Farming system legacy impacts on the storage and persistence of soil organic carbon and understanding the different types carbon in northern cropping systems – science that value adds in field farming systems research

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Take home message

- These important findings highlighted that persistence of soil organic carbon (i.e. its ability to accumulate and store in soil) is not related to the formation of complex carbon structures as traditionally assumed
- But rather, the organic carbon that is retained in soil appears to be similar in molecular composition to that which is labile and is less stable
- Instead, it is likely that the retention and stability of soil organic carbon appears to be related to the ability of soil to physically protect that carbon from being broken down as opposed to chemical complexity of the soil organic carbon preventing its breakdown by soil organisms
- For action now, our findings suggest that we should not emphasise identifying management practices that increase complexity of carbon, but rather practices that increase the physical protection of soil organic carbon
- This is a marked shift in thinking from what we have traditionally assumed, and hence, we now need to be thinking about land management practices and carbon modelling in a different manner
- Specifically, farming systems with high carbon input, such as high crop intensity, have the potential to increase SOC as particulate organic matter in the short term and improve physical protection of SOC over the long term as required for carbon sequestration and for building soil health and resilience for enduring profitability

Introduction

Challenges such as declining soil health and climate change demand strategic shifts in farming systems to adapt and regenerate agricultural productivity. However, northern grain production systems are underperforming, with only 29% of crops reaching 80% of their water use efficiency (Hochman *et al.,* 2014). Improvement in management practices and farming systems play an important role in delivering enduring profitability for grain producers.

Not only is there a need to increase food production, but it needs to be done in a manner which minimises environmental harm. The management of soil organic carbon (SOC) is a key strategy to regenerate soil health which in turn helps to sustain productivity and the resilience of agroecosystems to extreme conditions (Rumpel *et al.,* 2020). Soil carbon management has been recognised by the Australian Government as one of six priority low emissions technologies for lowering greenhouse gas emissions with highest abatement and economic potential. Thus, there is a clear need to better understand SOC, not only because increases in SOC increase soil fertility and productivity, but also because increasing SOC concentrations can contribute to climate change mitigation.

SOC can be separated into different fractions with each fraction having different turnover periods and functions in soil. Briefly, particulate organic carbon (POC) consists of degraded plant materials such as crop residues which can exist freely in the soil as free POC (fPOC) or can be physically protected through entrapment within soil aggregates, forming occluded POC (oPOC). In addition, SOC can be chemically bound to soil minerals (such as clay-sized particles), forming mineral-associated organic carbon (MAOC). There is a growing emphasis on assessing different pools of SOC for improving management of organic carbon stocks in soils, rather than solely focusing on the bulk SOC (Angst *et al.,* 2023, Cotrufo *et al.,* 2019).

In this study, we firstly explored how cropping duration exerts changes in SOC distribution and chemistry. We examined the changes in SOC across the different fractions of several Australian Vertosols in the northern cropping region which have been cropped for up to 82 years. To validate these mechanisms in Australian farming systems, we further examined a range of modifications to farming systems and evaluated their relative impact on SOC persistence in a subtropical Vertosol in a farming system site in southern Queensland at Pampas (Eastern Darling Downs near Brookstead).

The distribution of soil organic carbon in Vertosols and how this is influenced by cropping

The surface soil (0–10 cm) was collected from a series of Vertosols in the Darling Downs region of southern Queensland, Australia (26.5°S and 28°S and 150°E to 152°E) (Table 1). Mean annual rainfall within the study region ranges from 480 to 670 mm, with more than 60% received during summer months. Mean annual temperature ranges from 18.5 to 20.5 °C, with the highest monthly temperature in January and the lowest in July.

Table 1. Properties of Vertosol series including texture, bulk-C, total N and pH of native soils (0–10 cm depth). Bulk-C data for cropped soils only includes soils that have been continuously cropped for 20 years or more.

