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Extreme weather dominates farm management effects on long-term trends in soil carbon

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ABSTRACT

Classical reductionist experimentation tends to conceptually compartmentalise mitigation and adaptation into binary categories, shielding insight into how greenhouse gas (GHG) emissions and climate change interact. Here, our primary aim was to examine how a key tenant of the global climate crisis – drought – is likely to influence soil organic carbon (SOC). We deconstruct these paradigms using case study farms in Tasmania, Australia, using state of the art models to simulate pasture production and SOC under historical and 2050 climates, the latter encapsulating more frequent extreme weather events. We show that longitudinal changes in SOC stocks correlate positively with standard precipitation evapotranspiration index (SPEI) via the mediating effects of seasonal pasture growth. Drought elicited notable SOC losses, particularly when antecedent SOC stocks were high, whereas high rainfall years amplified SOC sequestration. Renovating pastures with perennial legumes enhanced sequestration under 2050 climates, as did introducing irrigation and increasing soil fertility. In most cases however, the influence of aridity on SOC dominated over that of farm management, suggesting that climate change - and by extension, seasonal rainfall distribution - are likely to engender greater influence on SOC stocks compared with farm management or practice change. As such, aspirations to maintain SOC stocks at ceiling levels over the long-term are likely to be challenged by the changing climate and particularly drought. Even so, we contend that adoption of practices aimed at improving soil organic matter can benefit productivity through enhancement of soil fertility, water-holding capacity and health, and as such should be encouraged, particularly where *status quo* agro-ecosystems are degraded.

1. Introduction

Extreme weather and water-related hazards realised between 1970 and 2019 elicited US$3.64 T in damages, with drought and extreme temperature accounting for 650,000 and 55,736 deaths, respectively (WHO, 2021). While drought impacts all facets of society, the agricultural sector is perhaps the most vulnerable given the intimate dependency of agri-food system productivity on climatic drivers (Hughes & Gooday, 2021). The Australian agricultural sector has long been impacted by drought, both from climate variability and change (Liu et al., 2021). Average annual farm business income in Australia decreased by 23% in 2001–2020 compared with 1950–2000 (Hughes et al., 2019), primarily due to drought-induced yield penalties associated with winter crops. While livestock systems are generally more resilient than cropping systems to adverse weather (Shahpari et al., 2021), they are not immune. Indeed, many livestock systems derive the majority of forage from pastures and/or rangelands, and thus are susceptible to the vicissitudes of the weather and climate change (Harrison, 2021; Langworthy et al., 2018).

The vulnerability of agricultural production systems is expected to be amplified if or when global temperature change exceeds 1.5 °C above pre-industrial levels (IPCC, 2019). Changes in the extent and seasonal distribution of precipitation and temperature may influence livestock directly (e.g., intake, growth, weight, metabolism and reproduction) (Chang-Fung-Martel et al., 2021) and indirectly, for example through reduced access to pastures and grain crops, deterioration of

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Table 1
Rainfall indices under historical (1980-2018) and 2050 (2036-2074) climate in the Midlands and northwest, Tasmania, Australia.

Index	Unit	Midlands		North-west	
		Historical	2050	Historical	2050 (
Average total rain	mm/ year	496	473	802	716
Avg. number of dry days	days/ year	282	288	242	250
Avg. number of wet days	days/ year	83	77	123	115
Avg. max contiguous duration of dry days	days/ year	24	25	22	23
Avg. max contiguous duration of wet days	days/ year	5.2	4.7	9	8
Avg. max wet day event	mm/ day	36	36	46	42
Average wet day rain	mm/ day	5.7	5.8	6.3	6.0
St. dev. of rain day	mm/ day	1	1	1.1	1.1
10th percentile of rain day	mm/ day	1	1	1.3	1.3
50th percentile of rain day	mm/ day	3	4	4.0	3.9
90th percentile of rain day	mm/ day	13	13	13.8	12.9
95th percentile of rain day	mm/ day	18	18	18.4	17.3
99th percentile of rain day	mm/ day	31	31	33.6	32.6

forage/protein quality, land degradation, impaired soil health, and constrained ecosystem functioning (Eldridge & Beecham, 2018). Such biophysical and environmental projections often do not account for increased frequencies of extreme events – such as heat waves, extreme rainfall and flooding, droughts, and compound extremes (Harrison et al., 2021). This is due to the implicit difficulty of deriving long-range projections with reasonable confidence, even though nascent work demonstrates that projected productivity under future climates is likely to be lower when extreme events are better accounted for (Harrison et al., 2016).

While numerous adaptations to the climate emergency have been explored hitherto (e.g., management, genetic and economic), most have been applied with a cropping lens (Ibrahim et al., 2018; Phelan et al., 2018). Adaptations purported for livestock systems include changes in the proportions of cropping and livestock enterprise within a farm business (Bowen & Chudleigh, 2021), herd size and management (Young et al., 2020), stocking rates, genetic adaptation, and forage diversification (Chapman et al., 2008). Of these studies, many have focussed on productivity; few have assessed economic implications associated with climate change impacts on livestock systems (Ho et al., 2014). We argue that the economic impacts of climate change are equally as important as changes in productivity, wherein the latter contributes to food security, while the former drives farm prosperity, national gross domestic product, and international competitive advantage.

While it is widely acknowledged that increasing anthropogenic greenhouse gas (GHG) emissions have and will continue to elicit dangerous climate change, most studies tend to conceptually compartmentalise mitigation and adaptation, even when the changing climate may be implicit to data used to examine GHG emissions (viz. Meier et al., 2020). In this way, studies that focus on adaptation for example may ignore effects of global warming on soil organic carbon (SOC), which may exhibit lower sequestration and greater losses of stocks, depending on soil temperature, respiration and plant growth (Singhal et al., 2023). As such, it is plausible that the changing climate may elicit greater landscape scale GHG efflux due to constrained carbon removals, which would further contribute to the changing climate. Put another way, climate change creates climate change due to the positive feedback loop between GHG emissions, global temperature change, and the global water cycle (Harrison et al., 2021).

Here, our aim was to assess the impact of seasonal climatic conditions on soil organic carbon and pasture growth with specific attention to rainfall under historical and future climates. We then explore and contrast a range of livestock, pasture and carbon farming interventions to determine implications for SOC stocks under future climates.

2. Methods

2.1. Study overview

We developed an approach for simulating future climate encapsulating more extreme weather events following Harrison et al. (2017) and Harrison et al. (2016). We then analysed climate data for the future climate period centred on 2050 using standard and bespoke climatic statistics, including the standardised precipitation evapotranspiration index (SPEI). Changes in extreme weather events under future climates were compared with a historical period of 1980–2018. We simulated biophysical indicators for case study livestock farms in two diverse regions of Tasmania, Australia: a sheep production system (hereafter, ‘sheep farm’) in a medium rainfall zone in central Tasmania, and a beef production system (hereafter, ‘beef farm’) in the high rainfall zone in the north-west of the state. Simulated pasture growth and soil organic carbon stocks were examined for each farm and climate horizon through an aridity lens, using SPEI to bin climatic years. We employed a transdisciplinary participatory approach to co-design adaptations to the changing climate. Environmental, economic and social adaptations for each case study farm were co-designed with industry practitioners (hereafter, the Regional Reference Group or RRG). Climate change impacts and whole farm systems adaptations were identified and refined over a series of workshops with the RRG based on feedback relating to supplementary feed, pasture growth, management practices and economic metrics. Individual adaptations were modelled as well as stacked together in a mutually synergistic way to develop contextualised bundled adaptation options, called low hanging fruit and towards carbon neutral scenarios. Further details of this process are given in Tables 1, S1 and S2 in Bilotto et al. (2023a).

Table 2
Drought indices categorised using historical (1980-2018) and 2050 (2036-2074) soil moisture for high rainfall (beef farm, **Midlands**) and medium rainfall (sheep farm, **Midlands**) zones of Tasmania.

Drought index	Midlands		North-west	
	Historical	2050	Historical	2050
Moderate dry	−1.327<=SPEI<-0.837	−1.38 <=SPEI< −0.91	−1.278<=SPEI<-1.00	−1.34<=SPI<-0.84
Mild dry	−0.837 <=SPEI <=-0.034	−0.92 <=SPEI <= −0.17	−0.892<=SPEI<=-0.003	−0.841<=SPEI <=-0.04
Mild wet	0.072 <=SPEI< 0.682	0.52 <=SPEI< 0.99	0.360<=SPEI<0.983	0.062<=SPEI<0.967
Moderate wet	0.683 <=SPEI <1.285	−1.38 <=SPEI< −0.91	1.433<=SPEI<1.498	0.967<=SPEI<1.301
Extreme wet	1.51 <=SPEI <2.001	1.5 <=SPEI< 2.10	1.584<=SPEI<2.00	1.51<=SPEI<2.001
Overall	1.51<=SPEI<2.001	−1.28 <=SPEI< 2.10	−1.278<=SPEI< 2.00	−1.34<=SPI<2.05

Table 3
Temperature indices under historical and 2050 climate in the Midlands and northwest Tasmania.

Index	Unit	Midlands		North-west	
		Historical	2050	Historical	2050
Avg. daily min. temperature	°C	5.8	6.4	8.7	9.5
Avg. daily max. temperature	°C	17.7	19.5	17.0	18.6
Avg. daily temperature range	°C	11.9	13.1	8.3	9.1
Avg. no. days max T > 90phistmax	Days/ year	32.9	66.0	32.2	81.4
Avg. no. consecutive days max T > 90phistmax	Days/ year	3.3	3.9	3.4	4.7
Avg. max no. consecutive days max T > 90phistmax	Days/ year	6.0	9.6	6.1	13.2
Avg. no. days min T < 10phistmin	Days/ year	33.0	37.3	28.8	28.8
Avg. min no. consecutive days min T < 10phistmin	Days/ year	2.9	2.9	2.7	2.7
Avg. max no. consecutive days min T < 10phistmin	Days/ year	4.9	5.3	4.0	4.0
St. dev. of daily max T (°C)	°C	5.47	6.08	3.66	4.25
St. dev. of daily min T (°C)	°C	4.69	5.12	3.82	4.24
10th percentile of max daily T	°C	11.0	12.0	12.5	13.3
50th percentile of max daily T	°C	17.0	18.5	16.5	18.0
99th percentile of max daily T	°C	31.5	35.1	26.0	29.1
10th percentile of min daily T	°C	−0.5	−0.6	3.5	4.0
50th percentile of min daily T	°C	6.0	6.5	8.5	9.5
99th percentile of min daily T	°C	16.0	17.6	17.5	19.5

Abbreviations: 90phistmax = 90th percentile of historical maximum daily temperature; 10phistmin = 10th percentile of historical daily minimum temperature.

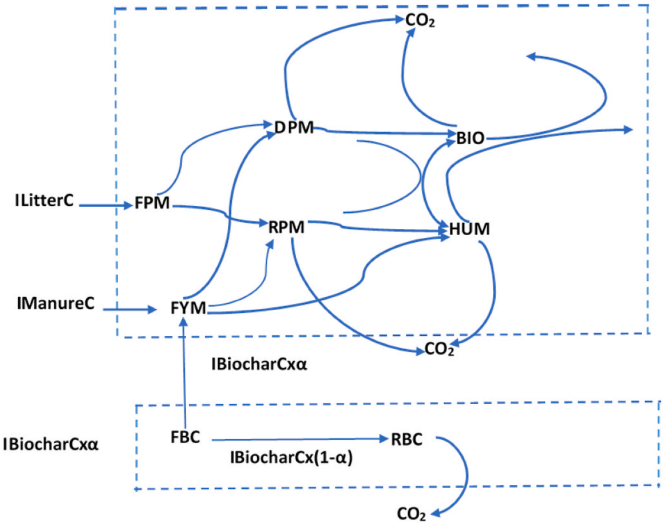


Fig. 1. Schematic for modelling soil organic carbon changes from manure C enrichment with biochar. The biochar sub-model was adapted from Lefebvre et al. (2020) and Bilotto, Christie-Whitehead, Malcolm, Barnes, et al. (2023) for the decomposition of fresh biochar combined with fresh manure and litter.

