Using a digital twin approach to measure soil organic carbon changes in legume cropping rotations in Western Australia

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Abstract

In this study, we deployed a digital twin approach, using data fusion of *in situ* and remote sensing measurements, to investigate the impacts of crops and crop rotation on soil health, and in particular on soil carbon sequestration. We examined the impact of incorporating Australian sweet lupin (*Lupinus angustifolius*), a valuable nutritional plant protein food source, into crop rotations over a property in Western Australia with ~3200ha split across 60 separate fields. The analysis of soil organic carbon (SOC) was undertaken at 10m resolution, every 10 days over a six-year period (2017 – 2022). The crop rotations included 5 arable crops and pasture in 17 different crop rotation types.

Our results showed an increase in SOC for four of the crop transitions into lupins, while for two of the transitions into canola the increase was greater than for lupins. These results suggest that certain cropping rotations involving legumes destined for plant-based protein products for human consumption could be designed to store additional soil carbon.

This study also demonstrates the effectiveness and affordability of using a digital twin and data fusion approach to remotely generate high-resolution data to monitor seasonal and annual changes in SOC at multiple scales. The same data approach can be used to evaluate different cropping practices, support traceability in net zero food supply chains, underpin policy-development, and support progress-tracking of national commitments and international initiatives such as the UN SDGs and 4p1000.

Introduction

Soil organic carbon (SOC) is vital for soil health, climate change mitigation, as well as soil fertility and agricultural yields (Lal 2016). Healthy soils also contribute significantly to the global economy and compared to degraded soils, retain more nutrients and cations (van Erp et al. 2001), have an enhanced capacity to absorb, store and filter water (Singh Brar et al. 2015; Minasny and McBratney 2018), show greater resilience to climate change and extreme weather events, drought and floods (Iizumi and Wagai 2019), have higher levels of biodiversity (Flores-Rios et al, 2020) and support a wide range of ecosystem services (Rumpel and Chabbi 2021).

Over the past sixty years, agricultural production has focused on delivering maximum harvest yields and increased crop productivity, through intense tillage and widespread application of nitrogen-based fertilisers. The result has been a widespread loss of soil health coupled with significant greenhouse gas emissions from topsoil that are putting the agricultural and food sectors at risk.

To counteract these trends, many governments are implementing policies to encourage sustainable land management and regenerative farming practices (European Commission 2021; McDonald H., et al. 2021). These types of practices aim to restore soil health, regenerate cropland, and pasture, and reduce costs by shifting production away from nitrogen intensive input strategies to low input carbon positive cropping systems. Consumer preferences are also helping in this regard with the growth in demand for net zero, nature friendly and carbon positive products. Legumes, such as soybean, pea, lupin, chickpea, Faba bean, lentil, grass pea, cowpea, and pigeon pea, are growing in importance not only because of their significant role in nitrogen fixation and as cover crops but also to provide plant-based protein for human consumption (e.g., Beans Is How SDG2 Advocacy Hub Campaign 2023).

Different management practices, such as no-low tillage, can produce a range of soil carbon storage outcomes (Ogle et al. 2019). This is because soil carbon sequestration depends heavily on local conditions, such as soil type and edaphic factors, and the balance between inputs (e.g., from litter, residues, roots, manure, fertilisers) and losses (mostly through respiration, increased by soil disturbance) (e.g., Olson et al. 2010; Meier et al., 2020; Singh Brar et al., 2015; Yeboah et al. 2016; Zhang et al. 2016). Soil carbon levels strongly influence soil organic matter (SOM) levels which in turn can lead to nitrogen (N) leaching and water pollution (Abdalla et al. 2019). Measuring changes in soil carbon regularly throughout the year on a local scale, i.e., below 1 ha, is thus vital to understanding the effects of weather conditions, climatic events, shifts in practice and crop removals on soil health. Unfortunately, the prohibitive costs of physical soil sampling and laboratory testing has made it impractical to undertake real-world, farm-level studies of soil carbon storage, especially in low- and middle-income countries where such information is vital for restoring soil health and ensuring food security.

