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Comparison of vertical transport of ^{137}Cs and organic carbon in agricultural cracking soils

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ABSTRACT

The movement of soil organic carbon (SOC) down the soil profile has been compared to that of the environmental tracer ^{137}Cs at two neighbouring field sites sharing the same land management history but comprising clay soils with different cracking characteristics (cracking black Vertisol and a red Luvisol). A finite element model (FEM) simulation of the vertical transport of SOC and ^{137}Cs was developed for each site which accommodates the differing spatial and temporal trends of input and decay of the two species. From these models the diffusion and convection coefficients which best describe the movement of ^{137}Cs at each site were determined. Both convection and diffusion coefficients were found to be substantially higher in cracking Vertisol soils ($D_{Cs} = 721$ mm^2/yr, $V_{Cs} = -0.84$ mm/yr) than in the neighbouring Luvisol soils ($D_{Cs} = 94$ mm^2/yr, $V_{Cs} = 0$ mm/yr). Finally the ^{137}Cs transport coefficients determined for each site were used in modelling the SOC profile. The excellent match between predicted and observed SOC profiles suggests that transport of the SOC and ^{137}Cs down the soil column at the Luvisol site follows the same pathways. While the match between predicted and observed SOC profiles at the Vertisol site was weaker this was concluded to be more likely due to the impact of extensive soil cracking which is not explicitly accounted for in the SOC FEM rather than the result of the use of ^{137}Cs transport coefficients.

1. Introduction

The supply of carbon to the soil and its subsequent rate of decomposition are determined by climatic factors, vegetation type, land use and management practices as well as soil structure. The impact of land management on soil organic carbon (SOC) inventory has, in particular, been the subject of numerous studies (for example Cerri et al., 2003; Houghton and Goodale, 2004; Jarecki and Lal, 2005; S. Wang et al., 2004; W.J. Wang et al., 2004). Many studies however have focused on SOC distribution in the 0–30 cm soil layer where changes in SOC are normally most dynamic. Recent studies of SOC distribution down the full soil profile though have shown that the entire SOC profile needs to be taken into account when assessing the impact of soil type and land use on SOC stocks (Baisden et al., 2002; Don et al., 2007; VandenBygaart, 2001). This is particularly the case when cracking soils are involved (Young et al., 2005).

Most SOC turnover models implicitly assume that soils are well-mixed reservoirs of constant concentration extending down to 20 to 30 cm depth despite numerous studies of the vertical distribution of SOC which show this to be unrealistic in many soil scenarios (Jobbágy and Jackson, 2000; Meersmans et al., 2009; Mendham et al., 2003; Minasny et al., 2006; Van Dam et al., 1997; Young et al., 2005). Furthermore, while it is generally understood that diffusive and convective processes redistribute SOC from regions of high concentration in upper soil layers to greater depths, the vertical transport of SOC is largely ignored in most SOC turnover models (one exception is the ROTHPC-1 model (Jenkinson and Coleman, 2008; Jenkinson et al., 2008)). To improve turnover models and thereby better comprehend SOC dynamics over the entire soil profile it is essential that we understand the nature of, and be able to quantify, SOC movement throughout the profile.

In this study SOC transport down the soil profile will be modelled and compared to that of the environmental tracer, ^{137}Cs, using data obtained at two neighbouring field sites with identical land management histories. The use of environmental tracers, such as ^{137}Cs, in determining the relationship between soil erosion and SOC distribution patterns is well established (Li et al., 2006; Mabit et al., 2008; Martinez et al., 2010; Ritchie et al., 2007; Takenaka et al., 1998; VandenBygaart, 2001). A number of these studies have concluded that the lateral (e.g. Li et al., 2006) as well as the vertical distribution (Takenaka et al., 1998) of ^{137}Cs and SOC are significantly correlated thereby suggesting that ^{137}Cs and SOC are moving along similar physical pathways. By way of contrast, studies such as that conducted by Cox and Fankhauser (1984) have found no relationship between ^{137}Cs and SOC distribution while studies of the vertical SOC and ^{137}Cs transport in sandy soils at an untilled improved pasture site (Wells et al.,

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2012) and in a forested site (Dörr and Münnich, 1989) have concluded that downward movement of SOC was significantly slower than ^{137}Cs.

A valid comparison of vertical SOC and ^{137}Cs movement from soil profile data can only be determined after the different modes of formation, decay and entry of the two species into the soil structure are taken into account. All of these factors vary in a complex fashion over time and space and are influenced by climate, soil structure as well as land management practices. In this study SOC and ^{137}Cs vertical distribution data will be modelled and compared using a convection/diffusion finite element model (FEM). The advantage in adopting an FEM approach is that it allows the complex spatial and temporal patterns of input, decay and transport of the different chemical species that arise from changing fallout patterns, root/shoot architecture and land use practices to be fully accommodated in a single model. Only after doing so is it possible to examine whether ^{137}Cs and SOC are transported through the soil column by similar processes.

This research is part of an ongoing programme examining the vertical and horizontal transport of SOC and ^{137}Cs (Hancock et al., 2010; Martinez et al., 2010; Wells et al., 2013). A previous study, (Wells et al., 2012), used an FEM approach to quantify the vertical transport of SOC and ^{137}Cs in a sandy soil. In this study the same approach is adopted to quantify the vertical transport of SOC and ^{137}Cs in two high, clay content soils distinguished by different levels of soil cracking. While the physical processes responsible for the downward movement of SOC and environmental tracers in cracking soils (crack infilling and self-mulching) are well known in a qualitative sense, this study seeks for the first time to quantify the effect of soil cracking on the mix and magnitude of diffusive and convective transport taking place.