Table 4
Incremental and bundled adaptation of the case study sheep production system co-designed with a regional reference group (RRG) of expert practitioners, following Bilotto et al. (2023a; 2023b).

Treatments	Details
Baseline	•Sheep farm baseline 3170 ha: (1) prime wool: 2777 ha, (2) lamb flocks: 393 ha; further details provided in the methods.
Low hanging fruit scenario	•Baseline plus the following: •Adopting pasture species with increased root depth maximum by 10% (Langworthy et al., 2018; Cullen et al., 2014) •Shifting lambing date two weeks earlier (mating two weeks earlier) selling wool flock lambs and prime lambs in February and replacement surplus 10 days later than historically and increased stocking rate (per ha from 2.8 ewes and 2.7 wethers to 3.3 and 3.2, respectively) to better match seasonal pasture supply. •Increasing soil fertility with single superphosphate by 3% (Harrison et al., 2014; Rawnsley et al., 2019); all paddocks except the native pastures for the sheep farm. •Increasing feed conversion efficiency by 15% following Alcock, Harrison, Rawnsley, & Eckard (2015). •Introduce Talish clover (*Trifolium tumens*) in the pasture mix of the sheep farm (Hayes et al., 2019).
Toward carbon neutral scenario	•Low hanging fruit with selling replacement surplus 14 days later •Adopting lucerne pasture to available paddocks as deep-rooted species, mixed with rainfed Phalaris and subclover pastured paddocks •Injecting animals with an enteric CH_4 inhibitor vaccine to reduce CH_4 by 30% following Reisinger et al. (2021) •Thickening of 200 ha of existing nature pasture (non-grazed) land for sheep farm with environmental plantings (trees, shrubs and understory species endemic to the region)
Increase rooting depth of pasture	•Increase in rooting depth for all introduced pasture species by 10%.
Increase soil fertility	•Increasing soil fertility with single superphosphate by 3% (Harrison et al., 2014); all paddocks except the native pastures for the sheep farm.
Introduce talish clover	•Introduction of Talish clover (*Trifolium tumens*) in the rain-fed pasture paddocks of the sheep farm (Hayes et al., 2019).
Increase feed conversion efficiency	•Increase feed conversion efficiency of sheep by 15% following Alcock and Hegarty (2011).
Shifting lambing date (LD)	•Shifting lambing date two weeks earlier (mating two weeks earlier) selling wool flock lambs and prime lambs in February and replacement surplus 10 days later than historically.
Increase stocking rate (SR)	•Increasing stocking rate per ha by 0.5 for ewes and wethers and 1.5 for prime lambs.
Shifting LD and increase SR	•Shifting lambing date (LD) and increase stocking rate (SR) were combined together (see details on shifting lambing date and increasing stocking rate in Table 4 above).
Introduce lucerne pasture	•Introduction of lucerne pasture into Phalaris/subclover/Talish pastures in about 1455 ha.
Increase TFCE	•Increasing transformational feed conversion efficiency (TFCE) of sheep by 30% (doubling of factors following Alcock and Hegarty (2011)).
Feeding biochar to weaned stock	•Feeding biochar to weaned stock is assumed to have no impact on livestock production but is expected to contribute to enhance SOC accumulation through the alteration of manure composition.

2.2. Baseline farming systems

Status quo operations of two case study farms were represented as 'baseline' farming systems; a beef farm in north-western Tasmania (mean rainfall 932 mm/year; mean annual maximum and minimum temperature are 16.1 °C and 9.4 °C, respectively), and a sheep farm in the Tasmanian Midlands (mean rainfall 560 mm/year; mean annual maximum and minimum temperature of 17.8 °C and 4.7 °C, respectively). The 569 ha beef farm located near the township of Stanley ran a self-replacing cow and calf enterprise. This comprised 367 mature cows calving in late winter (95% weaning rate, first calving at two years of age) from which 74 replacement heifers were sourced. Each year, a further 115 weaners were purchased at 6 months of age at 200 kg

Table 5
Incremental and bundled adaptation of the case study beef production system co-designed with a regional reference group (RRG) of expert practitioners, following Bilotto et al. (2023a; 2023b).

Details	
Baseline	•Farm size 569 ha: (1) breeder, weaned steers and heifers (402 ha) (2) Purchased weaners (127 ha) and (3) Agisted yearlings (40 ha)
Low hanging fruit scenario	•Baseline •Adopting pasture species with increased root depth maximum by 10% (Langworthy et al., 2018; Cullen et al., 2014) •Increasing soil fertility with single superphosphate by 3% (Harrison et al., 2014) •Shifting calving date by two weeks earlier and selling replacement surplus a week later, and selling at heavier target liveweight by 20 kg for steers and heifers •Increasing feed conversion efficiency by 15% following Alcock and Hegarty (2011). •Increasing stocking rates by 10%
Toward carbon neutral scenario	•Low hanging fruit •Adopting lucerne pasture to available paddocks as deep-rooted species, mixed with Perennial Ryegrass in all paddocks. •Injecting animals with an enteric CH_4 inhibitor vaccine to reduce CH_4 by 30%, following Reisinger et al. (2021). •Purchase 50 ha of land for the beef farm to establish a tree plantation of Tasmanian Blue Gums for increasing carbon.
Increase rooting depth of pasture	•Increasing rooting depth of all the introduced pasture species by 10%
Increase soil fertility	•Increasing soil fertility with single super phosphate and nitrogen by 3% (Harrison et al., 2014)
Increase feed conversion efficiency	•Increasing feed conversion efficiency of cattle by 15% following Alcock and Hegarty (2011)
Changing calving and selling dates	•Changing calving date by two weeks earlier and selling replacement surplus a week later and selling at heavier target liveweight by 20 kg for steers and heifers.
Increase stocking rate	•Increasing stocking rate by 10%
Introduce lucerne pasture	•Introduction of lucerne pasture into perennial ryegrass pastures (569 ha)
Increase TFCE	•Increasing transformational feed conversion efficiency (TFCE) of cattle by 30% (doubling of factors following Alcock and Hegarty (2011)).
Feeding biochar to young stock	•Feeding biochar to young stock is expected to contribute to an increase in the liveweight of young stock by approximately 10% and enhance SOC accumulation through the alteration of manure composition.

liveweight (LW), and 155 steers at 16 months of age at 375 kg LW each year. Mature cows were retained for five lactations before being cast for age. Farm-derived non-replacement heifers and steers were sold at 25 months at 550 and 600 kg, respectively, with purchased weaners sold at 25 months at 600 kg; purchased steers were sold at 28 months at 545 kg LW. Botanical composition primarily consisted of perennial ryegrass (*Lolium perenne* L.), cocksfoot (*Dactylis glomerata* L.), white clover (*Trifolium repens* L.), subclover (*Trifolium subterraneum* L.) and lucerne (*Medicago sativa*). The soil was a free-draining ferrosol (Uc2.3; Northcote 1979). Around 5% of the farm area (20 ha lucerne/ryegrass and 8 ha ryegrass/cocksfoot/white clover pastures) was irrigated between 21 Nov and 31 Mar each year (with 20 mm applied on a 14-day interval). Production feeding rules were implemented to either maintain LW (cows) or achieve target LWs (all other stock) using hay (dry matter digestibility (DMD) of 77% and crude protein (CP) of 20%). All stock grazed rainfed pastures, with farm-derived steers allowed to graze irrigated pastures year-round. Further details are provided in Bilotto et al. (2023a; 2023b).

The Midlands farm located near Campbell Town supported a self-replacing Merino superfine wool and prime lamb enterprise. Around 3170 ha of arable farm area were used for grazing, comprising 49% native grasslands, 48% rainfed developed pastures and 3% centre pivot irrigation (introduced grasses and legumes). Soil types included around 50% red-brown, strongly structured, gradational, clay-loam/clay soil ferrosols, around 40% black cracking clays with structured, swelling clay overlying a mottled grey clay, and 10% grey sandy loams overlaying red clay. Developed rainfed pastures were either pure stands of phalaris (*Phalaris aquatica* L.), or a mixture of phalaris and subclover. Irrigated land was also for dual-purpose wheat (*Triticum aestivum.* L*)* crops that were grazed for four months, and lucerne used for grazing and hay production. Lucerne and wheat paddocks were irrigated from early spring to the following autumn to fill the soil profile to 95% of field capacity whenever soil water deficit reached 50%. The farm ran 24,750 sheep in a self-replacing Merino flock (SMF) and a prime lamb flock (PLF). The SMF consisted of 5300 mature superfine Merino ewes, 7500 wethers and 5500 replacement ewes and wethers; SMF ewes first lambed at two years of age and were retained for three lambings before entering the PLF for two more annual births, then cast for age at seven years of age. Wethers were retained for five years then cast for age. All non-replacement SME ewe and wether lambs were sold post-weaning. The PLF contained 3450 Merino ewes mated annually with White Suffolk rams; 2950-lamb progeny were sold in at 27 kg LW. All sheep (except prime lambs) were shorn with clean fleece weights (CFW) of 3.3–4.1 kg with fibre diameters of 17.4–18.1 μm. Further details can be found in Bilotto et al. (2023a; 2023b).

2.3. Historical and future climates

Historical climate data from 1 January 1982 to 31 December 2018 (http://www.longpaddock.qld.au/silo) were used to generate future climate data following Harrison et al. (2016) and Bilotto et al. (2023a). Future climate data were downscaled from global circulation models (GCMs) (Harris et al., 2019) and altered using a stochastic approach to account for extreme weather events (Harrison et al., 2016). This approach generated future climate data that (1) included mean changes in future climates projected for a region by an ensemble of global climate models (GCMs), (2) preserved historical climate characteristics for a given site, which are often obviated by raw GCM data *per se* (Figs. S1 and S2) and (3), notwithstanding point (1), generated climatic projections with increased variability. Future climate projections were developed using monthly regional climate scaling factors based on Representative Concentration Pathway (RCP) 8.5 centred on 2050 (2042-2061) using raw data from GCMs provided in Harris et al. (2019). Atmospheric CO_2 concentrations were set at 350 ppm and 530 ppm for the historical and 2050 climate scenarios, respectively, following RCP8.5 projections from the Climate Change in Australia website (https://www.climatechangeinaustralia.gov.au/en/; CCIA 2020). The average number of wet days and the maximum contiguous duration of wet days per annum is shown in Table 1: for both sites, the average number of wet days decreased, the average contiguous duration of dry days (*viz.* drought) increased, and the intensity of extreme rainfall events (>95th percentile for each month) increased.