In this study, we apply an innovative data analytics approach for calculating and monitoring SOC changes at 10m resolution every 10 days, to examine the outcomes of growing different leguminous crops within a six-year rotation cycle of arable crops and pasture on a farm in Western Australia. The ancient soils of this region have naturally low levels of SOC; this coupled with the extreme climatic conditions regularly experienced, mean that very small changes in soil carbon can have a large impact on soil health. We also examine how this approach can be implemented more widely to underpin net zero food strategies and policies for negative emissions approaches using soils such as the 4 per mille (Paustian et al. 2016; Frank et al.; 2017; Minasny et al, 2017; Bossio et al. 2020; IPCC, 2021).

Methodology

The study location is a farm of ~3255ha located in Western Australia (Figure 1a); the farm is subdivided into 60 fields (Figure 1b). Over the six-year study period (2017-22), 5 arable crops (wheat, barley, oats, canola, lupin) and pasture were rotated, producing 17 different crop rotation combinations (Figure 1c).

Data fusion techniques were used to combine and mix multiple geospatial data sets and statistical distributions from existing, curated data sources of relevant variables to produce geo-coordinated, consistent, accurate models of land on which to build a digital twin of the area for every 10m pixel. Each digital twin uses millions of in situ and remotely sensed data points from open data sources relating to factors such as soil type and soil characteristics, land use and land cover, biome class, climatology and meteorology, terrain, topography and spectral signalling (Gholizadeh et al. 2018, 2020) (see Open Data Sources). It is possible to assimilate historical data from local on-farm observations and soil sampling to increase local data densities; however, in this instance just cropping histories for each field were included.

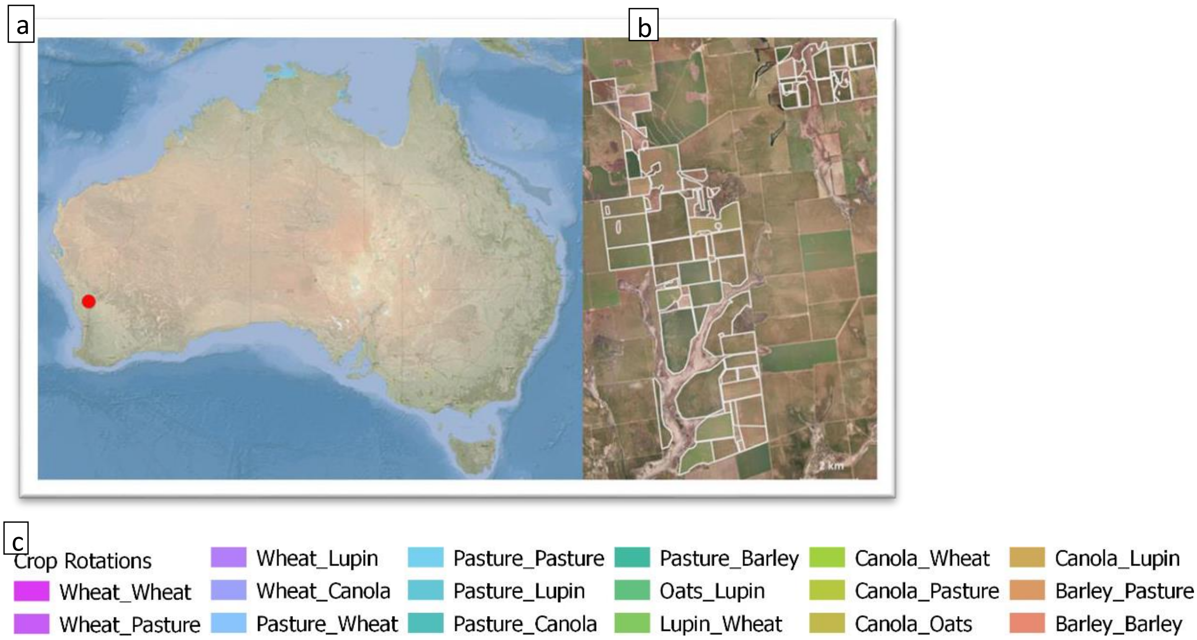


Figure 1: a) Location of the study site in Western Australia, b) Layout of the fields in the study site, c) Crop rotation combinations within the studied farm over the 6-year study period

The SOC was calculated for each pixel within the farm boundaries every 10 days from 2017 – 2022 (Figure 1b). Statistical analysis of variability of SOC (%) outcomes in topsoil (0-30cm) were calculated for each field in the cropping rotation for the cropping period from April to December for each of the six years.

