# final report

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Prepared by: Matthew Harrison, Karen Christie, Franco Bilotto, Nicoli Barnes (TIA); Bill Malcolm (UoM), Alison Hill (TIA), Lydia Turner (TIA), Emily Hall (TIA)
Tasmanian Institute of Agriculture (TIA), University of Tasmania and University of Melbourne (UoM)

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# NEXUS project: exploring profitable, sustainable livestock businesses in an increasingly variable climate

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# Abstract

While society increasingly demands emissions abatement from the livestock sector, farmers are concurrently being forced to adapt to a changing climate. Using people-centred design with industry stakeholders, we examined how combining multiple interventions ('stacking') impacted on the productivity, profitability, greenhouse gas emissions of livestock farms under future climates underpinned by more frequent extreme weather events. Our prognostics indicate that while 2030 and 2050 climates in the Australian State of Tasmania will have modest positive impacts on livestock productivity and profitability, soil carbon sequestration rates will fall by 45-133%. Transformational gains in feed conversion efficiency, enterprise climatic diversification and renovating grass pastures with perennial legumes were prospective adaptations. Use of *Asparagopsis* seaweed as a feed supplement and planting trees had the greatest mitigation potential, but also the greatest cost. New business skills, improvements in agility, and partnerships with learned people were perceived as critical precursors for successful adaptation. Priorities for future research included assessments of (1) co-benefits and trade-offs of adaptation, (2) costs associated with transitioning to net-zero, (3) enterprise climatic diversification, (4) feed-conversion efficiency, (5) improving natural capital and carbon removals. The transdisciplinary approaches co-developed were highly commended given emphasis placed on development of solutions are credible, legitimate and fit-for-purpose.

# Executive summary


## Background

The prevailing climate across eastern Australia has undergone a step-change in recent decades, with annual rainfall trending downwards since around the year 2000. At the same time, the livestock sector is under burgeoning societal demand to improve sustainability, for example by reducing greenhouse gas (GHG) emissions, improving land custodianship and maintaining a 'social licence' to operate, while simultaneously supplying the bulk of global protein needs. The NEXUS programme elicited contextualised farming systems changes enabling improved production, profit and environmental stewardship against background changes in climates, markets and consumer attitudes.

## Objectives

The primary aim of NEXUS was to co-develop demand-driven farming systems enabling adaptation to future conditions, focussing on systemic opportunities for improving productivity, profitability and social licence to operate, while concurrently reducing GHG emissions. A secondary objective was to identify research, development and extension priorities to guide future investment in adaptation and mitigation.

## Methods

We invoked transdisciplinary research approaches encompassing biophysical and economic modelling, social research, on-farm experimentation, and iterative co-design with a regional reference group of experts (RRG) to explore adaptation and mitigation pathways under 2030 and 2050 climates underpinned by more frequent extreme weather events. The RRG and project team co-designed interventions modelled, with the former providing feedback on the credibility, legitimacy and realism of simulated interventions. Using a beef- and sheep farm in the north-west and central Midlands of Tasmania respectively, we calibrated omnibus modelling packages and conducted social research to assess farm and farmer adaptive capacity required to implement the interventions modelled. For each farm, five interventions were co-developed: (1) the Base farm, primarily assuming continuation of *status quo* operations, (2) Low Hanging Fruit (LHF), wherein simple, immediate and reversible technologies and/or practices were adopted to improve pasture and animal production, (3) Towards Carbon Neutral, comprising several contextualised mitigation options stacked onto the LHF option, (4) Income Diversification, through implementation of enterprises designed to be rainfall invariant, in some cases also shifting part of the business to distinct regions to diversify climatic exposure, and (5) Carbon Neutral bundles, wherein several transformational technologies or practices were stacked together to achieve net-zero annual GHG emissions. For conservatism, we assumed *de minimus* livestock productivity co-benefit for feed supplement interventions (e.g., *Asparagopsis taxiformis*).

## Results

The Towards Carbon Neutral and Carbon Neutral packages elicited the greatest GHG emissions abatement, with several alternative packages comprising the latter achieving net-zero emissions.