2.4. Drought indices

Drought indices can be computed based on moisture stress and wetness (Yimer et al., 2022). Two common tools for drought assessment include the Palmer drought severity index or PSDI (Palmer, 1965), and the McKee Standardised Precipitation Index (SPI) (McKee et al., 1993; Yimer et al., 2022). PDSI cannot be used to distinguish between multi-scale (i.e., monthly, quarterly, half-year, annual and biannual, etc.) drought types (Vicente-Serrano et al., 2010), while SPI does not account for temperature, wind speed, evapotranspiration and soil water-holding capacity (Palmer, 1965). With climate change, it is plausible that drought severity and duration could change under rising temperatures and higher evaporative demand, which may invalidate the use of SPI (Phelan et al., 2015). To address these limitations, Vicente-Serrano (2010) developed a multi-scalar drought index, the Standard Precipitation Evaporation Index (SPEI), which accounts for precipitation,

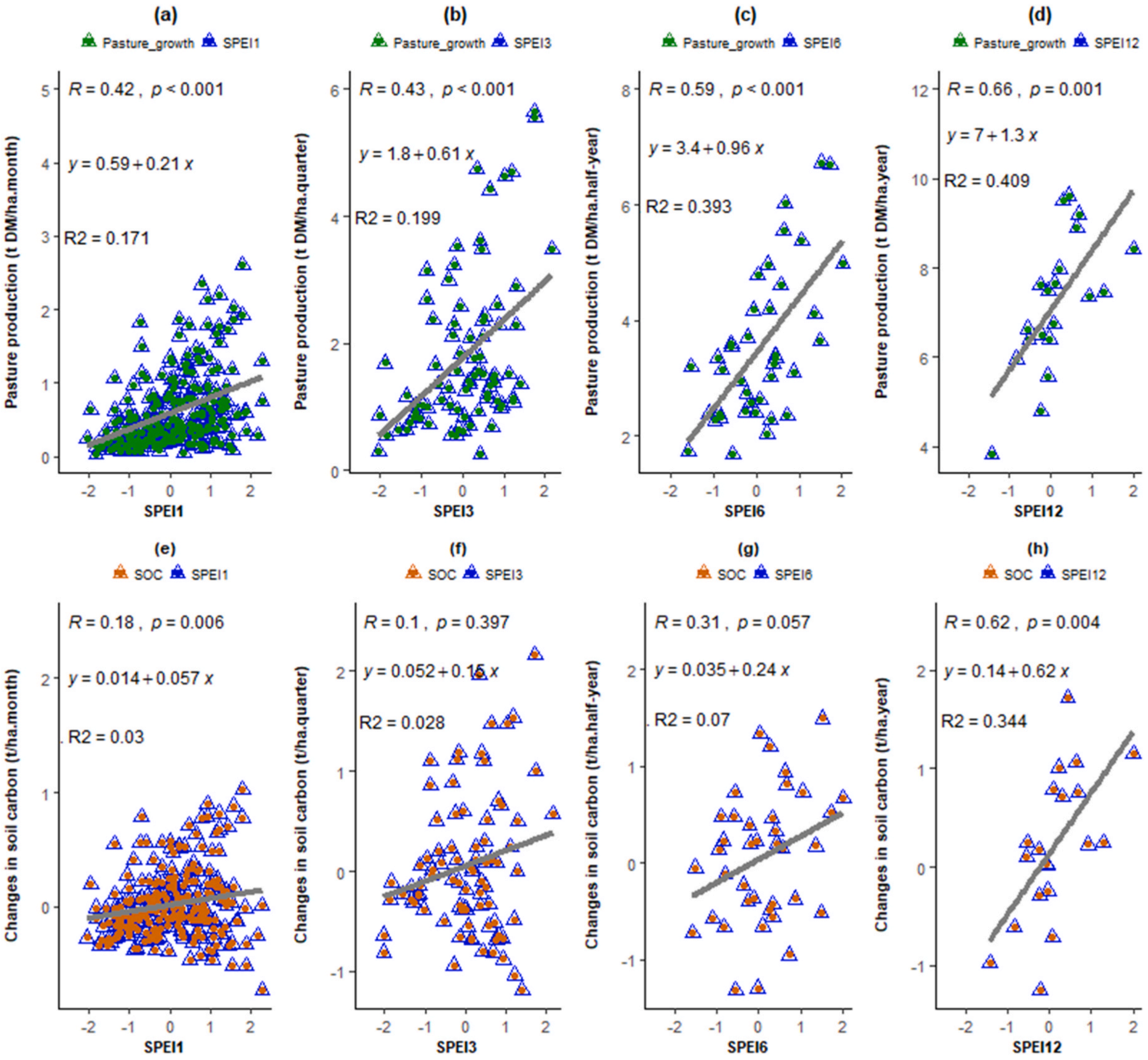


Fig. 2. Relationships between standardised precipitation evapotranspiration index (SPEI), pasture production and soil organic carbon (SOC) stocks under historical climate (1986-2006) for the sheep farm. SPEI1, SPEI3, SPEI6 and SPEI12 respectively indicate monthly, quarterly, biannual and annual SPEI.

potential evapotranspiration and temperature influence on deficit water balance across time scales. We used R version 4.0.3 (Team, 2018) to examine the association between (i) pasture growth and SPEI, (ii) pasture growth and SOC, and (iii) SOC and SPEI. The Shapiro-Wilk test was employed to evaluate normality (Shapiro & Wilk, 1965): if both SOC and pasture growth were normally distributed, we computed Pearson correlation (Schober et al., 2018); for all other cases, we computed Spearman's rank correlation (Mukaka, 2012). SPEI were respectively classified into five and four bins for the beef and sheep farms, respectively, using the distributions of pasture production and SOC accrual or loss. This classification allowed insight into impact of drought and superfluous moisture on pasture growth and SOC accrual/loss (Table 2).

2.5. *Temperature indices*

By 2050, daily average minimum and maximum temperatures in the beef farm in Midlands and sheep farm in the north-west increased by 0.6 °C and 1.8 °C, respectively, compared with the historical climate (1980-2018; Table 3), while average consecutive days with maximum temperature over the 90th percentile increased by 18% and 38%. The 90th, 95th, and 99th percentile daily maximum temperatures increased by 10–12% under the 2050 climate.

2.6. *Pasture growth dynamics*

GrassGro has been widely used in Australia to simulate the biophysical and economic performance of farm systems (Cottle et al., 2016). The software includes computation of feed intake and ruminant nutrition models from GrazPlan, enabling simulation of herbage intake and ruminant production (Freer et al., 1997). Daily pasture and livestock production for historical and future climate horizons was simulated using the process-based dynamic vegetation and livestock model, GrassGro® [Moore et al. (1997); version 3.3.10]. GrassGro® combines climate, soils, pastures and livestock with farm management (soil fertility, paddock size and layout, pasture grazing rotations, stocking rate) and economics, enabling simulation of ruminant grazing enterprises. GrassGro® has been used to explore the effects of climate, pasture, soils and management on livestock productivity and profitability (Harrison et al., 2014) and climate change assessments for pasture-based industries across Australia, North America and Northern China (Sándor et al., 2020). GrassGro® computes daily values of soil moisture, pasture production and pasture quality for a range of pasture species (annual and perennial grasses and legumes), paddock and farm. The model dynamically computes sward characteristics, pasture cover, persistence and pasture availability, pasture intake, feed supplement required, liveweight change and feed carry-over effects, as well as

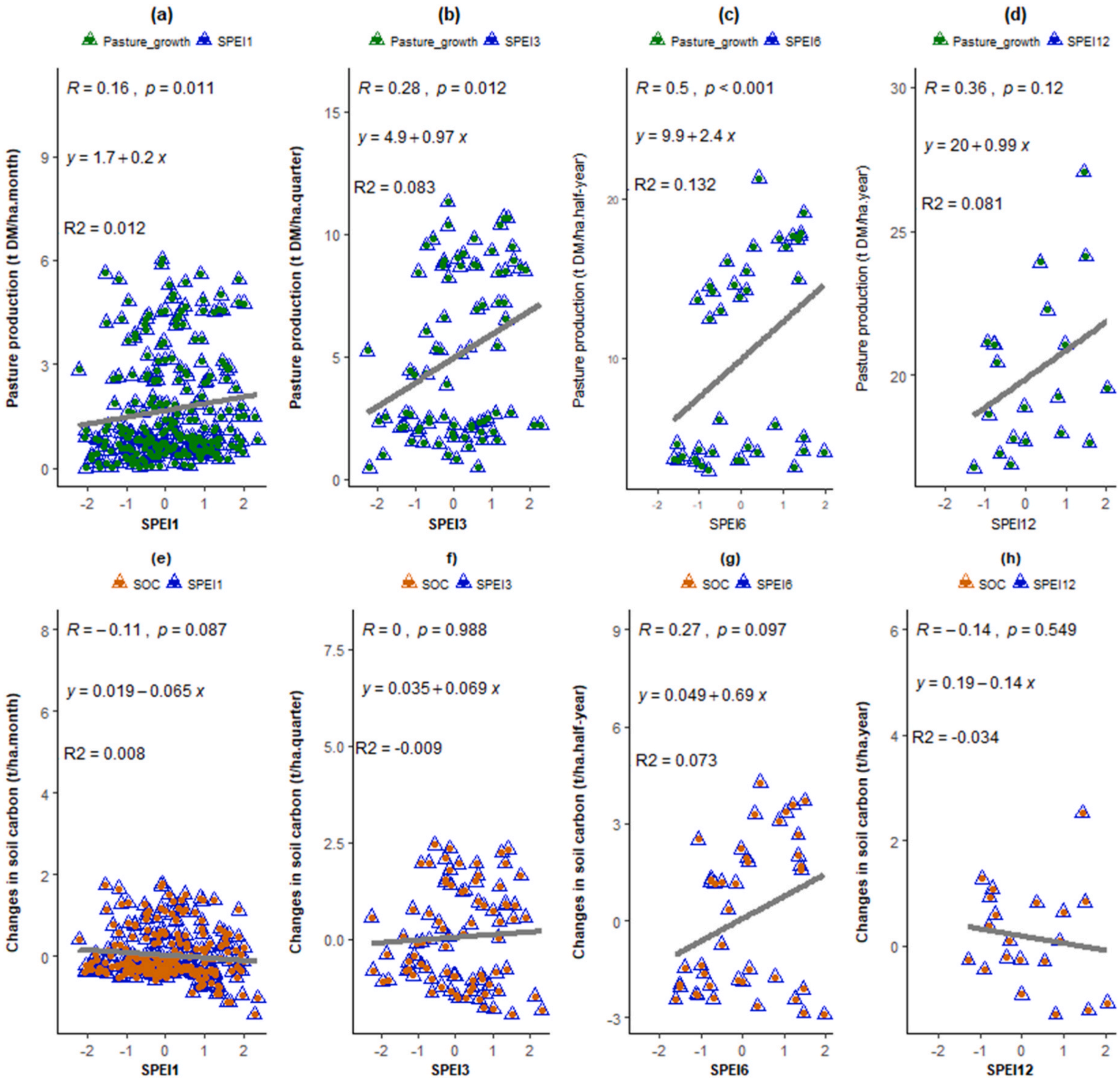


Fig. 3. Relationships between standardised precipitation evapotranspiration index (SPEI), pasture production and soil organic carbon (SOC) stocks under historical climate (1986-2006) for the beef farm. SPEI1, SPEI3, SPEI6 and SPEI12 respectively indicate monthly, quarterly, biannual and annual SPEI.

animal movement between paddocks depending on feed supply. We initialised and parameterised GrassGro® with baseline farm information for the two regions. Preliminary model outputs were iteratively refined with the RRG; outputs iteratively refined with the RRG included pasture growth rates, stocking rates, livestock and liveweight produced, wool production, supplementary feeding, costs, income, depreciation, net cash flows and wealth. Further details are provided in Bilotto et al. (2023a).

2.7. Soil organic carbon dynamics

Soil organic carbon dynamics were simulated following the comprehensive methodology outlined in Bilotto et al. (2023a). In this study, we employed the Rothamsted Carbon (RothC) model version 26.3, originally developed by Coleman and Jenkinson in 1996. We adapted RothC from a FORTRAN program to a Microsoft Excel spreadsheet, enabling use of historical weather time series data instead of relying solely on average weather conditions. This allowed us to account for irregular and seasonal rainfall patterns when computing topsoil moisture deficits, as demonstrated by Janik et al. (2002 and 2007).

In RothC, simulated soil organic carbon (SOC) turnover is driven by environmental factors including temperature, rainfall, and pan evaporation. To inform our model, we incorporated monthly average GrassGro outputs, encompassing root residues, dung and litter. These inputs were further refined by considering the allocation of net primary production among plant organs and root length density within distinct soil layers (0–30 cm and 30–100 cm). For historical SOC data, we adopted measured values from Cotching (2018). Clay contents for the 0–30 cm and 30–100 cm layers were sourced from https://maps.tern.org.au/#/.