To investigate whether there is a latent /residual impact of a crop or if a particular combination of crops (with the presumption that leguminous plants should improve soil health) we investigated whether specific crop rotations resulted in an increase in the SOC. The percentage change was calculated within a crop rotation (CR): $\%CR_{\Delta}=((Crop_{Y2}/Crop_{Y1})-1) * 100$ where $Crop_{Y2}$ and $Crop_{Y1}$ are the average SOC values for each field under the specific crop in first (Y1) and second (Y2) year of the crop rotation. These were compared within each rotation and over the entire study period against the aggregated results of the entire property to determine if any latent effects in the soil health could be determined for specific crop rotation combinations, and whether these resulted in clear SOC improvements and declines. In 2017, certain fields with lupins and canola, which had a late start and poor establishment due to the drought, were terminated before maximum biomass production to control weeds and avoid the costs of harvesting.

Results

Average SOC values over the six years for the whole property ranged from 0.513% in 2017 to 0.152% in 2022. Across the 360 individual fields (i.e., 60 fields * 6 years) the lowest and highest within field values of SOC % ranged from 0.29% in 2017 to 1.58% in 2022. The average of the Year 2- Year 1 SOC % differences for the six years was 0.045%. The SOC % changes were as follows: 2018 - 2017 +0.18%, 2019 - 2018 –0.01%, 2020 –2019 –0.004%, 2021 – 2020 +0.016%, 2022-2021 + 0.031%. The largest increase in a field was 0.8 SOC%, equivalent to an increase of 28.2t ha^{-1} yr^{-1}. This was observed in 2021 – 2022 for a wheat_lupin rotation. There was an overall increase in SOC for the whole property of 1.55t ha^{-1} yr^{-1} and for legumes crop rotations of 0.55t ha^{-1} yr^{-1}. In the instances where lupins and canola had been terminated before maximum biomass harvesting, there was an increase in SOC the following year, most probably due to the residues left in the fields.

A key objective of the analysis was to determine whether legumes in the crop rotations, and lupins in particular, improve soil health by increasing soil carbon levels. Of the eight different crop types included in the property's six-year cropping history, only four of the crop types had sufficient repetitions (i.e., > five) to be able to provide a degree of confidence in responding to the first objective. Lupins and canola produced higher SOC values than the property average in >60% of the observed years (Figure 2). Wheat fields on average had the lowest SOC levels but were also the most extensively planted and thus this imbalance in the sample numbers could have had a greater influence than the crop itself (Figure 2).

