

Understanding and quantifying whole soil-profile organic carbon transfer using an environmental tracer

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ABSTRACT

Context. Quantifying soil organic carbon (SOC) depth distribution and its vertical transport is needed for both improved understanding of soil properties and behaviour as well as enhanced organic carbon sequestration. This is a global issue, that if better understood, could result in both more agriculturally productive soils as well as enhanced environmental outcomes. Aims. Quantify whole soil-profile SOC and down-profile movement at a series of sites in south-east Australia. Methods. Soil is sampled at regular intervals using cores and assessed for SOC and environmental tracer (¹³⁷Cs) concentration. Key results. Soils that have a high clay content (Vertosols) and crack (i.e. self mulching) have the highest SOC content. In high clay content soils, ¹³⁷Cs is present at depths well below that at which it would be present by diffusive processes. Conclusions. Surface soil, labelled with ¹³⁷Cs is moving down the soil profile by advective processes to depths well below that possible by diffusive processes alone. Using local erosion rates and carbon input, it is estimated that less than 1% of SOC is delivered to the cracking soils by erosional processes and that the majority of SOC must be produced in situ. Implications. Given that ¹³⁷Cs is a relatively new environmental tracer (1945 onwards), this suggests that surface labelled soil is reaching depths of up to 80 cm at decadal time scales. The methods and findings here have global applicability and provide insights into potential enhancement of carbon sequestration in both cropping and grazing landscapes.

Keywords: 137-Cs, carbon sequestration, cesium-137, climate variability, pedogenesis, soil depth, soil properties, vertosol.

Introduction

Soil organic carbon (SOC) is well understood to have a wide range of biogeochemical roles. In recent years, increasing SOC has been seen as a way to improve soil productivity as well as reducing atmospheric CO₂ concentration (Minasny *et al.* 2017; Wang *et al.* 2022). Consequently there has been considerable effort into understanding the spatial and temporal distribution of SOC. However, there is considerable debate about the rate of change of SOC in terms of both increasing and decreasing concentration and different management practices for different soils (Cunningham *et al.* 2012; George *et al.* 2012; Davy and Koen 2013; Korkanç 2014; Baah-Acheamfour *et al.* 2015; Cardinael *et al.* 2015; Minasny *et al.* 2017; Dalal *et al.* 2021; Wang *et al.* 2022). There is also considerable debate regarding how SOC distribution changes spatially (Wang *et al.* 2022) and temporally down the soil profile (Lorenz and Lal 2005; Yoo *et al.* 2006; Luo *et al.* 2010; Mora *et al.* 2014; Murphy 2015; Olson and Al-Kaisi 2015; Dalal *et al.* 2021). Here we focus on SOC down the soil profile to bedrock.

Quantifying SOC and its spatial and temporal variability is complex as soil is heterogeneous in space and time (Murphy 2015). Soil is produced by a combination of intrinsic and extrinsic factors. Both organic and inorganic materials can be produced *in situ*, deposited from upslope and material lost downslope (erosion) (Willgoose 2018). Inorganic and organic material will also move down the soil profile by a variety of processes that can be diffuse (i.e. material moving along a wetting front, illuviation of clay) as well as more immediate (i.e. cracks allowing direct movement of surface material down the profile) (Wells *et al.* 2012, 2013; Wells and Hancock 2014).

Diffusive processes, where matter moves according to a gradient of chemical potential, activity or concentration are usually slow and controlled by soil texture in response to forcing factors such as soil moisture. Advection, or bulk movement, provides a more direct and potentially rapid transfer of material through soil cracks and fissures (Wells and Hancock 2014). Animal burrows and decaying tree roots may also provide a relatively rapid and concentrated (advective) transfer (Butler 1995, 2018). There is considerable theoretical knowledge regarding these processes; however, for the majority of soils the dominant processes are only qualitatively understood (Willgoose 2018). A quantitative understanding is yet to be fully developed. What is less well understood is the rate at which materials migrate vertically down the soil profile. This information is needed for improved soil management and increased agricultural productivity as well as the complementary goal of carbon sequestration.

Many studies have examined SOC both over short and longer time scales; however, the majority have focussed on the near surface (Jha *et al.* 2020). Quantifying whole-profile processes are non-trivial. While surface soil samples are relatively easy to obtain, collecting full soil profiles are much more labour intensive. Whole profile assessment is the focus of this work.

