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ORIGINAL ARTICLE

Carbon, cash, cattle and the climate crisis

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Abstract

While society increasingly demands emissions abatement from the livestock sector, farmers are concurrently being forced to adapt to an existential climate crisis. Here, we examine how stacking together multiple systems adaptations impacts on the productivity, profitability and greenhouse gas (GHG) emissions of livestock production systems under future climates underpinned by more frequent extreme weather events. Without adaptation, we reveal that soil carbon sequestration (SCS) in 2050 declined by 45–133%, heralding dire ramifications for CO_2 removal aspirations associated with SCS in nationally determined contributions. Across adaptation-mitigation bundles examined, mitigation afforded by SCS from deep-rooted legumes was lowest, followed by mitigation from status quo SCS and woody vegetation, and with the greatest mitigation afforded by adoption of enteric methane inhibitor vaccines. Our results (1) underline a compelling need for innovative, disruptive technologies that dissect the strong, positive coupling between productivity and GHG emissions, (2) enable maintenance or additional sequestration of carbon in vegetation and soils under the hotter and drier conditions expected in future, and (3) illustrate the importance of holistically assessing systems to account for pollution swapping, where mitigation of one type of GHG (e.g., enteric methane) can result in increased emissions of another (e.g., CO_2). We conclude that transdisciplinary participatory modelling with stakeholders and appropriate bundling of multiple complementary adaptation-mitigation options can simultaneously benefit production, profit, net emissions and emissions intensity.

Keywords Cross-disciplinary framework · Climate change adaptions · Greenhouse gas mitigation options · Livestock production · Carbon neutral · Future climates

Introduction

While agricultural productivity gains have contributed to local food security on one hand (Liu et al. 2020a, b), increasingly severe extreme weather events borne by the climate crisis continue to threaten the reliability of global food supply on the other (IPCC 2021). Ambient carbon dioxide (CO_2) concentrations have risen by 47% since the industrial revolution, while ambient methane (CH_4) and nitrous oxide (N_2O) concentrations have increased by 156% and 23%, respectively (IPCC 2021). The need to sustainably intensify agri-food systems production while concurrently reducing GHG emissions could appear a polarized aspiration, given the recalcitrant linkage between productivity and GHG emissions (Harrison et al. 2021; Hong et al. 2021; Sándor et al. 2020; Farina et al. 2021). The development of sustainable, transdisciplinary and enduring solutions that systematically disentangle the tight coupling between production and GHG emissions while also facilitating adaptation to the climate crisis is imperative (Cole et al. 2018; Harrison et al. 2016b).

The Australian red meat industry contributed AU$17.6B to the Gross Domestic Product in 2018–2019 from 25M cattle and 74M sheep (MLA 2022). In the absence of adaptation to climate change, livestock production and profitability across many regions will decline, driven largely by a truncated pasture growth duration and concerningly common compounding and cascading extreme weather events

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(Harrison 2021). While gradual climate change trends have had little effect on farm-level production, extreme weather events often result in deep cuts to farm income and can cause significant natural, human and social costs through animal mortality, loss of vegetation, biodiversity and soil carbon, staff redundancies and labour shortages, and destruction of farm infrastructure (Godde et al. 2021; IPCC 2021; Fleming et al. 2022). The global scientific community must now urgently prioritise new research on systemic adaptation to extreme weather events, rather than adaptations to gradual and long-term changes in climate. Indeed, complementarities between adaptation and mitigation options should be given closer attention (Henry et al. 2018). Herein we define 'climate change adaptation' as actions aiming to avoid, manage or reduce the detrimental impacts of climate variability through technological, management and policy options, while we define 'mitigation' as actions evoking GHG reduction, GHG avoidance, and/or carbon removal from the atmosphere (Harrison et al. 2021). Adaptation and mitigation goals may not always be symbiotic, for example, beneficial adaptation may result in additional GHG emissions, as a positive change in the farming sub-system is compensated for by other simultaneous negative changes (Snow et al. 2021).

Hitherto, scientists have generally focused on incremental adaptations in a unidisciplinary and reductionist manner, such as studies of adaptations to the feedbase or to animal management (Harrison et al. 2019). By way of example, investigation of new plant genotypes for climate change adaptation is common in the literature, often underpinned by studies with a drought or heat tolerance lens (Ibrahim et al. 2018, 2019; Langworthy et al. 2018; Meier et al. 2020). For example, adoption of deeper-rooted pastures can increase pasture production and soil organic carbon under drier conditions (Langworthy et al. 2018; Meier et al. 2020), increase profitability (Ho et al. 2014) and reduce net farm GHG emissions (Christie et al. 2020; Meier et al. 2020). However, while many studies have examined GHG emissions mitigation interventions in isolation (e.g., altering lambing or calving times, increasing ewe genetic fecundity, changing trading model/enterprise mix etc.) (Alcock et al. 2015; Harrison et al. 2014), few works have stacked (or combined) multiple GHG mitigation interventions and examined the combination in a holistic and dynamic spatiotemporal system (Harrison et al. 2021). Such work requires multidisciplinary input across social, environmental, economic and institutional dimensions; accordingly, multidisciplinary work tends to be more difficult and time expensive than unidisciplinary studies (Harrison et al. 2021). Documented assessments of stacked and contextually-customised climate change adaptions with concurrent mitigation GHG/carbon sequestration actions in the literature are very much in their infancy (Makate et al. 2019; Harrison et al. 2021). The present paper is designed to help fill this gap: here, we develop a generic multidisciplinary approach for participatory co-development of holistic systems-based adaptations, with a focus on innovations designed to mitigate or overcome the impacts of extreme events. The use of whole-farm system modelling may be one of the most suitable avenues for assessing farm management options to elicit adaptation and mitigation potential (Moore et al. 2014; Ash et al. 2015; Ho et al. 2014). Genuine involvement of stakeholders using participatory modelling increases end-user awareness and acceptance of perceived problems, stakeholder confidence in and legitimacy of modelled outcomes (Ara et al. 2021). The objective of this study was to develop a participatory approach for exploring the nexus between profitability, productivity and GHG emissions of stacked climate change adaptation and GHG emission mitigation/carbon offset options in livestock systems across a rainfall gradient under 2030 and 2050 climates in Tasmania, Australia. While we apply this process to climate change and livestock systems, the conceptual framework could be applied generically across disciplines and commodities.

Materials and methods

Study overview: people-centric cross-disciplinary co-design of thematic adaptations

An integrated, cross-disciplinary participatory modelling framework for farming systems adaptation to future climates was developed. In this way, biophysical, environmental and economic interventions (Fig. 1) were co-designed with an expert group of industry practitioners (hereafter, the Regional Reference Group or RRG). In a subsequent paper, we consider social aspects of co-designed adaptations, such as barriers to adoption, social license to operate, and new skills required for adoption. The first stage documented here includes the characterization of case study farms (see High rainfall beef production system and Low-rainfall sheep production system sections) and the simulation of current management under historical, 2030 and 2050 climate scenarios (see "Historical and future climate data"). Two diverse regions of Tasmania, Australia, were used to showcase this approach: a low rainfall zone in central Tasmania practicing a sheep production system (hereafter sheep farm) and a relatively high rainfall zone in north-western Tasmania practicing a beef production system (hereafter beef farm). Climate change impacts on farm outcomes and incremental adaptation elements were selected and refined over a series of workshops with the RRG. Refinement included feedback on supplementary feed requirements, pasture growth, management practices such as pasture renovation, and economic metrics such as key costs and income streams.

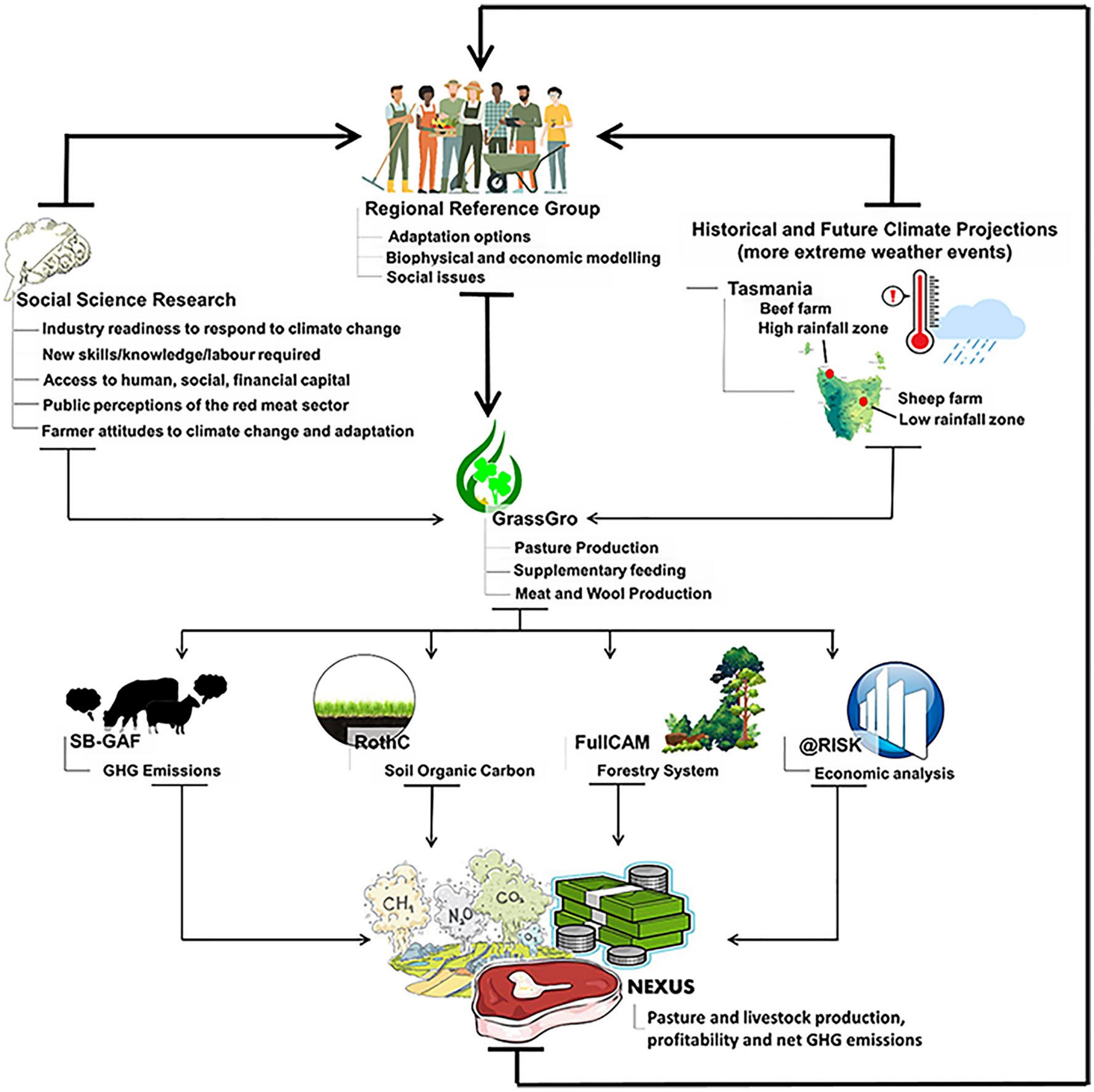


Fig. 1 Transdisciplinary approach pioneered in the present paper ('NEXUS project') including modelling frameworks used to examine the nexus between productivity, profitability, GHG emissions and social factors under historical and future climate scenarios that included more frequent extreme weather events

Once finalised, individual adaptation elements were stacked together in a mutually synergistic way, such that each incremental adaptation was contextualised and bundled with other appropriate adaptations (see The role of the Regional Reference Group: model calibration, testing of assumptions and adaptation co-design section, Table 1 and Tables S1 and S2). A range of modelling approaches were used to simulate future climate data, biophysical and economic aspects of the farm system (details below).