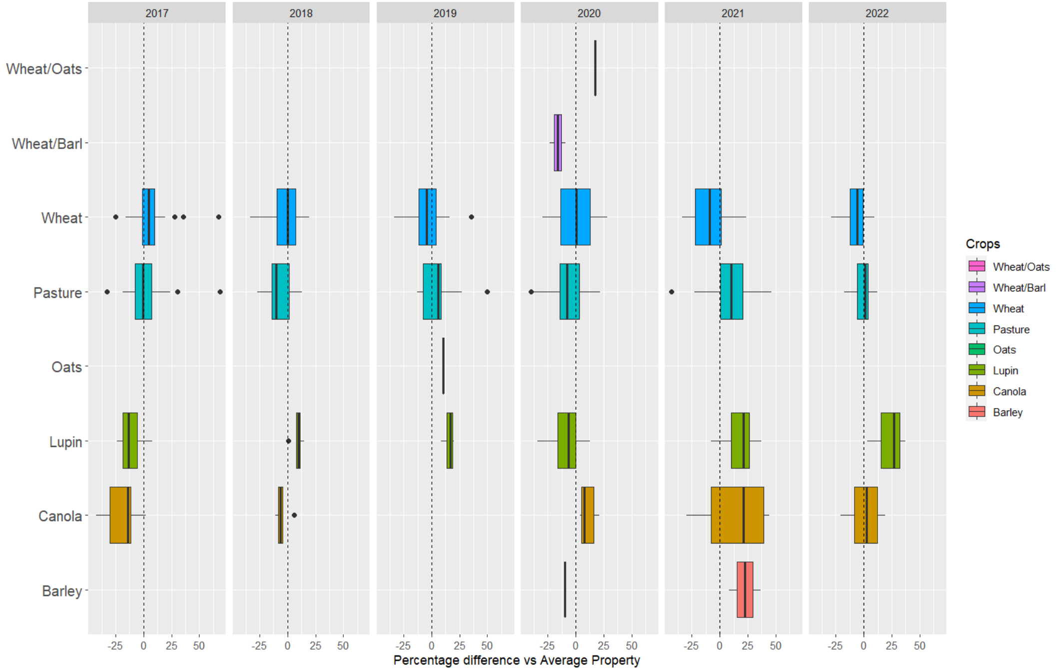
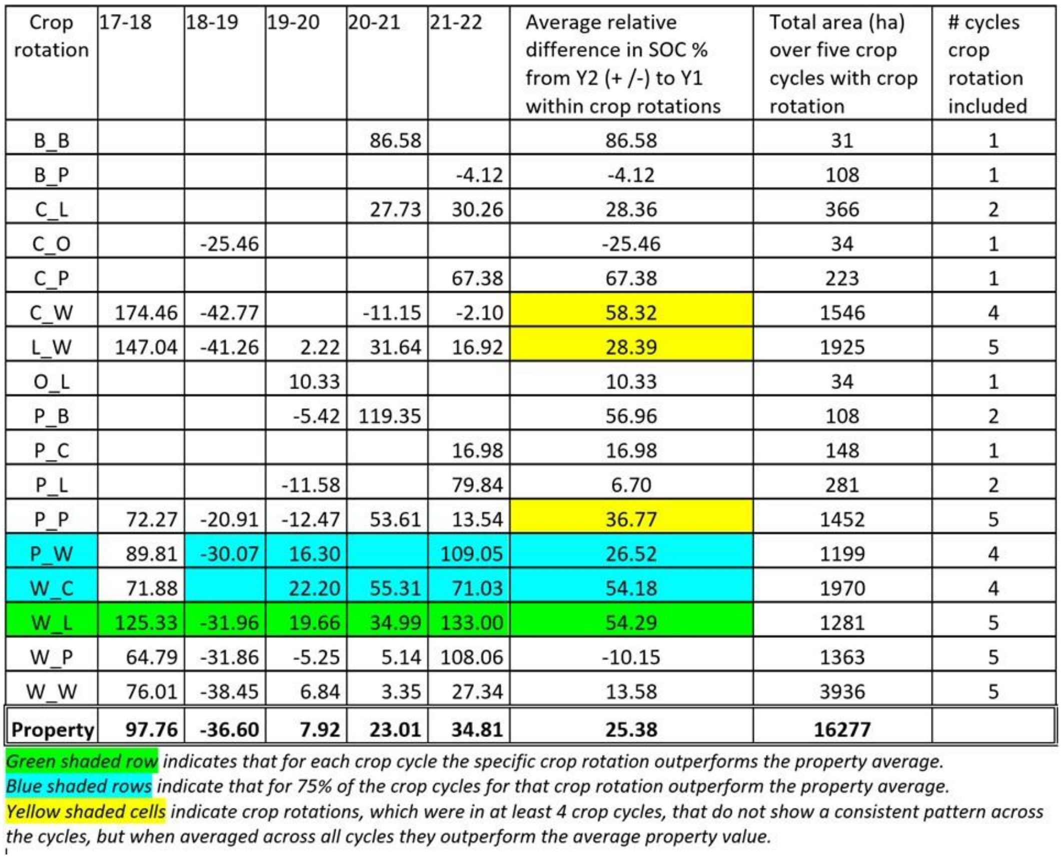


Figure 2: Relative difference of SOC between different crop types and whole property values over a six-year time period. Each field was compared to the property average for that year. A +ve median value indicates it had higher SOC than the property average (indicated by the vertical dashed line for each year).

Seventeen crop rotations were included in the analysis, occurring over five crop cycles; 8 of these rotations had more than 2 observations in the study period. These formed the basis for the analysis. We examined year to year changes; for example, as shown in the *green shaded row* (Table 1), wheat grown in Year 1 followed by lupins in Year 2 (wheat_lupin) had higher percentage SOC values in the second year compared to the whole property average. Crop rotations with pasture_wheat and wheat_canola showed this same behaviour in 75% of the crop cycles as shown in the *blue shaded rows* (Table 1). Although the patterns in the remaining crop rotations were inconsistent, as shown in the yellow shaded row (Table 1), canola_wheat, lupins_wheat and pasture_pasture outperformed the overall property SOC change.