Environmental tracers offer one approach to better understand the spatial and temporal distribution of soil components. During 1945–1972, ¹³⁷Cs (half-life of 30.2 years) was emitted globally into the atmosphere. It is an anthropogenically produced tracer and has been used extensively to determine erosion rates (Loughran 1994; Walling and He 1999, 2001; Walling et al. 2011). Upon arrival on the soil surface by both wet and dry deposition at the soil surface (Elliott et al. 1997), ¹³⁷Cs becomes strongly bound to the clay component of soil. The ¹³⁷Cs arrived via rainfall onto the soil surface and is known to migrate via diffusive processes (Wells et al. 2012, 2013). However, surface labelled soil can be eroded and transported both laterally and vertically. In particular, for Vertosols (a focus here) cracks develop as the soil dries, allowing surface soil materials to fall into the cracks (Wilding and Tessier 1988). Because ¹³⁷Cs is unique in the environment, it provides a tool to identify soil movement down the soil profile. The non-exchangeability of the cation once it comes into contact with soil particles (VandenBygaart 2001) means that the soil is essentially labelled with 137 Cs, which only changes through time as a result of natural decay and soil movement (Hao et al. 2001), thus making it a useful tracer. A downside of ¹³⁷Cs is its relatively short half life (30.2 years), which means that it has now had nearly two half-lives of decay and is now unable to be detected in some areas in Australia.

Several hillslope and catchment-scale studies have suggested a link between SOC and sediment transport (Gregorich *et al.* 1998; Starr *et al.* 2000; VandenBygaart 2001; Ritchie and McCarty 2003; Page *et al.* 2004; Van Oost *et al.* 2005; Li *et al.* 2006, 2007; Yoo *et al.* 2006; Huang *et al.* 2007; Mabit *et al.* 2008; Kuhn *et al.* 2009; Quinton *et al.* 2010; Doetterl *et al.* 2012, 2015, 2016; Fissore *et al.* 2017). The above studies suggest that (1) 137 Cs and SOC are moving along the same physical pathways, (2) 137 Cs and SOC are moving by the same physical mechanisms and (3) 137 Cs can be used to predict the spatial distribution of SOC. Therefore, the literature regarding the relationship between SOC and 137 Cs appears to be well established, with similar conclusions reported at various study sites throughout the world. The presence of 137 Cs in soil can therefore infer (1) depth of migration of surface material by both advective and diffusive processes and (2) a potential rate at which surface material migrates to that depth (Wells *et al.* 2012, 2013).

This study examines the issue of soil profile SOC distribution in a catchment in south-east Australia. The anthropogenic tracer 137 Cs is used as a means to determine the migration of surface soils to depth. The presence of 137 Cs further provides the ability to place an age constraint on the movement of surface materials down the soil profile. As 137 Cs was released to the atmosphere during 1945–1972, then any material movement must have been labelled by fallout received on the soil surface from within this period of release (27 years). This provides a range of age constraints on transported material down the soil profile.

Here a range of soils in a large catchment in the Hunter Valley located in the south-east of Australia are examined to bedrock. The environmental tracer ¹³⁷Cs is used to elucidate the movement of surface soil down the soil profile and hypothesise as to the rate of this soil movement and related SOC concentration. The methods here can be used elsewhere to better understand the movement of soil materials down the soil profile.

Site description

This study focusses on sites in the Krui River catchment in south-east Australia (Fig. 1) (Rüdiger et al. 2007). The catchment has been a major focus for understanding hydrology, sediment transport and SOC in south-east Australia (Martinez et al. 2010; Bissett, unpubl. BSc. Hons. thesis; Wells et al. 2012, 2013; Wells and Hancock 2014; Kunkel et al. 2016, 2019; Hancock et al. 2019). The Krui catchment extends over 31°49–32°13'S and 150°02–150°21'E, with elevations ranging from approximately 200 m in the south (Merriwa Plateau) to 1200 m in the north (Liverpool Range). The region is located in the temperate zone of eastern Australia. Average annual rainfall in the study area is 624 mm (the 139 year average recorded at the Cassilis monitoring station, www.bom.gov.au), with annual potential evaporation of approximately 1200 mm. The local landscape is open grassy woodland characterised by widely spaced eucalypt tress with very little shrub cover.