Future climate data were developed using novel methods that perturb historical climate data based on monthly global climate model projections, accounting for increased frequency and severity of extreme climatic events while preserving global climate model monthly projects in the future climate data (Harrison et al. 2016a). Daily pasture and livestock production for historical and future climate horizons was simulated using the whole-farm model, GrassGro® (Moore et al. 1997; version 3.3.10). GrassGro® outputs were used to compute soil organic carbon stocks and sequestration using the RothC model (Coleman and Jenkinson 2014; version 26.3 in Microsoft Excel format) and carbon sequestered in trees using the FullCAM model (Richards and Evans 2004; version 4.1.6). Outputs from GrassGro®, RothC, FullCAM were then used to compute net farm GHG emissions using the Sheep Beef-Greenhouse Accounting Framework (Dunn et al. 2020; SB-GAF version 1.4). Farm

Table 1 Summarised thematic adaptations co-designed with a Regional Reference Group (RRG)

Theme	Incremental adaptations stacked into holistic adaptation theme
LHF	Altered lambing/calving dates to better match seasonal pasture supply
	Altered selling dates/SR/LW to better match seasonal pasture supply
	Adopting pasture species with 10% improvements in maximum root depth (Cullen et al. 2014)
	Increasing soil fertility with SSP and N by 3% (Harrison et al. 2014; all paddocks except the native pastures for the sheep farm)
	Increasing FCE (Alcock and Hegarty 2011)
	Introduction of Talish clover (*Trifolium tumens*) to a proportion of the sheep farm
	Removing cattle from the sheep farm and increasing rainfed introduced pasture area to the two sheep flocks
TCN	Strategic manipulation of livestock selling dates/SR/LW to better match seasonal pasture supply
	Pasture renovation with (and increased farm area of) lucerne pastures
	Injecting animals with an enteric CH_4 inhibitor vaccine to reduce CH_4 by 30% (Reisinger et al. 2021)
	Purchase 50 ha of land for the beef farm to establish a tree plantation of Tasmanian Blue Gums to offset livestock GHG emissions
	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)

Each thematic adaptation comprised multiple stacked incremental adaptations suggested by the RRG; the extent to which each factor was varied from the baseline level was derived from feasible values from the literature. Further details are provided in Tables S1 and S2

LHF low-hanging fruit, *TCN* towards carbon neutral; this theme also included all incremental adaptations for LHF, *SR* stocking rate, *LW* liveweight per head, *FCE* feed conversion efficiency, *RD* rooting depth, *SSP* single superphosphate fertiliser, *N* nitrogen fertiliser

costs and profitability were modelled stochastically using the @Risk model (Palisade Corporation 2012) to account for market volatility (Fig. 1). Using a normalised multidimensional impact assessment, we ranked all interventions and climate horizons by integrating the relative benefits across economic, biophysical and environmental disciplines into a single indicator of impact (see “Normalised multidimensional impact assessments”).

Historical and future climate data

The beef farm was located at Stanley in the cool temperate zone in north-western Tasmania, Australia (40° 43′ 41″ S 145° 15′ 43″ E), while the sheep farm was located west of Campbell Town, in the Midlands of Tasmania (41° 56′ 30″ S 147° 25′ 02″ E). Long-term mean and standard deviation annual rainfall at Stanley and Campbell Town were 807 ± 139 mm and 499 ± 103 mm, respectively, with corresponding average daily temperatures of 16.5 °C and 16.7 °C in January and 9.1 °C and 6.5 °C in July, respectively (Fig. S1). Daily historical climate data for the baseline period of 1 January 1980 to 31 December 2018 were sourced from SILO meteorological archives (http://www.longpaddock.qld.au/silo). These data were used to generate future climate data (maximum and minimum temperature and rainfall) following Harrison et al. (2016a). Future climate projections were downscaled from global circulation models (GCMs) (Harris et al. 2019) and altered using a stochastic approach to account for extreme weather events, including heatwaves, longer droughts and more extreme rainfall events (Harrison et al. 2016a). The approach used to generate future climate data (1) includes mean changes in future climates projected for a region by an ensemble of global climate models (GCMs), (2) accounts for historical climate characteristics for a given site that are most often obviated by raw GCM data per se and (3) notwithstanding point (1), generates climatic projections with increased variability. Future climate projections were developed using monthly regional climate scaling factors (Table S1) based on Representative Concentration Pathway (RCP) 8.5 for 2030 and 2050 using raw data from GCMs provided in Harris et al. (2019). Atmospheric CO_2 concentrations were set at 350 ppm, 450 ppm and 530 ppm for the historical, 2030 and 2050 climate scenarios, respectively, following RCP8.5 projections adapted from the platform Climate Change in Australia (CCIA 2020).

The role of the Regional Reference Group: model calibration, testing of assumptions and adaptation co-design

We sense-checked model assumptions and results and co-designed adaptation themes using an iterative process with the RRG. Model outputs 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. After achieving consensus RRG agreement on the modelled outputs for each baseline farm, we ran several biophysical and economic models for each of two 26-year periods (first 6 years of data to allow for model stabilisation), with results data centered on 2030 (2022–2041) and 2050 (2042–2061) using the future climate data described above. Over the three workshops, we gleaned RRG thinking and feedback on tactical and strategic incremental and systems adaptation and mitigation opportunities in light of quantified holistic impacts of climate change on the two case study farms. We combined several incremental adaptations into two distinct themes; 'low hanging fruit' and 'towards carbon neutral' and compared outcomes of these themes with the baseline scenario (adaptation themes are detailed below). We again refined model parameters considering RRG advice on the feasibility and magnitude of variables simulated for each adaptation theme. Taken together, this process (1) ensured rigor and realism of modelled results, (2) allowed the research team to learn directly from expert practitioners about realistic adaptation and mitigation opportunities, (3) engendered confidence in the analytical process and simulated results by end-users and (4) helped raise endsuser awareness of a diverse and multi-disciplinary array of opportunities for climate crisis adaptation. Further details of the adaptation processes co-developed with the RRG are given below and detailed further in the supplementary information (Tables S2, S3).

Pasture and livestock production assessments

The model GrassGro® (Moore et al. 1997; version 3.3.10) combines biophysical (climate, soils, pastures and livestock), farm management (soil fertility, paddock size and layout, pasture grazing rotations, stocking rate and animal management) and economics (gross margins), enabling simulation of ruminant grazing enterprises of southern Australia (Moore et al. 1997; version 3.3.10). GrassGro® has been used to explore the effects of climate, pasture, soils and management on livestock productivity and profitability (Harrison et al. 2016b) and has reliably predicted climate change impacts and adaptation for pasture-based industries across Australia (Cullen et al. 2021), North America and Northern China (Duan et al. 2011; Lynch et al. 2005). On a daily basis, GrassGro® computes soil moisture, pasture production, pasture quality [Dry Matter Digestibility (%DMD) and Crude Protein (%CP)] for each pasture species, paddock and farm. The model also calculates sward characteristics, pasture cover, persistence and pasture availability, pasture intake, feed supplement required, liveweight change and feed carryover effects from 1 year to the next, as well as many other factors. Here, 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.

High rainfall beef production system

The beef farm at Stanley in NW Tasmania had a land area of 569 ha and ran a self-replacing cow and calf enterprise. This comprised 367 mature cows calving in late winter (1 Aug with 95% weaning rate, first calving at 2 years of age) from which 74 replacement heifers were sourced each year. An additional 115 of weaners were purchased at 6 months of age (1 Feb) at approx. 200 kg liveweight (LW) and 155 steers were purchased at 16 months of age (1 Feb) at approx. 375 kg LW each year. Mature cows were retained for five lactations before being cast for age on 10 Feb. Home-bred non-replacement heifers and steers were sold at 25 months (1 Sep) at approx. 550 and 600 kg, respectively. Purchased weaners were sold at 25 months (1 Sep) at approx. 600 kg, while purchased steers were sold at 28 months (31 Jan) at approx. 545 kg LW. Pasture species comprised perennial ryegrass (*Lolium perenne* L.), cocksfoot (*Dactylis glomerata* L.), white clover (*Trifolium repens* L.), subclover (*Trifolium subterraneum* L.) and lucerne (*Medicago sativa*). The soil type in GrassGro was described as Uc2.3 based on the Northcote classification (Northcote 1979). To replicate long-term average irrigation water applied, 5% of farm area (20 ha lucerne/ryegrass and 8 ha ryegrass/cocksfoot/white clover pastures) was irrigated between 21 Nov and 31 Mar each year (20 mm/event on a 14-day interval). Production feeding rules were implemented in GrassGro 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 the home-bred steers also accessing irrigated pastures on a year-round basis. Further details can be found in Supplementary Material (Table S2).

Low-rainfall sheep production system

The sheep farm was located west of Campbell Town in the low rainfall Midlands of Tasmania and ran a self-replacing Merino superfine wool, prime lamb and beef cattle enterprise. The arable farm area used for grazing was 3170 ha and consisted of 49% native grasslands, 48% rainfed developed pastures and 3% centre pivot irrigation (introduced grasses and legumes). The farm also had ~4600 ha of native woodlands that were not subjected to grazing. The soil type was described as Dy5.61 based on the Northcote classification (Northcote 1979). Developed rainfed pastures were either pure stands of phalaris (*Phalaris aquatica* L.), or a blend of phalaris and subclover. The land under the centre pivot irrigation was also for dual-purpose wheat that was grazed for 4 months and lucerne used for grazing and hay production. Lucerne and wheat paddocks were irrigated from 1 Sep to 31 Mar with 18 mm of water per application to fill the soil profile to 95% of field capacity whenever soil water deficit reached 50%, following actual farm practice.