As described by Coleman and Jenkinson (1996, pp. 237–246), RothC accounts for carbon transfers among various soil organic matter pools, including decomposable plant material (DPM), resistant plant material (RPM), fast and slow microbial biomass (BIOF and BIOS), humified organic matter (HUM), and inert organic matter (IOM). Our model inputs for IOM, RPM, and HUM fractions were aligned with historical data for dermosols and ferrosols, as reported by Cotching (2018) and Falloon et al. (1998). Following the validated approach by Hoyle et al. (2013) and Janik et al. (2002 and 2007), we initialised DPM, BIOF and BIOS parameters for Australian soils at 1%, 2%, and 0.2%, respectively; the ratios of which determine allocations of incoming carbon from plant residues. For our focus on improved pastures, we adopted a recommended DPM/RPM ratio of 1.44; this ratio signifies that 59% of plant

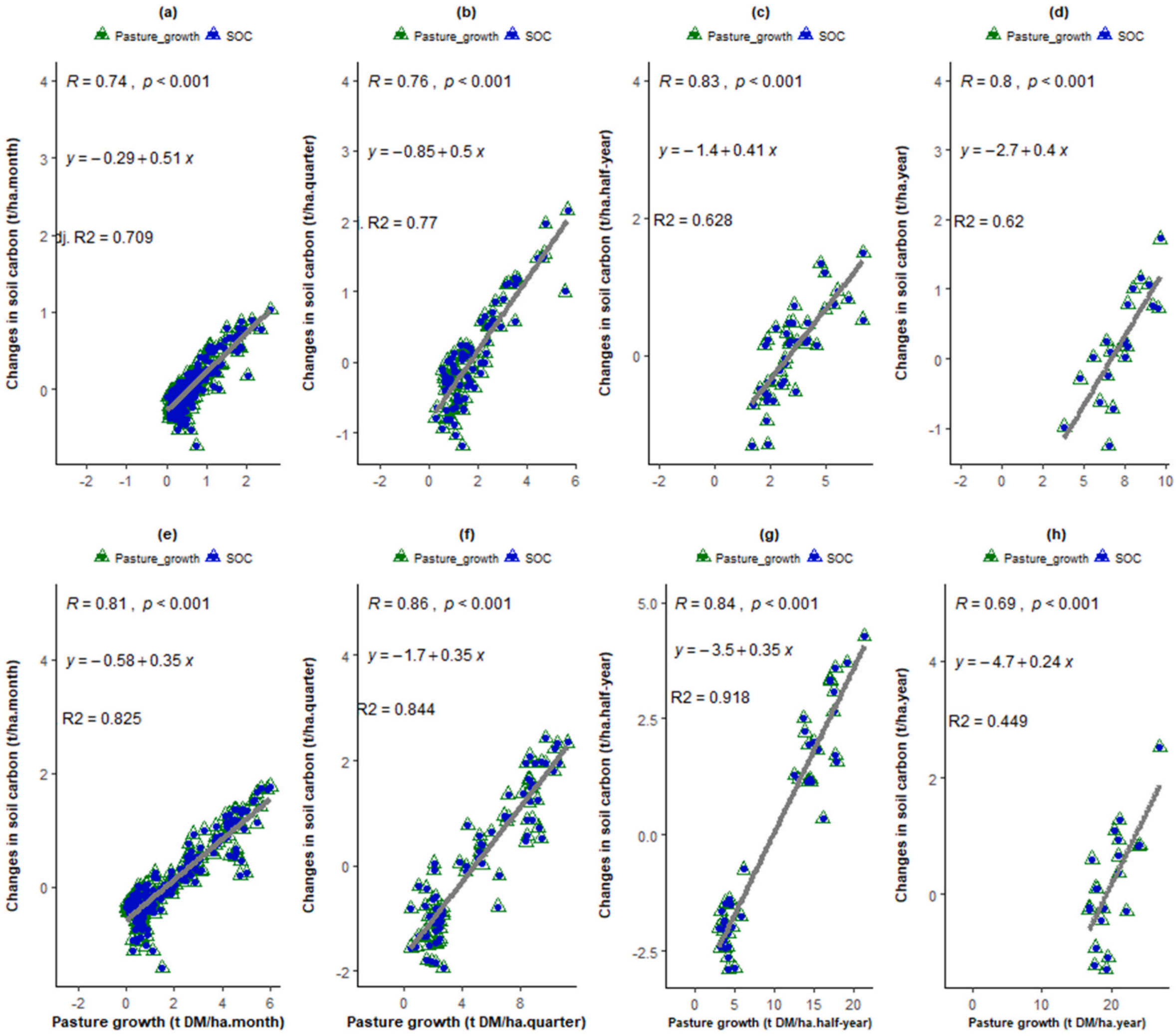


Fig. 4. Relationships between simulated seasonal pasture performance and change in soil organic carbon stocks for 0–100 cm layers under historical climate (1986-2006) for the sheep (Fig. a-d) and beef (Fig. e-h) farm.

material consists of DPM, with the remaining 41% comprising RPM. Both DPM and RPM undergo decomposition processes, resulting in the release of CO_2, which is subsequently lost from the system, along with BIO and HUM. The distribution of carbon between BIO + HUM and CO_2 is influenced by the clay content of the soil. Subsequently, the carbon allocated to the combined BIO + HUM fraction is partitioned as 46% BIO and 54% HUM. The ongoing decomposition of BIO and HUM generates additional BIO, HUM and CO_2. Allocations of FYM (manure) were 49% to DPM, 49% to RPM, and the remaining 2% to HUM. Decomposition constants at 30 cm were derived following the methodology outlined by Jenkinson and Coleman (2008), except for the decomposition rate of RPM, which was set to 0.17 following Richards and Evans (2004) to better align with Australian conditions. This adjustment was made considering the free-draining clay soils prevalent in the region, resulting in decomposition rate constants of 10 for DPM, 0.17 for RPM, 0.66 for BIO, and 0.02 for HUM. At depths of 30–100 cm, decomposition rates were calculated following Jenkinson and Coleman (2008), yielding values of 0.334 for DPM, 0.01 for RPM, 0.022 for BIO, and 0.001 for HUM.

2.8. Tree carbon dynamics

Long-term annual pasture residue (0–30 cm and 30–100 cm) and manure (0–30 cm) carbon inputs, estimated by GrassGro and imported into RothC, are reported in the Supplementary Information Table S3 (sheep farm) and Table S4 (beef farm). Simulation of tree carbon sequestration was modelled in FullCAM, with detail in Bilotto et al. (2023a). Briefly, FullCAM is used in Australia's National Carbon Accounting System and is driven using mean monthly temperature, rainfall and open-pan evaporation. Soil organic matter and carbon in FullCAM is simulated by RothC; all soil parameters were matched with those we used for RothC described above. FullCAM simulates C cycling between forest and soil components, including litter, surface and subsurface debris. We modelled planting of Tasmanian blue gum and 'environmental' plantings (combination of trees, understory and shrubs native to the region) for the beef and sheep farms, respectively. We modelled planting of shelter belts for the beef farm and woody thickening of pre-existing woody vegetation for the sheep farm; livestock grazing beneath trees (silvopasture) was not permissible following advice from the RRG. Further details are provided in the supplementary material.

2.9. Biochar dynamics

Following Bilotto, Christie-Whitehead, Malcolm, Barnes, et al. (2023), we used RothC with a sub-model for biochar decomposition to simulate use of biochar as a feed supplement (Fig. 1). Given the novel use of biochar as an ingredient in the ruminant diet (pasture intake + supplements), we targeted total biochar intake rates between 0.5 and 1.0% (dry matter (DM) basis) from experiments developed under Australian grazing conditions (Fernandez, 2020). Assuming almost

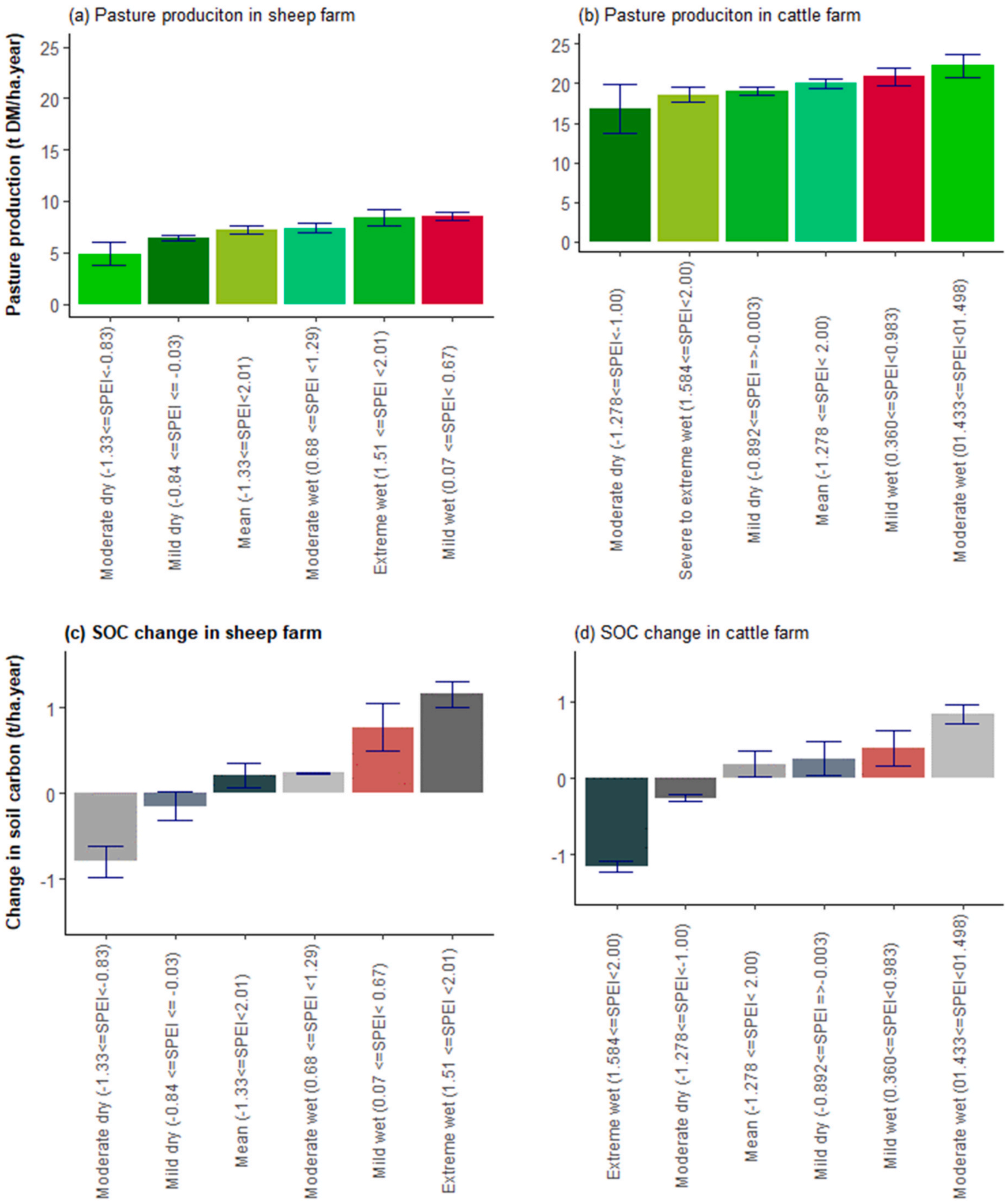


Fig. 5. Simulated pasture production and SOC accrual/loss binned according to long-term aridity using historical climate data (1986-2005) for the sheep and beef case studies.