The study examines a range of soils at locations in the Krui catchment (Illogan, Roscommon and Pembroke properties) that are used for both grazing and cropping and all with the same approximate rainfall and climate (Fig. 1). Soil pits to



Fig. I. Location of the study sites.

bedrock were excavated at all sites. These sites are described below (Table 1, Fig. 2).

Illogan

At the Illogan property, two sites were examined. First, a site with red basaltic clays (Euchrozems, upon which the 'Dog Paddock' site is located) and, second, a site with black earths (Vertosols, upon which the 'Shed Paddock' site is located) (Fig. 2). The slope (1%), aspect and elevation of each site were similar. The Dog Paddock pit was excavated 10 m to the east of a permanently mounted weather and soil moisture monitoring station ('K1', see Rüdiger et al. 2007). The Shed Paddock site was established ~1.5 km to the west of the Dog Paddock site. There was no evidence at either site of erosion/deposition or any disturbance other than that produced by cultivation practices associated with minimum tillage cereal and grain production. Cracking of the soil has been observed on many occasions at the Shed Paddock site during dry periods. No cracking has been observed in Dog Paddock. Further site details can be found in Wells et al. (2013).

Table I. Site location and landuse.

Site	Landuse	Soil type
Roscommon (K2)	Pasture	Solodic soil, sandy loam
Illogan (Dog Paddock)	Cropping	Red basaltic clays (Euchrozems)
Illogan (Shed Paddock)	Cropping	Black basaltic clay (Vertosol)
Pembroke South cropped (K3)	Cropping	Black basaltic clay (Vertosol)
Pembroke South pasture (K3)	Pasture	Black basaltic clay (Vertosol)
Pembroke North pasture (K4)	Pasture	Black basaltic clay (Vertosol)

For further site detail see Rüdiger et al. (2007).



Fig. 2. Photographs of the study sites and equipment used for the soil pits from which the soil samples were collected. The sites were a mix of both cropping and grazing land use. Further details can be found in Rüdiger *et al.* (2007) or https://www.eng.newcastle.edu.au/sasmas/SASMAS/sasdata.html.

Roscommon

The Roscommon site (K2) was located on sandy loam (Solodic) soil and comprised improved pasture and has been used for grazing (Fig. 2). There has been no cropping at the site. No soil cracking has been observed at this site. The property has been owned by the same family for over 50 years with a consistent grazing management programme.

Pembroke South

Pembroke South (K3) had Vertosol soil and had areas of both cropping and grazing (Fig. 2). Two sites were examined: one that had been cropped (Pembroke South Cropping) and an adjacent site in the same paddock (100 m to the north) adjacent to the K3 soil moisture monitoring site (Rüdiger *et al.* 2007) that had not been cropped and managed as pasture and grazing (Pembroke South Grazing). Large cracks have been observed at both sites here.

Pembroke North

Pembroke North (K4) had Vertosol soil and had been managed for pasture and never cropped (Fig. 2). Cracks have been observed at this site.

Site summary

All sites had low slope of 1–3% and approximately the same rainfall. All sites were well away from trees and any farm infrastructure. In summary, the sites were a mix of both pasture (grazing) and cropped sites. All sites were considered to have deep soils (depths over 1 m) and good fertility and agricultural productivity (Table 1). The Illogan site allowed an assessment of two different soils on the same property that were both managed for cropping in the same way. While K3 (Pembroke South), allowed an assessment of the same soil under both cropping and pasture.

A summary of the sites is provided in Table 1.

Methodology

Soil sampling

At all sites a backhoe was used to cut trenches down to bedrock. The pits were 3–4 m long and approximately 1 m wide to allow access. Soil samples were collected by inserting steel cores into the site wall of each trench in a continual sequence down the soil profile. Each vertical profile was sampled using 200 mm long by 65 mm or 200 mm by 100 mm internal diameter cores, which were hammered into the side wall of the trench at regular intervals in a vertical line from the soil surface down to bedrock. Less deep cores (i.e. 50 and 150 mm) were collected at the surface. For insertion a steel cap or dolly was placed on top of the core. No lubricants were used on the cores when inserted.