Soil series	Rainfall (mm/y)	Period of cropping (y)	Clay content (%)	Total N (g/kg)	pH (1:5 H_2O)	Native bulk-C (g/kg)	Cropping bulk-C (g/kg)
Billa Billa	610	0–25	42	1.4	7.8	17.7	11.1
Cecilvale	670	0–35	44	1.3	7.7	18.2	10.1
Langlands-Logie	630	0–82	50	1.8	7.8	22.2	9.2
Thallon	480	0–23	60	0.6	7.6	7.1	4.5
Waco	650	0–70	75	1.3	8.2	17.5	11.4

In these clay rich Vertosols, most SOC was stored as MAOC followed by oPOC (Figure 1). Regarded as the most labile fraction, fPOC, contributed the least to the total SOC content even in the native soils. Cropping resulted in losses up to 78% of total SOC with these losses occurring in all fractions. However, the POC fractions display the greatest change, especially the fPOC as this fraction is not physically or chemically protected by the inorganic mineral component of the soil.

Although in the case of these Vertosols, POC fractions are most susceptible to land use change and only make up a small component of the soil's total SOC, these fractions should not be overlooked for the management of SOC. The fPOC and oPOC fractions can be considered a precursor to more stable fractions through several pathways, such as occlusion within aggregates or dissolution in the soil solution, and eventual binding to mineral surfaces. As such, land management which focusses on increasing or maintaining this fraction through stubble retention and reduced soil disturbance can translate to long-term benefits for total SOC.

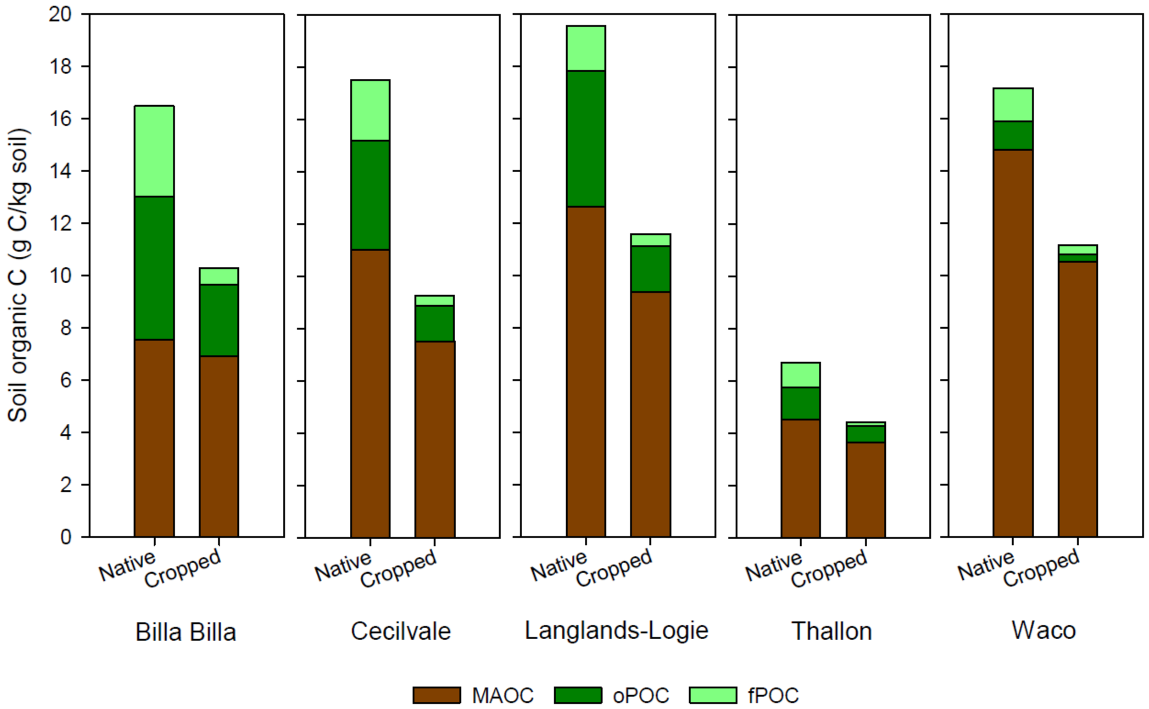

Figure 1. Changes to the average distribution of SOC across the different fractions as a result of cropping. MAOC = mineral-associated organic carbon; oPOC = occluded particulate organic carbon; fPOC = free particulate organic carbon.