The farm ran 24,750 sheep in two flocks: 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. The SMF ewes first lambed at 2 years of age and were retained for three lambings before entering the PLF for two more annual births then cast for age at 7 years of age (16 Dec). Wethers were retained for 5 years before cast for age (14 Oct). All non-replacement ewe and wether lambs were sold 1 Feb. The PLF contained 3450 Merino ewes from the SMF and were mated with White Suffolk rams; the 2950-lamb progeny were sold in mid-December at 27 kg LW. All sheep (except prime lambs) were shorn 20 Jul, fleeces weights were 3.3–4.1 kg [clean fleece weight (CFW)] with fibre diameters of 17.4–18.1 µm (variation in CFW and micron depended on stock class and age). Maintenance and production feeding rules and grazing rotations are further detailed in Supplementary Material (Table S3). The self-replacing beef cattle herd consisted of 340 mature cows and 60 replacement heifers per age group. Mature cows calved for the first time (30 Aug) at 2 years of age and were retained for 8 years of age before being cast for age. Non-replacement heifers (90 head) were sold post-weaning (1 Apr) at 200 kg LW, while steers (150 head) were sold at 18 months of age (28 Feb at ~460 kg LW).

Quantifying net farm greenhouse gas emissions

Net farm greenhouse gas emissions were calculated using the Sheep-Beef Greenhouse Accounting Framework (Dunn et al. 2020; SB-GAF version 1.4), which incorporates Intergovernmental Panel on Climate Change methodology and is detailed in the Australian National Greenhouse Gas Inventory. The use of biophysical model outputs (Harrison et al. 2012a, b) as SB-GAF inputs (and predecessor software, S-GAF and B-GAF) has been previously undertaken for sheep (Harrison et al. 2014) and beef enterprises (Herd et al. 2015). SB-GAF has 100-year global warming potentials (GWP_{100}) of 28 and 265 to convert CH_4 and N_2O, respectively, into carbon dioxide equivalents (CO_2e). Twenty-year seasonal mean data from GrassGro were used as input data to estimate GHG emissions in SB-GAF. Greenhouse gas outputs were calculated as net farm emissions (t CO_2e/annum) and emissions intensity (t CO_2e/t product). Allocation of emissions between meat and wool was based on protein mass ratio following Wiedemann et al. (2015). Greenhouse gas emissions considered included enteric and manure CH_4 from livestock; N_2O from nitrogenous (N) fertiliser, waste management, urinary deposition and indirect N emissions via nitrate leaching and ammonia volatilization (Smith et al. 2021); CO_2 from synthetic urea applications, electricity and diesel consumption, as well as CO_2e pre-farm embedded emissions for fertiliser and supplementary feed. Annual electricity and diesel consumption are computed as a function of location, enterprise type, cultivation and machinery use, as well as livestock numbers and use of farm infrastructure.

Soil organic carbon in grazed pastures

The Rothamsted Carbon model (RothC) was used to simulate dynamic soil organic carbon (SOC) (Coleman and Jenkinson 2014; version 26.3 in Microsoft Excel format). RothC has been used extensively to model the impacts of climate and management on SOC stocks around the world (Morais et al. 2019). RothC is driven by monthly means of temperature, rainfall and pan evaporation. Monthly average GrassGro outputs were input into RothC including dung and litter. Root residue C inputs were derived considering the allocation of net primary production between plant components, active root length density and proportion of root by layer (0–30 cm and 30–100 cm depth). Soil types primarily consisted of Vertosols on the river flats and Dermosols on the slopes adjacent to native vegetation on sheep farm (Smith et al. 2012) and clay loam Red Ferrosols on beef farm (Cotching 2018). Historical SOC was derived from regional sources (Cotching 2018). Soil clay contents in the 0–30 cm and 30–100 cm layers were sourced from the TERN-ANU Landscape Data Visualiser (https://maps.tern.org.au/#/). RothC considers C transfers between several 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) (Coleman and Jenkinson 2014). The IOM, RPM and HUM fractions were comparable to historical data for Dermosols and Red Ferrosols (Cotching 2018). The IOM fraction was similar to that reported by Falloon et al. (1998); allocations across SOC pools given by Hoyle et al. (2013) for initial fractions of DPM, BIOF and BIOS were adopted here (1%, 2% and 0.2% of initial SOC stocks, respectively). Decomposition constants at 30 cm were derived following Jenkinson and Coleman (2008), except for the decomposition rate for RPM, which was set to 0.17 following Richards and Evans (2004), similar to 0.15 reported by Cotching (2018), such that decomposition rates constants for DPM, RPM, BIO and HUM were 10, 0.17, 0.66 and 0.02, respectively. At 30–100 cm, decomposition rates were calculated following Jenkinson and Coleman (2008); all values were lower than values at 0–30 cm, reflecting lower decomposition rates at depth. Decomposition rates constants for DPM, RPM, BIO and HUM were 0.33, 0.01, 0.02 and 0.00, respectively.

Tree growth, carbon in wood and soil carbon beneath tree canopies

We invoked the FullCAM model (Richards and Evans 2004; version 4.1.6) to simulate dynamic temporal tree growth, along with carbon sequestration in biomass and in soils beneath trees. FullCAM is currently 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. FullCAM simulations were run continuously from 2022 to 2062 by combining the climate data for the two future time frames, as opposed to two individual simulations commencing 2022 and 2042. 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.

Economic analyses

In concert with GrassGro outputs, we used the @Risk Software (Palisade Corporation 2012) to stochastically simulate annual feed supply, changes in annual carrying capacity and added annual supplementary feed requirements, commodity prices and animal farm incomes, following approaches outlined in previous studies (Bell et al. 2015). Long-term wool, meat and livestock prices adjusted for inflation were adopted from Thomas Elder Markets, Data and Consultancy (http://thomaseldermarkets.com.au). The probability distribution of each price variable was derived from analysis of the price data series using BestFit software (Accura Surveys Ltd) (Tables S4–S7). Prices of livestock products were correlated. Economic assessments of the baseline and adaptations were assessed using the @Risk model. To account for economic risk and uncertainty, we performed Monte Carlo simulations using 10,000 iterations of runs of 10-year annual NCFs, as well as measures of profit and addition to net worth. Changes in annual average net cash flows were used as proxies for changes in annual average profit. To attribute a cost for carbon offsetting (purchasing carbon external to the farm to reduce farm GHG emissions compared to baseline), we also computed NCF plus a carbon 'tax', in which each tonne of CO_2e above baseline GHG emissions was taxed at \$60–\$100/t CO_2e, following Stiglitz et al. (2017). The farmer shares of the total carbon tax paid were 35% and post-farm gate (i.e., consumers and the value chain) received or afforded the remaining 65% (Zhang et al. 2018).

Normalised multidimensional impact assessments

Normalised multidimensional impact assessments were used to rank all interventions and climate horizons through integration of the relative benefit of each adaptation across economic, biophysical and environmental disciplines into a singular unified metric. Following principles outlined by Gephart et al. (2016), liveweight production, net cash flow (pre-carbon taxes) and net farm GHG emissions were selected for normalisation by the maximum value for each corresponding metric, such that normalised values ranged from 0 to 1. Normalised net farm GHG emissions were computed as the additive inverse of 1 (i.e., 1—normalised net farm GHG emission factor) given that lower values for this specific metric are desired. Normalised multidimensional impact was calculated as the sum of three key normalised metrics with equal weighting for each metric, such that each normalised output value ranged from 0 (very low impact) to 3 (representing very high beneficial impact in each of the productivity, profitability and GHG emissions dimensions). In addition, to better distinguish the relative impacts of future climates and the effects of adaptation options for multiple variables analysed, we compared long-term averages (20 years simulation) supplementary feeding (kg DM ha^{-1}), pasture production (kg DM ha^{-1}), liveweight production (kg protein production ha^{-1}), net cash flows (\$), emission intensity (kg protein kg^{-1} CO_2e), total greenhouse gas emissions (t CO_2e) and net farm emissions (t CO_2e).

Stacking incremental adaptations into contextualised thematic adaptations

Prospective incremental adaptations were shortlisted through a multi-stage engagement and refinement process between the project team and the RRG as described above. The outcome of this process was the co-design of two distinct adaptation themes where incremental adaptations suggested by the RRG were selectively stacked (Table 1): the first, "low-hanging fruit" or LHF, consisted of simple, immediate and reversible changes to existing farm systems that were considered good management practice and may occur over time in the absence of the present study. Incremental adaptations for LHF included changes in animal management/genetics, feedbase management, plant breeding and improved soil fertility (further details shown in Tables 1, S2 and S3). The second thematic adaptation was co-designed with an overarching aspiration of reducing net farm GHG emissions year on year, such that the trajectory of net farm GHG emissions over time diminished. We called this theme "towards carbon neutral" or TCN. Incremental adaptations subset within

TCN comprised longer term, more difficult, higher cost and sometimes irreversible interventions imposed on top of those in LHF including, but not limited to, pasture renovation with deep-rooted genotypes, injecting livestock with an enteric CH_4 inhibition vaccine and planting regionally appropriate trees on a portion of existing farmland or on newly purchased land. A summary of each adaptation theme together with subset incremental adaptations are shown in Table 1 (further details are provided in Tables S2 and S3).

Results

Climate crisis impacts on status quo operations

Despite a 3–7% and 5–11% reduction in annual rainfall in 2030 and 2050 and 4–14% higher monthly temperatures (Fig. S1), elevated atmospheric CO_2 concentrations under future climates improved annual pasture production for the beef and sheep farms by 2–3% and 7–8%, respectively. This result was primarily attributed to a 10–30% increase in late winter and early spring pasture growth rates (Fig. S2). However, the lower rainfall and higher temperatures in 2050 decreased late spring pasture production falling below the historical herbage growth rates (Fig. S2).