Laboratory analysis

After collection, soil samples were immediately bagged and transported to the University of Newcastle soils laboratory, where they were weighed and then dried at 40°C for 7–10 days. The dried samples were gently disaggregated with a mortar and pestle and passed through a 2 mm sieve and the coarse (>2 mm) fraction separated. The <2 mm fraction was further disaggregated with a mortar and pestle and weighed. The bulk density of each sample was calculated using the dried soil mass and volume of each core.

The <2 mm soil fraction was ground in a mill to a fine powder and the total carbon and nitrogen content measured using a LECO 2000 analyser (LECO method, www.leco.com). The SOC is reported here in units of mass (t ha⁻¹) using the bulk density of the soil determined from the sample core and depth of the sample core. The hydrometer method outlined by Smith and Atkinson (1975) was employed to establish the particle size distribution of the <2 mm soil fraction. Bulk density of each sample was determined based on dry mass of each sample and core volume. The pH was determined using a 1:5 solution with distilled water using a Eutech pH instrument (Rayment and Higginson 1992).

¹³⁷Cs analysis

Dried soil samples of approximately 1000 g (<2 mm fraction) were placed in Marinelli containers and gamma emissions were counted on a hyper-pure germanium spectrometer (GEM Series HPGe Coaxial Detector System) over a period of 24 h with counting errors of approximately $\pm 10\%$ or less achieved. The Loughran (1994) method was utilised to determine the concentration of ¹³⁷Cs in the soil samples, which were then converted to areal activity (Loughran *et al.* 2002).

Statistical analysis

Assessments were conducted using linear regression and Student *t*-tests with KaleidaGraph software (www.synergy. com) and GraphPad Prism (https://www.graphpad.com). Significance was P < 0.05 unless stated otherwise, where $P \le 0.05$ means that the test hypothesis is false or should be rejected. All figures were created using the KaleidaGraph program.

Results

All trenches were dug to bedrock, with samples collected to the maximum depth practicable. All sites had soil depths exceeding 1 m (Table 2). The samples were collected from the Illogan site in 2010, while the other sites were collected in 2011. At time of sampling, cracks were visibly evident at Illogan (Shed Paddock) and Pembroke South and North. No cracks were evident at Illogan (Dog Paddock) or Roscommon. Slickensides were evident down the soil profile at Illogan (Shed Paddock), Pembroke North and South but not at the other sites.

At Illogan, soil depth for both Dog and Shed Paddocks was approximately 1.4 m (including \sim 0.1 m of weathered bedrock or saprolite at the base of the profile) (Table 1). Four individual vertical profiles were sampled from the walls of

 Table 2.
 Soil depth, SOC stock and surface core SOC for the study sites.

Site	Soil depth (cm)	SOC stock (t ha ⁻¹)	SOC (%) at surface
Roscommon (K2)	140	64.8	1.04
Illogan (Dog Paddock)	118 (100–135) ^A	86 (77–84) ^A	2.23 ^B
Illogan (Shed Paddock)	118 (100–135) ^C	128 (94–166) ^C	1.81 ^D
Pembroke South cropped (K3)	140	178	1.05
Pembroke South pasture (K3)	160	305	5.01
Pembroke North pasture (K4)	140	402	7.35

^ARange of soil depth and SOC stock from four profiles within the same trench. ^BAverage SOC from four surface samples from top of each sampled profile. ^CRange of soil depth and SOC stock from three profiles within the same trench. ^DAverage SOC from three surface samples from top of each sampled profile. the Dog Paddock trench and three from the Shed Paddock trench.

Seven to eight core samples were taken for each vertical profile in the Dog Paddock trench (31 samples in total) and 8–10 cores for each Shed Paddock profile (27 samples in total).

At Roscommon and Pembroke North and South, a single set of samples was collected using steel cores inserted vertically down the sidewall of the trench to bedrock. These cores were 200 mm long with an internal diameter of 94 mm.

Soil properties

Observation of the trench wall of the Vertosol sites showed a small number of fine roots from the present and past cereal crops at depths greater than 1 m. However, the majority of roots were concentrated in the near surface. There were also well-defined vertical lines of darker material, suggestive of either decayed plant roots or organic rich surface material that had been transported down cracks. No texture difference (by hand) was found despite the darker colour.



