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What lurks beneath the surface: Contribution of profile soil to total organic carbon pools in vertosols of central Queensland, Australia

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Abstract

The standard practice for calculating carbon stocks in soil is tonnes per hectare (t/ha) to a depth of 0.3 m. Such calculations are influenced by the greater proportion of carbon in the 0.0 to 0.1 m depth, but sampling to 0.3 m provides additional information on the impact of management practices. Regardless, only sampling to a depth of 0.3 m neglects a substantial portion of carbon in profile soil. Intrigued by this conundrum, profile samples from the Brigalow Catchment Study were analysed for Walkley and Black soil organic carbon (SOC) for three land uses: remanent brigalow woodland, cropping and grazing. Samples were collected from Vertosol soils to a maximum depth of 4.4 m in 2018, 36 years after clearing of the two agricultural land uses. In agreement with earlier studies, there was less carbon under cropping than grazing or brigalow woodland. On average there was 42 t/ha of carbon in the top 0.3 m of soil under grazing and woodland which accounted for 56% of the SOC stock to 4.4 m, compared with only 28 t/ha under cropping which accounted for 48% of the SOC stock to 4.4 m. Carbon stocks were steady below 1.8 m for all three land uses, and carbon in the 0.3 to 1.8 m depths accounted for 30% of the total SOC stock to 4.4 m. Root biomass is the main input of organic carbon into soil, and land management practices that promote perennial pastures and native vegetation with deeper root systems increase the opportunity of profile soil to sequester carbon.

Introduction

Many studies focus on SOC in the top 0.3 m of soil due to its concentration at the surface and ease of sampling, but this depth has limited potential to sequester further carbon due to its high mineralisation rates and subsequently shorter residence times (Button *et al.* 2022; Hicks Pries *et al.* 2023). Globally, 68% of SOC is in the 0.3 to 2.0 m depth yet many studies still focus on carbon in the 0.0 to 0.3 m depth (Hicks Pries *et al.* 2023). Whether soil becomes a sink or source of atmospheric CO_2 depends on plant growth (carbon input into soil) and organic matter decomposition (carbon output to the atmosphere), and estimates under future climate warming scenarios indicate that SOC globally will become a source of carbon to the atmosphere but that losses would be proportionally lower from the subsoil (Wang *et al.* 2022). This indicates that subsoils have the potential to offset anthropogenic emissions by sequestering carbon into stabilised pools which decompose more slowly with turnover times of thousands of years (Button *et al.* 2022). However, it is possible that new plant inputs in profile soil may alternatively increase the decomposition rate of extant carbon due to priming (Hicks Pries *et al.* 2023). The present study demonstrates the substantial contribution of carbon in the 0.3 to 1.8 m depths under native vegetation with two agricultural systems to the total organic carbon (TOC) pool to 4.4 m and discusses opportunities to optimise carbon sequestration in the subsoil.

Methods

This study was conducted at the Brigalow Catchment Study located in central Queensland, Australia. The area has a semi-arid to subtropical climate, with a long-term (1965 to 2023) mean annual rainfall of 643 mm. Data was collected from three land uses: 1) virgin brigalow woodland representative of the pre-European landscape; 2) cropping, typically with annual wheat or sorghum; and 3) grazing on a perennial improved grass pasture. The three land uses are adjoining paddocks within an area of about 80 ha and have similar soil and landscape characteristics. The two agricultural systems were cleared and developed in the early 1980s with commencement of their respective land uses in 1983. The cropping system also had a ley pasture of butterfly pea planted in 2010 to improve soil fertility. Further details are provided in Elledge and Thornton (2022).

Samples were collected in 2018 from all three land uses, which was 36 years after the commencement of grazing and cropping in the two agriculture systems. Soil was sampled at 0.1 m increments to a depth of 2.0 m and then 0.3 m increments until either bedrock or a maximum depth of 5 m. However, only data for key depths is presented in this paper: 0.0 to 0.1, 0.1 to 0.2, 0.2 to 0.3, 0.5 to 0.6, 0.8 to 0.9, 1.1 to 1.2, 1.4 to 1.5, 1.7 to 1.8, 2.0 to 2.3, 2.6 to 2.9, 3.2 to 3.5, and 4.1 to 4.4 m. There were two Vertosol sites within each of the three land uses. Five cores per site were bulked by sampling depth, and then analysed for Walkley and Black organic carbon (method 6A1, Rayment and Lyons 2010). Organic carbon concentrations (%) were converted to total carbon pools (t/ha) using bulk density for each of the key depths with values standardised to a 0.1 m increment for the 0.3 m cores. Bulk density was determined by weighing individual cores after air drying, oven drying a subsample of each core, and then correcting the sample mass to the equivalent oven dry soil mass (Thornton and Shrestha 2021). Averages are presented for the two Vertosol soils, with values graphed using the sample mid-point depth.