Legacy of farming system strategies on the persistence of soil organic carbon

After 4-y implementation of various management practices, changes in total SOC content in bulk soil and C fractions have been observed across all farming systems (Table 2). All farming systems except for the low intensity system significantly increased the organic C content of bulk topsoils (0-10cm) compared with the permanent fallow (13 mg C g^{-1}, $P<0.01$), with a 26% increase in the high intensity treatment (16 mg C g^{-1}) and a 37% increase in the grass ley pasture (17 mg C g^{-1}) (Table 2).

The impact of farming systems on the C fractions varied depending on management practices. In absolute terms, the largest increase in C was for the oPOC fraction, with an increase of 3.1 mg oPOC g^{-1} bulk soil for grass ley pasture compared with the permanent fallow. The fine MAOC content remained similar across all farming systems except an increase of 1.5 mg MAOC g^{-1} bulk soil for high nutrient system (Table 2). In relative terms, the oPOC increased from 3.3% (permanent fallow) to 16% (baseline and high intensity) and 22% (grass ley pasture), with a relative decrease in the fine MAOC from 90% (permanent fallow) to 76–78% (baseline and high intensity) and 70% (grass ley pasture) although total MAOC concentrations did not change.

Table 2. The total organic C content for each soil fraction within the bulk soil (mg C g^{-1} bulk soil) from topsoil (0–10 cm) collected across farming systems at Pampas. fPOC is free particulate organic C, oPOC is aggregate-occluded particulate organic C, coarse MAOC is coarse grained (>53 µm) mineral-associated organic C and fine MAOC is fine grained (<53 µm) mineral-associated organic C. Standard errors are presented (n = 4). The mass recovery across all farming systems was over 91%.

Management practice	**Bulk soil mg C g^{-1}**	**fPOC mg C g^{-1}**	**oPOC mg C g^{-1}**	**Coarse MAOC mg C g^{-1}**	**Fine MAOC mg C g^{-1}**
Baseline	14 ± 0.1	0.56 ± 0.10	2.3 ± 0.37	0.13 ± 0.03	11 ± 0.45
Permanent fallow	13 ± 0.2	0.53 ± 0.04	0.41 ± 0.15	0.27 ± 0.10	11 ± 0.66
Grass ley pasture	17 ± 0.1	0.99 ± 0.05	3.5 ± 0.50	0.21 ± 0.16	11 ± 0.79
Lower intensity	13 ± 0.6	0.45 ± 0.05	0.31 ± 0.06	0.34 ± 0.13	12 ± 0.62
Higher intensity	16 ± 0.8	1.0 ± 0.17	2.8 ± 0.43	0.18 ± 0.07	11 ± 0.84
Higher nutrient	14 ± 0.6	0.79 ± 0.23	0.35 ± 0.04	0.41 ± 0.17	13 ± 0.59

From the bulk near edge X-ray absorption fine structure (NEXAFS) spectroscopy analyses, the relative proportion of C forms in bulk soils was compared semi-quantitatively through deconvolution of C K edge peak areas (Table 3). Quinones can be sourced from plant biomass or microbial products, aromatic-C is often an indicator for pyrogenic materials, aliphatic-C can be derived from wax layers on roots and leaves of terrestrial higher plants and metabolites and sugars from microbial debris, carboxylic-C can be used as a marker for plant biomass, and O-alkyl-C can result from microbial degradation of the organic materials (Lehmann and Solomon, 2010).

For the 53–250 µm fraction, the most dominant C forms were carboxylic-C (44–68%), followed by O-alkyl-C (12–21%) and aromatic-C (8–19%). The grass ley pasture system had the highest level of carboxylic-C (68%) whereas the high nutrient system was the lowest (44%). For O-alkyl-C, the permanent fallow and the high nutrient systems had the highest O-alkyl-C (21%) and the grass ley pasture had the lowest (12%). The level of aromatic-C in the low intensity (18%) and the high nutrient systems (19%) was higher compared with the baseline system (11%).

Table 3. Relative proportion of organic C functional groups in the soil under various farming systems identified by C (1s) near edge X-ray absorption fine structure (NEXAFS) spectroscopy.