Fig. 3. Clay content depth concentration at Illogan: (top) Dog Paddock and (bottom) Shed Paddock. Dog Paddock had four soil profiles and Shed Paddock had three individual soil profiles samples in each trench, with each profile approximately I m apart to provide replicates.

The sites had different clay content based on soil type (Figs 3 and 4). For Illogan (Dog Paddock) (Fig. 3) and Roscommon sites (Fig. 4), the clay content was lower than that of the Vertosol sites. Roscommon had clay concentration of less than 10% for the top 60 cm, which increased after this depth. Illogan (Dog Paddock) had a clay content of less than 40% for the top 25 cm, which increased after this depth. The Vertosols of Illogan (Shed Paddock) and Pembroke South all had clay concentrations >50% down the profile. Pembroke



Fig. 4. Clay content depth concentration for (top) Roscommon, (middle) Pembroke South cropped and pasture and (bottom) Pembroke North.

North had clay content >50% for the top 1 m, which declined after this depth. All soil cores had pH less than 7 (range 5–7). There was a generally increasing trend in bulk density with depth for all sites.

Total SOC varied considerably for each site (Table 2). Here SOC is expressed in terms of carbon stock. Roscommon had the lowest stock (\sim 65 t ha⁻¹) and Pembroke North the highest (402 t ha⁻¹). For the Illogan sites, there was considerable variability at each trench. Stocks had range of 77–84 t ha⁻¹ for Dog Paddock and 94–166 t ha⁻¹ for Shed Paddock. In general, the lower clay sites (Roscommon and Dog Paddock) had the lowest SOC stocks, with the higher clay Vertosols having the largest stock.

All sites had unique SOC depth distribution profiles. For Illogan (Dog Paddock), SOC was concentrated at the 5–10 cm depth and for Shed Paddock, SOC was concentrated at greater depths (Figs 5 and 6). The lower clay Roscommon site had SOC concentrated in the top 20 cm, with a rapid decline at depth. For Pembroke North and South, SOC was highest at the surface and declined down the profile.

Environmental tracer

All sites had a unique 137 Cs depth distribution (Figs 7 and 8). All sites displayed a decrease in 137 Cs with depth, except for



Fig. 5. SOC depth distribution for (top) Dog Paddock and (bottom) Shed Paddock.



Fig. 6. SOC stocks for (top) Roscommon, (middle) Pembroke cropped and pasture and (bottom) Pembroke North.

Roscommon where it was present in the top 20 cm only. In the non-Vertosols (Illogan Dog Paddock and Roscommon), the migration of ¹³⁷Cs appeared limited to approximately 20–25 cm maximum depth. For Vertosols, ¹³⁷Cs was detected to depths of 60–80 cm (Pembroke North). For the Vertosol sites, the ¹³⁷Cs depth distribution inconsistently declined in concentration down the profile. However, for Pembroke North, there was an absence of ¹³⁷Cs at 40–60 cm, with detectable concentrations at 60–80 cm. Similarly for Pembroke South (cropped), there was an absence of ¹³⁷Cs at 20–40 cm, with detectable concentrations at 40–60 cm.



Fig. 7. ¹³⁷Cs depth concentration at Illogan: (top) Dog Paddock and (bottom) Shed Paddock.

While we do not have data on cracking depths, this increased concentration suggests that this was a maximum potential crack depth and was the maximum depth that material labelled with ¹³⁷Cs was translocated.

Discussion

All sites were selected based on their representativeness of the local area, landuse and being typical of local soils. All sites had soil depths greater than 1 m. Climatically the sites were very similar, yet there was a considerable difference in SOC content both on the soil surface and down the soil profile. A major difference at each site was soil texture. The Vertosol sites had high clay contents that varied little down the profile. The non-Vertosol soils all had less clay, with Dog Paddock having increasing clay down the soil profile and Roscommon having relatively little clay compared to the other sites. In general, more clay equated to greater SOC stock at these sites.