Results

TOC to 4.4 m was 80 t/ha under grazing, 71 t/ha under brigalow woodland, and 59 t/ha under cropping. Unsurprisingly, most of the carbon was in the 0.0 to 0.3 m soil depths. However, across all three land uses there was on average 30% of TOC in the 0.3 to 1.8 m depths and 17% in the 1.8 to 4.4 m depths (Table 1). Differences were observed in the 0.0 to 0.6 m soil depths with SOC lower under cropping than from brigalow woodland and grazing, which had similar TOC. Although carbon stock declined with depth for all three land uses, it tended to stabilise below 1.8 m (Figure 1).

***Table 1*:** Soil organic carbon under virgin brigalow woodland compared with two agricultural systems.

Total Organic Carbon	Woodland	Cropping	Grazing
t/ha in 0.0 to 0.3 m depth	42	28	43
t/ha in 0.3 to 1.8 m depth	19	19	24
t/ha in 1.8 to 4.4 m depth	10	12	13
% in 0.0 to 0.1 m depth	26	18	25
% in 0.1 to 0.2 m depth	16	16	16
% in 0.2 to 0.3 m depth	16	15	13
% in 0.0 to 0.3 m depth	59	48	54
% in 0.3 to 1.8 m depth	27	32	30
% in 1.8 to 4.4 m depth	14	20	16

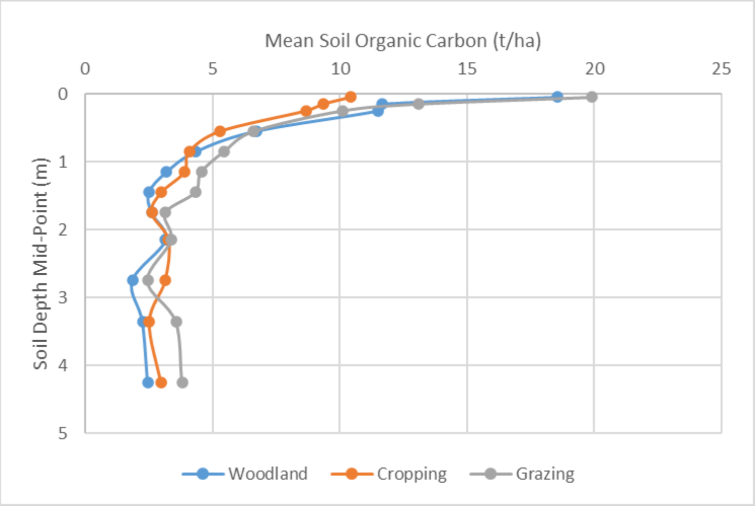

Figure 1: Soil organic carbon under virgin brigalow woodland compared with two agricultural systems.

Discussion

SOC under brigalow woodland and grazing were similar throughout the soil profile, but cropping typically had less, especially in the 0.0 to 0.6 m depths. This is logical given the considerably greater removal of carbon in the form of harvested grain from cropping compared to cattle live weight gains from grazing (Radford *et al.* 2007). A study by Dalal *et al.* (2021), also conducted at the Brigalow Catchment Study, reported an initial 12% decline in SOC when brigalow woodland was converted to grazing due to land development and pasture establishment (≤1.75 years). But particulate, humus and resistant fractions of carbon remained constant over the following 33 years in the 0.0 to 0.4 m depths due to ongoing inputs from root biomass. In contrast, conversion of brigalow woodland to cropping decreased SOC by 38% in the 0.0 to 0.3 m depths over 26 years (declines reported for all carbon fractions), but there was no statistical difference for the 0.3 to 0.4 m depth indicating that deeper carbon stock remains steady (Dalal *et al.* 2021). Furthermore, the planting of a ley pasture to improve soil fertility in this cropping system had arrested further decline (Dalal *et al.* 2021). These carbon trends between land uses are consistent with other studies (Murty *et al.* 2002).

It is important to note that although grazing appears to have greater TOC than brigalow in this study, which occurred 36 years after clearing and development for agriculture, this is not the case when the pasture catchment was compared to its original condition with multiple studies reporting a decline in TOC over time (Dalal *et al.* 2021; Thornton and Shrestha 2021). An earlier study by Dalal *et al.* (2013) at the study site also found that 62% of SOC under the two agriculture systems was derived from the original brigalow woodland. That is, 23 years after land use change, carbon incorporated into the soil (0.0 to 0.3 m) from either pasture or crops had replaced 41% and 36% of the carbon source, respectively. Although these results are from a long-term (decadal) study, the turnover of SOC at this site was reported to be 31 years in the 0.0 to 0.1 m depth which almost doubled to 60 years in the 0.1 to 0.2 m depth, where it then retained a similar age to the maximum sampled depth of 0.4 m (Dalal *et al.* 2011). However, SOC in the subsoil can have turnover times from 1,000 to more than 10,000 years which is where the potential for climate change mitigation via the sequestration of carbon occurs (Hicks Pries *et al.* 2023). This highlights the important contribution of carbon in profile soil below 0.3 m depth.

