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Clarifying confusions over carbon conclusions: antecedent soil carbon drives gains realised following intervention

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A R T I C L E I N F O

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A B S T R A C T

Carbon removals associated with incremental gains in soil organic carbon (SOC) at scale have enormous potential to mitigate global warming, yet confusion over contexts that elicit SOC accrual abound. Here, we examine how bespoke interventions (through irrigation, fertiliser, crop type and rotations), antecedent SOC levels and soil type impact on long-term SOC accrual and greenhouse gas (GHG) emissions. Using a whole farm systems modelling approach informed using participatory research, we discovered an inverse relationship between antecedent SOC stocks and SOC gains realised following intervention, with greater initial SOC levels resulting in lower *ex poste* change in SOC. We found that SOC accrual was greatest for clays and least for sands, although changes in SOC in sandy loam soils were also low. *Diversified* whole farm adaptations – implemented through inclusion of grain legumes within wheat/canola crop rotations – were more conducive to improvement in SOC stocks, followed by *Intensified* systems (implemented through greater rates of irrigation, farm areas under irrigation, nitrogen fertiliser and inclusion of rice and maize in crop rotations). Adaptations that *Simplified* farm systems by reducing irrigation and fertiliser use resulted in the lowest SOC accrual. In most cases, long-term SOC stocks fell when SOC at the outset was greater than 4–5%, regardless of intervention made, soil or crop type, crop rotation, production system or climate. We contend that (1) management interventions primarily impacted SOC in the soil surface (0–30 cm) and had *de minimus* impact on deep SOC stocks (30–100 cm), (2) crop rotations including wheat, canola and faba beans were more conducive to improvement in SOC stocks, (3) scenarios with high *status quo* SOC had little impact on crop productivity, and not necessarily the lowest GHG emissions

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intensity, (4) productivity and GHG emissions intensity were largely a function of the quantum of nitrogenous fertiliser added, rather than SOC stocks, and (5) aspirations for improving SOC are likely to be futile if antecedent SOC stocks are already high (4–5 %). We conclude that potential for improving SOC stocks exists in contexts where antecedent stocks are low (<1%), which may include regions with land degradation, chronic erosion and/or other constraints to vegetative ground cover that could be sustainably and consistently alleviated.

1. Introduction

The land use sector faces increasing pressure from society to sustainably intensify food production and improve environmental stewardship on the one hand, yet also to reduce greenhouse gas (GHG) emissions and engender carbon removals on the other (Ara et al., 2021; Ibrahim et al., 2019; Sándor et al., 2020). Globally, agriculture accounts for around 18.4 % of the GHG inventory, with 5.5 % from croplands and agricultural soils (Balogh, 2022; Ritchie et al., 2020). *Ceteris paribus*, GHG emissions from the agricultural sector are expected to rise in parallel with expansion of intensified agricultural land use (Hunter et al., 2017; Taylor et al., 2016). While irrigated croplands offer unique opportunities to modulate both agricultural GHGs and soil carbon sinks (McGill et al., 2018; Sapkota et al., 2020), our knowledge of potential GHG mitigation through SOC sequestration associated with irrigated systems is very much in its infancy (McGill et al., 2018). Irrigated systems conceivably provide necessary impetus for greater production and presumably SOC sequestration, yet greater production is often driven by higher use of nitrogenous fertilisers (Adnan et al., 2022; Rawnsley et al., 2019), which in turn may increase nitrous oxide (N_2O) emissions, causing net GHG emissions to overcompensate for mitigation realised by enhancement of SOC stocks (Bilotto et al., 2021; Christie et al., 2014; Henry et al., 2022). Indeed, recent work has suggested that greater SOC stocks may not ultimately result in lower whole farmnet GHG emissions due to the tight coupling between productivity and GHG emissions (Bilotto et al., 2023; Harrison et al., 2021), since greater soil organic matter and SOC may be conducive to greater crop or pasture production, thereby potentially allowing nitrous oxide and/or methane emissions to rise in parallel with SOC accrual.

Contemporary scholarly research of sustainable intensification via irrigation has primarily focused adopted a productivity and/or economic lens (Ash et al., 2017; Monjardino et al., 2022; Muleke et al., 2022a,b; Muleke et al., 2023; Muleke et al., 2022c). For example, Muleke et al. (2023) concluded that productivity and profitability could be sustainably raised through integration of grain legume crops into existing rotations, while Muleke et al. (2022b) show that the number of profitable crop types fell from 35 to 10 under future climates, reflecting an interplay between commodity price, yield, crop water requirements, water costs and variable costs, wherein water use and costs increased, while crop yields decreased under future climates. In their study, effects of climate change on profit were not related to long-term rainfall, with future climates depressing profit by 11–23 % relative to historical climates, but rather impacts of future climates were more closely related to crop type and maturity duration, with many crop types that were traditionally profitable under historical climates being no longer profitable in future. Such studies demonstrate that productivity (e.g., crop yield) and profitability have often been the motivation of previous work, primarily to the exclusion of associated or interacting effects on soils, including implications of systems interventions on soil health, carbon and greenhouse gas (GHG) emissions.

Confusion among the scientific and practitioner community abounds as to the contexts with which SOC increases following intervention. Previous research has shown that weather conditions (largely precipitation), management and soil texture drive SOC sequestration (Emde et al., 2021; Henry et al., 2022; Singhal et al., 2023), primarily through modulating influence on pasture or crop productivity (Langworthy et al., 2018; Yan et al., 2022). Conversely, other field studies have concluded that tillage and residue management practices manifest greater control over SOC sequestration (Chao, 2019; Karstens et al., 2022; Saurabh et al., 2021). Others argue that changes in SOC sequestration are contingent upon type of crop, genotype, and crop rotation (Antón et al., 2022; Sándor et al., 2020; Yang et al., 2023). Such treatment effects are further confounded by regional differences in global warming, with soil carbon sequestration expected to fall depending on regional specificity and extent of the climate crisis (Bilotto et al., 2023) and frequency of extreme events (Harrison, 2021; Langworthy et al., 2018; Liu et al., 2023). Within such studies, particularised conclusions may well be robust (e.g. Liu et al., 2020), but valid interpretations while bespoke can be voided when extrapolated to new contexts, agroecological regions and/or production systems.

We posit that much of this confusion can be attributed to initial (antecedent) SOC stocks: experiments beginning from SOC levels close to their floor (e.g., less than 1 %) could be reasonably expected to improve SOC, whereas antecedent SOC at ceiling levels (e.g., >6 %) might be expected to demonstrate less gain, because stocks are already close to their maximum levels. While scientists and practitioners often focus on within-experiment activities to assess the relative promise associated with an intervention – such as treatments and climatic conditions – they tend to downplay or even completely overlook the influence of initial SOC on their results. Experimental results may be further confounded by limited duration of field experiments, which canconfine interpretations drawn to parochial weather conditions realised during the finite window within which the experiment is conducted. Trost et al. (2013) note that it is difficult to estimate the effects of factorial combinations caused by the environment and management on SOC sequestration and, as such, the present study aims to address this knowledge gap.

Here, we build on foundational insights of previous work (Muleke et al., 2023) to investigate how initial SOC stocks influence long-term trajectories of SOC accrual using a real irrigated grains farm as a use case. We invoked three whole-farm adaptations and compared directional change with the existing system (*Baseline*) to examine how management (crop type, rotation, irrigation, fertilisation) and soil type (sand, clay, sandy loam) impacted on SOC over the long-term. Specifically, our aims were to (1) examine the impacts of antecedent SOC on sequestration for varying whole-farm adaptations and soil types, and (2), quantify effects of these adaptations and soil types on net farm GHG emissions.

2. Methods

2.1. Study overview

An irrigated broadacre farm situated in the Riverina region of New South Wales (NSW), Australia (−34.8016S, 145.8904E) was used as a case study. A detailed description of the case study, including climate, soils, farm layout, crop rotation, irrigation methods and source of irrigation water supply is provided in Muleke et al. (2023) and Monjardino et al. (2022). In brief, our study was conducted by initialising our biophysical model (APSIM) according to the cropping production system operating on the case study farm. This step was made to ensure that the simulations were realistic and regionally representative. This included initialisation of farm management (fertiliser and irrigation use, crop rotation etc) and soil physical characteristics. Soil and climatic details were derived from publicly available scientific databases (Sections 2.2 and 2.3). Soil data were used to initialise APSIM, while daily climate data drives APSIM (daily computations of crop growth and development are driven by climate inputs, similar to other contemporary cropping systems models).

We next developed three generic adaptations scenarios in consultation with a regional reference group of experts comprising farmers, farmer groups, consultants and extension staff with the aim of improving SOC stocks. These adaptations comprised *Simplification* (reducing inputs), *Diversification* (increasing crop type and genotype diversity in rotation) and *Intensification* through use of greater inputs and crops requiring irrigation (detailed in Section 2.3.3). Because net greenhouse gas (GHG) emissions depend on the balance of nitrous oxide (N_2O) and SOC sequestration, we computed net emissions associated with each adaptation. Adaptations were compared with the baseline (*status quo* operation) to assess direction and extent of change. Each adaptation was made in the model by changing farm management (sowing time, irrigation, fertiliser, crop rotation) as shown in Table 1. Thus, our primary focus in this study was on farming systems adaptation and on change relative to the baseline (fractional and percentage), rather than on absolute values (e.g., actual tonnes SOC/ha).

2.2. Historical climate data

We conducted simulations using 110 years of historical climatic data (1 January 1910–31 December 2019). Data for daily maximum and minimum temperature, rainfall and solar insolation were sourced from SILO (Scientific Information for Land Owners) Patched Point Dataset (Jeffrey et al., 2001) (shown in Fig. S1). Historical annual rainfall of the case study location was 403 mm, with 218 mm in winter and 185 mm in summer (Jeffrey et al. (2001). These data have been rigorously screened for anomalies by the data provider using a two-pass interpolation system; erroneous values were excluded from the interpolation, so they did not adversely affect the gridded surface (https://www.longpaddock.qld.gov.au/silo/about/about-data/).