Crop rotation	17-18	18-19	19-20	20-21	21-22	Average relative difference in SOC % from Y2 (+ /-) to Y1 within crop rotations	Total area (ha) over five crop cycles with crop rotation	# cycles crop rotation included
B_B				86.58		86.58	31	1
B_P					-4.12	-4.12	108	1
C_L				27.73	30.26	28.36	366	2
C_O		-25.46				-25.46	34	1
C_P					67.38	67.38	223	1
C_W	174.46	-42.77		-11.15	-2.10	58.32	1546	4
L_W	147.04	-41.26	2.22	31.64	16.92	28.39	1925	5
O_L			10.33			10.33	34	1
P_B			-5.42	119.35		56.96	108	2
P_C					16.98	16.98	148	1
P_L			-11.58		79.84	6.70	281	2
P_P	72.27	-20.91	-12.47	53.61	13.54	36.77	1452	5
P_W	89.81	-30.07	16.30		109.05	26.52	1199	4
W_C	71.88		22.20	55.31	71.03	54.18	1970	4
W_L	125.33	-31.96	19.66	34.99	133.00	54.29	1281	5
W_P	64.79	-31.86	-5.25	5.14	108.06	-10.15	1363	5
W_W	76.01	-38.45	6.84	3.35	27.34	13.58	3936	5
Property	**97.76**	**-36.60**	**7.92**	**23.01**	**34.81**	**25.38**	**16277**	

Green shaded row indicates that for each crop cycle the specific crop rotation outperforms the property average.
Blue shaded rows indicate that for 75% of the crop cycles for that crop rotation outperform the property average.
Yellow shaded cells indicate crop rotations, which were in at least 4 crop cycles, that do not show a consistent pattern across the cycles, but when averaged across all cycles they outperform the average property value.

Table I: Relative change in SOC (%) within a crop rotation. +ve value indicates an increase in SOC in the second year of the crop rotation (and vice versa for -ve value)

Although the number of observations for each crop rotation was too small to provide a robust suite of statistics and uncertainty measures, the results do provide an indication of the importance of taking crop rotations into account when measuring the effects of farming practices on carbon storage. Measurement of the effects should also be extended over more than one transition cycle, i.e., three-years to get a more robust picture of any crop-related differences. The high-resolution digital twin approach described here can minimise the costs of repeated soil sampling and enable accurate measurements to be made of the carbon sequestration associated with cropping rotations under different farming practices.

Discussion

One of the major problems in determining the scale and speed at which soil carbon sequestration occurs under different land uses and agricultural practices is the prohibitive cost of soil sampling on a large scale. This study examines an innovative affordable alternative to soil sampling, in which data fusion techniques are applied across a range of key variables to build a digital twin of land. This digital twin can be used to generate high-frequency, localised SOC measurements over multiple years, to analyse the effects of different practices such as cropping rotations on soil carbon sequestration. This approach can also be used to improve the effectiveness of localised sampling by assimilating the information into larger-scale curated databases.

The results of this study of SOC outcomes from cropping rotations with legumes for a property in Western Australia, showed an increase in SOC for four of the crop transitions into lupins, and a larger increase in two of the transitions into canola. The overall increase in SOC for legumes (0.55t ha^{-1} yr^{-1}) and for the whole property (1.55t ha^{-1} yr^{-1}) are in line with previously published results from other parts of the world e.g., Europe (Dupla et al. 2022; Rosinger et al. 2023; Mattila et al. 2023). The maximum uplift of 0.8% SOC, equivalent to an increase of 28.2t ha^{-1} yr^{-1}, occurred in a field with a wheat-legume (canola) crop transition. These results suggest that combining legumes in certain cropping rotations can help to improve both nitrogen fixation and contribute to net zero management plans through soil carbon removals. It also opens the possibility for crops such as lupins and other legumes to be grown within a greater range of domestic, cropping systems to support plant-based protein products for human consumption.