Income Diversification was, for the most part, dependant on external or specialist input – including collaboration with wind turbine companies or ready access to irrigation water – and as such, Income Diversification interventions were not considered accessible to the industry at large. The cost of continuing 'business as usual' and purchasing carbon credits to offset *status quo* GHG emissions was the most expensive option. This result was perhaps serendipitous, since purchasing offsets to reduce farm GHG emissions was also considered the least socially acceptable option. In contrast, stacking together three synergistic interventions (planting trees for carbon, reducing enteric methane with *Asparagopsis* feed supplement, and adopting animal genotypes with higher genetic feed conversion efficiency) not only transitioned farming systems to net-zero emissions, but also raised profit by 2-30%. Several forms of new knowledge were identified as important in adapting to a changing climate and/or reducing GHG, including (1) new business skills, (2) partnerships with learned people, (3) proactive strategy adaptation and (4) failing well; learning from mistakes was perceived as a critical precursor to successful and dynamic adaptation to changing climates, markets and consumer attitudes.

## Benefits to industry

NEXUS revealed the fortuitous result that projected climate change to 2050 is likely to have little impact on the Tasmanian sheep and beef sector, and, for farms proximal to the north-west coast at least, may even have modest benefit. While our engagement showed that the majority of the public perceive that more action must be taken to adapt to the changing climate, we concurrently showed that Tasmanian livestock producers have and are doing a great deal to adapt to the changing climate while protecting and conserving natural resources. Indeed, pasture management, improvements to sward legume content and control of feral animals have been regularly actioned hitherto. Our work showed that more than 80% of the Tasmanian public regularly consume dairy and red meat products, with surveys suggesting greater consumer preference for livestock products derived from farms prioritising animal health and welfare and practices to reduce carbon footprint. This suggests that improved awareness of existing environmental stewardship conducted by landholders would further improve consumer confidence in the red meat sector.

## Concluding remarks and recommendations

NEXUS underscored several research, development and extension issues required for the industry to adapt and prosper under future conditions. Some of these include investigation of the co-benefits and trade-offs associated with (adaptation/mitigation) interventions, stacking of several synergistic interventions (e.g. carbon removals, GHG mitigation, improved pasture fertility), and approaches for improving both natural capital (e.g. biodiversity) and carbon sequestration at the farm and landscape scales. In all cases, the development of technologies and practices to profitably decouple the tight coupling between productivity and GHG emissions was highly prospective, given the need to ensure mitigation of global warming, farm prosperity, international competitiveness together with resilient, inclusive and sustainable food security.

# Extended summary

While society increasingly demands emissions abatement from the livestock sector, farmers are concurrently being forced to adapt to a changing climate. Using participatory approaches with industry stakeholders, we examined how stacking together multiple individual adaptations impacted on farm productivity, profitability, greenhouse gas (GHG) emissions in future climates underpinned by more frequent extreme weather events. We also identified human capacities and capabilities required to implement these co-designed adaptations at the farm and industry scale.

We first modelled the impacts of 2030 and 2050 climates on representative beef and sheep farms in high- and low-rainfall zones of the Tasmanian State of Australia. Despite reduced annual rainfall in 2030 (3-7%) and 2050 (5-11%), higher monthly average temperature (4-14%) and higher atmospheric $CO_2$ (28-51%), future climates improved annual pasture production in the high- and low- rainfall by 2-3% (beef cattle farm) and 7-8% (sheep farm), respectively. Using these climate change impacts as narrative in people-centred design, we conceptualised several interventions aimed at both *adapting* farm systems to future climates but also *reducing* GHG emissions. By co-designing adaptations with a 'regional reference group' (RRG) comprised by industry stakeholders in this way, we framed then iteratively refined model outputs in line with end-user feedback. As such, the RRG gained knowledge of and confidence in the modelling frameworks invoked, while the project team improved scientific framing of contemporary farm systems, the skills and technology required to adapt, and end-user propensity to change.

Future climates resulted in warmer conditions year-round; in winter, this elevated pasture growth rates and reduced supplementary feed requirements (such as hay and silage). These factors modestly improved livestock productivity (wool and meat production) and farm profits. While these results herald a bright outlook for livestock production in Tasmania, we found that the future for soil carbon sequestration is less optimistic, with sequestration rates declining by 45-133% by 2050 under *ceteris paribus* management. Higher livestock pasture intakes under future climates (2-3%) and projected SOC losses by 2050 for the beef farm or decline in accumulation of SOC for the sheep farm, relative to historically, increased net GHG emissions by 6-12%, demonstrating a tight coupling between growth in GHG emissions and productivity gains.