53-250 µm Management practice	Quinine	Aromatic	Phenolic	Aliphatic	Carboxylic	O-alkyl-C
	------------------------------------			(%)	--	
Baseline	12.0 ± 4	11 ± 2	0.6 ± 0.1	6.2 ± 1	55 ± 6	15 ± 4
Permanent fallow	1.5 ± 0.1	12 ± 7	1.0 ± 0.2	5.1 ± 1	59 ± 6	21 ± 6
Grass ley pasture	1.8 ± 0.1	12 ± 6	0.8 ± 0.2	6.7 ± 1	68 ± 5	12 ± 3
Lower intensity	2.0 ± 1	18 ± 3	2.6 ± 0.3	9.2 ± 1	50 ± 5	18 ± 7
Higher intensity	8.4 ± 2	7.5 ± 4	0.3 ± 0.1	4.5 ± 2	61 ± 8	19 ± 3
Higher nutrient	6.5 ± 1	19 ± 5	4.1 ± 0.5	6.0 ± 1	44 ± 3	21 ± 4

Rethinking the paradigm for increasing organic carbon in the northern cropping systems

At the Pampas site, all farming systems except for the low intensity treatment increased the total SOC content as oPOC in the topsoil compared with the permanent fallow. The high crop intensity and grass ley pasture systems had the highest increase in SOC. Our results highlight the possibility of building up SOC as particulate organic matter in the short term (i.e., four years following implementation) and later physical occlusion through organo-mineral associations for protecting this C for the long term.

Greater fresh C inputs in the high intensity treatment and pasture system sustain SOC level whereas the permanent fallow system had been plant-free for four years. Higher SOC content in the high intensity can be partially explained by greater use of N-rich legumes that may have contributed to the greater concentrations of mineral-associated organic C and mineral-associated organic N. Legume residues with a low C:N ratio have been reported to enhance formation of N-rich microbial necromass and subsequent organo-mineral associations (Kopittke *et al.,* 2018; Kopittke *et al.,* 2020). Furthermore, crop residue, root growth and exudation can be increased by living vegetation cover that supplies C resources to fuel microbial processing. This may explain the higher SOC content and increase in oPOC in the high intensity treatment and grass ley pasture. Rhizodeposits and microbial by-products contribute to a significant proportion of SOC that can be preserved through interactions with soil minerals and formation of organo-mineral associations. Indeed, when further examining the SOC fractions, MAOC contributes the majority of C.

Despite these modest increases in total SOC and oPOC, we found that C forms did not change in bulk soils across various farming systems. Our data supported the previous findings that persistent SOC is molecularly simple and less diverse (Jones *et al.,* 2023). This is likely due to the decomposition of complex organic matter derived from plants and residues into simpler C forms. This was confirmed by the NEXAFS analysis showing that carboxylic-C, O-alkyl-C, and aromatic-C are the dominant C forms (Table 3). The grass ley pasture had the highest SOC and oPOC content and highest level of carboxylic-C whereas the high nutrient treatment had the lowest. Carboxyl C can serve as a marker for plant biomass indicating higher fresh organic matter input in the grass ley pasture system. The permanent fallow and the high nutrient systems had lower SOC content but the highest O-alkyl-C whereas the grass ley pasture had the lowest. The O-alkyl-C component represents mostly polysaccharides and fractions of alcohol and ether-C after microbial processing (Lehmann and Solomon, 2010). Without any fresh organic input, the high O-alkyl-C in the permanent fallow system may result from microbial degradation of the remaining residue. Aromatic C is often an indicator for pyrogenic materials (Lehmann and Solomon, 2010). The high proportion of aromatic C suggested that there was increased aromaticity over time as soil organic matter gradually decomposed.

Conclusions

We examined the impact of continuous cropping on the SOC content within different C fractions across five Vertosols from subtropical southern Queensland. Long-term cropping decreased SOC content across all fractions. Despite being vulnerable to land use change, POC has the potential for restocking SOC. Therefore, a new paradigm is required for the management of SOC in these cropped soils, with increases in SOC concentrations requiring that POC concentrations be increased by adapting soil management practices to increase inputs and decrease outputs.

This was evident at the Pampas farming system site where we showed that high crop intensity treatment and ley pasture can increase total SOC content compared with other farming systems. The majority of this SOC gain occurred in the oPOC fraction. Despite increases in SOC as oPOC, C forms in bulk soils did not vary across farming systems. Our findings challenged the traditional assumption that SOC persistence results from the formation of complex C compounds; rather we showed persisting SOC is molecularly simple. Our findings suggest that farming systems with high crop intensity including legumes can build up oPOC in the short term and improve the physical protection of SOC over the long term.

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