Under future climates, liveweight produced by the beef farm increased by around 1% (Table 2). The liveweight production of the sheep farm increased by 3% and 4% for 2030 and 2050, respectively, while wool production remained similar to historical values (Table 3). Future climate change resulted in a 1–3% reduction in supplementary feed requirement for the beef farm and a 6–13% reduction for the sheep farm. Warmer future climates facilitated higher stocking rates through longer retainment of juvenile animals before sale and reduced lamb mortality, coupled with a significant reduction in SOC fluxes of 45–133% by 2050. Collectively, these changes increased net GHG emissions and emissions intensities (Tables 2 and 3). Increased pasture and livestock production combined with lower supplementary feed inputs requirements under future climates increased net cash flows (NCF; per-carbon tax) by 13% for the beef farm for both time horizons (Fig. 2a) and by 16–18% for the sheep farm (Fig. 2b) by 2030 and 2050, respectively.

Table 2 Long-term average historical, 2030 and 2050 biophysical, environmental, and economic outcomes for the high rainfall beef production system

Variables	Scenarios						
	Hist	Base30	Base50	LHF30	LHF50	TCN30	TCN50
Livestock system							
Stocking rate (DSE ha^{-1} year^{-1})	24.2	24.4	24.4	25.3	25.2	25.8	25.6
Farm liveweight production (t LW year^{-1})	287	291	290	332	332	344	349
Protein production (t protein year^{-1})	52	52	52	60	60	62	63
Pasture production (t DM ha^{-1} year^{-1})	20.0	20.5	20.3	21.5	21.2	22.6	19.8
Supplementary feeding (t DM ha^{-1} year^{-1})	0.80	0.78	0.79	0.67	0.67	0.30	0.29
Total livestock GHG emissions (t CO_2e)	3864	3881	3892	4364	4364	4496	4619
Methane vaccine (t CO_2e ha^{-1} year^{-1}, CH_4 reduction)	–	–	–	–	–	1.53	1.55
Initial SOC stocks (t C ha^{-1}, 1 m depth)	235	240	241	240	243	240	249
Final SOC stocks (t C ha^{-1}, 1 m depth)	238	241	241	243	244	249	254
SOC change (t C ha^{-1} year^{-1})	0.14	0.06	– 0.05	0.12	0.06	0.45	0.21
SOC change (t CO_2e ha^{-1} year^{-1})	0.53	0.21	– 0.18	0.44	0.20	1.65	0.77
Forestry system							
Site C change (t C ha^{-1} year^{-1})	–	–	–	–	–	8.3	4.6
Site C change (t CO_2e ha^{-1} year^{-1})	–	–	–	–	–	30.5	16.7
Site C change × 50 ha (t CO_2e year^{-1})	–	–	–	–	–	1527	836
Net farm emissions (t CO_2e)	3563	3762	3992	4114	4250	1161	2462
Net emission intensity (kg CO_2e kg^{-1} LW produced)	12.4	12.9	13.8	12.4	12.8	7.8	9.5
Net emission intensity (kg CO_2e kg^{-1} protein)	69	72	76	69	71	43	53
Net cash flow-pre-carbon tax/income (‘000 AU$, mean 5 years)	446	512	513	525	532	579	573
Net cash flow-post-carbon tax/income (‘000 AU$, mean 5 years)				515	524	661	623

Hist historical, *Base* baseline farm with no adaptation, *LHF* low hanging fruit, *TCN* towards carbon neutral

Table 3 Long-term average historical, 2030 and 2050 biophysical, environmental and economic outcomes for the low rainfall sheep production system

Variables	Scenarios						
	Hist	Base30	Base50	LHF30	LHF50	TCN30	TCN50
Livestock system							
Stocking rate (DSE ha^{-1} $year^{-1}$)	9.0	9.1	9.1	9.1	9.1	10.0	10.4
Farm liveweight production (t LW $year^{-1}$)	371	384	387	371	380	476	495
Farm wool production (t CFA $year^{-1}$)	70	70	70	86	86	95	95
Protein production (t protein $year^{-1}$)	137	139	139	152	154	181	184
Pasture production (t DM ha^{-1} $year^{-1}$)	7.2	7.7	7.8	7.8	8.0	8.2	8.6
Supplementary feeding (t DM ha^{-1} $year^{-1}$)	0.32	0.30	0.28	0.12	0.12	0.08	0.06
Total livestock GHG emissions (t CO_2e)	7037	7094	7081	7666	7676	8479	8650
Methane vaccine (t CO_2e ha^{-1} $year^{-1}$, CH_4 reduction)	–	–	–	–	–	0.62	0.63
Initial SOC stocks (t C ha^{-1}, 1 m depth)	175	183	185	183	185	183	186
Final SOC stocks (t C ha^{-1}, 1 m depth)	179	185	187	185	188	186	189
SOC change (t C ha^{-1} $year^{-1}$)	0.21	0.12	0.11	0.15	0.13	0.16	0.15
SOC change (t CO_2e ha^{-1} $year^{-1}$)	0.77	0.42	0.42	0.53	0.48	0.57	0.55
Forestry system							
Site C change (t C ha^{-1} $year^{-1}$)	–	–	–	–	–	1.5	1.7
Site C change (t CO_2e ha^{-1} $year^{-1}$)	–	–	–	–	–	5.4	6.2
Site C change × 200 ha (t CO_2e $year^{-1}$)	–	–	–	–	–	1071	1247
Net farm emissions (t CO_2e)	4612	5753	5762	5980	6144	3623	3680
Net emission intensity (kg CO_2e kg^{-1} LW produced)	6.0	7.4	7.4	7.0	7.2	4.7	4.8
Net emission intensity (kg CO_2e kg^{-1} CFW produced)	33.5	41.1	41.1	39.1	39.8	20.0	19.8
Net emission intensity (kg CO_2e kg^{-1} protein)	33.8	41.5	41.4	39.2	39.9	20.1	20.0
Net cash flow-pre-carbon tax/income (‘000 AU$, mean 5 years)	937.4	1122	1147	1223	1188	1311	1330
Net cash flow-post-carbon tax/income (‘000 AU$, mean 5 years)				1215	1177	1377	1399

Hist historical, *Base* baseline farm with no adaptation, *LHF* low hanging fruit, *TCN* towards carbon neutral

Low-hanging fruit (LHF) thematic adaptation

The LHF adaptation theme generally improved annual productivity and economic outcomes, but also increased total and net GHG emissions relative to the historical and baseline 2030/2050 conditions (Tables 2 and 3). These changes reflect the fact that higher productivity (animals/ha) resulted in greater methane from enteric fermentation (CH_4/ha), demonstrating the tight coupling between production and GHG emissions in livestock production systems.

Similar to other livestock production systems studies (Phelan et al. 2015), outcomes were, however, dependent on site and time horizon. Relative to 2030 and 2050, annual pasture production on the beef farm increased by 5% and 4%, respectively, while pasture produced on sheep farm increased by 1% and 3%. Combined with a 10% increase in animal genetic feed conversion efficiency (FCE), increased stocking rate and pasture production boosted liveweight production of the beef farm by 14–15%. Removal of the cattle from the sheep farm for the LHF adaptation—as suggested by the RRG—reduced total livestock production (− 3% and − 2% for 2030 and 2050, respectively), but wool production increased by 23%, increasing protein production by 10–11% (Fig. 3, Table 3).

Higher livestock production and lower annual supplementary feeding (16% reduction for the beef farm and > 50% for the sheep farm; Fig. 3) increased annual average pre-carbon tax NCF by 2–8% in 2030 and 4–3% in 2050, respectively. For the beef farm, SOC sequestration rates doubled in 2030 with the introduction of LHF, but in 2050, LHF reversed SOC change from negative to positive under the adaptation (i.e. from − 0.18 t CO_2e ha^{-1} $year^{-1}$ with the 2050 baseline to + 0.20 t CO_2e ha^{-1} $year^{-1}$ with the 2050 LHF; Table 2). For the sheep farm, LHF interventions increased annual SOC changes by 14–26% under the future climates.

Despite significant removal of atmospheric CO_2 by sequestration in soil organic matter, higher stocking rates and pasture intake on the sheep farm resulted in higher net GHG emissions compared with the baseline. The beef and sheep farm net emissions increased by 9% and 4% in 2030, respectively, and by 6% for both farms in 2050, respectively, mainly due to higher enteric CH_4 associated with greater production and minor changes in CO_2 emissions from higher

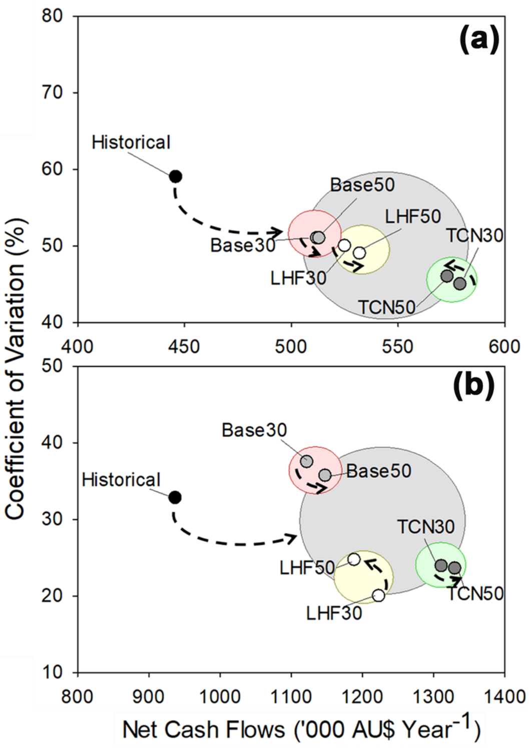


Fig. 2 Mean and coefficient of variation of net cash flow (NCF) for the beef farm (**a**) and sheep farm (**b**). Black, white, grey and dark grey circles represent the historical period, future climates (2030 and 2050, red bubbles), low hanging fruit (LHF, yellow bubbles) and towards carbon neutral (TCN, green bubbles) thematic adaptations, respectively. The grey bubbles depict the results from the scenarios reported under future climates. Arrows represent direction of change between 2030 and 2050 within each adaptation

fertilisation and N_2O from dung and urine. Compared with the baseline, LHF30 and LHF50 net GHG emission intensities decreased 4–7% and 4–6% in the beef and sheep farms, respectively, due to additional liveweight production diluting the additional net GHG emissions. Such results demonstrate that while the LHF intervention was conducive to adaptation, it was less effective in terms of mitigation. For the beef farm, the environmental impact in terms of net farm emissions, the higher animal production and high NCF ranked the LHF thematic adaptation relatively well in the multidimensional analysis, with better performance than the baseline farm systems and historical periods (Fig. 4a). For the sheep farm, the LHF30 farm system was only slightly better than LHF50, baseline farm systems and the historical period with respect to the multidimensional analysis. Increased livestock production and profits under future climates regardless of adaptation were eroded by additional GHG emissions (Fig. 4b).