Over the course of several workshops, we gleaned RRG and broader industry feedback on adaptation and mitigation opportunities in light of quantified impacts of climate change. We used a combination of modelling packages to examine incremental adaptations (for example, FullCAM for trees, @Risk for economic analyses) then stacked together incremental adaptations into four co-designed themes; 'Low Hanging Fruit' (LHF; being simple, reversible changes), 'Towards Carbon Neutral' (TCN; interventions allowing carbon sequestration and/or $CH_4$/$N_2O$ avoidance/reduction), 'Income Diversification' (ID), and 'Transformational' (TR; such as feeding *Asparagopsis* seaweed to reduce enteric $CH_4$).

Several important messages emerged from this research:

1. The impact of farming system interventions (e.g. feed supplements and tree planting) was much greater than the impact of climate change between 2030 and 2050.

2. There were few triple-win interventions allowing GHG emissions mitigation, improved productivity and improved profitability under future climates. Of those that enabled such change, the most promising interventions included transformational animal feed conversion efficiency (TFCE, at 30% gain in current FCE by 2050), feed conversion efficiency (FCE, 15% improvement in FCE by 2050) and renovating existing grass pastures with lucerne to improve digestibility per hectare to increase carrying capacity/livestock production and improve soil carbon stocks.
3. Purchasing an extra farm block in a new climatic zone diversified climatic exposure and significantly raised profit and production but was considered by the RRG more difficult to implement due to geographical separation and additional labour requirements to manage separate operations.
4. Altering lambing time (two weeks earlier) had a significant impact on productivity and profit, although altering calving time (two weeks earlier) for the high rainfall beef farm had less impact.
5. Use of *Asparagopsis taxiformis* (seaweed) as a livestock feed supplement had the greatest impact of all interventions on GHG emissions, but also came with the greatest negative impact on farm profit. Due to the absence of analytical measurements, we did not include productivity co-benefits associated with feeding of *Asparagopsis* in the modelling.
6. Biochar as a livestock feed supplement had significant potential for the modelled beef production system but was counterproductive and costly for the sheep production system.
7. Changes in stocking rates to match seasonal changes in pasture supply under the warming climate resulted in modest improvements in productivity and profitability.
8. Planting trees or thickening of existing tree groves had high carbon removal potential (less than *Asparagopsis* as a feed supplement) but disadvantaged both productivity and profit (again noting that no co-benefit for livestock production was assumed),
9. However, there comes a point in time when annual accumulation of carbon in trees diminishes, tree plantings ‘buy us time’ for other interventions to become available.
10. With regards to stacked interventions, the LHF adaptation theme had the greatest impact on pasture production in late winter/early spring, transiently improving baseline growth rates by 30-60%. In contrast, the TCN adaptation improved pasture growth rates by 60-120% in late summer/early autumn, particularly for the beef production system.
11. Several forms of new knowledge and/or skills were identified as important in adapting to a changing climate or GHG emissions abatement. These included (1) new business skills, (2) partnerships and collaboration with learned people, (3) being proactive in developing a strategy for the farm system while acknowledging that in some years, change may not be possible, and (4) failing well: learning from mistakes and refining management going forwards was perceived as positive and necessary in adapting to future changes in climates, markets and consumer attitudes.
12. Several social, environmental and institutional factors were shown to influence adoption, even when an adaptation could be profitable and reduce GHG emissions. Broadly these factors included (1) the need for ‘real’ solutions that were economically and environmentally beneficial, (2) impact on stewardship of the land and people, including intergenerational sustainability (3) ability to dissect complexity, particularly that pertaining to climate change and (4) level of trust that could be placed in information purporting viable change; information derived from large corporate institutions (real estate, fertiliser manufacturers to abattoirs) was often perceived as conflicted with commercial

interests and/or not fully transparent, and (5) agility of adaptation, with many stakeholders commenting on the need to 'think fast and adapt quicker'.