Down-profile SOC movement and SOC stock

There are two methods of delivery of labelled soil to depth: local and non-local supply (Murphy 2015). The Vertosols



Fig. 8. ¹³⁷Cs depth distribution for (top) Roscommon, (middle) Pembroke cropped and pasture and (bottom) Pembroke North.

examined here have shrink–swell properties, with cracks developing as soil dries and allowing surface soil materials to fall into the cracks (Wilding and Tessier 1988). This material is then incorporated into the subsoil (i.e. pedoturbation) (Yaalon and Kalmar 1978). This process is responsible for the peaks in ¹³⁷Cs activity found at depth, as labelled soil is transported down into the subsoil via cracks. Southard and Graham (1992) found ¹³⁷Cs present in Vertosols at depths up to 72 cm. Al-Masri (2006) found the vertical distribution of ¹³⁷Cs to be related to soil type, allowing movement of material to depth. Curtis (1996) also suggested that surface

cracks enable soil fines labelled with ¹³⁷Cs to move down the soil profile. Several other studies have examined the depth distribution of ¹³⁷Cs and SOC. The oldest sites sampled to depth in the local area were sampled to bedrock in 2006 (Stanley catchment, Martinez *et al.* 2010) with ¹³⁷Cs being present to depth. This suggests that transport of material down the soil profile predates the time of later sampling here.

For untilled non-cracking soils, the ¹³⁷Cs depth distribution profile is that of an exponential decline within the top \sim 20 cm, with little ¹³⁷Cs below this. The authors have demonstrated this to be the case for sites within the Krui catchment and surrounds (Martinez *et al.* 2009; Hancock *et al.* 2015). The relatively shallow presence of ¹³⁷Cs at the non-Vertosol sites (Dog Paddock and Roscommon) suggests that the movement of SOC and other soil components from the surface is via diffusive processes (Wells *et al.* 2012, 2013; Wells and Hancock 2014).

There were contrasting relationships with SOC and clay for the Vertosol and non-Vertosol sites. For the Dog Paddock, there was a significant result with SOC and clay (Fig. 9 top); however, there was no relationship at Shed Paddock (Fig. 9 bottom). This finding is a result of Dog Paddock having an increase in clay with depth (Fig. 3 top), with Shed Paddock having a constant clay content down the profile and no evident pattern (Fig. 3 bottom). Similar relationships were found for Pembroke South and North, with no significant relationship found with clay (not displayed for brevity). No relationship was found at Roscommon, likely due to the low SOC content and low clay (not shown for brevity).

There was a consistent and significant relationship with SOC and ¹³⁷Cs for Dog and Shed Paddocks (r = 0.92, P < 0.001) (Fig. 10). Similar relationships were found for Pembroke South and North, but there was no relationship between SOC and clay or SOC and ¹³⁷Cs for Roscommon. This suggests that clay is not the sole control on SOC movement at these sites (and likely other sites), and a portion of SOC associated with clay will move along pathways traced by ¹³⁷Cs also fixed to clay.

The data here allow a means to determine an approximate age and rate of SOC movement down the profile. If we assume a maximum depth of 80 cm for the labelled material and that ¹³⁷Cs arrived on the surface during 1945–1972, then this suggests that an age range of between 65 (2010 subtract 1945) and 38 years (2010 subtract 1972) of material using 2010 as an average date of sampling. Therefore, at the earliest, material has migrated to its maximum depth 65 years prior,



Fig. 9. Relationship between SOC and clay for Illogan: (top) Dog Paddock and (bottom) Shed Paddock.



Fig. 10. Relationship between SOC and ¹³⁷Cs for the Illogan: (top) Dog Paddock and (bottom) Shed Paddock. SOC and ¹³⁷Cs were significantly correlated for both Dog Paddock (r = 0.92, P < 0.001) and Shed Paddock (r = 0.82, P < 0.002) when all profile data were combined.

with material assumed to be still migrating. At the other extreme, if labelled soil was only transported at the end of the fallout period in 1972, then the labelled material has a maximum age of approximately 40 years.

The age of 65 years can be considered a maximum age because there was no fallout prior to this. However, it is more likely that the labelled material is much younger than these ages and transported in less time. Soil would be continually migrating down the soil profile. The authors have observed cracks large enough to place an entire arm down in 2005 at Pembroke South. It is also likely that modern material is continuing to move down the profile. It is also recognised that the SOC quantified here may be much older than the ¹³⁷Cs fallout period. However, dating (i.e. using carbon-14) of this SOC is beyond the scope of this project and using the approach here provides a first pass assessment of age and migration rate.

