout ^{210}Pb is commonly termed unsupported or excess ^{210}Pb, when incorporated into soils or sediments in order to distinguish it from the ^{210}Pb produced *in situ* by the decay of ^{226}Ra. Given its continuous fallout, $^{210}Pb_{ex}$ can provide information over an approximate 100-year period (Zapata *et al.* 2002; Zapata 2003; Walling *et al.* 2003; Zhang *et al.* 2006; Mabit *et al.* 2014).

For the ^{137}Cs and $^{210}Pb_{ex}$ analysis, soil core samples (<2 mm) of mass 400–1000 g were stored for a minimum of 28 days to ensure equilibrium between ^{226}Ra and its daughter ^{222}Rn (an inert gas with half-life 3.8 days) was established. The ^{137}Cs and $^{210}Pb_{ex}$ concentrations were then measured using a hyper-pure coaxial Ge detector coupled to a multi-channel analyser. The $^{210}Pb_{ex}$ concentrations were calculated by subtracting ^{226}Ra-supported ^{210}Pb concentration from the total ^{210}Pb concentration. The concentrations of ^{137}Cs were determined using peak at 662 keV, of ^{210}Pb at 46.5 keV and of ^{226}Ra at 609.3 keV. The counting time in all cases was over 80 000 s, which provided an analytical precision of ±6% for ^{137}Cs and ±10% for $^{210}Pb_{ex}$.

Topographic data

A digital elevation model for the Upper and Lower hillslopes was created by systematic traverse using a Trimble 4700 base station and rover (Differential Global Positioning System or DGPS). Coordinates were automatically recorded every 2 m. Additional points were collected along and around each hillslope transect. These ungridded data were gridded using ordinary kriging to a regular 1 m grid. System accuracy was approximately 20 mm in the *X* and *Y* (horizontal) and 25 mm in the *Z* (vertical) directions by comparison with local fixed survey points. Topographic attributes such as slope, hillslope distance, upslope area and the topographic wetness index (TWI) (Beven and Kirkby 1979) were derived from these data. Sample points were recorded using the DGPS also.

Results

Hillslope and soil properties

The transects both had linear hillslope profiles with approximately the same slope (~30%) and length (~150 m) (Fig. 4, Table 1). At the time of sampling vegetation consisted of low grass cover (Figs 2, 3).

Soil texture (sand, silt and clay), in particular clay, can influence SOC concentration. Clay for the Upper transect (average = 35%, s.d. = 10) was significantly lower ($P < 0.05$) compared to the Lower transect (average = 49%, s.d. = 12). There was no distinct observable pattern in silt and sand along either transect nor with elevation or distance from the divide (Fig. 4). However, clay was negatively (non-significantly) ($P > 0.05$) correlated with elevation or distance from the catchment divide. That is, clay increased down the hillslope, but being non-significant may be due to chance. For both transects, SOC was significantly and negatively correlated with clay ($P < 0.005$).

For both transects, SOC concentration was 'high' (3.0–5.15%) to 'very high' (>5.15%) (Hazelton and Murphy 2007), being

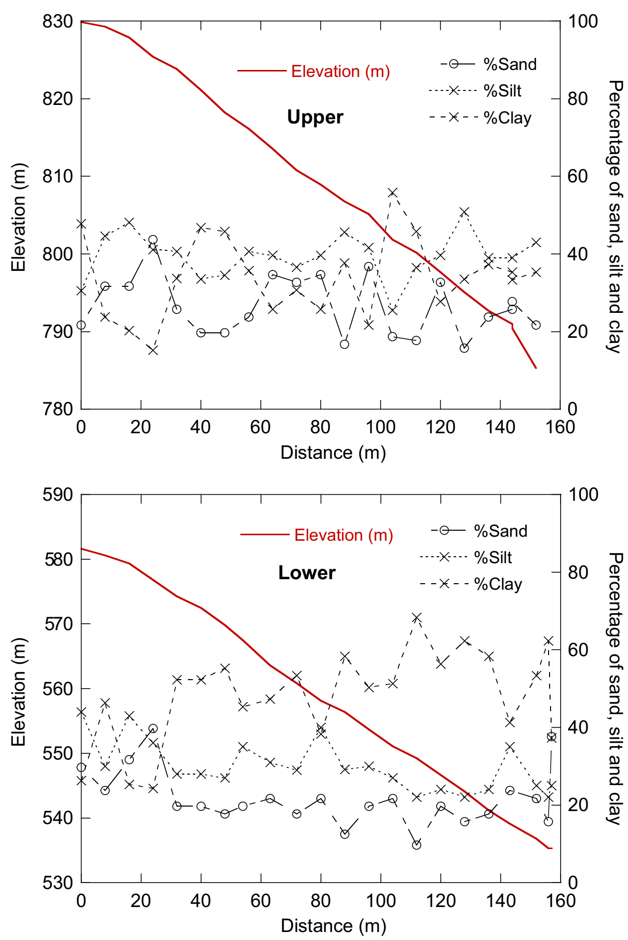

Fig. 4. Hillslope profile and soil texture for the Upper and Lower transects.

significantly higher ($P < 0.05$) for the Upper than the Lower transect (Table 2). The SOC for both transects was significantly negatively correlated ($P < 0.05$) with elevation and distance from the divide (Table 3). Combining both data sets also showed a significant correlation. There was no relationship of SOC with slope, and of SOC with upslope area or TWI for any of the data sets.