100% of the biochar supplied is excreted as dung with an average carbon concentration of 65%, we estimated a cumulative monthly amount of C excreted from biochar (I_{BiocharC}) as:

$$I_{BiocharC}\left(kg\ C\ ha^{-1}\ month^{-1}\right)=Biochar\ intake\left(kg\ DM\ ha^{-1}\ month^{-1}\right)\times 0.65$$

Here, a proportion, α, of the C in I_{BiocharC} is treated as manure and added to FYM pool in RothC as labile biochar. The remaining fraction of I_{BiocharC} was simulated as recalcitrant material (RBC). Following Lefebvre et al. (2020), we assumed a constant rate of 3% for α added to FYM pool per month (I_{BiocharC} x 0.03). For simplicity, the remaining 97% of RBC [I_{BiocharC} x (1–0.03)] decomposes at annual decay rate (*d*CRCB, kg C yr^{-1}) of 11.89% over 100 years (mean residence time of 840 years):

$$d\mathrm{CRCB}\left(\mathrm{kg\ C\ ha^{-1}\ yr^{-1}}\right)=RCB\left(\mathrm{kg\ C\ ha^{-1}\ yr^{-1}}\right)\times\frac{0.1189}{100}$$

$$RCB_{i+1}\left(\mathrm{kg\ C\ ha^{-1}\ yr^{-1}}\right)=\left[I_{BiocharC_i}\times(1-0.03)\right]-d\mathrm{CRCB}_i+\mathrm{RCB}_i$$

Where *d*CRCB is the annual decay rate considering the accumulated recalcitrant biochar per hectare (RCB). Actual accumulated RCB (RCB_{i+1}) is thus the result of the influx of C excreted from biochar fed ($I_{biocharCi}$) considered recalcitrant and the previous (*i*) annual decay rate

Table 6

Analysis of variance (ANOVA) for the effects of adaptations and extreme weather events (e.g., SPEI12) on pasture performance for the sheep and cattle farms.

Items	Sheep farm				
	Degree of freedom	Sum square	Mean square	F value	Degree of freedom
Pasture production across adaptation options	12	18.5	1.54	0.984	0.465
Extreme weather events (e.g., SPEI12) vs Pasture production	1	233.1	233.1	148.8	<2e-16
Adaptation options vs SPEI12	12	1.6	0.13	0.086	1
Residuals	234	366.5	1.57		
Items	Cattle farm Degree of freedom	Sum square	Mean square	F value	Degree of freedom
Pasture production across adaptation options	10	62.1	6.2	1.288	0.239
Extreme weather events (e.g., SPEI12) vs Pasture production	1	397.2	397.2	82.37	<2e-16
Adaptation options vs SPEI12	10	2.4	0.2	0.05	1
Residuals	198	954.8	4.8		

($d\mathrm{CRCB}_i$) over the accumulated RCB_i.

2.10. Incremental and bundled climate change adaptations

Adaptation themes were iteratively co-designed by refining pasture growth rates, stocking rates, liveweight produced, wool production and supplementary feeding based on RRG advice. After achieving consensus for each baseline and adaption, each was modelled in GrassGro, with the first six years of data discarded to allow for model equilibration. Over several workshops, RRG thinking on tactical and strategic incremental and systems adaptation was gleaned in light of quantified climate change impacts (Bilotto et al., 2023a; 2023b). We then contextualised and bundled incremental adaptations into two distinct themes; 'Low Hanging Fruit', being simple, immediate and reversible changes; and 'Towards Carbon Neutral', this adaptation theme being aimed at temporal emissions reduction and/or carbon removals. This process (1) ensured rigor and realism of modelled results, (2) allowed the research team to learn from expert practitioners, (3) engendered end-user confidence in the analytics and credibility of the process and (4), enabled ends-user awareness of multi-disciplinary opportunities for adaptation (Tables 4 and 5). Further details of the co-design process are provided in the supplementary information of Bilotto et al. (2023a).

3. Results

3.1. Association between pasture production, SOC accrual/loss, and SPEI for the sheep farm

We found a moderate positive correlation between Standard Precipitation Evaporation Index (SPEI) and pastures growth at monthly ($r = 0.42$, $p < 0.001$, Fig. 2a), quarterly ($r = 0.43$, $p < 0.001$, Fig. 2b), biannual ($r = 0.59$, $p < 0.001$, Fig. 2c) and annual ($r = 0.66$, $p < 0.001$, Fig. 2d) time scales. These results indicate that higher SPEI, which reflects improved soil moisture, significantly positively affect pasture growth. The strength of the linear association between SPEI and pasture growth increased with the length of the SPEI aggregation, suggesting that prolonged moisture stress has a highly detrimental effect on pasture yield, while better access to moisture for an extended period promotes better pasture growth. These findings confirm an inverse association between drought and pasture growth.

Impacts on SOC were less transparent. While the relationship between SPEI and monthly ($r = 0.18$, $p < 0.006$, Fig. 2e) and quarterly ($r = 0.1$, $p < 0.397$, Fig. 2f) was weak, we found a moderately positive correlation between SPEI and biannual ($r = 0.31$, $p < 0.057$, Fig. 2g) and annual ($r = 0.62$, $p < 0.004$, Fig. 2h) SOC stocks. These results suggest that extreme weather had a limited impact on SOC perturbations in the short term, while dry and wet conditions driven by pasture production significantly influence SOC stocks over the long term.

3.2. Association between pasture production, changes in SOC stocks and SPEI for the beef farm

While the correlation between SPEI and monthly pasture growth was weak ($r = 0.16$, $p < 0.011$, Fig. 3a), the correlation between SPEI and quarterly ($r = 0.28$, $p < 0.012$, Fig. 3b), biannual ($r = 0.5$, $p < 0.001$, Fig. 3c), and annual ($r = 0.36$, $p < 0.12$, Fig. 3d) pasture growth were moderate. These findings suggest that fluctuations in soil moisture availability for three to six months moderately impact pasture growth, whereas variability in soil moisture availability for a shorter period are less discernible. Superfluous soil moisture and/or waterlogging may also adversely affect pasture production in northwest Tasmania (Liu et al., 2020), although this can be mediated by genetic potential and resilience of pasture cultivars to extreme climate indices, soil water holding capacity, and soil fertility (Liu et al., 2021, 2023).

Fig. 3 demonstrates negative correlations between SPEI and monthly ($r = -0.11$, $p < 0.087$, Fig. 3e) and annual ($r = -14$, $p < 0.549$, Fig. 3h) changes in SOC stocks, suggesting that neither short-term nor long-term extreme weather events significantly impacted on SOC stocks. In contrast, the correlation between SPEI and bi-annual changes in SOC stocks were weak ($r = 0.27$, $p < 0.097$, Fig. 3g).

3.3. Association between pasture growth and changes in soil organic carbon stocks

Fig. 4 shows a positive correlation between changes in SOC stocks and monthly ($r = 0.74$, $p < 0.001$, Fig. 4a), quarterly ($r = 0.76$, $p < 0.001$, Fig. 4b), half-yearly ($r = 0.83$, $p < 0.001$, Fig. 4c), and annual ($r = 0.8$, $p < 0.001$, Fig. 4d) pasture production in the sheep farm. Similarly, in the beef farm, monthly ($r = 0.81$, $p < 0.001$, Fig. 4e), quarterly ($r = 0.86$, $p < 0.001$, Fig. 4f), half-yearly ($r = 0.84$, $p < 0.001$, Fig. 4g) and annual ($r = 0.69$, $p < 0.001$, Fig. 4h) changes in SOC stocks were positively associated with pasture production. These results indicate that improved pasture biomass drives upward SOC accrual, regardless of aggregation period.

3.4. Binning pasture growth and SOC accumulation according to seasonal rainfall

In moderately dry years, pasture production (4.9 t DM/ha.annum) on

Fig. (a) Pasture production under moderate dry years compared with mild dry years and mean of all years

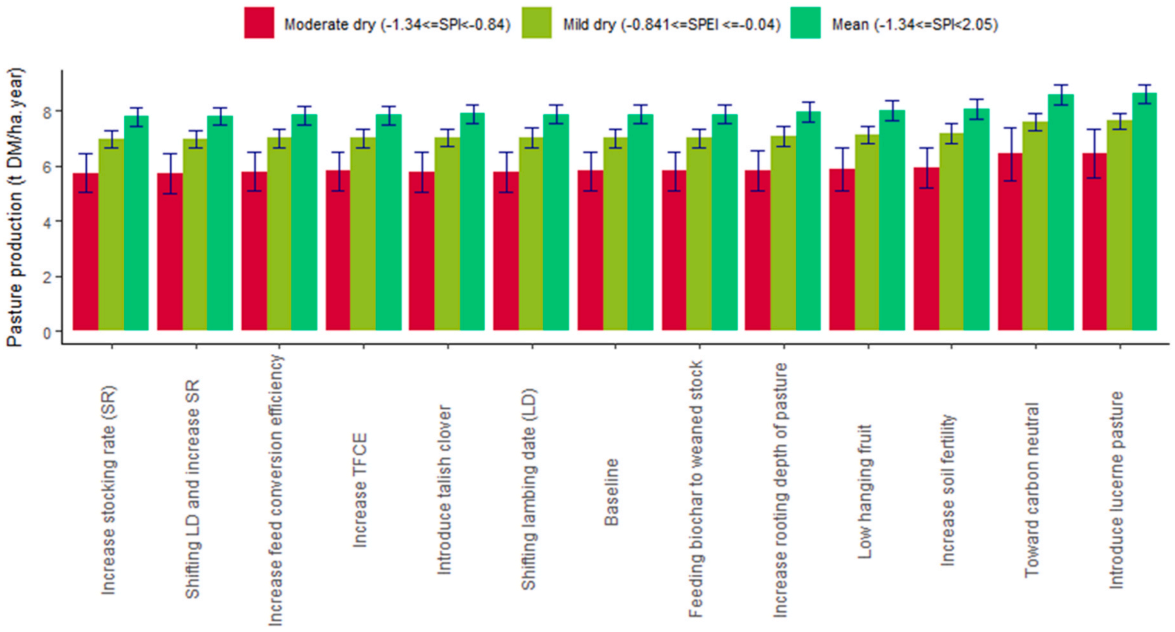


Fig. (b) Pasture production across moderate dry years compared with various wet conditions years

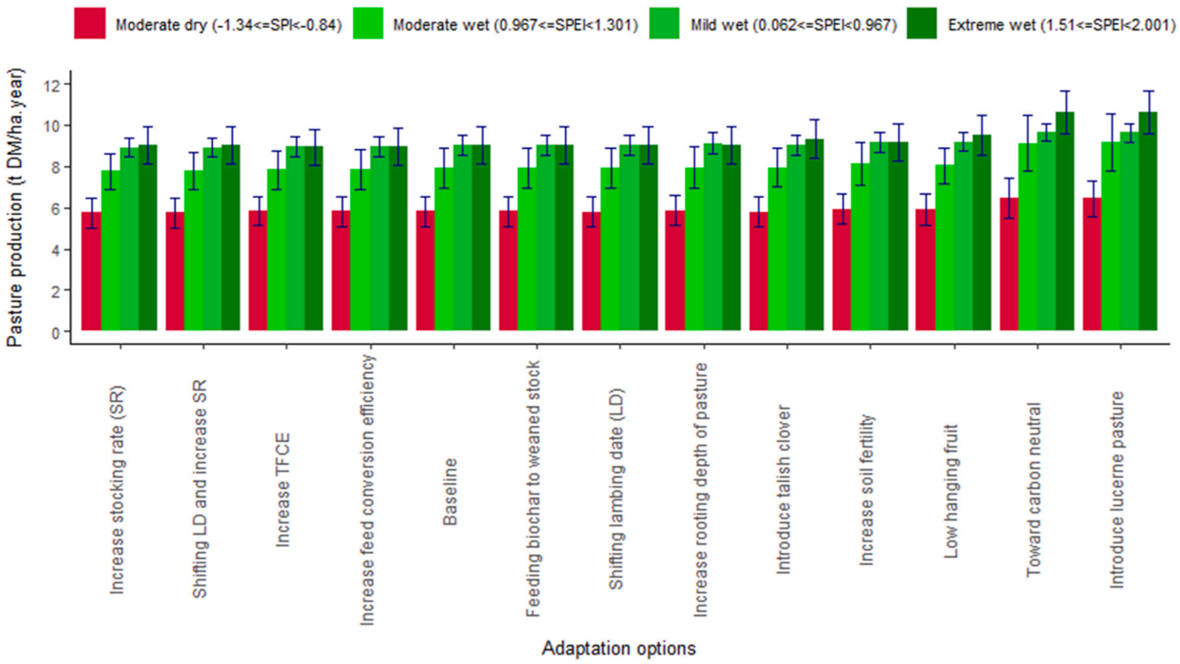


Fig. 6. Influence of adaptation on pasture growth under dry, mid and wet seasonal conditions for the sheep case study farm for a 2050 future climate. Error bars represent the standard error of the mean. Adaptation strategies were compared with the baseline (no adaptation). See Table 4 for a more detailed explanation of the adaptation strategies. The TFCE stands for Increased Transformational Feed Conversion Efficiency.