SOC contribution by erosion to depth and age

Murphy (2015) suggests that there are no definitive data to suggest a SOC content threshold for soil productivity. Smith *et al.* (2015) suggest that a SOC content of 2% is a threshold for soil erosion stability for Vertosols. Below 2%, soil aggregates slake, this being an inherent property of Vertosols. They found that that when SOC was greater than 3.5% in surface soil, aggregate stability was improved, suggesting an increase in SOC can reduce erosion. Here, there was a range of surface SOC concentration, with Illogan (Shed Paddock) having SOC of 1.81% while the Pembroke sites had range of 1.05–7.35% (Table 2). There was no visual evidence of soil structural decline or erosion at any of the sites.

There are no specific erosion rates for each site examined here. However, if we assume that the erosion rate is 5 t ha⁻¹ year⁻¹ (Martinez et al. 2009, 2010), and hillslope soils have an approximately 2-3% OC on the surface (assuming this is the most erosionally active or mobile layer), this provides 0.1–0.2 t ha^{-1} of eroded or potentially mobilised OC per year for the pasture sites. If all eroded sediment was captured by soil cracks then this would be a maximum of 0.2 t ha⁻¹ year⁻¹ (on average) of OC delivered down the soil profile. This is a likely gross overestimate and would be a maximum rate of delivery, as cracks will not always be present due to wetting up of the soil and closure of the cracks with eroded material and OC being transported over the cracks and downslope. Given that the SOC stock for the Vertosol sites exceeded 30 t ha^{-1} in the top 0.2 m (Figs 5 and 6), this suggests that only a small fraction of available SOC is provided by external delivery.

If we assume a maximum SOC age of approximately 40 years (based on the last atmospheric fallout in 1972) and that this material does not degrade once down in the profile, then this suggests a maximum of 4-8 t ha⁻¹ of OC may be a result of external delivery. Therefore the majority of SOC is likely from *in-situ* production.

SOC and sequestration

There are several implications for carbon sequestration. The ability and extent to which SOC can be increased in the agricultural environment by adoption of different management and landuse is not well understood (Badgery *et al.* 2014; Murphy 2015; Hobley *et al.* 2016; Conrad *et al.* 2017). Some authors have concluded that the potential for increased SOC accumulation is limited in agricultural settings (Robertson and Nash 2013). Hoyle *et al.* (2013) suggest that the capacity to store more SOC in the surface is limited and that the subsoil has additional storage capacity.

The findings here demonstrated that SOC was highest for high clay sites and also suggests that organic carbon can be more readily translocated to depth in Vertosols than for other soils. In several soil pits (Illogan Shed Paddock and Pembroke South), the presence of ¹³⁷Cs was not continuous down the profile, with an absence at one depth and detectable concentrations below. However, while having potential for rapid translocation, the exposure to oxygen and water provides an environment for breakdown of organic material. These feedbacks are likely to be complex, as the addition of organic matter at depth will change the soil shrink–swell properties and may either enhance or reduce OC breakdown (Murphy 2015). Long-term studies would provide insights into the capabilities of these soils to sequester OC.

There is potential for increasing SOC stocks at these sites. The similarity between the Shed Paddock and Pembroke South in terms of soil depth and clay content suggests that both sites have the potential to have similar SOC stock. However, Shed Paddock had considerably lower SOC stock than Pembroke South. The property is currently a well-run enterprise using no tillage for cropping and advanced management practices. How more biomass can be produced to increase SOC both at the surface and at depth while maintaining farm profitability is an open question.

Several authors have questioned how land management and vegetation can influence soil properties at depth (Pringle *et al.* 2011; Murphy 2015; Hobley *et al.* 2016; Conrad *et al.* 2017). Dalal *et al.* (2021) found that the introduction of a pasture phase in the cropping cycle may reduce SOC loss. Given that Roscommon and Pembroke North have never been cropped and, in recent decades, there have been no fertiliser inputs, how SOC can be increased is an important question, given that they are optimally economically managed (Badgery *et al.* 2014; Murphy 2015; Minasny *et al.* 2017).