Environmental tracers

For both transects, the concentrations of ^{137}Cs, ^{210}Pb$_{ex}$ and SOC followed similar patterns (Figs 5, 6). The Upper and Lower transects both had the highest SOC and ^{137}Cs concentrations at the top of the transect, which rapidly reduced at 20–50 m distance from the divide. A similar pattern was observed for ^{210}Pb$_{ex}$.

The ^{137}Cs was positively and significantly correlated with ^{210}Pb$_{ex}$ for both the Upper ($r = 0.92$, $P < 0.0001$) and Lower ($r = 0.94$, $P < 0.0001$) data sets (Fig. 7). For all data sets, SOC was significantly positively correlated with ^{137}Cs and ^{210}Pb$_{ex}$ (Table 3, Fig. 8). This suggests that a lower SOC concentration is related to erosion while a higher SOC concentration is related to areas of deposition. Both ^{137}Cs and ^{210}Pb$_{ex}$ were positively correlated with elevation and negatively correlated with distance from the catchment divide for both the Upper and Lower data sets (Table 3).

Combining both data sets, ^{137}Cs and ^{210}Pb$_{ex}$ were positively correlated with normalised elevation (elevation for both Upper and Lower transects was scaled between 0 and 1 for comparison) and negatively correlated with distance from the divide (Table 3). Both ^{137}Cs and ^{210}Pb$_{ex}$ were significantly positively correlated with SOC (%) and negatively correlated with clay.

Table 2. Upper and Lower transect SOC (%) data.

	No. of samples	Average	Standard deviation	Minimum	Maximum
Upper	21	5.53	1.39	3.15	8.26
Lower	22	4.09	1.44	1.35	6.71

Table 3. Environment tracer relationships with topography and SOC for the Upper and Lower transects.

	Elevation (m)	Distance (m)	SOC (%)	Clay (%)
Lower				
^{137}Cs	0.6***	−0.61***	0.83***	−0.57*
^{210}Pb$_{ex}$	0.62**	−0.63**	0.82***	−0.58**
Upper				
^{137}Cs	0.49*	−0.48*	0.80*	−0.64**
^{210}Pb$_{ex}$	0.45*	−0.42*	0.82***	−0.61**
Lower and Upper data sets combined				
^{137}Cs	0.54**,^{A}	−0.54**	0.80***	−0.59***
^{210}Pb$_{ex}$	0.51**,^{A}	−0.50**	0.78***	−0.56***

***$P < 0.0001$; **$P < 0.005$; *$P < 0.05$.
^{A}Elevation has been normalised for comparison.

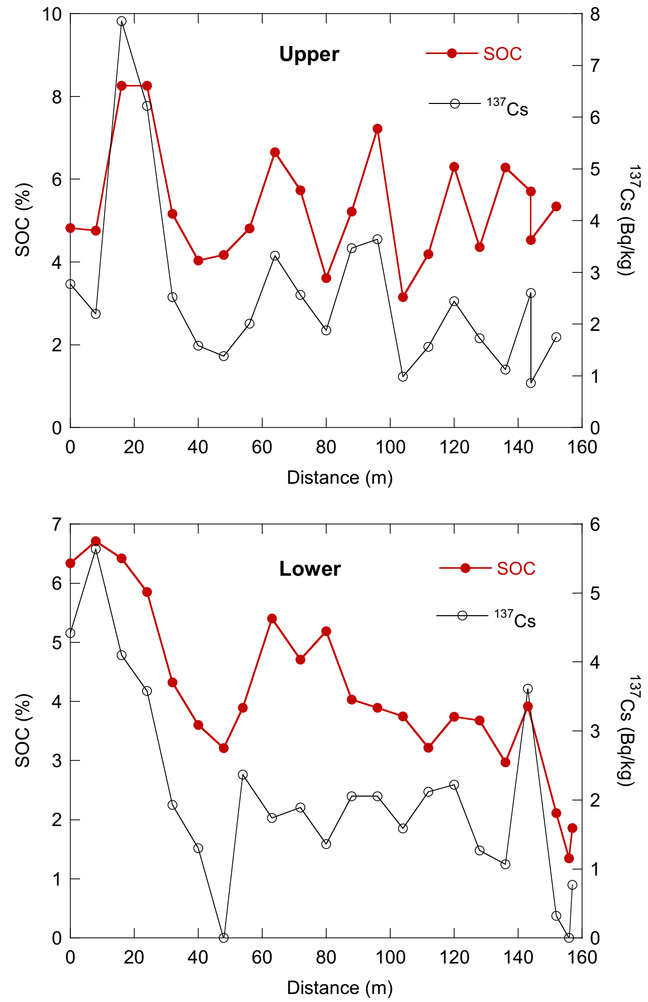

Fig. 5. SOC and ^{137}Cs for the Upper and Lower transects.

Discussion

SOC and topography

Both transects demonstrated a landscape with high SOC concentrations suggesting good structural stability (Hazelton and Murphy 2007). Here SOC was significantly higher for the Upper transect yet clay was significantly lower. Combining both data sets demonstrated that the relationship with elevation was consistent across the varying elevation regimes of the two transects. We can only speculate that more rainfall is received at higher altitudes and together with lower temperatures (the Upper transect is ~250 m higher than the Lower transect), decay rates are slower and more SOC can be stored. Given