The aims of this study are (1) to determine if the transport of SOC and ^{137}Cs is driven by the same physical processes in a lightly tilled agricultural environment involving soils of high clay content, and (2) determine the impact of soil cracking on the mix and magnitude of transport processes taking place.

2. Study site

The foci of this study are two field sites (the "Dog" and "Shed" paddocks) located on the Illogan property which lies in the Goulburn River catchment, in the Upper Hunter region of New South Wales, Australia. The property is located in the temperate zone of eastern Australia and has an average annual rainfall of 620 mm however rainfall is highly variable both within and between years. Average daily air temperatures recorded at the Illogan property over the period 2003 to 2008 varied from 24 °C in summer down to 9 °C in winter. Average annual potential evaporation is approximately 1300 mm. In the mid 1950s both sites were cleared and the native vegetation was replaced by improved pasture which was grazed until 1970 after which time both sites were devoted to cereal cropping activities (predominantly barley, oats and wheat). Between 1970 and 1990 the soil at both sites was lightly tilled (to 10 cm depth). Since 1990 minimal tillage practices (maximum depth of disturbance <5 cm for seeding and fertiliser application) have been employed, again at both sites.

The Dog paddock site is dominated by strongly structured, red basaltic clays (Luvisols) and the Shed paddock by heavy black swelling clays (Vertisols). Soil clay content at the Dog paddock site varies from 35 to 40% at the surface increasing to approximately 80% at 70 cm depth before decreasing again at greater depths. Average clay content for the Dog paddock site is 56%. At the Shed paddock site clay content lies between 60 and 80%, (average 65%) and is uniform with depth. Cracking of the soil has been observed at both sites during dry periods however crack width, depth and density are significantly greater in the Vertisol soil during these periods. No surface cracks were observed at the time of sampling at the Dog paddock however small cracks (<5 mm) were observed down the soil profile. At the Shed paddock cracks up to 50 mm wide were observed at the surface at the time of sampling. These cracks continued down the soil profile for at least 1 m. Fine roots were observed running along the faces of the cracks. Sampling was undertaken away from visible cracks. The Dog paddock Luvisols were more acidic (pH = 5) than the Shed paddock Vertisols (pH = 6.5, Table 1). Base saturation levels were high at both sites (0.96 and 1.0 for the Dog and Shed paddock sites respectively). Selected soil chemistry characteristics for the two sites are listed in Table 1.

SOC and ^{137}Cs profiles were obtained by multiple coring of the exposed faces of 3 m long trenches dug to bedrock at each of the field sites. Soil depth was approximately 1.4 m at each site. After drying and disaggregation the carbon content of the <2 mm soil fraction of each core sample was determined (LECO 2000 analyser) and ^{137}Cs content was evaluated using a hyper pure germanium detector. The LECO carbon results were corrected for inorganic carbon content determined by monitoring CO_2 evolution following FeCl and HCl digestion of the soil sample. The soil profile characteristics (clay and rock content, colour, ^{137}Cs content as well as SOC levels) of individual profiles within a given trench, (four at the Dog paddock site and three at the Shed paddock site), showed little variation. The individual profiles were averaged to generate a composite profile for each species at each site. The ^{137}Cs and SOC concentration profiles for both sites are shown in Fig. 1.

3. Modelling of the ^{137}Cs and SOC profiles

The distribution of ^{137}Cs and SOC within the soil profile is driven by a number of complex processes involving physical, physiochemical and biological input, decay and transport mechanisms (Nakane and Shinozaki, 1978; Schuller et al., 1997; Zhang et al., 2008). In this study the concentration of ^{137}Cs or SOC at a given depth (z) and time (t) is determined from: (1) surface/subsurface deposition of the species, (2) the transportation of the species down the soil profile, and (3) the decomposition of that species over time. A one dimensional (1D) finite element discretisation of the ^{137}Cs and SOC profile development process was adopted. The 1D FEM comprises a number of domains starting at the soil surface (z = 0 m) and extending down to bedrock at a depth of z = 1.4 m (Fig. 2). In order to better capture ^{137}Cs and SOC changes in the more dynamic 0–30 cm soil region, the depth of individual domains in this region was set at 2 cm. The size of deeper individual soil domains was set at 5 cm (30–60 cm depth) and 10 cm thick (60–140 cm depth).

For calculation purposes each domain was divided into 1 mm spatial increments throughout the soil column. Utilisation of finer mesh sizes resulted in negligible changes to the model solutions. Simulations were run from the year 1950 (time of first ^{137}Cs fallout) to 2008 (time of sampling) for the environmental tracer species and from 1956 to 2008 for SOC reflecting the time period over which the two field sites were set to agricultural use. Time increments of 0.01 years were employed in calculating the model solutions. Further reduction of the temporal step size produced no significant changes in the model solution.

The boundary and transport conditions for both species and below ground input of carbon in the SOC model are functions dependent on land use and therefore time. The FEM incorporated changes to these parameters as the two sites moved from improved pasture grazing (1956–1970) to cereal cropping with 10 cm tillage (1970–1990) and

Table 1
Selected soil properties from the two field sites (top 10 cm).

Soil property	Dog paddock	Shed paddock
pH (1:5 water)	5.0	6.5
Calcium (meq/100 g)	8	24
Magnesium (meq/100 g)	3	17
Potassium (meq/100 g)	1.0	1.3
Sodium (meq/100 g)	0.04	0.34
Aluminium (meq/100 g)	0.54	0.0
Electrical conductivity (1:5 soil:water) dS/m	0.11	0.12
Cation exchange capacity (CEC, meq/100 g)	12.6	42.6
Base saturation (B_{sat})	0.96	1.00