2.3. Simulation of crop growth, yield and soil carbon stocks

We adopted the farming systems outlined in Muleke et al. (2023) to examine the impact of initial SOC and whole farm adaptation on SOC accrual and nitrous oxide (S-N_2O) emissions using the Agricultural Production Systems sIMulator (APSIM) v7.10, (Holzworth et al., 2014; Keating et al., 2003). APSIM has been comprehensively validated under a wide range of conditions, with such studies showing that the model performs well in simulating crop growth, soil C dynamics and soil nitrogen (N) cycling (Bilotto et al., 2021; Harrison et al., 2019; Holzworth et al., 2014; Keating et al., 2003; Luo et al., 2011; Mohanty et al., 2020; O'Leary et al., 2016; Wang et al., 2003a).

Table 1
Details of the *Baseline* and whole-farm adaptations modified after Muleke et al. (2023) and Muleke et al. (2022a).

Whole-farm adaptation	Crop	Sowing date	Irrigated area (ha)	N applied (kg N/ha/yr)
Baseline	Canola	17-May	750	100
	Wheat	7-Jun	750	150
Diversified	Canola	17-May	750	100
	Wheat	7-Jun	750	150
	Faba bean	29-Mar	750	50
Intensified	Canola	17-May	750	150
	Maize	29-Dec	188	400
	Wheat	7-Jun	750	250
	Cotton	1-Oct	188	300
	Rice	15-Nov	188	500
Simplified	Canola (Dry)	10-May	750	100
	Wheat	7-Jun	375	150

2.3.1. Surface and soil organic matter and carbon

Daily climate data are used in APSIM to compute biophysical values, including plant growth, labile soil carbon inputs, mineralisation, plant senescence and soil water infiltration and extraction. Management in the model further influences growth and carbon inputs, with irrigation improving growth during periods of plant water deficit, and nitrogen improving growth during periods of nitrogen stress. Plant growth, soil inputs and soil carbon in the model are derived by rate-state equations: the rate of any given biophysical process depends on the state of that variable on the prior day. For example, growth is greater when leaf area index on the prior day is relatively high. APSIM simulates surface and soil organic matter, of which soil organic carbon is subset. When surface organic matter is added (e.g., from wheat straw at harvest), that residue will be added to the existing pool of surface organic matter. For all simulations, we assumed an initial surface organic matter pool of 1000 kg DM/ha. Each organic matter pool has separate C:N ratios, decomposition rates and specific areas. Leaching of soluble inorganic N (nitrate and ammonium) is determined by rates of rainfall or irrigation. Soil organic matter is partitioned into fresh (FOM), medium (BIOM) and a more stable humus (HUM) decomposition pool, with fractionation between these pools dependent on the type of organic matter and crop residues. A subset of the HUM pool is defined as inert. Residue decomposition is dynamically determined by soil moisture, temperature, C:N ratio of the substrate, whether the residue is standing or prostrate, and the amount of material contacting the soil surface. Decomposition results in some loss of carbon in surface organic matter as CO_2 and transfer of C and N to the soil; material with higher C:N ratios creates an immobilisation demand, which is satisfied from mineral N in surface layers; inadequate mineral N can restrict decomposition of residues in surface layers. For detailed accounts of surface and soil organic matter models in APSIM, readers are referred to Dimes and Revanuru (2004) and Probert et al. (2005).

Given that soil water holding capacity and growth differs across soil types, we adopted three regionally representative soil types: brown vertosol clay, sand and sandy loam, following soil classification nomenclature of Isbell (2021). We used default hydraulic attributes for saturated water flow in APSoil (Table S2; Dalgliesh et al., 2016). To examine effects of initial SOC stocks, we sourced measured data for bulk density and soil organic matter pools (fresh organic matter pool (FOM), microbial biomass pool (BIOM) and humic pool (HUM); Probert et al., 1998) from the APSoil database (Dalgliesh et al., 2012) (Table S1), then initialised APSIM with six initial SOC concentrations (0.5 %, 2 %, 3 %, 4 %, 5 % and 6 %) within the top 100 cm of soil profile, following Dalgliesh et al. (2016). SOM and SOC in the APSoil database were determined by Dalgliesh et al. (2016) using Walkley Black or Leco analytical methods on soil cores taken in the Coleambally region of the case study farm; historical management associated with these data were assumed to be similar to status quo operations on the case study farm (default parameters shown in Table S1). Neither bulk density nor management were altered within any 110-year simulation (except for crop rotation specified in Section 2.3.3). In line with our underpinning aim – to examine the effect of initial SOC on subsequent change in the simulation – and to account for SOC variability due to historical climate and management types, we specified a range of SOC values that were used to initialise APSIM. Ensuing changes in simulated SOC over the 110 years were an emergent property, driven by climate, and modulated by interactions between antecedent SOC, soil type and management over the course of the simulation.

2.3.2. Management and cropping systems

We used various APSIM crop modules to simulate growth and development of wheat (Brown et al., 2014; Wang et al., 2003b), canola (Robertson et al., 1999), faba bean (Turpin et al., 2003), maize (Harrison et al., 2014), rice (Bouman et al., 2001) and cotton (Hearn, 1994). Irrigated crops were sown on fixed dates (mid-May for winter crops, mid-November for summer crops); dryland crops were sown when sufficient autumnal rainfall occurred (25 mm over four days). Sowing dates were set according to information outlined in Muleke et al. (2022a), shown in Table 1. Default soil parameters were adopted from the APSIM soil library following Dalgliesh et al. (2012). Plant available soil water at sowing and application of irrigation and nitrogen (N) fertiliser for each adaptation was set following Muleke et al. (2023) (details provided in Section 2.3.3, Table 2 and Fig. S2). Maximum potential long-term yields were estimated by identifying optimal flowering periods (OFPs), defined as the window that minimises long-term risk of abiotic stress exposure. OFPs for irrigated and dryland crops were computed as the flowering dates corresponding to ⩾95 % of the maximum 15-day running average frost-heat yield following Muleke et al. (2022a), Liu et al. (2020) and Liu et al. (2021).

2.3.3. Whole farm systems adaptations

Three whole farm systems adaptations suggested by regional experts were compared with the existing farm system (the *Baseline*), which comprised 750 ha of irrigated canola–wheat–wheat in serial rotation, with each winter crop followed by a summer fallow (Table 2, Fig. S1). Summer fallows stored water and nitrogen, incurring weed control costs (0–4 herbicide spray events). Thematic adaptations included *Intensification* (including higher rates of irrigation and fertiliser, greater farm area under irrigation, and inclusion of rice and maize in the rotation); *Diversification* (including a grain legume to diversify the crop rotation) and *Simplification*, being the opposite of *Intensification*. Further details are provided in Tables 1, 2 and Fig. S1 and previous studies (Monjardino et al., 2022; Muleke et al., 2023).

Diversified scenarios included a canola–wheat–faba bean rotation, with each winter crop followed by a summer fallow (750 ha). Relative to the *Baseline*, *Simplified* scenarios were allocated lower irrigation rates and irrigated farm area (only 50 % of wheat area; 375 ha); dryland canola was sown on 750 ha of the farm area (Table 2 and Fig. S1). *Intensified* scenarios were irrigated at higher rates (ML/ha), assuming 750 ha for the winter crops (canola, wheat) and 25 % of the farm area (188 ha) for summer crops (maize, cotton, rice), with the remaining 75 % of farm area fallowed in summer. Nitrogen fertiliser rates for each crop type in the *Baseline* scenario were obtained from the case study region. We then applied these fertiliser rates for corresponding crops in the *Diversified* and *Simplified* scenarios. We assumed 50–100 kg N/ha greater application rates for each crop in the *Intensified* scenario, as our aim for this adaptation was to examine the impact of intensification through greater application of N and irrigation (Table 1).

2.3.4. Greenhouse gas (GHG) emissions and global warming potential (GWP)

2.3.4.1. Soil emissions.

To quantify direct net farm soil GHG, we converted S-N_2O and the change in SOC over the simulation duration (ΔSOC) to carbon dioxide equivalents (CO_2-e). For S-N_2O, we used a 100 year GWP of 298 (Eq.1; IPCC, 2013):

$$Soil \quad N_2O \quad emissions(tonnes \quad \mathrm{CO_2\text{-}e}) = \frac{N_2O_{(Layer)} \quad \times 298}{1000} \tag{1}$$

Where *Soil N_2O emissions* represent tonnes of carbon dioxide equivalents (tonnes CO_2-e) from simulated S-N_2O and $N_2O_{(Layer)}$ represents simulated S-N_2O in uppermost (0–30 cm) and deeper (30–100 cm) soil layers.

SOC stocks (0–30 and 30–100 cm) were converted into CO_2-e by multiplying SOC by 3.67 using Eq. 2 (IPCC, 2013):

$$\Delta SOC \quad emissions(tonnes \quad CO_2\text{-}e) = SOC_{(Layer)} \times 3.67 \tag{2}$$

Where Δ*SOC emissions* represent tonnes of carbon dioxide equivalents from ΔSOC (difference between SOC at start and end of 110-year period), while $SOC_{(Layer)}$ represents simulated SOC in each of the upper (0–30 cm) and deeper (30–100 cm) soil layers in tonnes C per hectare.