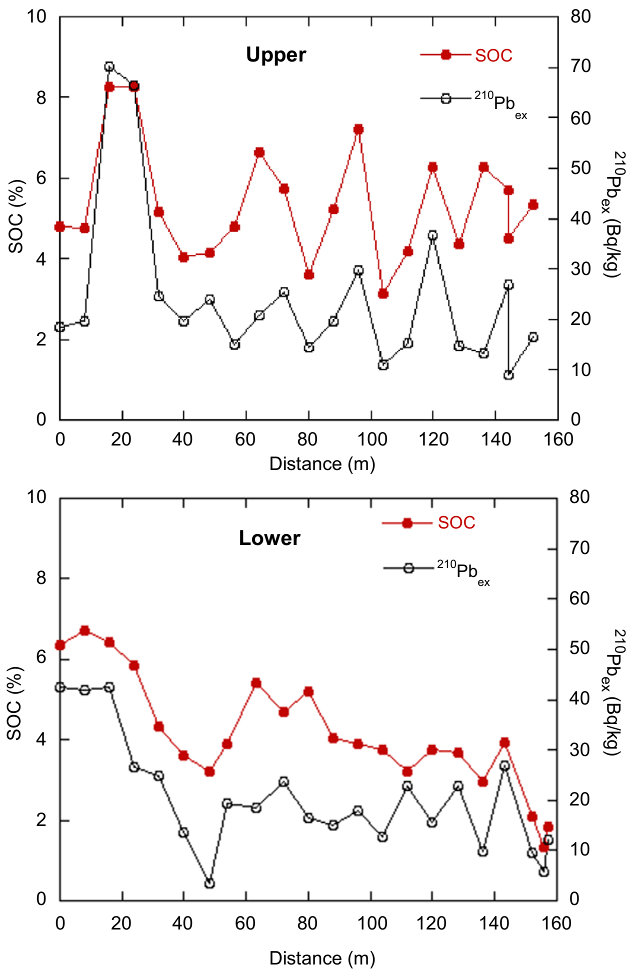

Fig. 6. SOC and $^{210}Pb_{ex}$ for the Upper and Lower transects.

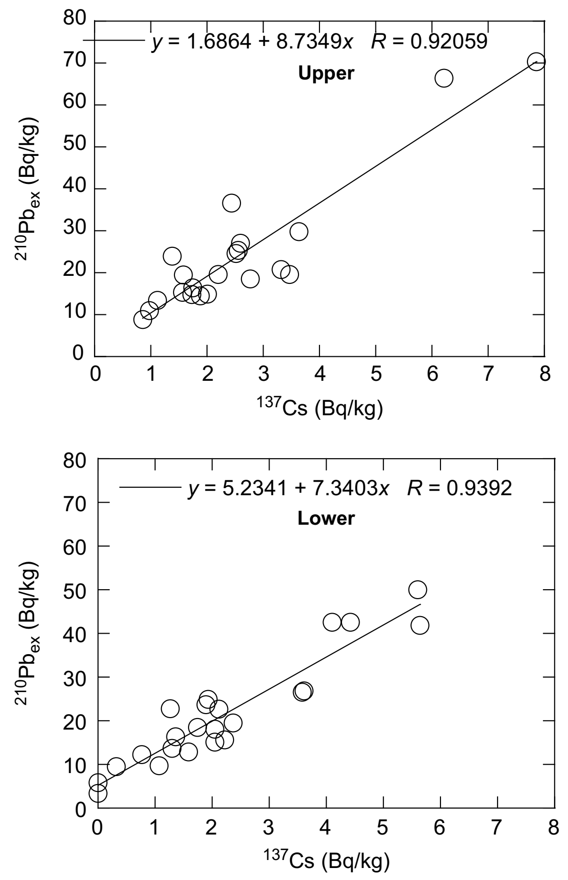

Fig. 7. ^{137}Cs and $^{210}Pb_{ex}$ for the Upper and Lower transects.

the high SOC concentration, it is possible that the soil is saturated and that there is an export of SOC as suggested by the pattern of environmental tracers. On uncultivated hillslopes (albeit at lower slopes and lower rainfall but with similar management), no relationship was observed between SOC and environmental tracers over a number of years (Martinez *et al.* 2010; Hancock *et al.* 2015). Whether the soil at Springhills (and other sites) can increase SOC is open to question (Minasny *et al.* 2017).

We also found that despite a significantly higher SOC concentration for the Upper transect, clay percentage was significantly lower. This inverse relationship contrasts to much of the literature, where it is generally accepted that clays inhibit microbial and physical oxidation of SOC (Oades 1988; Arrouays *et al.* 1995; Grigal and Berguson 1998; Percival *et al.* 2000; Müller and Höper 2004; Wei *et al.* 2014; O'Brien *et al.* 2015; Singh *et al.* 2016). However, this understanding is not clear for all environments. Other studies in the area examining the Krui and Merriwa catchments also found that SOC decreased with increasing clay (Kunkel *et al.* 2019). We are currently examining this issue at other areas in the catchment with lower rainfall and different soils and texture (Martinez *et al.* 2009).

SOC and environmental tracers

Both transects had decreasing SOC down the transect (Table 3). There was a significant negative relationship of SOC with elevation as well as with distance down the hillslope (Table 3). This reduction is likely a result of the erosion and deposition processes occurring as demonstrated by ^{137}Cs and $^{210}Pb_{ex}$ (discussed further below). Therefore, SOC at this site is being lost from the hillslope at rates commensurate with the erosional loss.

Many studies have speculated or proposed a relationship between SOC and soil erosion and deposition (Lewis 1977; Dorr 1995; Kuhn *et al.* 2009; Martinez *et al.* 2009; Gaspar and Navas 2013; Gaspar *et al.* 2019). Several have employed ^{137}Cs as a surrogate for erosion and deposition (Mabit *et al.* 2008). Here, a consistent and robust relationship between SOC and the environmental tracers ^{137}Cs and $^{210}Pb_{ex}$ was demonstrated (Walling *et al.* 2003; Fukuyama *et al.* 2008; Teramage *et al.* 2013, 2015; Özden *et al.* 2013).