TOC in the three land uses of this study stabilised at about 1.8 m depth, which is logical given the known rooting depths of the different plants. That is, annual crops such as wheat and sorghum used in this study have a maximum rooting depth of 1.8 m, but with most of the root biomass in the top 0.3 m (Fan *et al.* 2016; GRDC 2017; Demissie *et al.* 2023). Cropping also involves the harvesting of above ground biomass and soil disturbance from machinery which leads to a decline in soil organic matter, which may have contributed to the apparent difference in SOC in the top 0.6 m depth in this study. This is aligned with a global meta-analysis that reported reforestation of croplands increased SOC to 0.6 m (Hicks Pries *et al.* 2023). The rooting depth of grass pasture on brigalow soils was also reported to be about 2 m (Shelton and Dalzell 2007), but with the added benefit of no disturbance to the soil surface. Considering that native vegetation in this region have rooting depths greater than 5 m (Shelton and Dalzell 2007) and that the original brigalow woodland contributed to most of the SOC under all three land uses (Dalal *et al.* 2013), this highlights the importance of adopting plants with deeper root systems for SOC sequestration. That is, the progression from annual crops to a perennial pasture and then to native vegetation not only increases the potential for carbon sequestration in the subsoil, but also improves drought tolerance under future climate warming scenarios by allowing for the enhanced use of water and nutrients at depth (Button *et al.* 2022).

Furthermore, a vegetation survey at the Brigalow Catchment Study in 2015 found that there was 10 times more live tree biomass (overstorey and understory) in brigalow woodland than the grazing system (56.8 t/ha vs 5.1 t/ha, respectively) (Elledge, pers. comment), and brigalow trees (*Acacia harpophylla*) at the site have been estimated to be about 100 to 150 years old (Brooks English 2024). This indicates that if agricultural land is converted back to native vegetation for the purposes of carbon sequestration, it may take more than a century to reach a stable state of carbon at depth.

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References

Brooks English, N. (2024) Brigalow radiocarbon age summary. Report to the Department of Resources for the Brigalow Age and Genetics project. Central Queensland University.

Button ES, Pett-Ridge J, Murphy DV, Kuzyakov Y, Chadwick DR, Jones DL (2022) Deep-C storage: Biological, chemical and physical strategies to enhance carbon stocks in agricultural subsoils. *Soil Biology and Biochemistry* **170**, 108697.

Dalal RC, Cowie BA, Allen DE, Yo SA (2011) Assessing carbon lability of particulate organic matter from δ13C changes following land-use change from C3 native vegetation to C4 pasture. *Soil Research* **49**, 98-103.

Dalal RC, Thornton CM, Allen DE, Owen JS, Kopittke PM (2021) Long-term land use change in Australia from native forest decreases all fractions of soil organic carbon, including resistant organic carbon, for cropping but not sown pasture. *Agriculture, Ecosystems and Environment* **311**, 107326.

Dalal RC, Thornton CM, Cowie BA (2013) Turnover of organic carbon and nitrogen in soil assessed from d13C and d15N changes under pasture and cropping practices and estimates of greenhouse gas emissions. *Science of the Total Environment* **465**, 26-35.

Demissie HS, Mindaye TT, Teklu DN, Kebede FG (2023) Root system architecture analysis of sorghum genotypes and its effect on drought adaptation. *Rhizosphere* **27**, 100772.

Elledge A, Thornton C (2022) Hydrology and runoff water quality from three improved pastures compared with virgin brigalow (*Acacia harpophylla*) woodland over 8 years in semiarid Australia. *The Rangeland Journal* **44**, 177–192.

Fan J, McConkey B, Wang H, Janzen H (2016) Root distribution by depth for temperate agricultural crops. *Field Crops Research* **189**, 68-74.

GRDC (2017) Grow notes: Sorghum. Grains Research and Development Corporation (GRDC).

Hicks Pries, Caitlin E, Ryals R, Zhu B, Min K, Cooper A, Goldsmith S, Pett-Ridge J, Torn M, Berhe AA (2023) The deep soil organic carbon response to global change. *Annual Review of Ecology, Evolution, and Systematics* **54**, 375-401.

Murty D, Kirschbaum MUF, Mcmurtrie RE, Mcgilvray H (2002) Does conversion of forest to agricultural land change soil carbon and nitrogen? a review of the literature. *Global Change Biology* **8**, 105-123.

Radford BJ, Thornton CM, Cowie BA, Stephens ML (2007) The Brigalow Catchment Study: III. Productivity changes on brigalow land cleared for long-term cropping and for grazing. *Australian Journal of Soil Research* **45**, 512-523.

Rayment GE, Lyons DJ (2010) 'Soil chemical methods: Australasia.' (CSIRO Publishing: Victoria)

Shelton M, Dalzell S (2007) Production, economic and environmental benefits of leucaena pastures. *Tropical Grasslands* **41**, 174-190.

Thornton CM, Shrestha K (2021) The Brigalow Catchment Study: V. Clearing and burning brigalow (*Acacia harpophylla*) in Queensland, Australia, temporarily increases surface soil fertility prior to nutrient decline under cropping or grazing. *Soil Research* **59**, 146-169.

Wang M, Guo X, Zhang S, Xiao L, Mishra U, Yang Y, Zhu B, Wang G, Mao X, Qian T, Jiang T, Shi Z, Luo Z (2022) Global soil profiles indicate depth-dependent soil carbon losses under a warmer climate. *Nature Communications* **13**, 5514.