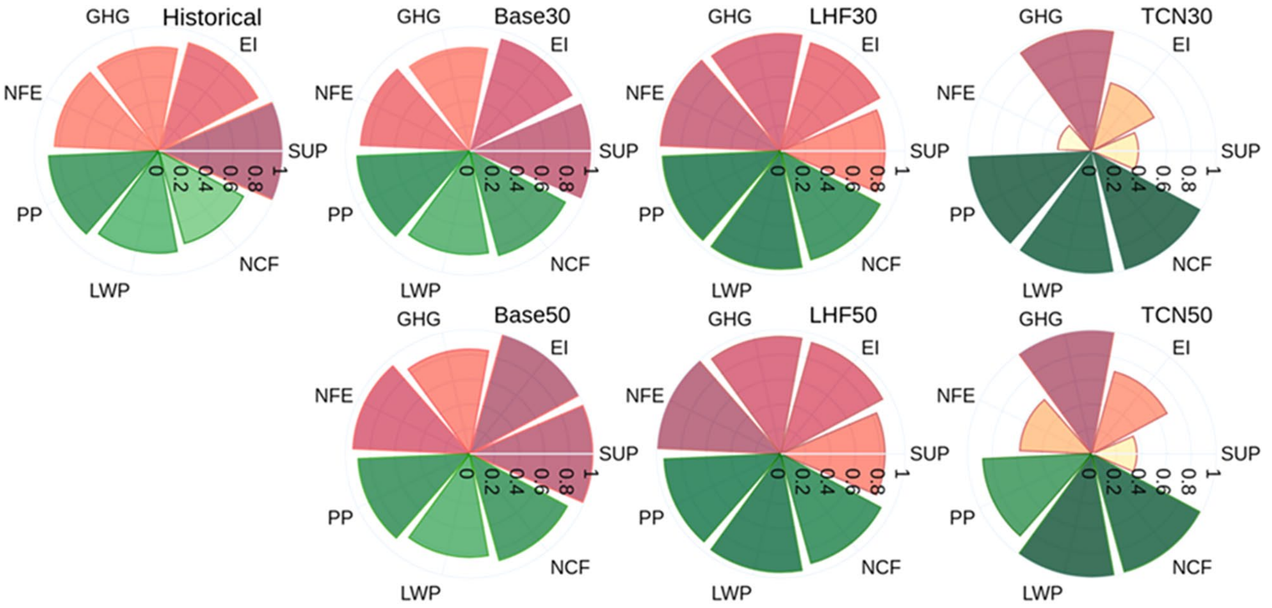
Towards carbon neutral (TCN) thematic adaptation

The TCN adaptation theme resulted in further improvements in productivity and profitability, and, notably, resulted in deep cuts in GHG emissions (Fig. 4). Pasture production of the beef farm increased by 10% in 2030 but decreased 2% by 2050, relative to corresponding baselines (Table 2). The lower cumulative annual production for the beef farm by 2050 was counterbalanced by higher pasture quality (+2.3 DMD%; data not shown), a 14% increase in metabolisable energy (data not shown) and shifts in the seasonal herbage growth pattern towards late summer and autumn months. In contrast, pasture production for the sheep farm increased by 6% and 10% for 2030 and 2050, respectively (Table 3).

Relative to the baselines, liveweight and wool production increased under TCN by up to 20% for the beef farm and 32% for the sheep farm. Livestock GHG emissions increased, but after accounting for changes in SOC associated with the deep-rooted legume (*Medicago sativa*), avoidance of enteric CH_4 with the vaccine and sequestration of carbon in woody biomass and soil beneath them, net GHG emissions fell by 69% and 37% for the beef and sheep farms in 2030, respectively, and by 38% and 36% in 2050, respectively (Fig. 5). Emissions intensities also declined substantially, decreasing by 31–40% for the beef farm and by as much as 52% for the sheep farm (Fig. 3). Together, these stacked interventions that together comprised TCN significantly reduced net farm GHG emissions, improving multidimensional outcomes for both farms (Fig. 4).

To extricate the GHG emissions mitigation contributed by each incremental adaptation, we disaggregated TCN (as shown in Fig. 5 by green segments). Relative to total farm emissions, the additional mitigation provided by adding a deep-rooted legume (lucerne) to the existing pasture base was smallest (1–13%), followed by background SOC sequestration (2–20%), and planting trees (13–33%), while the use of the enteric CH_4 vaccine provided the greatest relative mitigation benefit (20–24%) under future climates. These results highlight the need to define adaptations to specific regions, as well as the importance of stacking together emissions reduction and CO_2 removal technologies to maximise cumulative abatement. Despite high costs of tree establishment (\$1500 ha^{-1}), both livestock systems maintained (sheep farm) or increased pre-carbon tax NCF (beef farm) relative to the baselines (Fig. 2). Introducing carbon taxes on the net GHG emissions associated with the adapted farm systems slightly reduced annual average NCF for the LHF scenarios, and significantly increased TCN annual average NCF under future climates (Tables 2 and 3).

(a) Beef farm



(b) Sheep farm

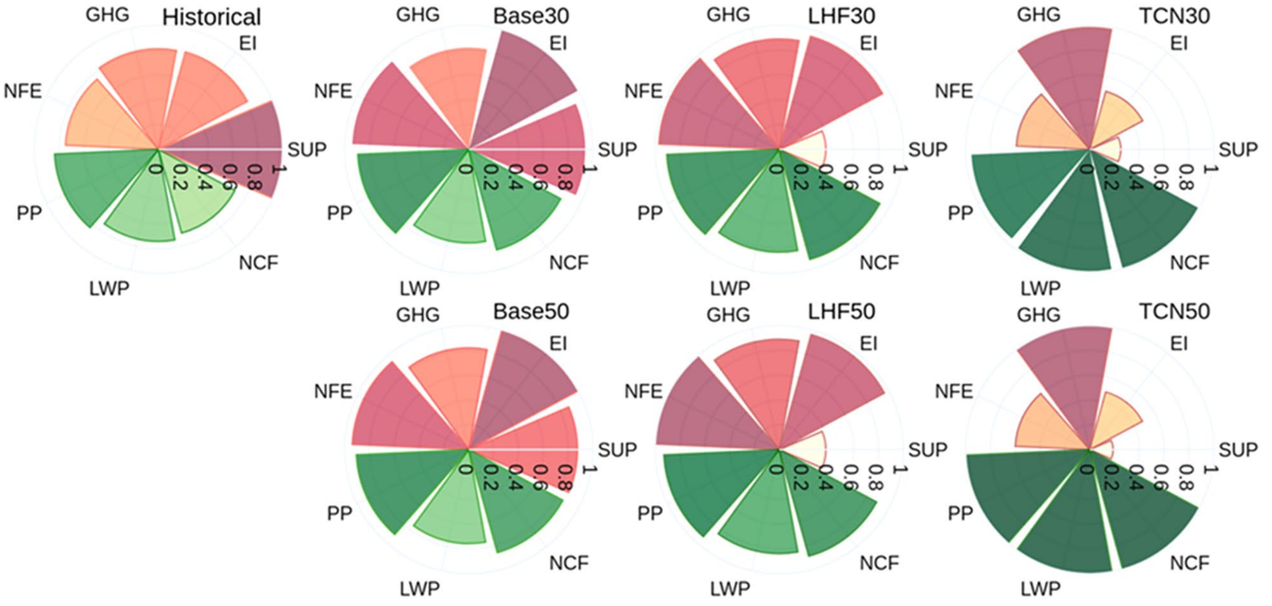


Fig. 3 Relative change in production, profit and GHG emissions in 2030 and 2050 for the beef and sheep farms relative to the historical period. Changes are computed relative to the ceiling of the same metric across all other time horizons and adaptations. *SUP* supplementary feeding (kg DM ha^{-1}), *PP* pasture production (kg DM ha^{-1}), *LWP* liveweight production (kg protein production ha^{-1}), *NCF* pre-carbon taxes net cash flow ($), *EI* emission intensity (kg protein kg^{-1} CO$_2$e), *GHG* total greenhouse gas emissions (t CO$_2$e), *NFE* net farm emissions (t CO$_2$e). Green segments: positive outcomes. Red segments: negative outcomes. Darker colours indicate values close to 1 and lighter colours indicate values close to 0

Discussion

Wicked problems faced by the agricultural sector urgently call for collaboration between institutions, disciplines and sectors to ensure that proposed adaptation/mitigation interventions are peer-reviewed and refined, environmentally and economically sustainable, and socially acceptable (Jones et al. 2017; Rawnsley et al. 2019). To empower local communities during the process, it is essential that aspiring adaptation proponents engage a range of stakeholders

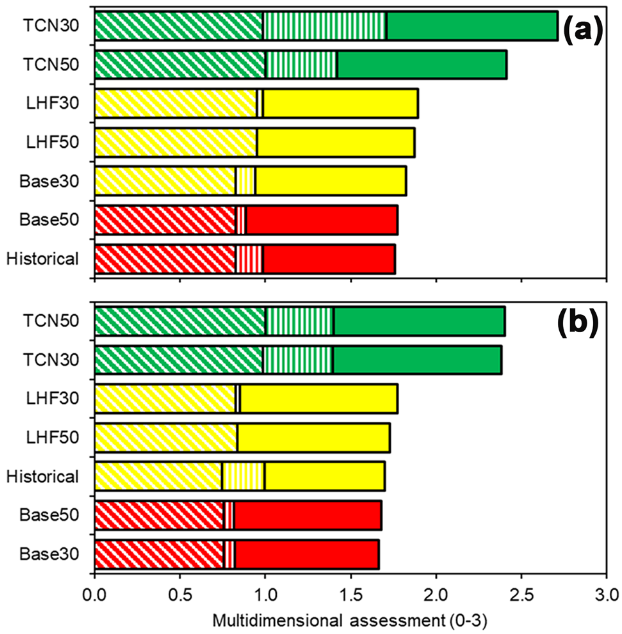


Fig. 4 Normalised multidimensional assessment across climate horizons and thematic adaptations for the beef farm (**a**) and sheep farm (**b**). Bars depict the sum of normalised biophysical, economic, and environmental metrics: liveweight production (diagonal stripes), inverse net farm emissions (1 − normalised net farm emissions, vertical stripes) and net cash flows (solid fill). Green, yellow and red bars indicate scenarios ranked above the 75th percentile, between 75 and 25th percentile, and below the 25th percentile, respectively

directly or indirectly affected by the climate crisis (Shahpari et al. 2021). Here, we engaged farmers and livestock industry professionals to co-design thematic innovation bundles. For this purpose, real farm systems and adaptations were iteratively defined and contextualised by a regional group of experts (RRG), providing industry guiderails for the modelling and social research teams to ensure that our results were fit-for-purpose.