The ^{137}Cs and $^{210}Pb_{ex}$ concentrations observed here represent erosion and deposition patterns during the past

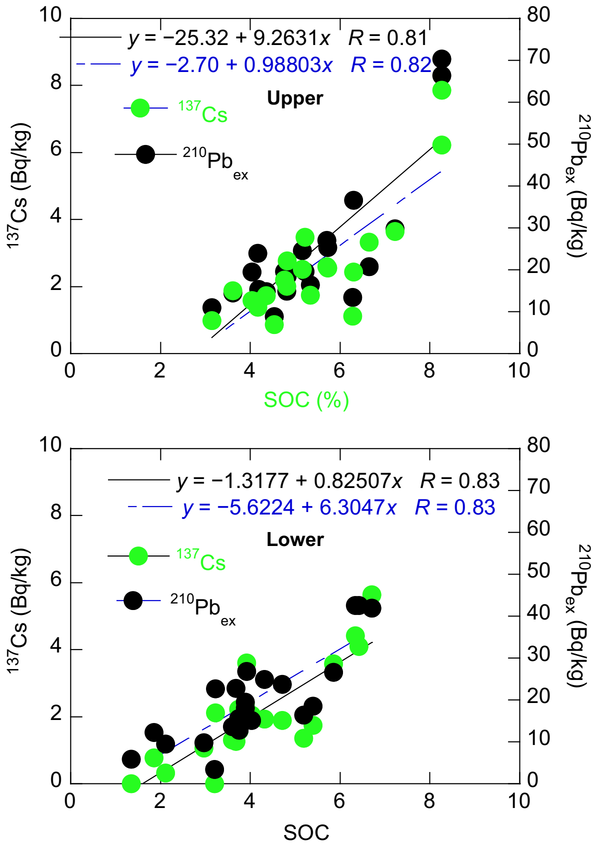

Fig. 8. SOC and relationship with ^{137}Cs and $^{210}Pb_{ex}$ for the Upper and Lower transect soil cores.

(approximately) 50 and 100 years, respectively (Zapata *et al.* 2002; Walling *et al.* 2003; Zhang *et al.* 2006; Teramage *et al.* 2013; Mabit *et al.* 2014; Gaspar *et al.* 2019). The author believes that this is the first report of $^{210}Pb_{ex}$ used to examine the spatial and temporal distribution of SOC in a grazing pasture environment in Australia. The consistency of patterns between the two tracers suggests that the same erosion and deposition patterns occur across different time scales (Walling *et al.* 2003). The advantage of $^{210}Pb_{ex}$ is that it is a naturally occurring product that is continually being replenished, and with a half-life of 22.3 years it appears to be a viable alternative to ^{137}Cs. Further, given that ^{137}Cs fallout terminated in the early 1970s and $^{210}Pb_{ex}$ is continually replenished, the findings here suggest that SOC and its relationship with erosion and deposition is consistent at decadal time scales (Walling *et al.* 2003). With the consistent replenishment of $^{210}Pb_{ex}$, the patterns could be considered to be a function of the present hillslope behaviour, not an average of the last 50 years as provided by the ^{137}Cs method. Therefore, the tracers have the ability for assessing and detecting change in SOC transport patterns. However, Kato *et al.* (2010) found that the use of $^{210}Pb_{ex}$ may be problematic for soil erosion understanding in semi-arid areas (although not the environment examined here). This needs to be explored further in Australia. This suggests that the SOC patterns in relation to erosion and deposition are robust and consistent at longer than the 50-year history of ^{137}Cs and $^{210}Pb_{ex}$ in this environment (Walling *et al.* 2003; Mabit *et al.* 2009; Gaspar *et al.* 2019).

Study limitations and further work

Understanding SOC movement can be a complex exercise as SOC can be transported by a variety of surface and subsurface processes at different rates (Hassink 1997; Oades 1988; Rumpel and Kögel-Knabner 2011; Schwanghart and Jarmer 2011; Ruiz Sinoga *et al.* 2012; Gaspar and Navas 2013; Jandl *et al.* 2014). The environmental tracers here are well-accepted and understood (Zapata *et al.* 2002; Zapata 2003). These tracers provide information on erosion and deposition at decadal time scales and therefore reflect longer-term trends.

The use of the two different (and unrelated) tracers suggest that the observed patterns are robust. The method can be applied at a site after a major storm event to assess any change (Hancock *et al.* 2015, 2019). Interestingly, Hancock *et al.* (2015, 2019) found significant differences in ^{137}Cs concentration between 2006 and 2014 in a subcatchment of the Krui as well as the entire Krui catchment. This difference was attributed to a major storm event in the area (Mills *et al.* 2010). However, it is recognised that the information provides little insight into short-term or storm-event time scale processes. Short-term tracers such as ^{7}Be would also provide insight into storm-scale events (Zapata *et al.* 2002; Zapata 2003; Taylor *et al.* 2013). The $^{210}Pb_{ex}$ is continually replenished and offers the opportunity to determine decadal-scale erosion rates. While there are conversion models available to determine erosion rates, these models have not been fully developed and evaluated, particularly for Australia. This is a major undertaking and the focus of ongoing work by the research team.