13. A survey of red meat producers across Tasmania revealed that more than 94% of people believed in climate change and suggested that more action must be taken to help address this challenge. Pasture management, improving legume content and better controlling feral animal browsing of pastures were common adaptations farm managers had previously actioned to adapt to climatic variability or change.
14. An extensive survey of 1,176 Tasmanians revealed that 85% of people regularly consume red meat, with 95% of people frequently consuming dairy. Around 89% and 79% of males and females regularly ate red meat; people with higher education ate less red meat; people who were older, had children, or had higher salary consumed more red meat in general. Consumer preference was stronger for livestock products derived from farms that prioritised animal health and welfare, environmental stewardship, and low-emissions premium products.

An important question posed by the RRG was the economic cost of transitioning farm systems to net zero emissions if there was a price placed on farm net GHG emissions. In addressing this question, we found that the cost of purchasing carbon credits to offset all farm emissions was greatest (33-64% of farm operating profit), while stacking together three synergistic interventions (planting trees for carbon, reducing enteric methane with *Asparagopsis* as a feed supplement and adopting an animal genotype with higher feed conversion efficiency) not only resulted in net-zero emissions, but also raised profit by 2-30%. The cost of attaining carbon neutrality was thus likely to be low (or negative) if several beneficial interventions were imposed simultaneously.

We also deployed a nascent GHG mitigation opportunity on a northern Tasmanian farm following MLA guidelines for 'Involve and Partner' (I&P) activities. The feeding of biochar was suggested for further investigation based on anecdotal evidence that biochar feed supplement could improve liveweight gain and animal health, reduce enteric methane and improve soil carbon through enrichment of organic carbon in manure. We conducted workshops both on the I&P farm as well as two other farms who had adopted biochar feeding at an earlier stage, the latter allowing insight into longitudinal farmer learning with regards to use of biochar. At the time of writing, our evaluation indicates little difference between the liveweight gain and manure organic carbon content of the control and biochar treatments. Feedback from workshops indicated that participants were overall very pleased with the information they received, and, notwithstanding results from the I&P experiment *per se*, most participants documented an intent to use biochar as a feed supplement for reasons related to animal health, soil carbon and long-term sustainability.

Based on our research, development, extension and end-user feedback, a number of future research priorities emerged. High priority opportunities included:

1. **Quantification of co-benefits and trade-offs** associated with various interventions, e.g., potential livestock productivity co-benefits associated with planting shelter belts or renovating pastures with lucerne, or with feeding of *Asparagopsis*, as interventions that improved liveweight gain generally resulted in improved profitability. Trade-offs evaluate downside risk associated with change, e.g.

losses in pasture area elicited by tree planting, or additional labour needed to manage an additional paddock that is geographically isolated from an existing farm.

2. **Stacking of synergistic combinations of GHG mitigation options:** Overlaying combinations ("stacking") of two or three beneficial adaptations that combined mitigation, sequestration, avoidance and adaptation (e.g. planting trees, renovating pastures with lucerne, feeding *Asparagopsis* and improving animal feed conversion efficiency) often resulted in the greatest benefit in terms of production, GHG emissions and profitability. However, difficulties in adoption increased with the number of stacked interventions due to additional skills, knowledge, labour and capital needed to implement more complex stacked interventions. Aspirations of Australia's nascent 'Integrated Farm Management' greenhouse gas emissions policy align well with the benefits obtained by stacking adaptations.
3. **Economic costs of transitioning to net-zero:** due to the varied and multidimensional pathways with which GHG emissions could be reduced, further research is needed on the costs of pathways for modifying farming systems to attain net-zero emissions.
4. **Reducing downside risk associated with climates and markets** by improving the agility of adaptation through trusted knowledge sources offering well-grounded solutions (agronomic, environmental, social) including academics, including knowledge of when (and when not) to change the *modus operandi*.
5. **Climatic exposure diversification:** purchasing an additional farm or block in a different climatic zone to the current farm to diversify climatic exposure and risk.
6. **Animal genetics:** genetic and husbandry approaches for transformational improvement in feed conversion efficiency, including implications of such at the whole farm scale across climatic zones.
7. **Feed supplements:** GHG and economic implications of the type of biochar feed supplement (e.g. whether the derivative product from wood or crop residues) and *Asparagopsis* on the consumption, animal health and liveweight responses.
8. **The carbon-natural capital nexus:** approaches for improving natural capital (e.g. biodiversity) and carbon sequestration at the farm and landscape scales.
9. **Feedbase:** productive digestible legumes that can be incorporated into existing pastures to improve pasture available energy per hectare.
10. **Transdisciplinary approaches:** application of the approach developed here – across disciplines and institutions (refining economic and biophysical modelling with social research and stakeholder discussions) could be generically scaled to any agricultural system, location or problem. Such approaches are urgently needed with nascent research items above to ensure that proposed solutions are credible, legitimate and fit-for-purpose.