the sheep farm decreased by 75% and 33% compared with typical or mild-wet years (8.5 t DM/ha.annum) and mild-dry (6.4 t DM/ha.annum) years, respectively. Similarly, in moderate dry years, the beef farm experienced losses of 2.3 and 4.1 tonnes of pasture dry matter production per hectare compared with mild dry (19.1 t DM/ha.annum) and typical or mild wet years (20.9 t DM/ha.annum) years. Furthermore, the sheep farm experienced losses in pasture dry matter production ranging from 2.5 to 3.5 tonnes during the moderate dry years compared to moderate to extreme wet years. Additionally, the beef farm showed significant differences in pasture dry matter production losses during the moderate dry years, ranging from 1.8 to 5.5 tonnes compared to moderate to extreme wet years (Fig. 5). These results and figure indicate that (1) pasture production in both farms was significantly influenced by excessively wet and dry conditions, but most significantly affected by drought and (2) pasture growth on the sheep farm was more sensitive to soil moisture stress compared with the beef farm, perhaps because the latter site received more rainfall.

Fig. 5c and d demonstrate that changes in soil carbon in both farms varied considerably with soil moisture resulting from high seasonal variation in precipitation and temperature under historical climate

Fig. (a) Pasture production under moderate dry years compared with mild dry years and mean of all years

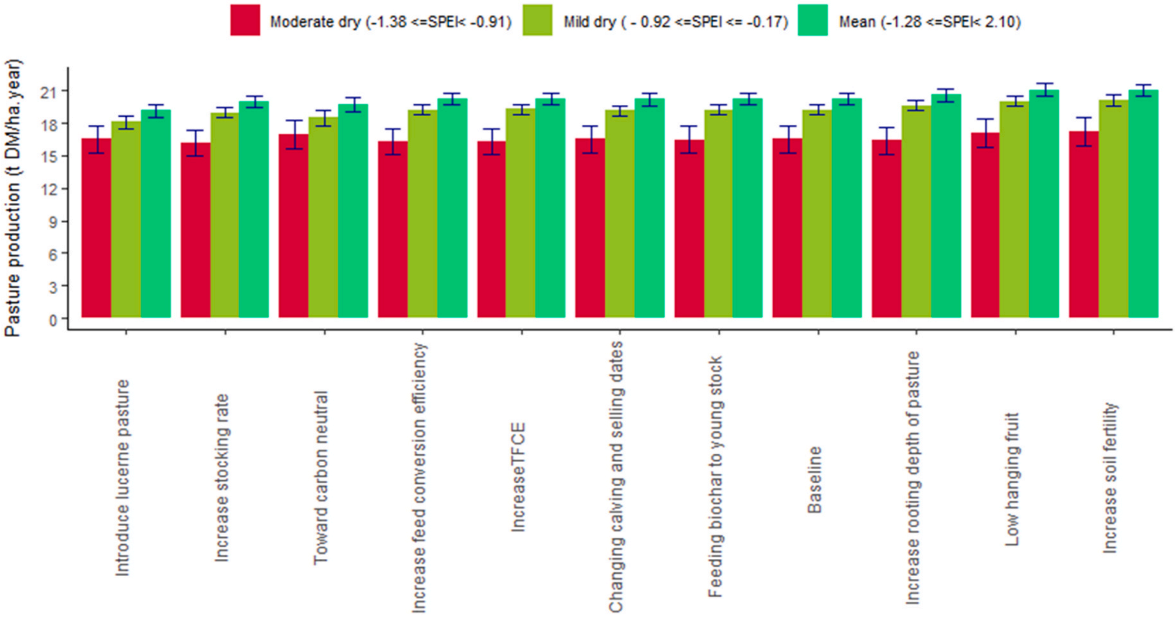


Fig. (b) Pasture production across moderate dry years compared with various wet conditions years

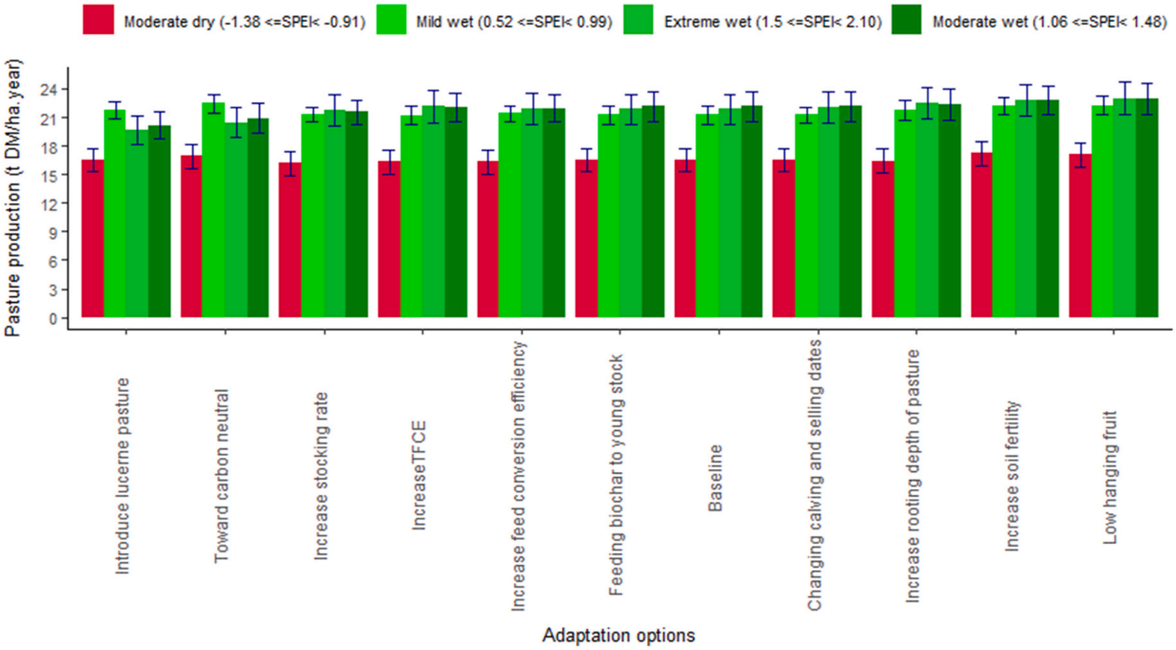


Fig. 7. Influence of adaptation on pasture growth under dry, mid and wet seasonal conditions for the beef case study farm for a 2050 climate. Error bars represent the standard error of the mean. Adaptation strategies were compared with the baseline (no adaptation). See Table 5 for a more detailed explanation of the adaptation strategies. The TFCE stands for Increased Transformational Feed Conversion Efficiency.

conditions. In moderately dry years, the sheep farm and beef farm experienced changing to declines in soil carbon by 0.45% and 0.11%, respectively, compared with the baseline.

3.5. *Adaptation potential to offset soil moisture deficit effects on pasture growth and SOC*

3.5.1. *Effects of adaptation on pasture growth by 2050*

The Analysis of Variance (ANOVA) indicate that pasture production in both the sheep ($p < 2e\text{-}16$) and cattle (p-value$<$2e-16) farms exhibits significant variability due to seasonal weather variation, driven by extreme weather events, including excessive precipitation, moisture surplus, and moisture stress. Notably, the ANOVA analysis suggests that the F-value for 'Pasture production across adaptations' were 0.984 (p-value = 0.465) and 1.288 (p-value = 0.239) in the sheep and cattle farms, respectively, which may indicate some variation, although it may not be statistically significant. Furthermore, the analysis confirms that there is no significant interaction ($p = 1$) between adaptations and seasonal weather conditions (Table 6).

Pasture production during dry years was 2.0–2.2 t DM/ha.annum lower across adaptations compared with mean across all treatments under the 2050 climate for the sheep farm (Fig. 6). Annual per ha

Table 7

Analysis of variance (ANOVA) for the effects of adaptation and extreme weather events (e.g., SPEI12) on changes soil carbon stocks in the sheep and cattle farm.

Items	Sheep farm				
	Degree of freedom	Sum square	Mean square	F value	Probability (>F)
Changes soil carbon stocks across adaptations	12	0.17	0.014	0.06	1
Extreme weather events (e.g., SPEI12) vs soil carbon stocks	1	17.87	17.87	74.27	1.31e-15
Adaptation options vs SPEI12	12	0.01	0.001	0.003	1
Residuals	221	53.18	0.241		
Items	**Cattle farm** Degree of freedom	Sum square	Mean square	F value	Probability (>F)
Changes soil carbon stocks across adaptations	10	2.13	0.213	0.198	0.996
Extreme weather events (e.g., SPEI12) vs soil carbon stocks	1	0.93	0.932	0.867	0.353
Adaptation options vs SPEI12	10	0.73	0.073	0.068	1
Residuals	198	213	1.076		

pasture production loss across adaptation options and the 2050 baseline was approximately three tonnes dry matter and two tonnes dry matter during moderate dry and mild dry years respectively, compared with typical or mild-wet years. Notably, pasture biomass during moderate wet years was also significantly lower compared with typical or mild wet years, perhaps due to waterlogging and/or nutrient leaching. However, some adaptations - such as towards carbon neutral and renovating pastures with lucerne with the 2050 baseline improved pasture production during extreme wet years compared to typical or mild wet years. These results indicate that despite adaptation efforts, pasture growth was more influenced by climatic conditions, particularly soil moisture deficit.

Fig. 7 shows that during moderately dry years, annual per ha pasture production was lower, ranging from 2.6 to 4.0 t DM/ha.annum, compared with the mean pasture dry matter production under the 2050 climate across potential adaptation options for the beef farm. The decrement of pasture dry matter across adaptations in mild-dry years ranged between 1.9 and 2.3 t DM/ha.annum compared with typical or mild-wet years. Although pasture production with most adaptations under moderate and extreme wet years was higher compared with typical or mild-wet years, pasture dry matter production in moderate and extreme wet years with adaptation, particularly when adding lucerne and adopting toward carbon neutral scenario, decreased by 1.5–2.1 t DM/ha.annum compared with pasture production in typical or mild-wet years.

Across adaptations, low hanging fruit scenario and increasing soil fertility yielded 0.59 and 0.72 t DM/ha.annum, respectively, compared with the 2050 baseline in moderate dry years and around 0.25 t DM/ha.annum more in mild dry years. Increasing pasture rooting depth provided some yield advantage over the 2050 baseline in mild dry, mild wet, moderate wet and extreme wet years (Fig. 7).