Conclusion

We examined a relatively high slope and high rainfall soil mantled environment for the spatial and temporal movement of SOC along two hillslope transects with similar lengths, slopes and aspect. Environmental tracers (^{137}Cs and $^{210}Pb_{ex}$) were used to understand the movement of SOC. The SOC concentrations were high, indicating good structural stability, soil productivity and health. We found that the movement of SOC was related to soil erosion and deposition patterns. In particular, $^{210}Pb_{ex}$ was shown to be a viable tracer to understand SOC patterns and this appears to be the first time that $^{210}Pb_{ex}$ has been used in this way.

Importantly, the results demonstrate that soil C concentration is related to erosion and deposition processes at decadal time scales, suggesting a continuity of sediment transport and deposition processes despite several major droughts, different land ownership (over 150 years) and likely differences in land management. The approach demonstrated here using environmental tracers can be readily applied at other sites to further enhance our knowledge of SOC distribution and transport.

References

Arrouays D, Vion I, Kicin JL (1995) Spatial analysis and modeling of topsoil carbon storage in temperate forest humic loamy soils of France. *Soil Science* **159**(3), 191–198. doi:10.1097/00010694-199515930-00006

Berhe AA, Harte J, Harden JW, Torn MS (2007) The significance of the erosion-induced terrestrial carbon sink. *BioScience* **57**, 337–346. doi:10.1641/B570408

Berhe AA, Arnold C, Stacy E, Lever R, McCorkle E, Araya SN (2014) Soil erosion controls on biogeochemical cycling of carbon and nitrogen. *Nature Education Knowledge* **5**(8), 2.

Beven KJ, Kirkby MJ (1979) A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin* **24**(1), 43–69. doi:10.1080/02626667909491834

Bunzl K, Kretner R, Schramel P, Szeles M, Winkler R (1995) Speciation of ^{238}U, ^{226}Ra, ^{210}Pb, ^{228}Ra, and stable Pb in the soil near an exhaust ventilating shaft of a uranium mine. *Geoderma* **67**, 45–53. doi:10.1016/0016-7061(94)00032-6

Campbell BL, Loughran RJ, Elliott GL (1988) A method for determining sediment budgets using caesium-137. In 'Sediment budgets, Porto Alegre Symposium (December 1988)'. International Association of Hydrological Sciences (IAHS) Publ. No. 174. pp. 171–179. (IAHS)

Chen M, Willgoose GR, Saco PM (2015) Evaluation of the hydrology of the IBIS land surface model in a semi-arid catchment. *Hydrological Processes* **29**, 653–670. doi:10.1002/hyp.10156

Doetterl S, Berhe AA, Nadeu E, Wang Z, Sommer M, Fiener P (2016) Erosion, deposition and soil carbon: a review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. *Earth-Science Reviews* **154**, 102–122. doi:10.1016/j.earscirev.2015.12.005

Dorr H (1995) Application of ^{210}Pb in soils. *Journal of Paleolimnology* **13**, 157–168. doi:10.1007/BF00678104

Fissore C, Dalzell BJ, Berhe AA, Voegtle M, Evans M, Wu A (2017) Influence of topography on soil organic carbon dynamics in a Southern California grassland. *CATENA* **149**, 140–149. doi:10.1016/j.catena.2016.09.016

Fukuyama T, Onda Y, Takenaka C, Walling DE (2008) Investigating erosion rates within a Japanese cypress plantation using Cs-137 and Pb-210$_{ex}$ measurements. *Journal of Geophysical Research* **113**, F02007. doi:10.1029/2006jf000657

Gaspar L, Navas A (2013) Vertical and lateral distributions of ^{137}Cs in cultivated and uncultivated soils on Mediterranean hillslopes. *Geoderma* **207–208**, 131–143. doi:10.1016/j.geoderma.2013.04.034

Gaspar L, Webster R, Navas A (2017) Fate of ^{210}Pb$_{ex}$ fallout in soil under forest and scrub of the central Spanish Pre-Pyrenees. *European Journal of Soil Science* **68**, 259–269. doi:10.1111/ejss.12427

Gaspar L, Quijano L, Lizaga I, Navas A (2019) Effects of land use on soil organic and inorganic C and N at ^{137}Cs traced erosional and depositional sites in mountain agroecosystems. *CATENA* **181**, 104058. doi:10.1016/j.catena.2019.05.004

Grigal DF, Berguson WE (1998) Soil carbon changes associated with short-rotation systems. *Biomass and Bioenergy* **14**(4), 371–377. doi:10.1016/S0961-9534(97)10073-3

Hancock GR, Wells T (2021) Predicting soil organic carbon movement and concentration using a soil erosion and landscape evolution model. *Geoderma* **382**, 114759. doi:10.1016/j.geoderma.2020.114759

Hancock GR, Murphy D, Evans KG (2010) Hillslope and catchment scale soil organic carbon concentration: an assessment of the role of geomorphology and soil erosion in an undisturbed environment. *Geoderma* **155,** 36–45. doi:10.1016/j.geoderma.2009.11.021

Hancock GR, Wells T, Martinez C, Dever C (2015) Soil erosion and tolerable soil loss: insights into erosion rates for a well-managed grassland catchment. *Geoderma* **237–238**, 256–265. doi:10.1016/j.geoderma.2014.08.017

Hancock GR, Kunkel V, Wells T, Martinez C (2019) Soil organic carbon and soil erosion – understanding change at the large catchment scale. *Geoderma* **343**, 60–71, doi:10.1016/j.geoderma.2019.02.012

Hassink J (1997) The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant and Soil* **191**(1), 77–87. doi:10.1023/A:1004213929699

Hazelton P, Murphy B (2007) 'Interpreting soil test results: what to do all the numbers mean?' (CSIRO Publishing: Melbourne, Vic., Australia)