Net farm GWP across whole-farm adaptations, soil types and initial SOC levels was calculated as the sum of S-N_2O and ΔSOC using Eq. 3, with positive gains in ΔSOC resulting in negative GHG emissions.

$$Net \ onfarm \ GWP(tonnes \ \mathrm{CO_2e}) = Soil \ N_2O \ emissions + \Delta SOC \ emissions \tag{3}$$

2.3.4.2. Emissions intensities of grain yield.

Emissions intensity (carbon footprints or CF) were computed as the annual per hectare direct emissions in kilograms of CO_2-e per kilogram of crop yield using equation Eq.4 (FAO, 2022).

$$EI(kg \quad CO_2\text{-}e \Big/ kg \quad crop \quad yield) = \frac{Annual \quad GHG \quad emissions(kg \quad CO_2\text{-}e/ha)}{yield(kg/ha)} \tag{4}$$

Where EI (kg CO_2-e/kg crop yield) represents emissions intensity, annual GHG emissions represents average direct GHG emissions in kilogram carbon dioxide equivalents (kg CO_2-e) and yield represents average simulated harvested crop yield (kg/ha).

2.3.5. Statistical analysis

Regression analyses were performed to test statistical significance of the impact of initial SOC, whole farm adaptation and soil type on relative change in long-term SOC storage. We fitted linear models using *R 4.2.2* (R Core Team, 2022) to predict change in SOC, using initial SOC, soil type and adaptation as predictor variables. We adopted confidence intervals (*CI*) of 95 %, a *p*-value of < 0.05 to denote significance, and adjusted R-squared (R^2) of 0.99 (refer to Table S3). We applied omnibus "analysis of variance" (ANOVA) to the linear model to test the statistical significance between initial SOC, soil type, adaptations and their interaction, while Tukey's post-hoc test was employed to identify disparities between paired level combinations (Tables S4-6). The relative variation contributed by each variable was computed using Eq. 5.

$$Variation \quad contributed = \frac{SS \quad associated \quad with \quad the \quad variable}{Total \quad SS} \times 100 \tag{5}$$

Where SS represents the sum of squares for each factor (initial SOC, soil type, adaptations and interactions therein) from ANOVA (Table 5); *Total SS* represents total sum of squares for all dependent factors and their interactions in the regression model.

Table 2
Description of the *Baseline* and whole farm adaptations, after Muleke et al. (2023).

Adaptation	Description
Baseline	The current farm system with gravity irrigation. The *Baseline* represents the current farm situation in terms of agronomy and irrigation.
Diversified	Diversification of the *Baseline* system using a grain legume (Faba beans; *Vicia faba*). This adaptation has similar average water usage and irrigated farm area as the *Baseline*, but a greater variety of winter crops grown within the year – i.e., wheat, canola and a grain legume – with similar inputs and costs.
Intensified	This was designed to be a high-input, high-output adaptation. Relative to the *Baseline*, this scenario applies higher amounts of water per unit area and per year and assumes a larger portion of the farm area is irrigated (i.e., less unirrigated fallow), and has higher inputs per unit area and year.
Simplified	This adaptation was designed as a low-input, low-output adaptation. Relative to the *Baseline*, the *Simplified* scenario was designed to require less irrigation water per unit area and year, has more rainfed crops, and reduced inputs per unit area.

3. Results

3.1. Antecedent SOC stocks determine SOC gain realised following intervention

Across soil types and adaptations, greater initial SOC stocks correlated inversely with long-term SOC change in the surface 30 cm (Table 3 and Fig. 1). In the deeper soil layers (30–100 cm), rate of change in SOC showed little association with initial SOC stocks (Table 3 and Fig. 3). Across all climate years (110 years), soil types and adaptations, a one unit increase in initial SOC within the upper 30 cm decreased temporal SOC accrual by 0.49 % (10 tonnes C/ha) (Fig. 1) or approximately 20 tonnes C/ha in SOC stocks over the whole soil profile (Table 3 and Fig. 1). Sandy loam and sandy soils had more pronounced reductions in SOC with increasing initial SOC stocks (0.07 to −1.6 % and 0.09 to −1.4 %, respectively; Table 3 and Fig. 1), whereas clay soils exhibited the lowest decrement in sequestered SOC (1.8 to −0.1 %), suggesting higher potential to accrue SOC in clay soils.

Simplified scenarios elicited reductions in long-term SOC in the uppermost 30 cm in response to increasing SOC levels (from 0.07 % to −1.3 %; Table 3 and Fig. 1). In contrast, *Diversified* and *Intensified* adaptations showed less decline in SOC accumulation (1.4 to −0.7 % and 1.2 to −1 %; Table 3), suggesting superior SOC accrual (Fig. 3) attainable through diversification and intensification. Lower initial SOC (0.5 %) elicited greater gains in SOC accumulation, whereas higher initial SOC concentrations (>2 % for sandy and Sandy loam soils, and >5 % for clay soil; Fig. 2) resulted in considerable SOC loss across adaptations (Table 3 and Fig. 2). This finding suggests that higher antecedent SOC or SOC that exceed ceiling SOC result in lower gains over the duration of a simulation or experimental period.

Table 3
Influence of antecedent SOC on long-term change (1910–2019) in soil organic carbon (ΔSOC) in upper (0–30 cm) and lower soil profiles (30–100 cm) as influenced by soil type (grey rows) and whole-farm adaptation (blue rows).

Soil Type	Initial SOC (%)	Percentage SOC (%) 0-30 cm			Percentage SOC (%) 30-100 cm			SOC stocks (*tonnes* C/ha) 0-30 cm			SOC stocks (*tonnes* C/ha) 30-100 cm		
		Start (1910)	End (2019)	ΔSOC	Start (1910)	End (2019)	ΔSOC	Start (1910)	End (2019)	ΔSOC	Start (1910)	End (2019)	ΔSOC
Clay	0.5%	0.5	2.3	1.8	0.1	0.1	0.0	15	65	50	9	8	-0.7
	2%	1.7	2.9	1.2	0.4	0.4	0.0	46	81	35	16	14	-1.6
	3%	2.5	3.4	0.9	0.6	0.5	-0.1	71	97	26	41	37	-4.1
	4%	3.5	4.2	0.6	0.5	0.4	-0.1	90	106	16	48	43	-4.9
	5%	4.4	4.7	0.3	0.6	0.5	-0.1	112	118	6	61	55	-6.2
	6%	5.3	5.2	-0.1	0.7	0.6	-0.1	135	131	-4	70	63	-7.1
Sandy	0.5%	0.5	1.1	0.7	0.1	0.1	0.0	12	29	16	3	5	1.7
	2%	1.8	1.9	0.1	0.2	0.2	0.0	44	46	2	11	11	0.0
	3%	2.6	2.3	-0.3	0.3	0.3	0.0	65	58	-7	17	16	-1.1
	4%	3.5	2.8	-0.7	0.4	0.4	0.0	86	70	-16	22	20	-2.3
	5%	4.4	3.3	-1.1	0.5	0.5	-0.1	107	81	-26	28	25	-3.4
	6%	5.2	3.8	-1.4	0.6	0.6	-0.1	128	93	-35	33	29	-4.6
Sandy loam	0.5%	0.5	1.2	0.7	0.1	0.1	0.0	13	30	17	5	7	2.1
	2%	1.8	1.9	0.1	0.2	0.2	0.0	45	47	2	12	13	1.4
	3%	2.7	2.3	-0.4	0.3	0.3	0.0	66	58	-8	19	20	0.9
	4%	3.6	2.8	-0.8	0.4	0.4	0.0	87	68	-18	24	24	0.5
	5%	4.4	3.2	-1.2	0.5	0.5	0.0	108	79	-29	30	30	0.0
	6%	5.3	3.7	-1.6	0.6	0.5	0.0	129	91	-39	35	34	-0.4
Whole farm adaptation													
Diversified	0.5%	0.5	2.0	1.4	0.1	0.1	0.1	14	52	39	4	7	2
	2%	1.8	2.6	0.9	0.3	0.3	0.0	45	69	24	12	13	1
	3%	2.6	3.1	0.5	0.4	0.4	0.0	68	81	14	24	24	0
	4%	3.5	3.7	0.1	0.4	0.4	0.0	89	92	4	29	28	-1
	5%	4.4	4.1	-0.3	0.5	0.5	0.0	110	103	-6	37	35	-2
	6%	5.3	4.6	-0.7	0.6	0.6	0.0	131	115	-16	43	40	-3
Intensified	0.5%	0.5	1.7	1.2	0.1	0.1	0.0	13	44	31	4	5	1
	2%	1.7	2.3	0.6	0.3	0.3	0.0	45	61	16	12	11	-1
	3%	2.6	2.8	0.2	0.4	0.4	0.0	67	73	6	23	21	-2
	4%	3.5	3.3	-0.2	0.4	0.4	0.0	87	83	-4	29	26	-3
	5%	4.4	3.8	-0.6	0.5	0.5	-0.1	109	95	-14	37	33	-4
	6%	5.3	4.3	-1.0	0.6	0.6	-0.1	130	106	-24	43	38	-5
Baseline	0.5%	0.5	1.4	0.9	0.1	0.1	0.0	13	36	23	4	5	1
	2%	1.8	2.1	0.3	0.3	0.3	0.0	45	53	9	12	12	0
	3%	2.6	2.5	-0.1	0.4	0.4	0.0	67	66	-1	23	22	-2
	4%	3.5	3.1	-0.4	0.4	0.4	0.0	88	77	-10	29	27	-2
	5%	4.4	3.6	-0.8	0.5	0.5	0.0	109	89	-20	37	33	-3
	6%	5.3	4.1	-1.2	0.6	0.6	-0.1	131	101	-29	43	39	-4
Simplified	0.5%	0.5	1.2	0.7	0.1	0.1	0.0	13	31	19	4	4	0
	2%	1.7	1.9	0.1	0.3	0.3	0.0	45	49	4	12	11	-1
	3%	2.6	2.3	-0.2	0.4	0.4	0.0	66	61	-5	23	21	-2
	4%	3.5	2.9	-0.6	0.4	0.4	0.0	87	73	-14	29	26	-3
	5%	4.4	3.4	-1.0	0.5	0.5	-0.1	109	85	-24	37	33	-4
	6%	5.3	3.9	-1.4	0.6	0.6	-0.1	130	97	-33	43	38	-5