The impact of NEXUS engagement (accounting for direct interactions only) is estimated be to very significant. Over the course of NEXUS, more than 3,920 people were *directly* engaged in workshops, on-farm demonstrations, webinar discussions and polls, or conferences, while *indirect* engagement is conservatively estimated at 169,000 people. The estimated cumulative impact of the modelling, social research and industry engagement includes removal of 333,000 tonnes $CO_2$-eq from the atmosphere via improvement in pasture and livestock production over 227,000 hectares, improving farm gate revenue by more than $11.7M. Global spatial extent and/or longitudinal impact is likely to be greater, as neither the impact of scientific publications nor information legacy post-project has been accounted for in these estimates. Overall, these values indicate significant potential for further impact through the development of new skills, technologies and practices that allow decoupling of the often-tight relationship between livestock productivity and GHG emissions. The need for and application of new knowledge will become increasingly crucial as the global climate changes and anthropogenic demand for premium quality low-emissions Australian livestock product burgeons in the years and decades to come.

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# 1 Background

While agricultural productivity gains have contributed to local food security on the one hand (Liu et al., 2020a; 2020b), increasingly frequent extreme weather events borne by the climate crisis continue to threaten the consistency of global food supply on the other (IPCC, 2021). During the last four decades, climate change has quadrupled the frequency of natural disasters, causing losses of more than US$280B in crop and livestock production (FAO, 2021). Ambient carbon dioxide ($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 highest average increase in decadal global net anthropogenic GHG emissions (56 ± 6.0 Gt $CO_2$e $yr^{-1}$) occurred between 2010 and 2019, with further increases expected by mid-century (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). The development of sustainable, inclusive, transdisciplinary and enduring solutions that systematically decouple production and GHG emissions while concurrently facilitating adaptation to a burgeoning climate crisis is now imperative (Harrison et al. 2021; Cole et al., 2018).

The Australian red meat industry contributed AU$17.6B to Gross Domestic Product in 2018-19 from 25M cattle and 64M sheep (MLA, 2022). In the absence of adaptation to climate change, livestock production and profitability across southern Australia is projected to decline, largely due to a truncated pasture growing season and compounded and cascading extreme weather events (Harrison et al. 2014; Ho et al. 2014; Cullen et al., 2021). While gradual climate change trends have had little effect on farm-level production, extreme weather events have and will result in deep cuts to farm income, often with significant natural, human and social costs through animal mortality, loss of vegetation, biodiversity and soil carbon, staff redundancies and labour shortages, and sometimes even catastrophic destruction of farm infrastructure (Farina et al. 2021; Harrison et al. 2021; Harrison 2021; Henry et al. 2022; Godde et al., 2021; IPCC, 2021; Sandor et al. 2020).

Hitherto, our colleagues have tended to focus on incremental adaptations with primarily unidisciplinary foci, such as effects caused by perturbations to the feedbase or animal management. By way of example, scholarly investigation of new plant genotypes for climate change adaptation is common, often underpinned by studies with an abiotic lens, such as drought or heat tolerance (Bell et al., 2013; Ghahramani and Moore, 2015; Ibrahim et al. 2018; 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 (Mueller et al., 2013; Langworthy et al., 2018; Meier et al. 2020), increase profitability (Phelan et al., 2015; Meyer et al., 2021) and reduce net farm GHG emissions (Meier et al., 2020). Many studies have examined GHG emissions mitigation interventions in isolation, such as altering lambing or calving times, increasing ewe genetic fecundity, changing trading model/enterprise mix etc (Alcock et al., 2015; Harrison et al., 2014). However, there are few assessments of how stacking (or layering) multiple GHG mitigation/climate change adaptation interventions (Harrison et al., 2021). Such work requires harmonised input across social, environmental, economic and institutional dimensions;

accordingly, multidisciplinary studies tend to be more difficult, time consuming and less common than unidisciplinary studies (Harrison et al., 2021; Liu et al. 2023).