An important insight of the present study was that—even in the absence of adaptation—average annual pasture growth in Tasmania will increase under 2050 climatic conditions. This result is particularly noteworthy given the emphasis on extreme climatic events encapsulated within our approach for generating climatic data (Harrison et al. 2016a). This was in part due to warmer winter temperatures improving growth rates, and in part due to elevated atmospheric CO_2 resulting in extended daily canopy photosynthesis that outweighed the truncated growing season over late spring and summer (Moore and Ghahramani 2013). Higher pasture production in 2050 translated to a small increase in livestock productivity, increasing net farm GHG emissions and net emissions intensity, but also reducing the need for purchased supplementary feed. Collectively these factors increased the quantum and inter-annual variability of NCF. For example, 5-year

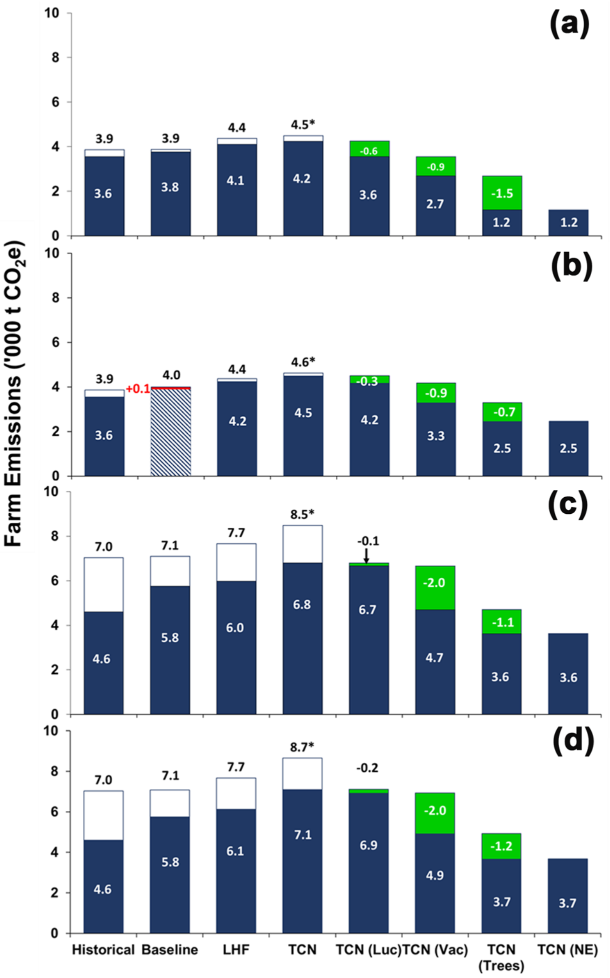


Fig. 5 Disaggregation of incremental adaptations stacked together to form the thematic TCN adaptation. Net GHG emissions (blue bars), total GHG emissions (white plus blue bars) and GHG abatement generated by incremental constituents of TCN (green bars) for the beef (**a** and **b**) and sheep farms (**c** and **d**) under 2030 (**a** and **c**) and 2050 climates (**b** and **d**). Bars to the right of the TCN bar indicate sequential disaggregation, with each subsequent bar containing one less incremental adaptation. White bar with blue stripes indicates farm GHG emissions without SOC sequestration and red bar represents SOC losses increasing net GHG emissions. *To show the effect of lucerne in TCN (LUC), the TCN white bar indicates SOC sequestration given in LHF scenarios and excluding the effect of lucerne. *Luc* incorporation of deep-rooted species (Lucerne), *Vac* injection of enteric CH4 inhibition vaccine to livestock. *Trees* planting tree species endemic to region

mean NCF variability of the sheep farm increased from a historical value of 33–37% in 2050. A significant contribution to higher net GHG emissions was produced by SOC fluxes (particularly for the beef farm to 2050) due to increasing temperatures combined with declining annual rainfall (Orgill et al. 2014). Declining soil carbon sequestration under future warmer climates may constrain nations from leaning too heavily on abatement provided by soil carbon in their Nationally Determined Contributions (Vermeulen et al.

2019). Collectively, these findings suggest that while the changing climate may be beneficial in terms of productivity and profitability for Tasmanian producers, this may come at the expense of additional GHG emissions. This again highlights the need for interventions that systematically decouple the often-tight linkage between productivity and GHG emissions (Harrison et al. 2021). In the present study, the addition of alfalfa in the pasture mix and the increase in feed conversion efficiency (reducing supplementary feeding and improving C sequestration in soils and vegetation) allowed such decoupling, decreasing emissions and increasing livestock production (Tables 2 and 3).

We showed that implementing simple, reversible, low-cost interventions (LHF thematic adaptation) further increased profitability and reduced emissions intensity by increasing pasture and liveweight production (due to the dilution of net emissions over more product) and lowering annual supplementary feeding (Tables 2 and 3). The increased availability of pasture and the reduced dependence on external inputs decreased the variability of economic indicators (NCF) and enabled more effective adaptation to climate change (Fig. 2). However, warmer future climates may affect the SOC sequestration, which plays an integral part into soil health (regulating soil biological, chemical, and physical properties, water-holding capacity, and structural stability) and farm resilience (Stevens 2018), with greater losses in SOC increasing net farm GHG emissions. Traditionally, the scientific community viewed reduced emissions intensity as beneficial, reflecting productivity improvements per unit GHG emissions produced (Ho et al. 2014). However, reductions in emissions intensity will in future not be enough to prevent global temperature change; even with lower emissions intensity, the atmosphere only perceives net GHG, with additional GHG further contributing to global warming. Indeed, international policy (e.g., COP26 Glasgow agreement in 2022) and industry roadmaps (e.g., Meat and Livestock Australia's Carbon Neutral 2030 Initiative) call for net-zero emissions by specified time horizons of 2050 or 2030, and rightly include interim targets to ensure longitudinal progress.

Our TCN intervention resulted in deep cuts in emissions in a profitable and sustainable way. TCN comprised a stacked combination of deeper-rooted pasture species (lucerne) across a greater proportion of the grazing platform, injecting all animals with a vaccine to inhibit enteric CH_4 and planting trees on farm. These interventions were prioritised by the RRG so to target multiple and differing pathways for emissions mitigation: avoidance, removal and offsetting GHG emissions. For both farms, pasture renovation with lucerne mostly increased pasture production, except for the TCN50 beef farm. However, livestock production was the highest of all scenarios explored, indicating that seasonal feed supply better matched herd demand for TCN50, decreasing need for supplementary feed by more than half (Tables 2 and 3) and making NCF for TCN the least variable to long-term shifts in temperature and weather patterns (Fig. 2). For the beef farm, planting trees resulted in the greatest reduction in net GHG emissions in 2030, due to the rapid growth and subsequent sequestration of carbon in the Tasmanian Blue Gums (*Eucalyptus globulus*) in the first 10–20 years of growth (data not shown). However, by 2050, the enteric CH_4 vaccine was more effective in reducing net GHG emissions, with consistent reduction across the two future climate horizons. For the sheep farm, enteric CH_4 vaccine was the most effective avenue for reducing GHGs, since lower rainfall at this site inhibited carbon sequestered in tree plantings. For both sites, inclusion of deep rooted lucerne into the pasture sward increased pasture production and carrying capacity, but had little effect on net GHG emissions. This suggests that any aspiration to mitigate farm level emissions must first consider the individual potential of each option, second consider the extent to which incremental adaptations can be stacked together for mutual (potentially multiplicative) benefit, and third consider potential co-benefits, including social implications (e.g., changes to farm management, increased risk of bushfires associated with trees on farm, need for new skills and knowledge to adopt). Overall, we show that bundling multiple climate change adaptation and GHG emissions mitigation options resulted in a triple win in terms of production, profit and GHG emissions (both net and emissions intensity).

Potential mitigation or adaptation is, however, not the only factor in determining whether or not farmers adopt a particular intervention, technology or knowledge product (Harrison et al. 2021). In fact, there is likely to be a trade-off between adoptability and emissions mitigation potential. This is clearly illustrated by contrasting the LHF with the TCN, the latter having more benefit, but also requiring more skills, time, labour and organisation to implement. Part of the LHF was improved animal feed conversion efficiency, which increases liveweight gain per unit feed intake and generally reduces enteric CH_4 kg^{-1} DMI. This was nominated by the RRG because improved FCE has and continues to occur over time as producers select more efficient animals to retain, breed from, or purchase (Mottet et al. 2017). Similarly, measuring soil fertility and applying fertiliser is considered status quo (Christie et al. 2018) for many farm businesses, and thus would not be expected to require additional skills or knowledge. As well, producers frequently adapt to the changing climate, selecting pasture or crop species with phenology more suited to their environment (Liu et al. 2020a, b), seasonally modifying whole farm stocking rates and the feedbase, or increasing the reliance of irrigation or supplementary feed to flatten the seasonal pasture supply curve. In contrast, interventions in the TCN adaptation could be considered higher risk, higher cost, or may require new skills and knowledge to realise collective benefit. While an enteric CH_4 inhibitor administered as a vaccine is presumably a relatively simple intervention, such vaccines do not exist commercially at the time of writing. Despite potential social licence and cost-effectiveness, commercial and large-scale production of such vaccines may be some time away (Reisinger et al. 2021). Similarly, planting trees requires knowledge of the type of tree species to plant and the time of year to plant, as well as the regular watering needed over summer until tree roots are established. Planting trees thus comes with financial, time and knowledge impost, and thus may be a less attractive intervention in contrast to traditional approaches, such as improving soil fertility under LHF. To be effective in Nationally Determined Contributions, forests should have enduring permanence (e.g., 100 years) (Wise et al. 2019). Therefore, monitoring, reporting and verification of carbon storage must be sufficient to demonstrate CO_2 removal with simple accounting but also clear incentives to encourage participation of multiple stakeholders, including smaller land holders, and the best management practices (Wise et al. 2019).