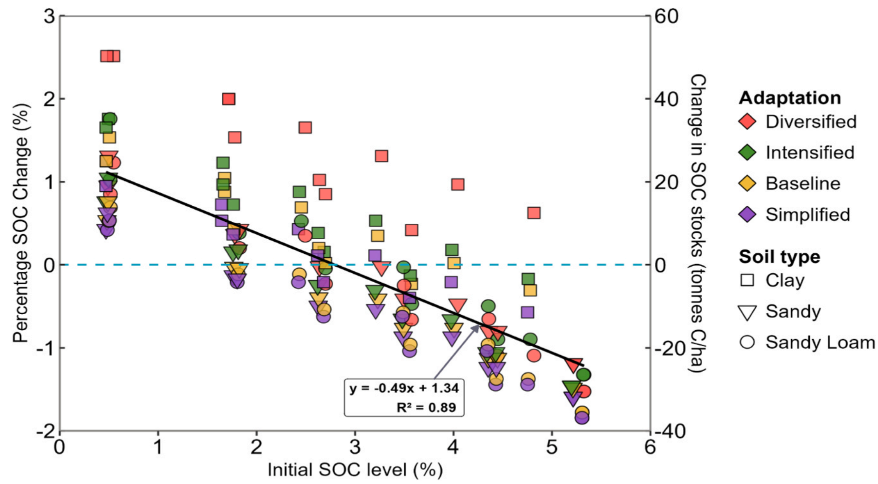

Fig. 1. Relationship between antecedent soil organic carbon (SOC) and long-term change in SOC in the uppermost 30 cm of soil. Colours represent whole farm adaptations and symbols represent soil type.

3.2. Absolute SOC accrual and long term delta SOC

Absolute SOC accrual - quantified as the change in SOC stocks over a 110-year timeframe (1910–2019) – decreased with higher initial SOC across soil types and adaptations (Table 4 and Fig. 3). Lower initial SOC (0.5 %) evoked greater SOC accrual in upper layers (0.02 t C/ha /yr), which significantly increased the absolute SOC gains (2.13 t C/ha) resulting in greater SOC accumulation over the 110 year simulation (28 t C/ha) across soil types and adaptations (Tables 4, 5, Figs. 3, 4 and S3). In contrast, initial SOC of 6 % (or above) in the topsoil resulted in SOC loss (−0.002 tonnes C/ha/yr), considerably diminishing absolute SOC accrual (−0.2 tonnes C/ha) and long-term SOC storage (−26 t C/ ha; Table 4, Figs. 3, 4, S3). Deeper soil layers (30–100 cm) exhibited *de minimus* SOC change per annum (−0.001 to 0.004 t C/ha/yr; Table 4) and change over time (−4 to 1 t C/ha; Table 4 and Fig. 2).

At lower initial SOC (0.5 %), clay soils had higher rates and absolute SOC change (0.03 t C/ha /yr and 3.4 t C/ha respectively), resulting in larger long-term gains in SOC (50 tonnes C/ha) in the uppermost soil layers. In contrast, sandy soils had lower accrual (0.01 t C/ha/yr and 1.3 t C/ha respectively), as shown in Tables 3, 4, 5 and Fig. 3. Lower SOC accrual with greater antecedent SOC was more evident in sandy soils compared with clay soils (Table 5).

Diversified and *Intensified* adaptations had higher potential for SOC gains at lower initial SOC content (0.5 %) in soil surface (2.8 and 2.4 t C/ ha respectively; Table 4 and S3) relative to the *Baseline* and *Simplified* adaptations (1.8 and 1.5 t C/ha respectively; Tables 4, 5 and Fig. 3). The increased SOC accrual resulted in greater gains in long-term SOC under *Diversified* and *Intensified* scenarios (39 and 31 t C/ha respectively) compared with the *Baseline* and *Simplified* scenarios (23 and 19 t C/ha respectively; Table 3, Fig. 4 and S6).

Diversified and *Intensified* scenarios accrued more SOC on clay soils (72 and 50 t C/ha respectively; Fig. 4), compared with *Baseline* and *Simplified* scenarios (44 and 35 t C/ha respectively). The greatest losses in SOC (−17 to −44 t C/ha) occurred in *Simplified* scenarios at high initial SOC (6 %), suggesting that simplifying cropping systems (or de-intensification) may not be an enabler for long-term SOC accrual.

High SOC accrual for wheat and canola underpinned larger SOC stock gains in *Intensified* and *Diversified* scenarios under clay and sandy soils, and *Diversified* scenarios under sandy loam soil. Enhanced SOC gains for summer crops (maize, cotton and rice) increased SOC stocks for *Intensified* scenarios relative to *Baseline* and *Simplified* scenarios (Fig. 5). Even so, increments in initial SOC elicited greater SOC losses for summer crops (cotton and rice) cultivated on clay and sandy soils under *Intensified* scenarios (Fig. 5).

3.3. Relative impact of initial SOC, adaptation and soil type on SOC stocks

Effects of initial SOC, adaptation and soil type on SOC and interactions therein were significant (Table 5 and S3). Initial SOC accounted for an average of 74 % of the variation in long term SOC stocks, in comparison to 12 % for soil type and 3 % across adaptations (Fig. 6). Clay soils had greater effects on long-term SOC stocks relative to sandy soils (Table S4), whereas *Intensified* and *Diversified* scenarios induced greater change in SOC stocks compared with *Baseline* and *Simplified* scenarios (Table S5). Low initial SOC (0.5–2 %) were conducive to considerable gains in SOC storage compared with high initial SOC (3–6 %) (Table S6).

3.4. Global warming potential (GWP) and GHG emissions intensity

Despite greater mean yield and significant carbon removal by SOC accrual, *Intensified* scenarios resulted in higher GWP (2.8–5.8 t CO_2-e) and emissions intensities (0.5–0.9 kg CO_2-e/kg crop yield, relative to the *Baseline* (−0.1 to 1.9 t CO_2-e and 0.1–0.5 kg CO_2-e/kg crop yield respectively). *Diversified* scenarios had the lowest net GWP (−0.7 to 1.5 t CO_2-e) and carbon footprint (−0.2 to 0.2 kg CO_2-e/kg crop yield). Conversely, *Simplified* scenarios evidenced lowest yields and greater emissions intensities (0.2–0.6 kg CO_2-e/kg crop yield) in comparison with the *Baseline* (Figs. 7 and 8). Summer crop rotations (maize, cotton and rice) accounted for a large portion of farm GWP and emissions intensities, associated with increased S-N_2O emissions resulting from higher application rates of N-fertilisers and irrigation on sandy soils (Fig. 9, S4 and S5). High N-fertiliser rates elicited greater N leaching in irrigated summer crops (in particular rice) on clay and sandy soils (Fig. S5). These results highlight a tight coupling between crop productivity, S-N_2O emissions and N-leaching, demonstrating that intensification with synthetic N fertiliser can increase net GHG emissions.

In addition to significant removal of atmospheric CO_2 via SOC accrual, *Diversified* scenarios were more effective in mitigating GHG emissions compared with *Intensification* (Figs. 7, 9 and S4), reflecting the potential for *Diversification* as a prospective climate change adaptation and mitigation intervention through addition of grain legumes (here, faba bean) to the baseline crop rotation, although *Diversification* had lower yields overall than those modelled for *Intensification. Simplification* caused relatively little difference to the *Baseline* (Table 1, Figs. 3, 4 and S5).

Sandy and clay soils exhibited greater vulnerability N-leaching compared with sandy loam soils, the former leading to elevated