The NEXUS project builds off a series of foundational research conducted in the recent past. For example, Southern Livestock Adaptation 2030 (SLA2030; B.SBP.0090) focussed on climate scenarios based on incremental or proportional changes to climate (e.g. Cullen et al., 2009; Cullen et al., 2010). The Dairy Business for Future Climates (DBFC) project built off SLA2030 by developing scientific frameworks for including more frequent extreme weather events, including extreme rainfall, drought and more severe heat waves (Harrison et al., 2016a) then examined the implications of such for dairy businesses (Harrison et al., 2017).

While previous research has examined the implications of isolated adaptations, there are few scientific assessments of layered (stacked) and contextually-customised studies in livestock production systems. Systems-based assessments that purport *adaptation* to future climates with concurrent *mitigation* to prevent global warming are uncommon and by extension, the human, social and institutional requirements associated with bundled adaptation and mitigation interventions are not well elucidated (Harrison et al., 2021).

The objectives of this project were thus to (1) explore the nexus between profitability, productivity and GHG emissions of stacked contextualised adaptation/mitigation interventions for livestock systems across a rainfall gradient under future climates in Tasmania, Australia; (ii) examine the human and social capacities and capabilities required to manage the modelled scenarios at farm and industry scales, including strategies to assess industry readiness to respond, (iii) implement an Involve and Partner on-farm experiment for exploring a nascent mitigation opportunity under commercial conditions, and (iv) communication and extension of project findings through a range of avenues, including peer-reviewed scientific journals, popular press, conferences and field days.

# 2 Project objectives

We have successfully completed all project objectives. These included:

**Objective one** – Modelled climate change scenarios against 2030 and 2050 horizons, incorporating coverage of climate modelling including extreme climate events for case study location.

**Objective two** – Greenhouse gas emissions and intensity benchmarking for two case study locations and reporting costed on abatement and sequestration models for each site.

**Objective three** – A minimum of 10 perspective and costed adaption options identified for each site.

**Objective four** – Accompanying prioritised researchable recommendations developed coving beef and sheep enterprises as applicable by region with demonstrated consideration of:

i. Animal management
ii. Animal genetics
iii. Landscape management

**Objective five** – Report on 'Involve and Partner' activity/ies and review implementation success, effect on business performance and opportunities or barrier to further uptake.

**Objective six** – Report on the human and social capacities and capabilities required to manage the modelled scenarios at farm and industry scale, including strategies to assess industry readiness to respond, and engage producers and farm advisors in building capacity for adaptation and transformation.

**Objective seven** - Project communications and engagement with regional and transformational reference groups as well as other wider industry stakeholders. This will include details of project presentations at a minimum of 5 industry events or conferences.

**Objective eight** – Submission of a minimum of two scientific journal articles for peer review.

# 3 Methods

The nexus between livestock productivity, profitability and GHG emissions under an increasingly variable climate was explored for two case study farms, a beef farm in the higher rainfall NW of Tasmania (herein referred to as the beef farm) and a Merino fine wool, prime lambs and beef farm in the lower rainfall Northern Midlands of Tasmania (herein referred to as the sheep farm). A summary of the farm systems can be found in section 3.3.1 and 3.3.2, with additional details found in Appendix 8.1 (Tables A81.2 and A81.3). Data from these farm baselines were used to calibrate models and gain stakeholder confidence in modelling approaches.

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). We sense-checked model assumptions and results and co-designed adaptation themes using an iterative process with the RRG. Over multiple 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 further conducted surveys and interviews of the RRG and general public to gauge perceptions on the modelled adaptations, including qualitative factors such as legitimacy, trust, agility, as well as requirements for new skills, knowledge and technology (Fig. 1).