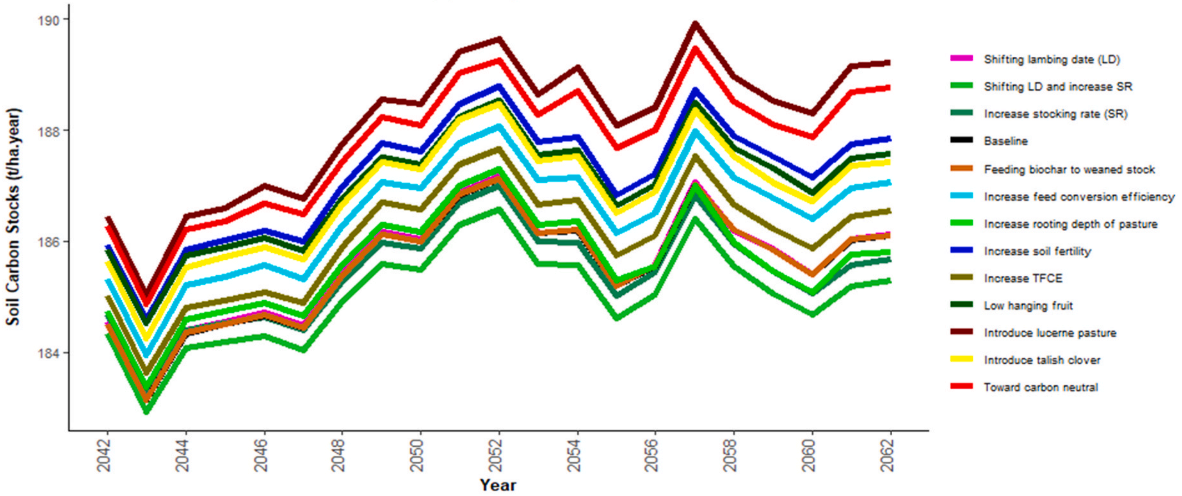
3.5.2. *Effect of climate change adaptation on SOC stocks in 2050*

The Analysis of Variance (ANOVA) revealed significant variability in soil carbon stocks within farms ($p < 1.31e\text{-}15$) attributed to factors such as excessive soil moisture and moisture stress. For the cattle farm, the ANOVA results indicate that changes in soil moisture levels do not exert a significant influence on soil carbon stocks, perhaps because this farm was positioned in a higher rainfall zone. The ANOVA F-values of 0.06 (p-value = 1) and 0.198 (p-value = 0.996) for soil carbon stocks across adaptations in sheep and cattle farms, respectively, suggest that climate (particularly the occurrence of extreme events) has greater effect on long term soil carbon stocks compared with farm management (Table 7).

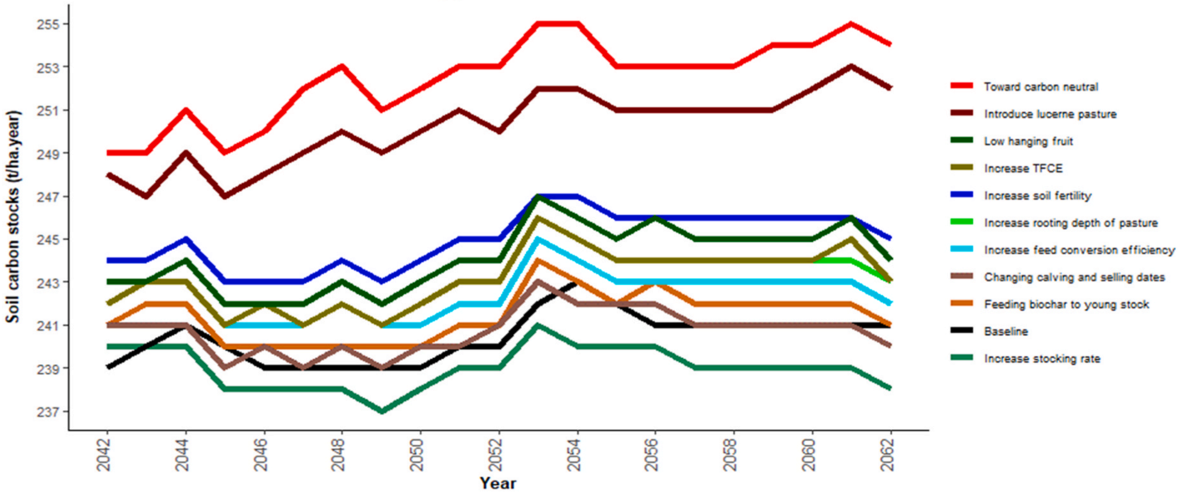
Adaptations applied to the sheep farm increased SOC stocks by 1.2–3.3 t C/ha of carbon over the 20-year period for 0–100 cm layers. Adoption of lucerne pasture and toward carbon neutral in 2050 yielded the most significant benefit in terms of SOC stocks, with a gain of over 3 t C/ha is equivalent to 0.17 t C/ha.annum. Increasing feed conversion efficiency of cattle, low hanging fruit scenario, introducing Talish clover, and increasing soil fertility improved SOC by over 2 t C/ha. On the other hand, the beef farm experienced SOC losses over the 20-year period ranging from 1.5 to 0.66 t C/ha with adoption of increased stocking rate, changes to calving time, and feeding biochar to sheep as a feed supplement. This occurred because the consumption of biochar per head per day was small (1–2% of daily dry matter intake) compared with the effects of climate on soil organic matter and SOC. Adoption of increasing transformational feed conversion efficiency of cattle and soil fertility, and low hanging fruit scenario resulted in modest gains in SOC. The greatest increase in SOC for the beef farm was achieved through the adoption of lucerne and toward carbon neutral scenario, which increased SOC stocks by 4.3 t C/ha and 4.8 t C/ha, respectively, over the 20-year period (Fig. 8).

The mean increases in SOC varied from 0.06 to 0.16 t C/ha.annum across adaptations in 2050 (Fig. 9). In typical or mild-wet years, SOC accrual ranged from 0.67 to 0.80 t C/ha.annum. In moderately dry and mild dry years, SOC declined by 0.33–1.0 t C/ha.annum, even after adaptations were imposed to improve pasture growth. SOC losses in moderately wet years ranged from 0.38 to 0.69 t C/ha.annum compared with changes in SOC in typical or mild-wet years. Across adaptations, altering seasonal stocking rate to better match feed supply, altering lambing date, low hanging fruit scenario, and increasing transformational feed conversion efficiency and feed conversion efficiency of sheep were able to offset SOC losses by 6–17 kg C/ha.annum in moderately dry years under the 2050 climate scenario. Enhancing soil fertility, adopting toward carbon neutral scenario, renovating pastures with Talish clover or lucerne was able to offset SOC loss by 9–69 kg/ha.annum in mild-dry years. These findings suggest that toward carbon neutral scenario and renovating pastures with deep rooted perennial legumes can enhance SOC sequestration under typical and severely wet conditions. As well, shifting forward lambing date and increasing stocking rate, low hanging fruit scenario, increasing transformational feed conversion efficiency of sheep, adding Lucerne pasture, and feeding biochar to weaned stock could potentially reduce SOC loss under moderately dry weather.

For the beef farm, effects of adaptation ranged from −0.001 to 0.24 t C/ha.annum under the 2050 climate scenario. During moderate-wet years, adaptation resulted in gains in SOC, ranging from 0.14 to 0.4 C/ha annum. However, during moderate-dry and extreme-wet years, adaptation led to SOC losses ranging from −0.2 to 0.6 t C/ha.annum and −0.5 to 1.9 t C/ha.annum, respectively. These findings highlight the detrimental and dominating impacts of drought and excessive rainfall on SOC accrual and/or losses over the long term (Fig. 10). it is plausible that the torrential rain has contributed to the washout of manure and



(a): Sheep farm



(b): Beef farm

Fig. 8. Simulated SOC stocks for the sheep case study farm in Midlands and in the beef case study farm in northwest for 0–100 cm layers, Tasmania, Australia. Adaptation strategies were compared with the baseline (no adaptation). See Tables 4 and 5 for a more detailed explanation of the adaptation strategies. The TFCE stands for Increased Transformational Feed Conversion Efficiency.

urine, which could have further contributed to the negative changes.

Across adaptations, incorporating lucerne and toward carbon neutral scenario were most beneficial. Adoption of lucerne and toward carbon neutral scenario improved SOC by 0.45 and 0.8 t C/ha.annum, respectively during moderate-dry years and mild-wet years compared with the 2050 baseline. These results suggest that these adaptations may mediate moisture stress impacts on SOC. Adoption of low hanging fruit scenario, increasing supplementary feed intake, and increasing feed conversion efficiency and transformational feed conversion efficiency of cattle offset yearly SOC losses by 31–88 kg C/ha during moderately dry years. During extreme-wet years, changing calving time, increasing stocking rate, increasing transformational feed conversion efficiency and feed conversion efficiency, and supplementary feed intake of cattle improved SOC sequestration (Fig. 10).

4. Discussion

Our work has implications for landholders aiming to improve SOC in the short term, as our results suggest that climate – and notably rainfall deficit – have a greater impact on SOC than does any form of management practice. Despite this, there was considerable variation between alternative management practices, locations and agroecological regions, suggesting that all land managers potentially have scope for improving soil organic matter and SOC.

Our findings support previous studies conducted in southern Mongolia (Munkhtsetseg et al., 2007), which show that precipitation and high temperature drove a strong positive correlation between SOC stocks and SPEI. This indicates that drought and rainfall-driven pasture production significantly influenced changes in SOC stocks in the long term, consistent with findings of Rantoa et al. (2015) in South Africa, who reported that SOC was associated with several soil-forming factors, including rainfall and evaporation. In Austria Oram et al. (2023) observed that increased drought intensity resulted in decreased carbon accumulation in the soil, with more carbon being directed toward leaves and microbial processes within grassland plant communities. However, improved moisture availability helped alleviate the effects of drought intensity on carbon and nitrogen dynamics in plants and soil, ultimately influencing plant recovery processes.

We revealed a positive correlation between changes in pasture growth and SOC sequestration, suggesting that aboveground growth dictates change in belowground carbon. This insight has implications for farmers and policymakers in developing sustainable strategies for managing pasture growth and soil health, regardless of whether climate change impacts are negative or positive (Phelan et al., 2015; Taylor et al., 2016; Ibrahim, Harrison, Meinke, & Zhou, 2019). Previous studies have shown that managing grazing land with moderate grazing pressure

Fig. (a) SOC accrual or loss under moderate dry years compared with mild dry years and mean of all years

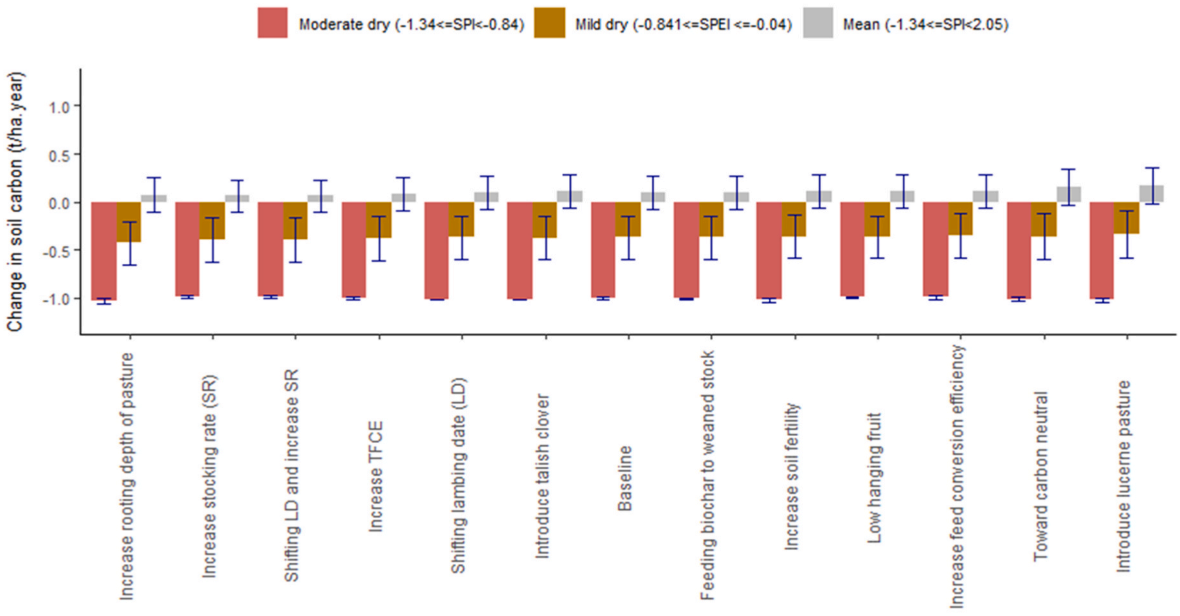


Fig. (b) SOC accrual or loss under moderate dry years compared with various wet conditions years