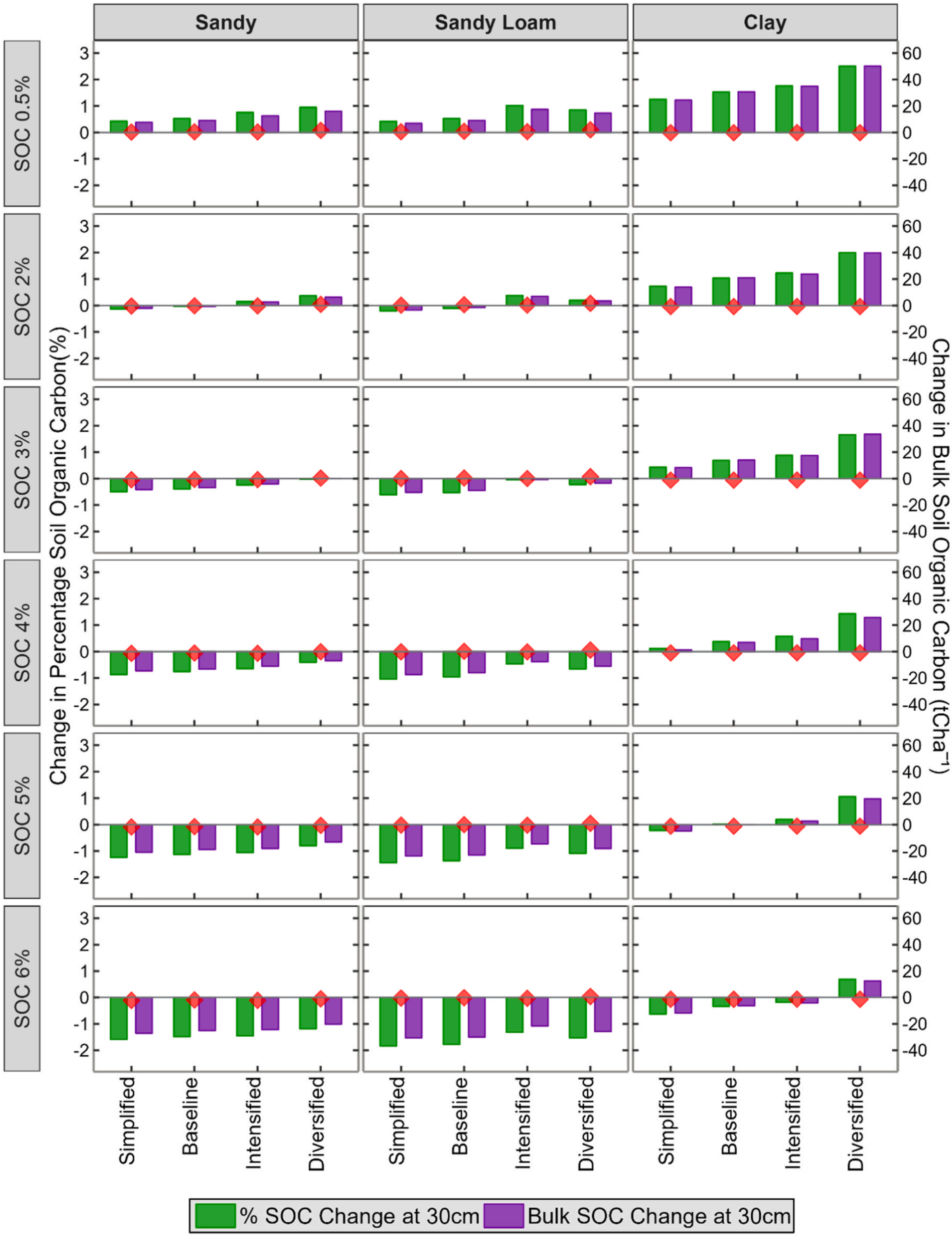

Fig. 2. Long-term (1910–2019) change in soil organic carbon (SOC) in the soil surface (0–30 cm; purple and green bars) and subsurface (30–100 cm; red points) at varying antecedent SOC, across soil-types (*clay*, *sandy* and *sandy loam*) and whole-farm adaptations (*Baseline, Diversified, Intensified* and *Simplified*).

emissions intensities (0.4–0.9 kg CO_2-e/kg crop yield) and GWP (1–4.7 t CO_2-e) from increased S-N_2O emissions (Fig. 7 and S5). Only sandy loam soils in *Intensified* systems generated noteworthy GHG emissions from subsoil layers (0.5–0.7 t CO_2-e) primarily due to leaching and S-N_2O (Fig. S5). Higher initial SOC increased GHG emissions and carbon footprint, but had no discernible impact on crop yield (Figs. 7 and 8).

4. Discussion

Past work has shown that sustainable intensification underpinned by higher rates of irrigation, greater farm area under irrigation and higher rates of N application may represent a financially viable alternative in the face of the climate emergency (Muleke et al., 2023). However, this may not always be the case, as (1) irrigation water may not always be physically available or economically affordable (Monjardino et al.,

Table 4
Absolute soil organic carbon (SOC) accrual in the upper (0–30 cm) and deep (30–100 cm) soil layers for varying antecedent SOC, soil-types (grey rows) and whole-farm adaptations (blue rows). Absolute SOC accrual was estimated as the change in SOC stocks over 110-years (1910–2019) relative to base period (1910).

Soil Type	Initial SOC level (%)	Absolute % SOC		Absolute SOC (tonnes C/ha)	
		0-30 cm	30-100 cm	0-30 cm	30-100 cm
Clay	0.5%	3.6	-0.1	3.4	-0.1
	2%	0.7	-0.1	0.8	-0.1
	3%	0.4	-0.1	0.4	-0.1
	4%	0.2	-0.1	0.2	-0.1
	5%	0.1	-0.1	0.1	-0.1
	6%	0.0	-0.1	0.0	-0.1
Sandy	0.5%	1.4	0.6	1.3	0.5
	2%	0.1	0.0	0.1	0.0
	3%	-0.1	-0.1	-0.1	-0.1
	4%	-0.2	-0.1	-0.2	-0.1
	5%	-0.2	-0.1	-0.2	-0.1
	6%	-0.3	-0.1	-0.3	-0.1
Sandy loam	0.5%	1.4	1.0	1.3	0.8
	2%	0.0	0.2	0.0	0.2
	3%	-0.1	0.1	-0.1	0.1
	4%	-0.2	0.0	-0.2	0.0
	5%	-0.3	0.0	-0.3	0.0
	6%	-0.3	0.0	-0.3	0.0
Holistic Adaptation					
Diversified	0.5%	2.8	1.0	2.7	0.9
	2%	0.5	0.2	0.5	0.2
	3%	0.2	0.1	0.2	0.1
	4%	0.0	0.0	0.0	0.0
	5%	-0.1	0.0	-0.1	0.0
	6%	-0.1	0.0	-0.1	0.0
Intensified	0.5%	2.4	0.3	2.3	0.3
	2%	0.3	0.0	0.3	0.0
	3%	0.1	-0.1	0.1	-0.1
	4%	-0.1	-0.1	0.0	-0.1
	5%	-0.1	-0.1	-0.1	-0.1
	6%	-0.2	-0.1	-0.2	-0.1
Baseline	0.5%	1.8	0.4	1.7	0.3
	2%	0.2	0.0	0.2	0.0
	3%	0.0	0.0	0.0	0.0
	4%	-0.1	-0.1	-0.1	-0.1
	5%	-0.2	-0.1	-0.2	-0.1
	6%	-0.2	-0.1	-0.2	-0.1
Simplified	0.5%	1.5	0.2	1.4	0.2
	2%	0.1	0.0	0.1	-0.1
	3%	-0.1	-0.1	-0.1	-0.1
	4%	-0.2	-0.1	-0.2	-0.1
	5%	-0.2	-0.1	-0.2	-0.1
	6%	-0.3	-0.1	-0.3	-0.1

2022), (2) intensification per se can increase N leaching and/or elevate N_2O emissions, or (3) catalyse other environmental problems, such as salinisation of the ground water and surface water (Bilotto et al., 2021; Christie et al., 2018, 2020; Rawnsley et al., 2019), underscoring a need for development of more comprehensive approaches that holistically account for environmental, economic, biophysical and social trade-offs evoked by purported adaptation or mitigation interventions (Harrison, 2021; Rawnsley et al., 2018; Shahpari et al., 2021). Here, our aim was to

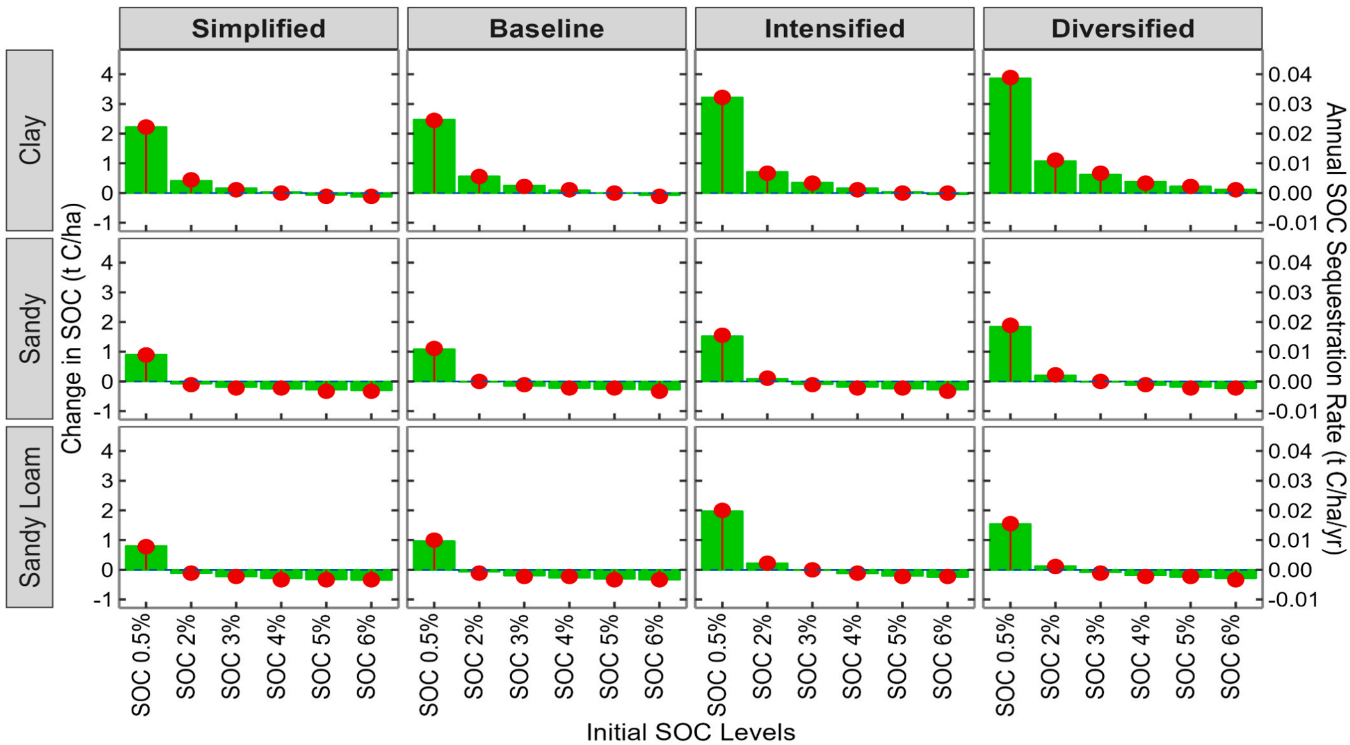

Fig. 3. Influence of antecedentsoil organic carbon (SOC) on the annual rate and long-term SOC accrual within the upper soil profile layers (0–30 cm) across soil-types and whole-farm adaptations. Green bars represent SOC change (t C/ha) over 110-years (1910–2019). Red points represent mean annual SOC change (t C/ha/yr).

disentangle the impacts of whole-farm intensification/simplification/diversification on (1) long-term SOC accrual and (2) global warming potential (GWP) resulting from adaptations across varying antecedent SOC levels and soil types. While we address our aims via use case, our concepts and systems approach underpinning *Simplification*, *Diversification* and *Intensification* could be generically adapted to any farming system or agroecological region; *Simplification* being aimed at reducing inputs and resource use, *Diversification* aimed at increasing diversity of enterprises employed on farm (here, crop types), and *Intensification* designed to increase irrigation and fertilisation per unit area and per farm area. While numerical results obtained for any production system or agroecological region are contextual, the approach we articulate hereto is amenable to generalisation.