Conclusions

The need for participatory, demand-driven and inclusive co-design processes with end-users in developing GHG emissions mitigation and climate change adaptations will be critical to ensuring improvement in the sustainability of future agri-food production systems. Even with explicit and deliberate account of extreme weather events, we found that future climates will generally improve pasture and livestock production in Tasmania at least to 2030, possibly even to 2050. A win–win outcome, stacking incremental climate change adaptations into singular contextually defined thematic adaptations further increased productivity, profitability and reduced GHG emissions of livestock farms. However, multidisciplinary studies of this type require more planning, labour and time commitment from proponents, and as such are often not easy to implement. The combination of technologies, skills and practices generated in such consortia will be, however, much more effective in achieving mitigation and adaptation compared with the benefit derived from any single intervention. In increasing order of magnitude, we showed that mitigation afforded by planting of deep-rooted legumes to increase soil carbon at depth, stimulating pasture growth to improve soil health and organic matter, planting of trees endemic to region, and use of enteric CH_4 inhibition technologies will be the most effective in the quest for GHG emissions reduction, offsetting or removals. We suggest that clear frameworks are necessary to encourage participation of multiple stakeholders to enable transdisciplinary collaboration and a continuum of research, development and extension. This will lead to greater end-user confidence in, and adoption of, purported technologies, skills or practices purported for mitigation, adaptation, or both. We opine that a net-zero or carbon neutral agriculture sector need not necessarily be attained by every farm adopting such technologies or being carbon neutral. Some farms and regions will need to be substantive carbon sinks, while others will always be net carbon polluters. To optimise land used for food production vs environmental services, future work should aim to identify regions within landscapes that would be better targeted for carbon sequestration or enhancement of ecosystems services and other regions more suited to agri-food systems. In this way, society could better optimise the balance between food security (agri-food production) and mitigation of global climate change (mitigation and carbon sequestration).

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Data availability All data will be made available by the authors on request.

Declarations

Conflict of interest The authors declare no competing interests.

References

Alcock DJ, Hegarty RS (2011) Potential effects of animal management and genetic improvement on enteric methane emissions, emissions intensity and productivity of sheep enterprises at Cowra, Australia. Anim Feed Sci Technol 166–167:749–760. https://doi.org/10.1016/j.anifeedsci.2011.04.053

Alcock DJ, Harrison MT, Rawnsley RP, Eckard RJ (2015) Can animal genetics and flock management be used to reduce greenhouse gas emissions but also maintain productivity of wool-producing enterprises? Agric Syst 132:25–34. https://doi.org/10.1016/j.agsy.2014.06.007

Ara I, Turner L, Harrison MT, Monjardino M, deVoil P, Rodriguez D (2021) Application, adoption and opportunities for improving decision support systems in irrigated agriculture: a review. Agric Water Manag 257:107161. https://doi.org/10.1016/j.agwat.2021.107161

Ash A, Hunt L, McDonald C, Scanlan J, Bell L, Cowley R, Watson I, McIvor J, MacLeod N (2015) Boosting the productivity and profitability of northern Australian beef enterprises: exploring innovation options using simulation modelling and systems analysis. Agric Syst 139:50–65. https://doi.org/10.1016/j.agsy.2015.06.001

Bell LW, Harrison MT, Kirkegaard JA (2015) Dual-purpose cropping—capitalising on potential grain crop grazing to enhance mixed-farming profitability. Crop Pasture Sci. https://doi.org/10.1071/CPv66n4_FO

CCIA (2020) Climate Change in Australia. Climate information, projections, tools and data. https://www.climatechangeinaustralia.gov.au/en/. Accessed 14 Feb 2022

Christie KM, Smith AP, Rawnsley RP, Harrison MT, Eckard RJ (2018) Simulated seasonal responses of grazed dairy pastures to nitrogen fertilizer in SE Australia: pasture production. Agric Syst 166:36–47. https://doi.org/10.1016/j.agsy.2018.07.010

Christie KM, Smith AP, Rawnsley RP, Harrison MT, Eckard RJ (2020) Simulated seasonal responses of grazed dairy pastures to nitrogen fertilizer in SE Australia: N loss and recovery. Agric Syst 182:102847. https://doi.org/10.1016/j.agsy.2020.102847

Cole MB, Augustin MA, Robertson MJ, Manners JM (2018) The science of food security. NPJ Sci Food 2(1):14. https://doi.org/10.1038/s41538-018-0021-9

Coleman K, Jenkinson D (2014) RothC: a model for the turnover of soil carbon model description and user guide. Rothamsted Research, Harpenden, UK (2014). https://www.rothamsted.ac.uk/sites/default/files/RothC_guide_WIN.pdf Accessed 26 May 2021

Cotching WE (2018) Organic matter in the agricultural soils of Tasmania, Australia—a review. Geoderma 312:170–182. https://doi.org/10.1016/j.geoderma.2017.10.006

Cullen BR, Rawnsley RP, Eckard RJ, Christie KM, Bell MJ (2014) Use of modelling to identify perennial ryegrass plant traits for future warmer and drier climates. Crop Pasture Sci 65:758–766. https://doi.org/10.1071/CP13408

Cullen B, Harrison M, Mayberry D, Cobon D, Davison T, Eckard R (2021) Climate change impacts and adaption strategies for pasture-based industries: Australian perspective. NZGA: Res Pract Ser 17:139–148. https://doi.org/10.33584/rps.17.2021.3476

Duan Q, Xin X, Yang G, Chen B, Zhang H, Yan Y, Wang X, Zhang B, Li G (2011) Current situation and prospect of grassland management decision support systems in China. In: Computer and computing technologies in agriculture IV. Springer, Berlin, pp 134–146

Dunn J, Wiedemann S, Eckard RJ (2020) A greenhouse accounting framework for beef and sheep properties based on the Australian National Greenhouse Gas Inventory methodology. Retrieved from http://piccc.org.au/Tools. Accessed 15 July 2021

Falloon P, Smith P, Coleman K, Marshall S (1998) Estimating the size of the inert organic matter pool from total soil organic carbon content for use in the Rothamsted carbon model. Soil Biol Biochem 30:1207–1211. https://doi.org/10.1016/S0038-0717(97)00256-3

Farina R, Sándor R, Abdalla M, Álvaro-Fuentes J, Bechini L, Bolinder MA, Brilli L, Chenu C, Clivot H, De Antoni Migliorati M, Di Bene C, Dorich CD, Ehrhardt F, Ferchaud F, Fitton N, Francaviglia R, Franko U, Giltrap DL, Grant BB, Guenet B, Harrison MT, Kirschbaum MUF, Kuka K, Kulmala L, Liski J, McGrath MJ, Meier E, Menichetti L, Moyano F, Nendel C, Recous S, Reibold N, Shepherd A, Smith WN, Smith P, Soussana J-F, Stella T, Taghizadeh-Toosi A, Tsutskikh E, Bellocchi G (2021) Ensemble modelling, uncertainty and robust predictions of organic carbon in long-term bare-fallow soils. Glob Change Biol 27:904–928. https://doi.org/10.1111/gcb.15441

Fleming A, O'Grady AP, Stitzlein C, Ogilvy S, Mendham D, Harrison MT (2022) Improving acceptance of natural capital accounting in land use decision making: barriers and opportunities. Ecol Econ 200:1–19. https://doi.org/10.1016/j.ecolecon.2022.107510

Gephart JA, Davis KF, Emery KA, Leach AM, Galloway JN, Pace ML (2016) The environmental cost of subsistence: optimizing diets to minimize footprints. Sci Total Environ 553:120–127. https://doi.org/10.1016/j.scitotenv.2016.02.050

Godde CM, Mason-D'Croz D, Mayberry DE, Thornton PK, Herrero M (2021) Impacts of climate change on the livestock food supply chain; a review of the evidence. Glob Food Secur 28:100488. https://doi.org/10.1016/j.gfs.2020.100488

Harris RMB, Love PT, Fox-Hughes P, Remenyi TA, Bindoff NL (2019) An assessment of the viability of prescribed burning as a management tool under a changing climate—stage 2. Technical Report, Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania

Harrison MT (2021) Climate change benefits negated by extreme heat. Nat Food 2:855–856. https://doi.org/10.1038/s43016-021-00387-6

Harrison MT, Evans JR, Moore AD (2012a) Using a mathematical framework to examine physiological changes in winter wheat after livestock grazing: 1. Model derivation and coefficient calibration. Field Crops Res 136:116–126. https://doi.org/10.1016/j.fcr.2012.06.015

Harrison MT, Evans JR, Moore AD (2012b) Using a mathematical framework to examine physiological changes in winter wheat after livestock grazing: 2. Model validation and effects of grazing management. Field Crops Res 136(0):127–137. https://doi.org/10.1016/j.fcr.2012.06.014

Harrison MT, Christie KM, Rawnsley RP, Eckard RJ (2014) Modelling pasture management and livestock genotype interventions to improve whole-farm productivity and reduce greenhouse gas emissions intensities. Anim Prod Sci 54:2018–2028. https://doi.org/10.1071/AN14421

Harrison MT, Cullen BR, Rawnsley RP (2016a) Modelling the sensitivity of agricultural systems to climate change and extreme climatic events. Agric Syst 148:135–148. https://doi.org/10.1016/j.agsy.2016.07.006

Harrison MT, Cullen BR, Tomkins NW, McSweeney C, Cohn P, Eckard RJ (2016b) The concordance between greenhouse gas emissions, livestock production and profitability of extensive beef farming systems. Anim Prod Sci 56:370–384. https://doi.org/10.1071/AN15515

Harrison MT, Roggero PP, Zavattaro L (2019) Simple, efficient and robust techniques for automatic multi-objective function parameterisation: case studies of local and global optimisation using APSIM. Environ Model Softw 117:109–133. https://doi.org/10.1016/j.envsoft.2019.03.010

Harrison MT, Cullen BR, Mayberry DE, Cowie AL, Bilotto F, Badgery WB, Liu K, Davison T, Christie KM, Muleke A, Eckard RJ (2021) Carbon myopia: the urgent need for integrated social, economic and environmental action in the livestock sector. Glob Change Biol 27(22):5726–5761. https://doi.org/10.1111/gcb.15816

Henry BK, Eckard RJ, Beauchemin KA (2018) Review: adaptation of ruminant livestock production systems to climate changes. Animal 12:s445–s456. https://doi.org/10.1017/S1751731118001301

Herd RM, Oddy VH, Bray S (2015) Baseline and greenhouse-gas emissions in extensive livestock enterprises, with a case study of feeding lipid to beef cattle. Anim Prod Sci 55:159–165. https://doi.org/10.1071/AN14222

Ho CKM, Jackson T, Harrison MT, Eckard RJ (2014) Increasing ewe genetic fecundity improves whole-farm production and reduces greenhouse gas emissions intensities: 2. Economic performance. Anim Prod Sci 54:1248–1253. https://doi.org/10.1071/AN14309