Further issues and data needs

There are several possible explanations for the presence of ¹³⁷Cs at depths greater than that driven by diffusive processes.

1. Soil disturbance or bulk mixing by mechanical means. Roscommon, Pembroke South (not cropped) and Pembroke North sites were selected due to the absence of any disturbance by tillage. At Illogan (both Dog and Shed Paddocks) tillage has occurred to a maximum depth of 30 cm, with no tillage since 1992 and minimum till practices employed since. The property owners reported that no tillage has occurred deeper than 30 cm since 1991. Therefore, bulk movement of material by mechanical means has not occurred at any of these sites.

2. Migration of soil along animal burrows (Butler 1995, 2018). Although rabbits are present in the area, they have not been present in large numbers. It could be that by chance we sampled sites where rabbits have been present but given the high clay soil and the difficulty of excavation (i.e. as observed by the author using a mechanical backhoe) it is unlikely that they have created deep burrows. Wombats are present in the area. However, the majority of their burrows are located in creek banks or sloping areas where the burrow commences laterally into the side of a slope. There were no wombat burrows anywhere near the sampling sites and no evidence of their former presence.

It is likely that soil has been, and continues to be, delivered to the cracks and moves down the profile via cracks – with cracking observed at Shed Paddock, Pembroke North and South sites. The process is likely to be episodic with drying periods opening up soil cracks and periods of rainfall that produce runoff delivering eroded surface soil to the cracks. We hypothesise that it is only large rainfall events that produce surface runoff in this environment to generate sufficient eroded material to be delivered to the cracks (Hancock *et al.* 2019).

Other tracers such as ⁷Be would provide storm-scale detail on the movement of surface materials (Zapata 2002; Walling *et al.* 2011). A pathway forward would be to sample down a soil profile with cracks immediately after a large storm and assess whether short-term tracers such as ⁷Be were detected. Dating of SOC (i.e. radiocarbon method) would provide information on longer ages. Carbon isotopes (i.e. δ^{13} C) would also provide insights (i.e. Pringle *et al.* 2011) into plant-based carbon inputs as well as geochemical analysis (Lawrence *et al.* 2015). This is currently being investigated.

All soil samples were collected in a vertical line down the soil profile. There was no attempt to seek cracks or areas of darker soil suggestive of organic enrichment. Therefore, it is possible that considerably more labelled material has made its way further down the soil profile than that captured using the sampling method here of samples collected in a vertical line. More targeted sampling would provide further insights.

At Illogan, multiple profiles were collected for each trench and were sampled approximately 1 m from each other. Both sites demonstrated considerable variability in SOC even within the same trench (Table 2, Fig. 5). For carbon accounting this presents an issue not just for quantifying SOC on the surface but also evaluating SOC whole-profile stocks. This raises the question of how many soil profiles should be sampled such that a statistically defensible value can be obtained, given the variability observed here.

The findings highlight the need for more long-term field data (i.e. Conrad *et al.* 2017; Jha *et al.* 2020) and model development to provide enhanced understandings of whole soil profile SOC distribution and change (Luo *et al.* 2010) across a range of soil types and climates (Murphy 2015) as well agricultural management practices (Badgery *et al.* 2014). Innovation in surface and subsurface methodology for SOC quantification is needed to advance spatial and temporal distribution of SOC at the point and hillslope scale (Robertson and Nash 2013).

Conclusion

Whole soil-profile SOC and its depth distribution at sites with different soils and landuse but with similar rainfall and climate was assessed. All sites had relatively deep soil. providing potential for increased SOC sequestration. Results demonstrated that within short length-scales SOC stock varied considerably. The highest SOC stocks were in soils with the highest clay content, with less SOC in the more sandy soils. Using an environmental tracer (137Cs) demonstrated that SOC was reaching depths of up to 80 cm in soils with a high clay content over a maximum period of 65 years. The discontinuous distribution of ¹³⁷Cs suggests an advective process of surface soil movement. The majority of this material was likely from *in-situ* production along cracks, with material delivered to depth during dry periods. In cracking soils, surface material can therefore be delivered relatively quickly down the profile.

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Data availability. Data are available from the author upon reasonable request.

Conflicts of interest. The authors declare that they have no conflicts of interest.

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