Although *Intensification* resulted in superior productivity and improved SOC accrual, this adaptation also rsulted in the highest GWP (5.8 t CO_2-e) and emissions intensity (0.9 kg CO_2-e/kg crop yield; Table 4, Figs. 4 and 7). *Diversification* manifested greater SOC, GWP mitigation (1.5 t CO_2-e) and carbon footprint (0.2 kg CO_2-e/kg crop yield) consistent with past work (Yang et al., 2023; Zou et al., 2022), but was accompanied by concomitant reductions in yield compared with *Intensification* (Figs. 7 and 8). *Simplification* increased emissions intensities (0.6 kg CO_2-e/kg crop yield), diminished SOC accrual and evoked significant yield penalties relative to the *Baseline* (Table 4, Figs. 3, 7 and 8). These findings suggest that diversifying irrigated systems would seem to be one solution for both adaptation and mitigation (McGill et al., 2018; Meier et al., 2020; Paustian et al., 2019; Sándor et al., 2016), albeit at the expense of yield and profitability (Monjardino et al., 2022; Muleke et al., 2023). On the other hand, intensification can elevate productivity and profitability (Muleke et al., 2023) but would exacerbate climate change through additional GHG (McGill et al., 2018; Phelan et al., 2015) even though *Intensification* is often the most resilient form of adaptation (Muleke et al., 2023). These findings suggest that the long-term sustainability and endurance of any purported mitigation or adaptation option will be a function of sustainable improvement in multiple dimensions (economic, environmental, social, institutional).

It is important to note that the conceptualisation of SOC processes in the model we used (APSIM) quantify change in SOC inputs relative to SOC mineralisation; as APSIM does not account for molecular SOC residence times; we thus refer to “SOC accrual” and “SOC stocks” rather than sequestration per se. SOC residence time, including sequestration and formation of mineral-associated organic carbon, are aspects worthy of future investigation. For example, Begill et al. (2023) assessed a wide range of SOC (5–118 g kg^{-1}) and clay contents (30–770 g kg^{-1}) and found that the proportion of mineral-associated organic carbon (MAOC) was stable across a range of cropland and grassland management types, and across SOC levels. While soil texture influenced the slope of the relationship between SOC and MAOC, no upper limit to MAOC was observed. These insights challenge the notion that MAOC accumulation is limited by the soil fine fraction, and thus may compriseamenable targets for conceptualisation and contrasting within contemporary agro-ecosystemsmodels, such as APSIM.

We showed that long-term SOC stocks in the topsoil (0–30 cm) and subsoil (30–100 cm) in irrigated cropping systems was primarily governed by initial SOC relative to practice changes, soil type and prevailing climate (74 % effect; Table 5 and Fig. 6). We found evidence suggesting that lower initial SOC (0.5–2 %) are likely elicit greater *ex poste* SOC accrual compared with contexts with higher initial SOC concentrations (3–6 %). Our findings clarify confusions over previous conclusions and are consistent with cross-site empirical studies demonstrating an inverse relationship between changes in SOC and initial SOC (Arndt et al., 2022; Emde et al., 2021; Slessarev et al., 2023).

We showed that clay-rich soils with low antecedent SOC (0.5 %) accrued more SOC (50 t C/ha) in topsoil (30 cm), relative to sandy soils (17 t C/ha; Tables 3–5 and Figs. 2–4). Notwithstanding our discussion above relating to MAOC, this result is consistent with previous research opining that incremental gains in SOC are associated with higher concentrations of silt and clay, wherein fine fractions (<50 μm) tend to protect SOC (Beare et al., 2014; Feng et al., 2013; Matus, 2021), such that C sorbed to mineral surfaces increases with soil specific surface area (Kaiser and Guggenberger, 2003). As such, sand-rich soils are more

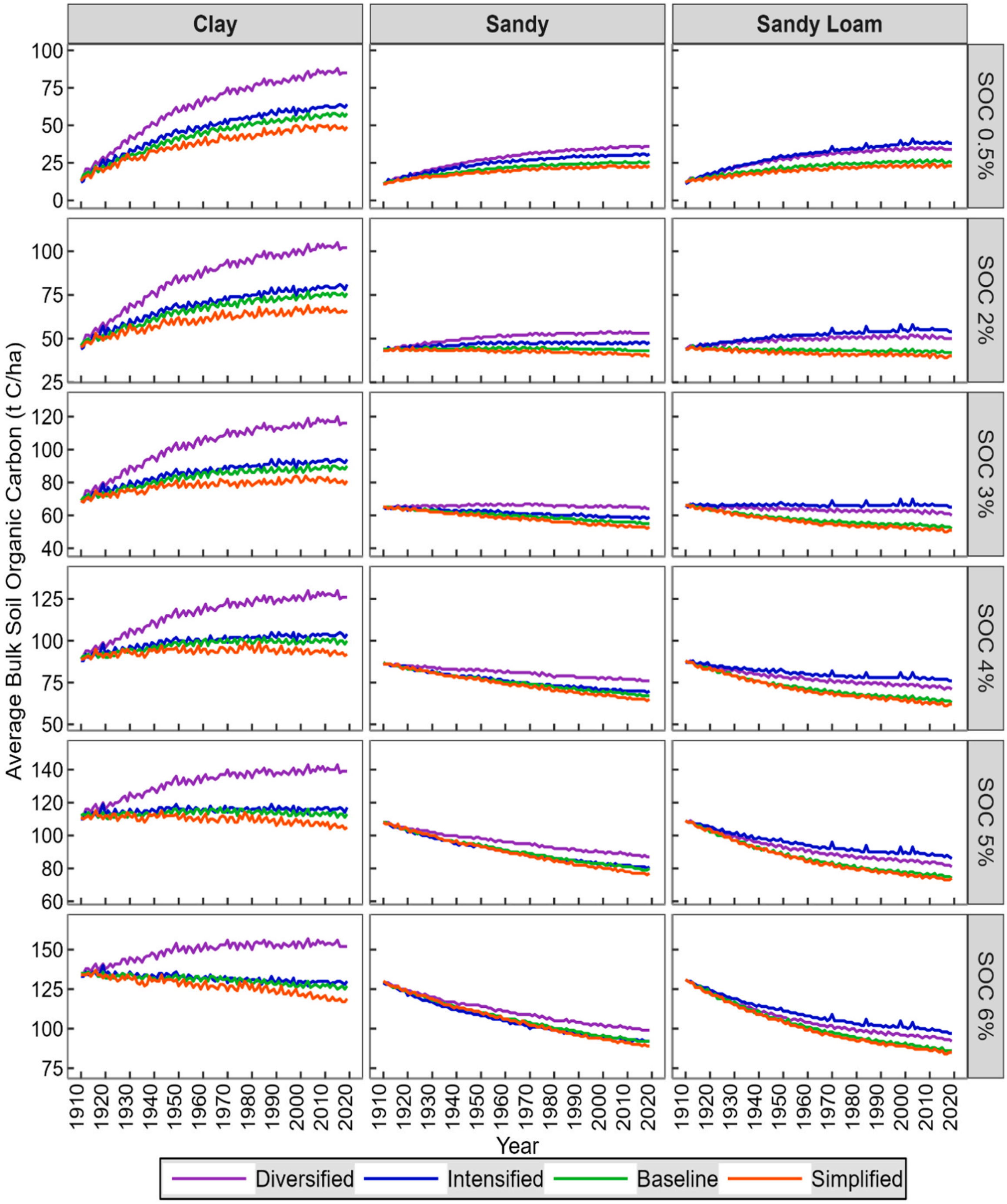

Fig. 4. Influence of antecedent soil organic carbon (SOC) on long-term SOC stocks in the uppermost 30 cm for three soil types and four whole farm adaptations.

likely to reach their C equilibrium at lower SOC due to lower SOC protective capacity in comparison to clay soils (Angers et al., 2011; Six et al., 2002; West and Six, 2007). We acknowledge that the presence of a theoretical equilibrium or "saturation" point is contextualised to the soil types in question, and indeed, is the subject of ongoing scholarly debate, with some authors suggesting that "mineral-associated organic carbon formation capacity" would be more appropriate nomenclature than use of the term "saturation" (Emde et al., 2022). Within the conceptual and mathematical boundaries of the present study however, our results suggest that sandy soils reached C saturation levels beginning from lower antecedent SOC levels (2 %) than clayey soils (5 %), evidenced by trends shown in Fig. 4. Incremental levels of initial SOC beyond this upper limit induced greater SOC losses in sandy soils compared with clayey soils. Taken together, our results suggest that management practices aimed at increasing carbon inputs may be futile where SOC is relatively high, as C-retention rate asymptotically diminishes as SOC approaches the equilibrium point (Castellano et al., 2015; Guillaume et al., 2022). Ascertaining SOC equilibrium thresholds across sites, climates and soil types would be fertile ground for future research, for knowledge of such thresholds would guide practitioners aspiring to improve SOC as to whether changing management practices would be worth while.