He Q, Walling DE (1997) The distribution of fallout ^{137}Cs and ^{210}Pb in undisturbed and cultivated soils. *Applied Radiation and Isotopes* **48**(5), 677–690. doi:10.1016/S0969-8043(96)00302-8

He Q, Walling DE, Wallbrink PJ (2002) Alternative methods and radionuclides for use in soil-erosion and sedimentation investigations. In 'Handbook for the assessment of soil erosion and sedimentation using environmental radionuclides'. (Ed. F. Zapata) pp. 185–215. (Kluwer Academic Publishers: Dordrecht, Netherlands)

Hoyle FC, O'Leary RA, Murphy DV (2016) Spatially governed climate factors dominate management in determining the quantity and distribution of soil organic carbon in dryland agricultural systems. *Scientific Reports* **6**, 31468. doi:10.1038/srep31468

Jandl R, Rodeghiero M, Martinez C, Cotrufo MF, Bampa F, Van Wesemael B, Harrison RB, Guerrini IA, Richter Dd Jr, Rustad L, Lorenz K, Chabbi A, Miglietta F (2014) Current status, uncertainty and future needs in soil organic carbon monitoring. *Science of The Total Environment* **468–469**, 376–383. doi:10.1016/j.scitotenv.2013.08.026

Kato H, Onda Y, Tanaka Y (2010) Using ^{137}Cs and ^{210}Pb$_{ex}$ measurements to estimate soil redistribution rates on semi-arid grassland in Mongolia. *Geomorphology* **114**(4), 508–519. doi:10.1016/j.geomorph.2009.08.009

Kirkels FMSA, Cammeraat LH, Kuhn NJ (2014) The fate of soil organic carbon upon erosion, transport and deposition in agricultural landscapes – a review of different concepts. *Geomorphology* **226**, 94–105. doi:10.1016/j.geomorph.2014.07.023

Knighton D (1998) 'Fluvial forms and processes: a new perspective.' (Routledge: Abingdon, Oxon, UK)

Kovac M, Lawrie JW (1991) Soil landscapes of the singleton 1:250 000 sheet. p. 456. Soil Conservation Service of NSW, Sydney, Australia.

Krause AK, Loughran RJ, Kalma JD (2003) The use of caesium-137 to assess surface soil erosion status in a water-supply catchment in the Hunter Valley, New South Wales, Australia. *Australian Geographical Studies* **41**(1), 73–84. doi:10.1111/1467-8470.00193

Kuhn NJ, Hoffmann T, Schwanghart W, Dotterweich M (2009) Agricultural soil erosion and global carbon cycle: controversy over? *Earth Surface Processes and Landforms* **34**, 1033–1038. doi:10.1002/esp.1796

Kunkel V, Wells T, Hancock GR (2016) Soil temperature dynamics at the catchment scale. *Geoderma* **273**(2016), 32–44. doi:10.1016/j.geoderma.2016.03.011

Kunkel V, Hancock GR, Wells T (2019) Large catchment-scale spatiotemporal distribution of soil organic carbon. *Geoderma* **334**, 175–185. doi:10.1016/j.geoderma.2018.07.046

Lal R (2001) Soil degradation by erosion. *Land Degradation & Development* **12**(6), 519–539. doi:10.1002/ldr.472

Lal R (2003) Soil erosion and the global carbon budget. *Environment International* **29**, 437–450. doi:10.1016/S0160-4120(02)00192-7

Lal R (2004) Soil carbon sequestration to mitigate climate change. *Geoderma* **123**(1–2), 1–22. doi:10.1016/j.geoderma.2004.01.032

Lal R (2019) Accelerated soil erosion as a source of atmospheric CO_2. *Soil and Tillage Research* **188**, 35–40. doi:10.1016/j.still.2018.02.001

Lewis DM (1977) The use of ^{210}Pb as a heavy metal tracer in the Susquehanna River system. *Geochimica et Cosmochimica Acta* **41**(11), 1557–1564. doi:10.1016/0016-7037(77)90167-3

Li Y, Poesen J, Yang JC, Fu B, Zhang JH (2003) Evaluating gully erosion using ^{137}Cs and ^{210}Pb/^{137}Cs ratio in a reservoir catchment. *Soil and Tillage Research* **69**, 107–115. doi:10.1016/S0167-1987(02)00132-0

Li Y, Zhang QW, Reicosky DC, Bai LY, Lindstrom MJ, Li L (2006) Using ^{137}Cs and ^{210}Pb$_{ex}$ for quantifying soil organic carbon redistribution affected by intensive tillage on steep slopes. *Soil and Tillage Research* **86**, 176–184. doi:10.1016/j.still.2005.02.006

Longmore ME, O'Leary BM, Rose CW, Chandica AL (1983) Mapping soil erosion and accumulation with the fallout isotope caesium-137. *Soil Research* **21**, 373–385. doi:10.1071/SR9830373

Loughran RJ (1994) The use of the environmental isotope caesium-137 for soil erosion and sedimentation studies. *Trends in Hydrology* **1**, 149–167.