Carbon removal and GHG emissions reduction strategies are both vital aspects of net zero pathways in agri-food systems (Ward 2023). Given the growth in agrifood GHG emissions, mitigation strategies to reduce emissions are a core part of the UN Framework Convention on Climate Change Paris Agreement (UNFCCC 2015). For example, in 2015 mean annual emissions from the global food system ranged from 10.8 - 19.1 $GtCO_2e$ (Mbow et al. 2019; Rosenzweig et al. 2020; Crippa et al 2021). In 2020, the Food and Agriculture Organisation estimated that emissions from the agri-food system were 16 $GtCO_2e$ (Food and Agriculture Organisation 2022), and emissions from agriculture, forestry, and other land-use change (AFOLU) were 9.5 $GtCO_2e$ (United Nations Environment Programme 2022). Among the three components of agrifood systems in 2020, farm-gate emissions were nearly half of the total (7.4 $GtCO_2e$), followed by emissions from pre- and post-production (5.6 $GtCO_2e$) and land-use change (3.1 $GtCO_2e$).

GHG removals via soil carbon sequestration relies on the many factors, as demonstrated in this study: soil type, lithology, geology, topography, biome, and climatology. Published global estimates of the technical potential to enhance soil carbon stocks go as high as 10 $GtCO_2e$ yr^{-1} with a mean of 7 $GtCO_2e$ yr^{-1} (Chambers et al. 2016, Lal 2016; Fuss et al., 2018). The '4 per mille (4p1000) Soils for Food Security and Climate' initiative has set a general guide of increasing soil organic carbon stocks by 0.4 percent per year (Minasny et al. 2017). However, individual practices may have much lower potentials: for example for croplands, published estimates range from 1.47 - 2.93 $GtCO_2e$ yr^{-1} (Lal 2011), for non-tillage croplands from 0.4-0.6 $GtCO_2e$ yr^{-1} (Powlson et al. 2014), for croplands and pastures from 1.36 - 2.71 $GtCO_2e$ yr^{-1} (Sommer and Bossio 2014), and for planting of legumes in grazing land 0.20 $GtCO_2e$ yr^{-1} (Henderson et al. 2015).

Conclusions

This study shows the effectiveness of using a data fusion and digital twin approach to generate high frequency, localised SOC measurements and estimates of soil carbon removals under different land management regimes and agricultural practices. This approach also provides an accurate and affordable alternative to current approaches based solely on soil sampling, as well as a method to improve localised soil characterisation through assimilation of in situ sampling data into larger curated databases.

In this study, we use a digital twin covering an area of 3200ha of farmland in Western Australia to analyse cropping rotations. The results indicate that cropping rotations which include legumes can produce an increase in soil carbon removals.

The effectiveness and affordability of using a digital twin approach to analyse changes in soil carbon arising from different interventions means that it can be used to support carbon insetting projects, provide traceability for net zero food supply chains, and underpin policy-development and progress-tracking of national commitments and initiatives such as the UN SDGs and 4p1000.

Contributions: NK undertook the cropping analysis and contributed to the methodology and results sections; JM developed the idea and drafted the paper; SM provided the cropping information and permission to use the property for the study; CL contributed to the methodology and reviewed the manuscript; JA reviewed the manuscript

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Conflict of Interests: None

Open Data Sources

ECMWF Meteorological https://www.ecmwf.int/en/forecasts/datasets;
FAO Land Use https://www.fao.org/faostat/en/#data/RL;
Global rainfall erosivity https://esdac.jrc.ec.europa.eu/content/global-rainfall-erosivity;
Global Lithology https://www.geo.uni-hamburg.de/en/geologie/forschung/aquatische-geochemie/glim.html;
Sentinel https://scihub.copernicus.eu/;
SoilGrids https://www.isric.org;
Dobarco, M., Wadoux, A., Malone, B., Minasny, B., McBratney, A. & Searle, R. (2022): Soil and Landscape Grid National Soil Attribute Maps - Soil Organic Carbon Fractions (3" resolution) - Version 1.0. Terrestrial Ecosystem Research Network. (Dataset). https://doi.org/10.25919/nf8v-p205
World Cover https://viewer.esa-worldcover.org/worldcover;
OpenStreetMapper https://www.openstreetmap.org

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