Our findings suggest that winter crops (wheat and canola), cultivated on clayey and sandy soils enhanced SOC accrual for *Diversified* and *Intensified* systems (72 and 23 t C/ha respectively; Table 3 and Figs. 4–5) whereas, when grown on sandy loam soils, these crops were only likely

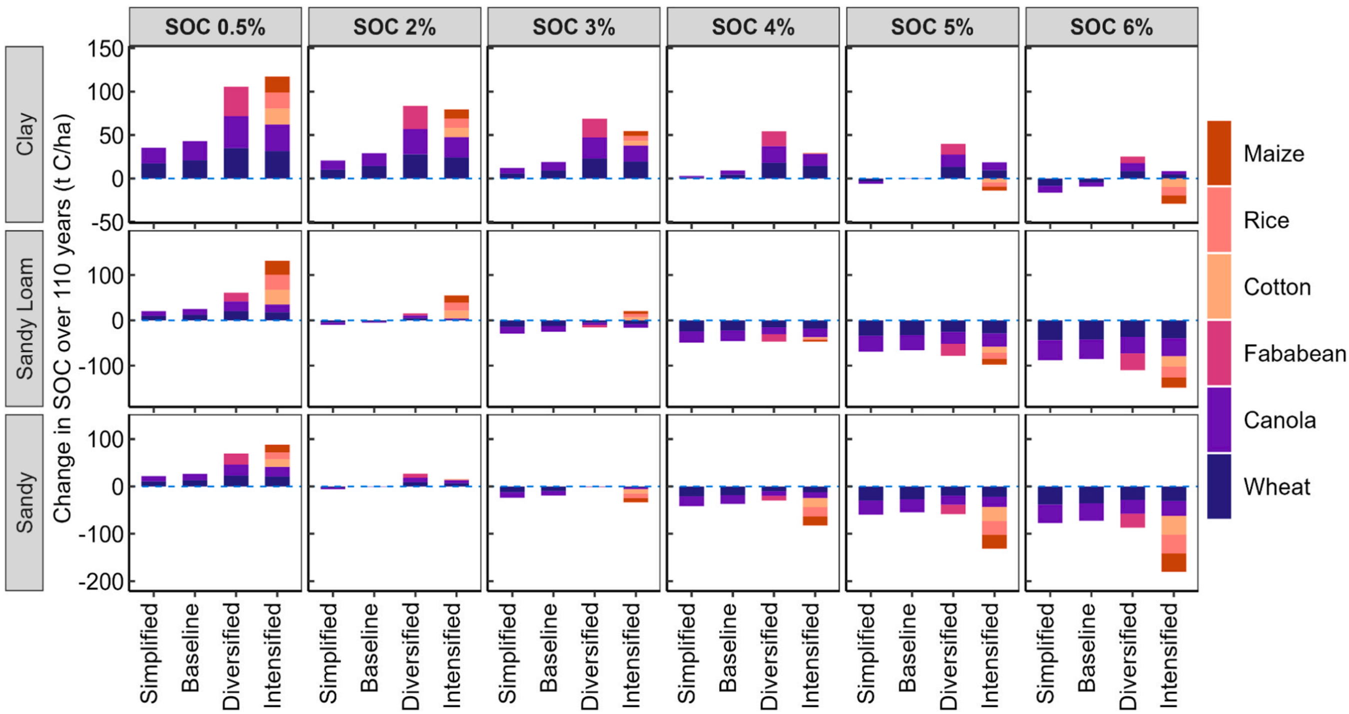

Fig. 5. Average annual change in soil organic carbon (SOC) storage disaggregated by crop types for three soil types and four whole-farm adaptations. Stacked columns represent cumulative SOC stocks in the surface 30 cm for six initial SOC levels.

Table 5
Influence of initial SOC, adaptation and soil type on long-term change in SOC stocks.

Source of variation	DF	Sum Sq	Mean Sq	*F* value	p-value
Initial SOC	5	37.4	7.5	1044.3	< 0.001
Soil type	2	5.9	3.0	412.9	< 0.001
Adaptation	3	1.6	0.5	74.4	< 0.001
Initial SOC × Adaptation	15	1.6	0.1	14.7	< 0.001
Initial SOC × Soil type	10	3.5	0.4	48.9	< 0.001
Adaptation × Soil type	6	0.4	0.07	9.51	< 0.001
Residuals	30	0.2	0.01		

DF = Degrees of Freedom, Sum Sq= Sum of Squares, Mean Sq= Mean Square, × = Interaction.

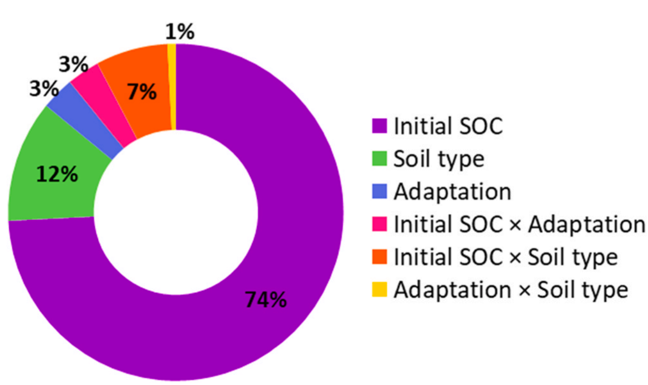

Fig. 6. Relative impact of initial SOC, adaptation, soil types and interactions therein on changes in SOC stocks.

to enhance SOC accrual under *Intensification* (25 t C/ha). Summer crops (maize, cotton, and rice) improved SOC accrual in *Intensified* scenarios relative to *Baseline* and *Simplified*. Nevertheless, these crops were prone to N-leaching on clay and sandy soils, and increased S-N_2O emissions on sandy loam soils, resulting in notable yield losses and increased global warming potential (Figs. 4–8 and S4–5). Broadly, this finding underscores the beneficial impact of winter crops on SOC accrual, and the potential integration into crop rotations aimed at reducing GHG emissions through improved C accrual.

Deeper soil layers (30–100 cm) exhibited minimal variability in SOC accrual, across initial SOC levels, soil types and whole-farm adaptations (as shown in Table 3 and Fig. 2). Notably, only sandy loam soils in intensified systems showed significant GHG emissions in subsoil layers (0.5–0.7 t CO_2-e), primarily due to elevated S-N_2O emissions (Fig. S5).

We found that increasing farm area under irrigation, and/or increasing nitrogen fertilisation rates can and does improve SOC stocks. We note however, that such increase is relative to the status quo farming system in operation and antecedent SOC. In general, we found that over the 110-year simulation, SOC of *Simplified* systems changed little compared with SOC of the Baseline, suggesting that farm area under irrigation had relatively little impact at the whole farm scale (*Simplification* irrigated 350 ha of wheat, whereas the *Baseline* irrigated 750 ha of wheat). When antecedent SOC was low, *Diversification* and *Intensification* elicited similarly high SOC increments, however when antecedent SOC was high (e.g., SOC 6 %), *Intensified* systems lost more SOC than *Diversified* systems. Inclusion of legumes (faba bean) into canola-wheat-wheat rotations (i.e. *Diversified* system) improved soil nitrogen fixation and reduced soil C:N ratios, increasing soil organic matter decomposition rates, improving subsequent temporal gains in SOC. *Intensified* systems generally improved soil organic matter inputs when initial SOC was low, particularly for the highly productive crops, such as maize, which required an average of 15 ML/ha/year compared with 2.8 ML/ha/year for wheat crops (averaged over the simulation). However, when initial SOC was high (6%), high production and residue crops immobilised more mineral nitrogen, subsequently accelerating SOC decrement over the 110-year simulation. In general, changes in total SOC were primarily attributable to changes in the labile pool (microbial biomass and products), and to a lesser extent the humic pool, with inert organic carbon pools remaining relatively stable over the simulation. In general, changes in the proportion of fresh and humic pools of soil organic matter relative to the change in total organic matter were relatively consistent across adaptations, soil types and climate years.

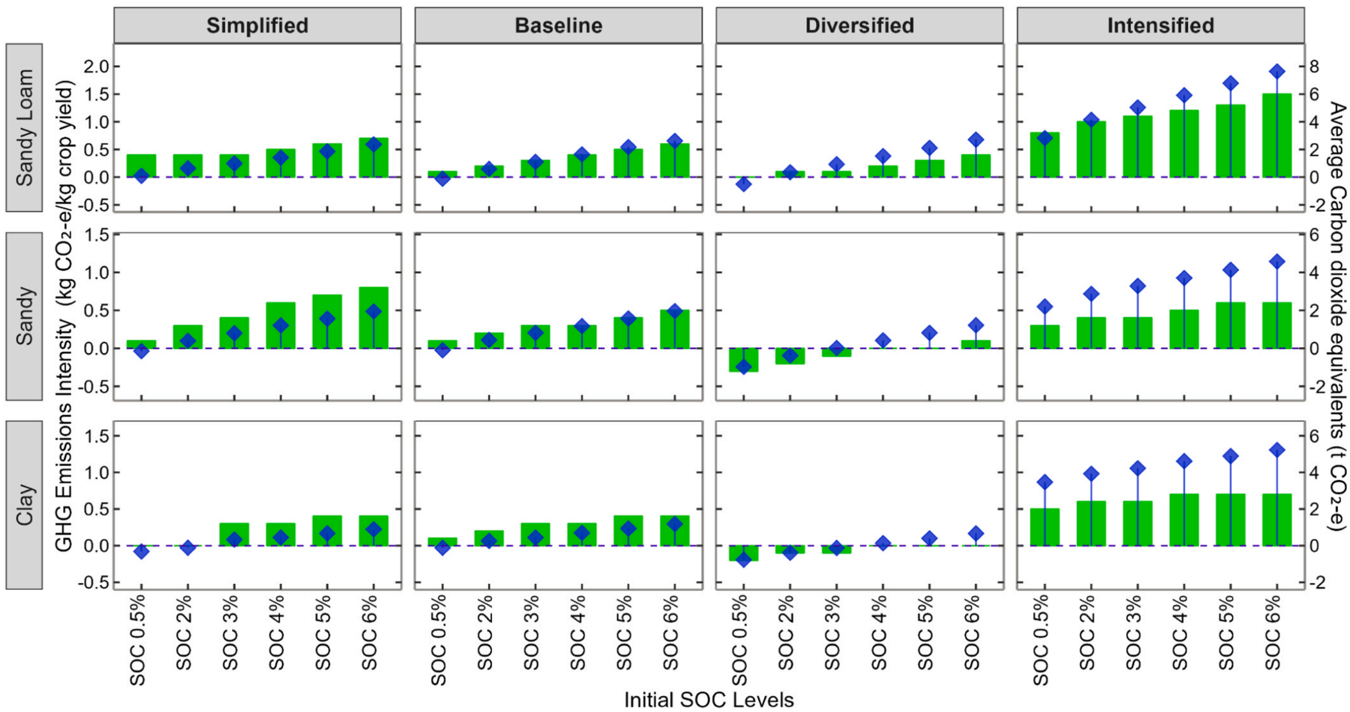

Fig. 7. Net global warming potential (GWP) and emissions intensities as a function of initial SOC, whole-farm adaptations (*Baseline, Diversified, Intensified* and *Simplified*) and soil type. Green bars represent emissions intensities estimated as the annual per hectare direct emissions in kg CO_2-e per kilogram of crop yield. Blue points depict net farm carbon dioxide equivalents (t CO_2-e) computed as the sum of direct emissions from soil nitrous oxide (S-N_2O) and net change in soil organic carbon (ΔSOC) stocks in 0–100 cm layers.