Loughran RJ, Pennock DJ, Walling DE (2002) Spatial distribution of caesium-137. In 'Handbook for the assessment of soil erosion and sedimentation using environmental radionuclides'. (Ed. F. Zapata) pp. 97–109. (Kluwer Academic Publishers: Dordrecht, Netherlands)

Loughran RJ, Elliott GL, McFarlane DJ, Campbell BL (2004) A survey of soil erosion in Australia using caesium-137. *Australian Geographical Studies* **42**(2), 221–233, doi:10.1111/j.1467-8470.2004.00261.x

Mabit L, Bernard C, Makhlouf M, Laverdière MR (2008) Spatial variability of erosion and soil organic matter content estimated from ^{137}Cs measurements and geostatistics. *Geoderma* **145**, 245–251. doi:10.1016/j.geoderma.2008.03.013

Mabit L, Klik A, Benmansour M, Toloza A, Geisler A, Gerstmann UC (2009) Assessment of erosion and deposition rates within an Austrian agricultural watershed by combining ^{137}Cs, $^{210}Pb_{ex}$ and conventional measurements. *Geoderma* **150**, 231–239. doi:10.1016/j.geoderma.2009.01.024

Mabit L, Benmansour M, Abril JM, Walling DE, Meusburger K, Iurian AR, Bernard C, Tarján S, Owens PN, Blake WH, Alewell C (2014) Fallout ^{210}Pb as a soil and sediment tracer in catchment sediment budget investigations: a review. *Earth-Science Reviews* **138**, 335–351. doi:10.1016/j.earscirev.2014.06.007

Martinez C, Hancock GR, Kalma JD (2009) Comparison of fallout radionuclide (caesium-137) and modelling approaches for the assessment of soil erosion rates for an uncultivated site in south-eastern Australia. *Geoderma* **151**, 128–140. doi:10.1016/j.geoderma.2009.03.023

Martinez C, Hancock GR, Kalma JD (2010) Relationships between ^{137}Cs and soil organic carbon (SOC) in cultivated and never-cultivated soils: an Australian example. *Geoderma* **158**, 137–147. doi:10.1016/j.geoderma.2010.04.019

Mcfarlane DJ, Loughran RJ, Campbell BL (1992) Soil erosion of agricultural land in Western Australia estimated by cesium-137. *Soil Research* **30**, 533–546. doi:10.1071/SR9920533

Mills GA, Webb R, Davidson NE, Kepert J, Seed A, Abbs D (2010) The Pasha Bulker east coast low of 8 June 2007. Centre for Australian Weather and Climate Research technical report 23. p. 62. Centre for Australian Weather and Climate Research.

Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, Chaplot V, Chen Z-S, Cheng K, Das BS, Field DJ, Gimona A, Hedley CB, Hong SY, Mandal B, Marchant BP, Martin M, McConkey BG, Mulder VL, O'Rourke S, Richer-de-Forges AC, Odeh I, Padarian J, Paustian K, Pan G, Poggio L, Savin I, Stolbovoy V, Stockmann U, Sulaeman Y, Tsui C-C, Vågen T-G, van Wesemael B, Winowiecki L (2017) Soil carbon 4 per mille. *Geoderma* **292**(15), 59–86. doi:10.1016/j.geoderma.2017.01.002

Moore ID, Gessler PE, Nielsen GA, Peterson GA (1993) Soil attribute prediction using terrain analysis. *Soil Science Society of America Journal* **57**, 443–452. doi:10.2136/sssaj1993.03615995005700020026x

Murphy BW (2015) Impact of soil organic matter on soil properties – a review with emphasis on Australian soils. *Soil Research* **53**(6), 605–635. doi:10.1071/SR14246

Müller T, Höper H (2004) Soil organic matter turnover as a function of the soil clay content: consequences for model applications. *Soil Biology and Biochemistry* **36**(6), 877–888. doi:10.1016/j.soilbio.2003.12.015

Oades JM (1988) The retention of organic matter in soils. *Biogeochemistry* **5**(1), 35–70. doi:10.1007/BF02180317

Olley J, Burton J, Smolders K, Pantus F, Pietsch T (2013) The application of fallout radionuclides to determine the dominant erosion process in water supply catchments of subtropical South-east Queensland, Australia. *Hydrological Processes* **27**, 885–895. doi:10.1002/hyp.9422

O'Brien SL, Jastrow JD, Grimley DA, Gonzalez-Meler MA (2015) Edaphic controls on soil organic carbon stocks in restored grasslands. *Geoderma* **251–252**, 117–123. doi:10.1016/j.geoderma.2015.03.023

Özden B, Uğur A, Esetlili T, Esetlili BC, Kurucu Y (2013) Assessment of the effects of physical–chemical parameters on ^{210}Po and ^{210}Pb concentrations in cultivated and uncultivated soil from different areas. *Geoderma* **192**, 7–11. doi:10.1016/j.geoderma.2012.08.025

Pennock DJ, Appleby PG (2002) Site selection and sampling design. In 'Handbook for the assessment of soil erosion and sedimentation using environmental radionuclides'. (Ed. F Zapata) pp. 219. (Kluwer Academic Publishers: Dordrecht, Netherlands)

Percival HJ, Parfitt RL, Scott NA (2000) Factors controlling soil carbon levels in New Zealand grasslands is clay content important? *Soil Science Society of America Journal* **64**, 1623–1630. doi:10.2136/sssaj2000.6451623x

Quinton JN, Govers G, Van Oost K, Bardgett RD (2010) The impact of agricultural soil erosion on biogeochemical cycling. *Nature Geoscience* **3**, 311–314. doi:10.1038/ngeo838

Ritchie JC, McHenry JR (1975) Fallout Cs-137: a tool in conservation research. *Journal of Soil and Water Conservation* **30**(341), 283–286.