Hong C, Burney JA, Pongratz J, Nabel JEMS, Mueller ND, Jackson RB, Davis SJ (2021) Global and regional drivers of land-use emissions in 1961–2017. Nature 589(7843):554–561. https://doi.org/10.1038/s41586-020-03138-y

Hoyle FC, D'Antuono M, Overheu T, Murphy DV (2013) Capacity for increasing soil organic carbon stocks in dryland agricultural systems. Soil Res 51:657–667. https://doi.org/10.1071/SR12373

Ibrahim A, Harrison M, Meinke H, Fan Y, Johnson P, Zhou M (2018) A regulator of early flowering in barley (*Hordeum vulgare* L.). PLoS ONE 13(7):e0200722. https://doi.org/10.1371/journal.pone.0200722

Ibrahim A, Harrison MT, Meinke H, Zhou M (2019) Examining the yield potential of barley near-isogenic lines using a genotype by environment by management analysis. Eur J Agron 105:41–51. https://doi.org/10.1016/j.eja.2019.02.003

IPCC (2021) Summary for policymakers. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds) Climate Change 2021: the physical science basis. Contribution of Working Group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. https://doi.org/10.1017/9781009157896

Jenkinson DS, Coleman K (2008) The turnover of organic carbon in subsoils. Part 2. Modelling carbon turnover. Eur J Soil Sci 59:400–413. https://doi.org/10.1111/j.1365-2389.2008.01026.x

Jones JW, Antle JM, Basso B, Boote KJ, Conant RT, Foster I, Godfray HCJ, Herrero M, Howitt RE, Janssen S, Keating BA, Munoz-Carpena R, Porter CH, Rosenzweig C, Wheeler TR (2017) Brief history of agricultural systems modeling. Agric Syst 155:240–254. https://doi.org/10.1016/j.agsy.2016.05.014

Langworthy AD, Rawnsley RP, Freeman MJ, Pembleton KG, Corkrey R, Harrison MT, Lane PA, Henry DA (2018) Potential of summer-active temperate (C_3) perennial forages to mitigate the detrimental effects of supraoptimal temperatures on summer home-grown feed production in south-eastern Australian dairying regions. Crop Pasture Sci 69(8):808–820, 813. https://doi.org/10.1071/CP17291

Liu Y, Chen J, Pan T, Liu Y, Zhang Y, Ge Q, Ciais P, Penuelas J (2020a) Global Socioeconomic Risk of Precipitation Extremes Under Climate Change. Earths Future 8(9):e2019EF001331. https://doi.org/10.1029/2019EF001331

Liu K, Harrison MT, Shabala SN, Meinke HB, Ahmed I, Zhang Y, Tian X, Zhou M (2020b) The state of the art in modeling waterlogging impacts on plants: what do we know and what do we need to know. Earths Future 8:e2020bEF001801. https://doi.org/10.1029/2020EF001801

Lynch DH, Cohen RDH, Fredeen A, Patterson G, Martin RC (2005) Management of Canadian prairie region grazed grasslands: soil C sequestration, livestock productivity and profitability. Can J Soil Sci 85(2):183–192. https://doi.org/10.4141/s04-053

Makate C, Makate M, Mango N, Siziba S (2019) Increasing resilience of smallholder farmers to climate change through multiple adoption of proven climate-smart agriculture innovations. Lessons from Southern Africa. J Environ Manag 231:858–868. https://doi.org/10.1016/j.jenvman.2018.10.069

Meier EA, Thorburn PJ, Bell LW, Harrison MT, Biggs JS (2020) Greenhouse gas emissions from cropping and grazed pastures are similar: a simulation analysis in Australia. Front Sustain Food Syst. https://doi.org/10.3389/fsufs.2019.00121

MLA (2022) State of the industry report: the Australian red meat and livestock industry. Meat & Livestock Australia, North Sydney, NSW, Australia. https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/soti-report/mla-state-of-industry-report-2020.pdf. Viewed 2 Feb 2022

Moore AD, Ghahramani A (2013) Climate change and broadacre livestock production across southern Australia. 1. Impacts of climate change on pasture and livestock productivity, and on sustainable levels of profitability. Glob Change Biol 19:1440–1455. https://doi.org/10.1111/gcb.12150

Moore AD, Donnelly JR, Freer M (1997) GRAZPLAN: decision support systems for Australian grazing enterprises. III. Pasture growth and soil moisture submodels, and the GrassGro DSS. Agric Syst 55(4):535–582. https://doi.org/10.1016/S0308-521X(97)00023-1

Moore AD, Eckard RJ, Thorburn PJ, Grace PR, Wang E, Chen D (2014) Mathematical modeling for improved greenhouse gas balances, agro-ecosystems, and policy development: lessons from the Australian experience. Wiley Interdiscip Rev: Clim Change 5:735–752. https://doi.org/10.1002/wcc.304

Morais TG, Teixeira RFM, Domingos T (2019) Detailed global modelling of soil organic carbon in cropland, grassland and forest soils. PLoS ONE 14(9):e0222604. https://doi.org/10.1371/journal.pone.0222604

Mottet A, de Haan C, Falcucci A, Tempio G, Opio C, Gerber P (2017) Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. Glob Food Secur 14:1–8. https://doi.org/10.1016/j.gfs.2017.01.001

Northcote K (1979) A factual key for the recognition of Australian soils, 4th edn. Rellim Technical Publishers, Glenside

Orgill SE, Condon JR, Conyers MK, Greene RSB, Morris SG, Murphy BW (2014) Sensitivity of soil carbon to management and environmental factors within Australian perennial pasture systems. Geoderma 214–215:70–79. https://doi.org/10.1016/j.geoderma.2013.10.001

Palisade Corporation (2012) The decision tools suite version 5. Palisade Corporation, Ithaca

Phelan DC, Harrison MT, Kemmerer EP, Parsons D (2015) Management opportunities for boosting productivity of cool-temperate grazed dairy farms under climate change. Agric Syst 138:46–54. https://doi.org/10.1016/j.agsy.2017.04.003

Rawnsley RP, Smith AP, Christie KM, Harrison MT, Eckard RJ (2019) Current and future direction of nitrogen fertiliser use in Australian grazing systems. Crop Pasture Sci 70:1034–1043. https://doi.org/10.1071/CP18566

Reisinger A, Clark H, Cowie AL, Emmet-Booth J, Gonzalez Fischer C, Herrero M, Howden M, Leahy S (2021) How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals? Philos Trans R Soc A: Math Phys Eng Sci 379(2210):20200452. https://doi.org/10.1098/rsta.2020.0452

Richards GP, Evans DMW (2004) Development of a carbon accounting model (FullCAM Vers. 1.0) for the Australian continent. Aust for 67(4):277–283. https://doi.org/10.1080/00049158.2004.10674947

Sándor R, Ehrhardt F, Grace P, Recous S, Smith P, Snow V, Soussana J-F, Basso B, Bhatia A, Brilli L, Doltra J, Dorich CD, Doro L, Fitton N, Grant B, Harrison MT, Kirschbaum MUF, Klumpp K, Laville P, Léonard J, Martin R, Massad R-S, Moore A, Myrgiotis V, Pattey E, Rolinski S, Sharp J, Skiba U, Smith W, Wu L, Zhang Q, Bellocchi G (2020) Ensemble modelling of carbon fluxes in grasslands and croplands. Field Crops Res 252:107791. https://doi.org/10.1016/j.fcr.2020.107791

Shahpari S, Allison J, Harrison MT, Stanley R (2021) An integrated economic, environmental and social approach to agricultural land-use planning. Land 10:1–18

Smith RW, Statham M, Norton TW, Rawnsley RP, Statham HL, Gracie AJ, Donaghy DJ (2012) Effects of wildlife grazing on the production, ground cover and plant species composition of an established perennial pasture in the Midlands region, Tasmania. Wildl Res 39(2):123–136. https://doi.org/10.1071/WR11032

Smith AP, Christie KM, Harrison MT, Eckard RJ (2021) Ammonia volatilisation from grazed, pasture based dairy farming systems. Agric Syst 190:103119. https://doi.org/10.1016/j.agsy.2021.103119

Snow V, Rodriguez D, Dynes R, Kaye-Blake W, Mallawaarachchi T, Zydenbos S, Cong L, Obadovic I, Agnew R, Amery N, Bell L, Benson C, Clinton P, Dreccer MF, Dunningham A, Gleeson M, Harrison M, Hayward A, Holzworth D, Johnstone P, Meinke H, Mitter N, Mugera A, Pannell D, Silva LFP, Roura E, Siddharth P, Siddique KHM, Stevens D (2021) Resilience achieved via multiple compensating subsystems: the immediate impacts of COVID-19 control measures on the agri-food systems of Australia and New Zealand. Agric Syst 187:1–10. https://doi.org/10.1016/j.agsy.2020.103025

Stevens AW (2018) Review: the economics of soil health. Food Policy 80:1–9. https://doi.org/10.1016/j.foodpol.2018.08.005

Stiglitz JE, Stern N, Duan M, Edenhofer O, Giraud G, Heal GM, La Rovere EL, Morris A, Moyer E, Pangestu M, Shukla PR., Sokona Y, Winkler H (2017) Report of the high-level commission on carbon prices. World Bank, Washington, DC. https://doi.org/10.7916/d8-w2nc-4103

Vermeulen S, Bossio D, Lehmann J, Luu P, Paustian K, Webb C, Augé F, Bacudo I, Baedeker T, Havemann T, Jones C, King R, Reddy M, Sunga I, Von Unger M, Warnken M (2019) A global agenda for collective action on soil carbon. Nat Sustain 2(1):2–4. https://doi.org/10.1038/s41893-018-0212-z

Wiedemann SG, Ledgard SF, Henry BK, Yan M-J, Mao N, Russell SJ (2015) Application of life cycle assessment to sheep production systems: investigating co-production of wool and meat using case studies from major global producers. Int J Life Cycle Assess 20(4):463–476. https://doi.org/10.1007/s11367-015-0849-z

Wise L, Marland E, Marland G, Hoyle J, Kowalczyk T, Ruseva T, Colby J, Kinlaw T (2019) Optimizing sequestered carbon in forest offset programs: balancing accounting stringency and participation. Carbon Balance Manag 14(1):16. https://doi.org/10.1186/s13021-019-0131-y

Zhang Y, Mounter S, Griffith G (2018) Updating and recalibrating equilibrium displacement models of the Australian livestock industries: beef. Australas Agribus Rev 26:48–67. https://doi.org/10.22004/ag.econ.285019