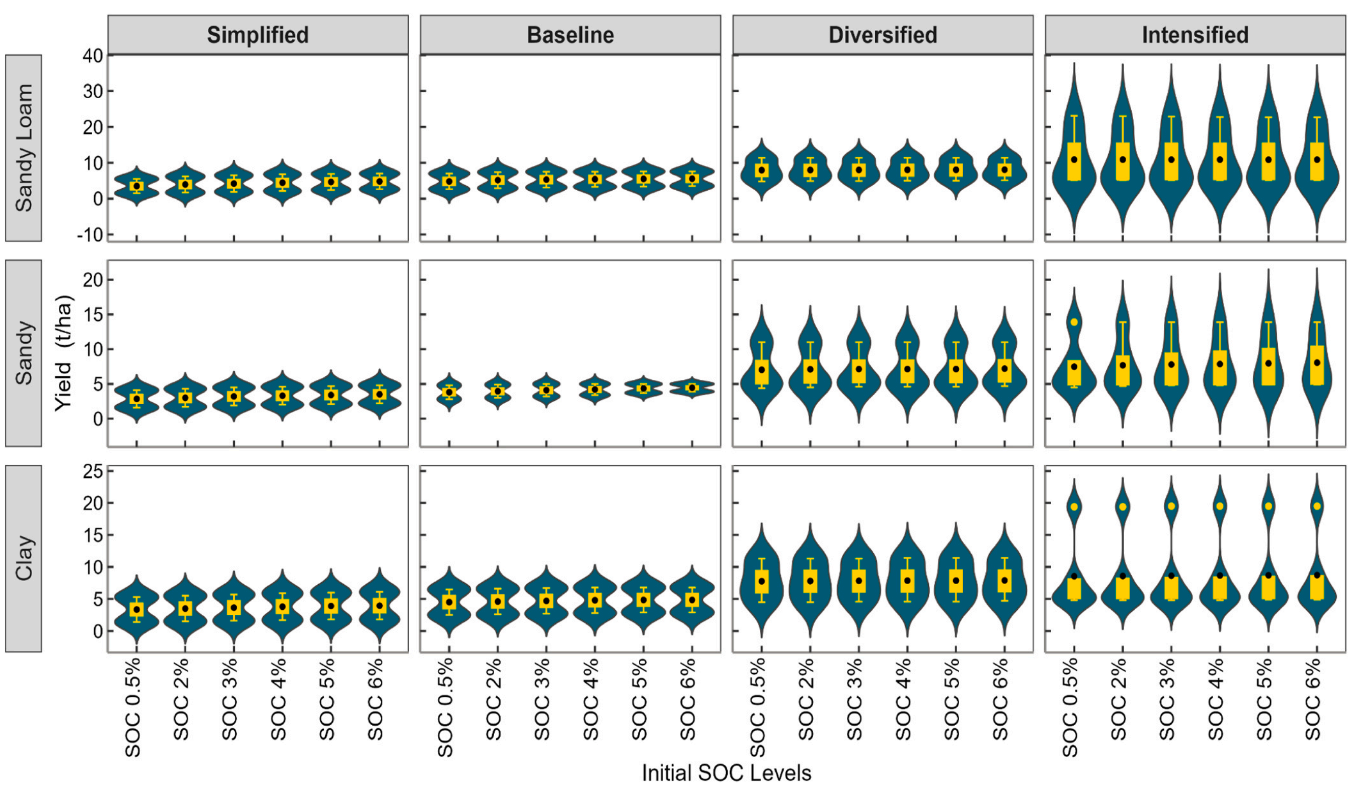

Fig. 8. Effect of antecedent soil organic carbon (SOC) stocks, whole farm adaptation and soil type on yield. Green violin plots represent distributions of crop yield. Yellow boxplots represent mean long-term crop yield. Black circles represent means of crop yield (averaged across adaptation and soil type).

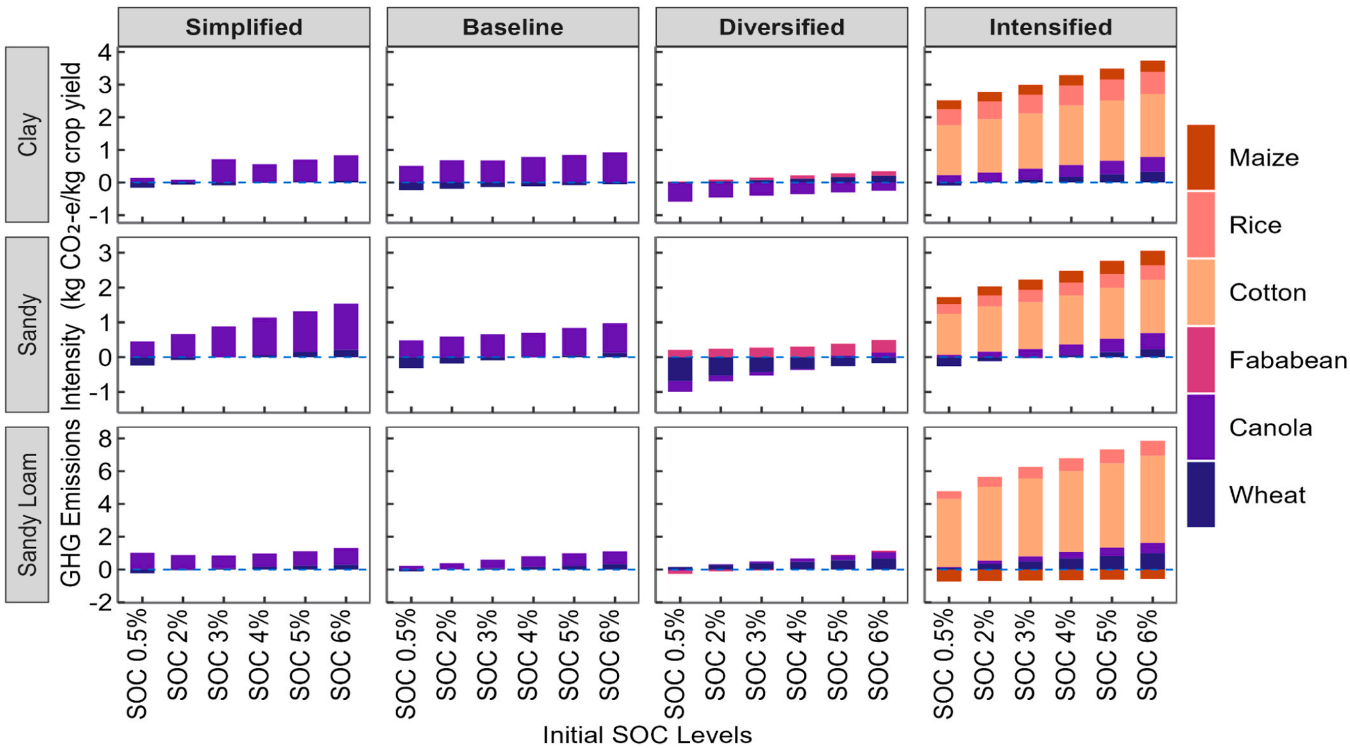

Fig. 9. Average emissions intensities disaggregated by crop type for various antecedent soil organic carbon (SOC) content and adaptations. Stacked columns represent cumulative carbon footprint in kg CO_2e per kilogram of yield.

5. Concluding remarks

This study has underscored existential challenges landholders face in balancing priorities for agri-food production aginst those of environmental stewardship and GHG emissions abatement, with *Intensification* enabling higher productivity and SOC accrual but also evoking greater global warming potential (5.8 t CO_2-e). Conversely, *Diversification* (via adding grain legumes to crop rotations) was more conducive to SOC accrual and GHG emissions mitigation, albeit with lower yields compared with *Intensification*. As well, *Intensification* (via additional irrigation and nitrogen fertiliser) was more likely to catalyse N_2O emissions, counterbalancing carbon removals associated with greater SOC stocks. Collectively, these results call for more holistic assessments of GHG emissions (e.g., N_2O, CH_4, CO_2) to account for pollution swapping associated with intervention. We showed that clay-rich soils have higher asymptotic carbon thresholds (>5 %) and accrue more SOC, while sandy soils have lower SOC ceilings (2 %), truncating SOC plateaus to lower thresholds, as shown in Fig. 4. We found that antecedent SOC exerted the greatest control over long-term SOC accrual relative to practice change, soil type, crop type and climate. We conclude that (1) contextualised identification and benchmarking of soil C-equilibrium thresholds may elicit more probable improvement in carbon removals and agri-food production, (2) improvement in SOC stocks had little impact on productivity compared with addition of N fertiliser, noting that the latter concurrently increased N_2O emissions, and (3) identification of antecedent SOC relative to SOC ceilings would help guide practitioners as to whether changing practices to improve SOC stocks would likely be a fruitful or futile endeavour.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecadv.2023.100001.

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