Ruiz Sinoga JD, Pariente S, Diaz AR, Martinez Murillo JF (2012) Variability of relationships between soil organic carbon and some soil properties in Mediterranean rangelands under different climatic conditions (South of Spain). *CATENA* **94**, 17–25. doi:10.1016/j.catena.2011.06.004

Rumpel C, Kögel-Knabner I (2011) Deep soil organic matter – a key but poorly understood component of terrestrial C cycle. *Plant and Soil* **338**, 143–158. doi:10.1007/s11104-010-0391-5

Rüdiger C, Hancock G, Hemakumara HM, Jacobs B, Kalma JD, Martinez C, Thyer M, Walker JP, Wells T, Willgoose GR (2007) Goulburn River experimental catchment data set. *Water Resources Research* **43**, W10403. doi:10.1029/2006WR005837

Schwanghart W, Jarmer T (2011) Linking spatial patterns of soil organic carbon to topography – A case study from south-eastern Spain. *Geomorphology* **126**(1–2), 252–263. doi:10.1016/j.geomorph.2010.11.008

Singh M, Sarkar B, Biswas B, Churchman J, Bolan NS (2016) Adsorption-desorption behavior of dissolved organic carbon by soil clay fractions of varying mineralogy. *Geoderma* **280**, 47–56. doi:10.1016/j.geoderma.2016.06.005

Smith RT, Atkinson K (1975) 'Techniques in pedology: a handbook for environmental and resource studies.' (Paul Elek: London, UK)

Story R, Galloway R, van de Graff R, Tweedie AD (1963) General report on the lands of the Hunter Valley. CSIRO Land Research Series No. 8. Commonwealth Scientific and Industrial Research Organization, Australia.

Taylor A, Blake WH, Smith HG, Mabit L, Keith-Roach MJ (2013) Assumptions and challenges in the use of fallout beryllium-7 as a soil and sediment tracer in river basins. *Earth-Science Reviews* **126**, 85–95. doi:10.1016/j.earscirev.2013.08.002

Teramage MT, Onda Y, Kato H, Wakiyama Y, Mizugaki S, Hiramatsu S (2013) The relationship of soil organic carbon to $^{210}Pb_{ex}$ and ^{137}Cs during surface soil erosion in a hillslope forested environment. *Geoderma* **192**, 59–67. doi:10.1016/j.geoderma.2012.08.030

Teramage MT, Onda Y, Wakiyama Y, Kato H, Kanda T, Tamura K (2015) Atmospheric ^{210}Pb as a tracer for soil organic carbon transport in a coniferous forest. *Environmental Science: Processes & Impacts* **17**, 110. doi:10.1039/c4em00402g

Wallbrink PJ, Olley JM, Murray AS (1994) Measuring soil movement using ^{137}Cs: implications of reference site variability. In 'Variability in stream erosion and sediment transport. Proceedings of the Canberra symposium'. December 1994, IAHS Publication no. 224. pp. 95–102. (IAHS)

Walling DE, He Q (1999) Improved models for estimating soil erosion rates from cesium-137 measurements. *Journal of Environmental Quality* **28**(2), 611–622. doi:10.2134/jeq1999.00472425002800020027x

Walling DE, He Q (2001) Models for converting 137Cs measurements to estimates of soil redistribution rates on cultivated and uncultivated soils, estimating bomb-derived 137Cs reference inventories (including software for model implementation). A contribution to the IAEA Coordinated Research Programmes on Soil Erosion (D1.50.05) and Sedimentation (F3.10.01). p. 32. University of Exeter, UK.

Walling DE, Collins AL, Sichingabula HM (2003) Using unsupported lead-210 measurements to investigate soil erosion and sediment delivery in a small Zambian catchment. *Geomorphology* **52**, 193–213. doi:10.1016/S0169-555X(02)00244-1

Walling DE, Zhang Y, He Q (2011) Models for deriving estimates of erosion and deposition rates from fallout radionuclide (caesium-137, excess lead-201, and beryllium-7) measurements and the development of user friendly software for model implementation. In 'Impact of soil conservation measures on erosion control and soil quality'. IAEA-TECDOC-1665. pp. 11–33. (International Atomic Energy Agency: Vienna, Austria)

Wei H, Guenet B, Vicca S, Nunan N, Asard H, AbdElgawad H, Shen W, Janssens IA (2014) High clay content accelerates the decomposition of fresh organic matter in artificial soils. *Soil Biology and Biochemistry* **77**, 100–108. doi:10.1016/j.soilbio.2014.06.006

Wells T, Hancock G (2014) Comparison of vertical transport of ^{137}Cs and organic carbon in agricultural cracking soils. *Geoderma* **214–215**, 228–238. doi:10.1016/j.geoderma.2013.09.007

Wells T, Hancock GR, Dever C, Murphy D (2012) Prediction of vertical soil organic carbon profiles using soil properties and environmental tracer data at an untilled site. *Geoderma* **170**, 337–346. doi:10.1016/j.geoderma.2011.11.006

Zapata F (2003) Introduction. *Soil and Tillage Research* **69**(2003), 1–2. doi:10.1016/S0167-1987(02)00123-X

Zapata F, Garcia-Agudo E, Ritchie JC, Appleby PG (2002) Chapter 1: Introduction. In 'Handbook for the assessment of soil erosion and sedimentation using environmental radionuclides'. (Ed. F Zapata) pp. 1–13. (Kluwer Academic Publishers: Dordrecht, Netherlands)

Zhang X, Qi Y, Walling DE, He X, Wen A, Fu J (2006) A preliminary assessment of the potential for using $^{210}Pb_{ex}$ measurement to estimate soil redistribution rates on cultivated slopes in the Sichuan Hilly Basin of China. *CATENA* **68**, 1–9. doi:10.1016/j.catena.2006.03.012

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