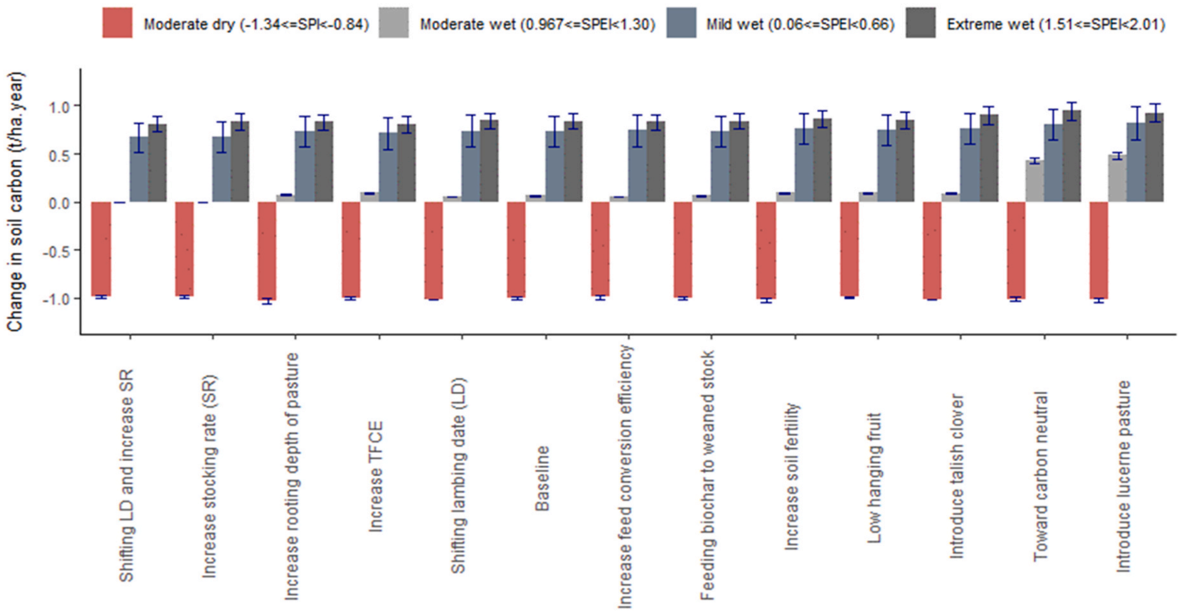


Fig. 9. Soil organic carbon accrual or loss across adaptations and seasonal conditions for the sheep case study farm for 0–100 cm layers. Adaptation strategies were compared with the baseline (no adaptation). See Table 4 for a more detailed explanation of the adaptation strategies. The TFCE stands for Increased Transformational Feed Conversion Efficiency.

can improve soil fertility and carbon storage in the soil, such as in grazing lands in the south-eastern USA (Franzluebbers, 2010). However, a meta-analysis (Deng et al., 2021) indicated that drought reduced SOC, primarily due to reduced plant litter input and decreased litter decomposition across all three ecosystem types. Taken together, these findings imply a need for the development of practitioner decision support tools enabling simplified contrasting of the effects of various management scenarios for any given climatic region (*viz.* Phelan et al., 2018), as such tools would facilitate more rapid contrasting compared with the biophysical and economic frameworks invoked here.

In addition to drought, we highlight the impacts of superfluous water and waterlogging on SOC decay. Waterlogging impacts SOC in several ways, including altering SOC fractionation, soil microbial community structure, mineral-associated carbon and microbial carbon metabolism, consequently affecting carbon storage and cycling in soils (Deng et al., 2021; Su et al., 2020). A study in the USA showed that periodic drying and shorter aerobic periods in rice fields afforded greater accumulation of organic soil carbon compared with non-cropped fields that were subject to prolonged waterlogging (Stallard, 1998). Furthermore, due to soil redistribution processes, depositional positions, and lower respiration rates, eroding landscapes store approximately 10% more carbon compared to non-eroding landscapes in Belgium (Doetterl et al., 2012). These findings emphasise the importance of managing soil health and moisture through the implementation of sustainable practices that conserve long-term ground cover, particularly under extreme dry or wet weather conditions.

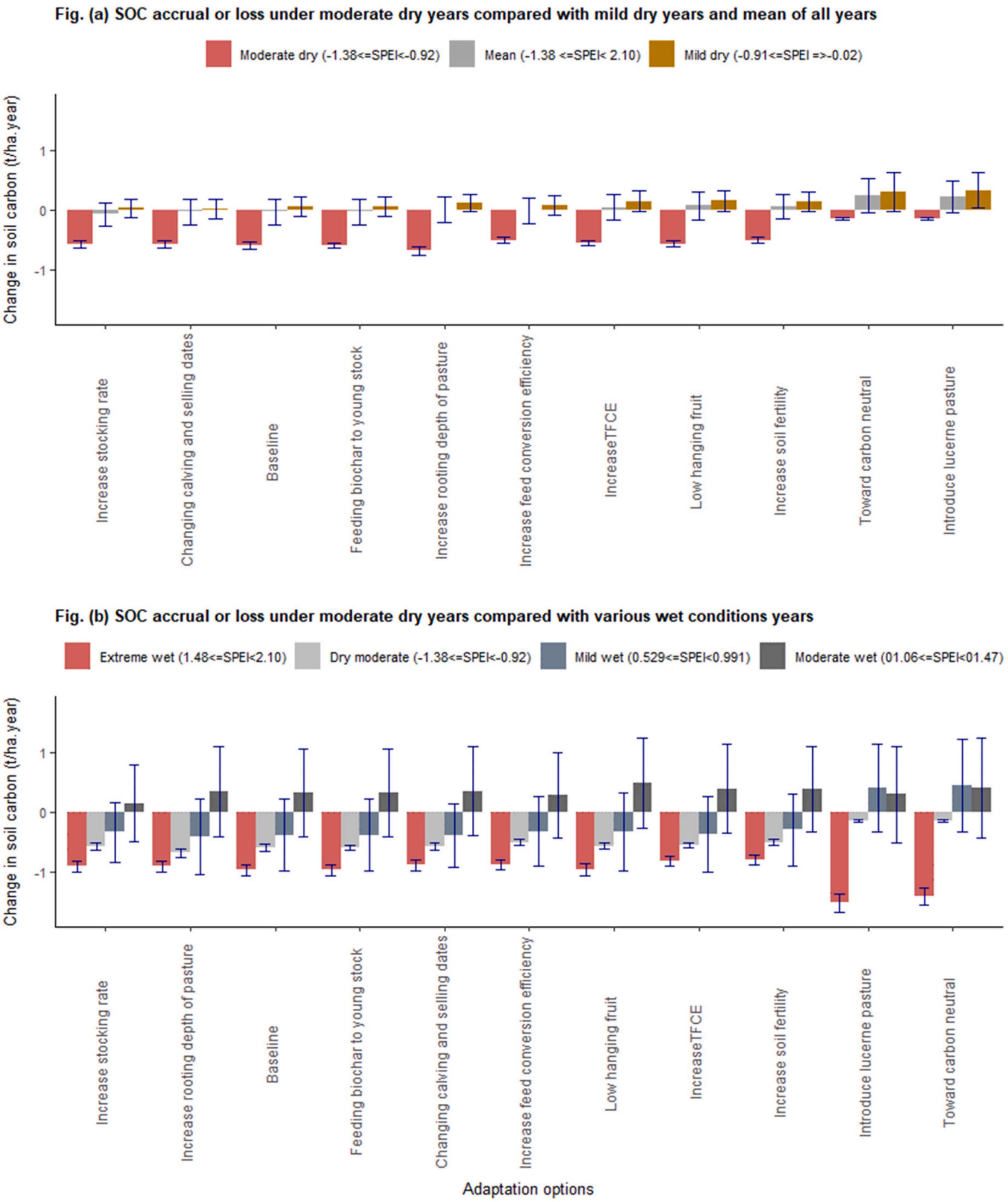


Fig. 10. Soil organic carbon accrual or loss across adaptations and seasonal conditions for the beef case study farm. Adaptation strategies were compared with the baseline (no adaptation). See Table 5 for a more detailed explanation of the adaptation strategies. The TFCE stands for Increased Transformational Feed Conversion Efficiency.

Our work also provides insight into adaptions that are more likely to drive SOC accrual under future climates. Of the adaptations examined, we showed that toward carbon neutral scenario and pasture renovation with lucerne at this location (existing pastures comprises phalaris, perennial ryegrass and to a lesser extent subterranean clover) resulted in the greatest yield advantage in 2050 under dry, mild dry, and mild wet years in the sheep farm. Similarly, the 'low hanging fruit' scenario intervention and increasing soil fertility had the potential to offset the adverse effects of drought and extreme rainfall events on pasture growth in the beef farm. Our work suggests that management interventions that impact on pasture biomass and ground cover rather than the magnitude of root depth – are more likely to beneficially impact on long-term SOC. We suggest that cell grazing, regenerative agriculture (enabling improvement of annual ground cover) and diversification of botanical composition may yield benefits for SOC accrual at these sites, although this requires further investigation. Nonetheless, adjacent studies imply that reducing stocking rate, diversification of pasture species, pasture renovation and forage cropping have the potential to offset drought impacts on pasture productivity (Lee et al., 2013). While our focus in this paper was the relationship between SOC and climate, we note that concurrent assessment of other GHGs may help provide a more holistic picture of how the interventions impact on productivity and environmental co-benefits and trade-offs. For example, the towards carbon neutral adaptation included pasture renovation with lucerne, a legume capable of nitrogen fixation, yet some studies have documented trade-offs between SOC sequestration and nitrous oxide emissions (e.g., Bilotto et al., 2021; Lugato et al., 2018). Such trade-offs could be used as foundations for future work.

5. Concluding remarks

We have shown that superfluous soil moisture and chronic water deficit (drought) have profound implications for seasonal pasture biomass accumulation and SOC accrual. We show that climatic effects on SOC over the long-term are likely to dominate the influence of management and/or practice change. However, we also reveal that across an array of pasture management, livestock husbandry, pasture and livestock genotype and farm enterprise interventions, considerable scope exists to improve long-term soil organic matter and SOC, provided sustainable management practices are maintained, and are transiently adapted to adverse weather conditions. Indeed, as part of this, we showed that drought and waterlogging detrimentally impact SOC stocks, over and above compensatory effects of management. Our work suggests that short-term aspirations for raising SOC may be futile (1–2 years), whereas longer term prospects for sustainably improving and maintaining SOC are more prospective albeit context-specific. We contend that further research is necessary to examine how such management practices influence other aspects of sustainability, including GHG emissions, farm profit, and social licence to operate.

Author statement

Conceptualisation: MTH, MJK. Biophysical modelling: KCW, KCW, MTH. Data analysis and plotting: MJK. Writing—original draft preparation: MJK, MTH. Writing—review and editing: MJK, MTH, KA, SM, KCW, KCW, FB.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tifs.2024.104409.

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