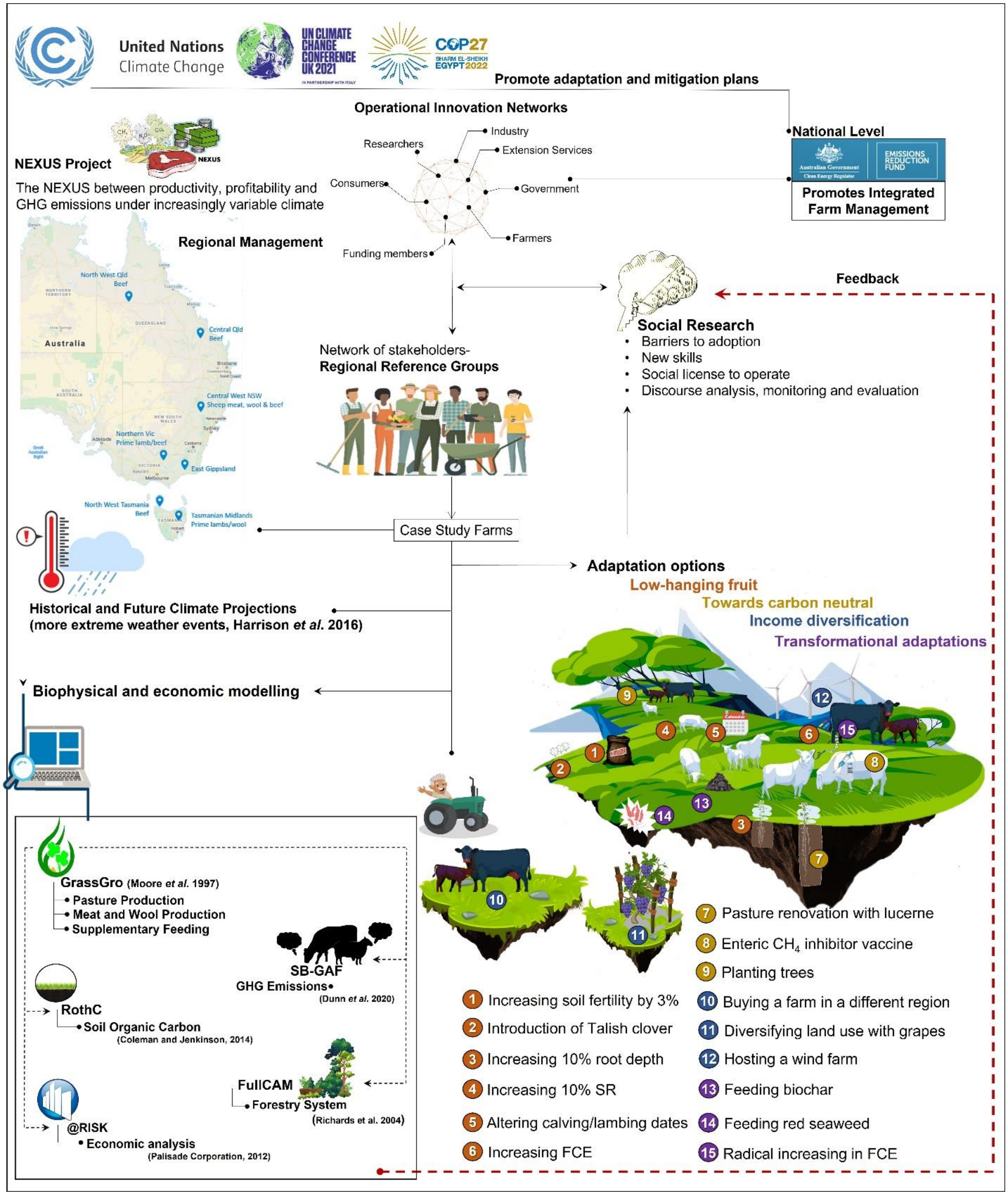


**Fig. 1.** Framework used for implementation of strategic international priorities in adaptation and mitigation into operational networks in the NEXUS project, including the co-design process for development of climate change adaptation and protocols for examining relationship between productivity, profitability and GHG emissions under historical and future climate scenarios. Orange, light brown, blue and purple circles represent low-hanging fruit (LHF), towards carbon neutral (TCN), income diversification (ID) and transformational (TR) adaptation themes, respectively.

## 3.1 Modelled climate change scenarios against 2030 and 2050 horizons, incorporating coverage of climate modelling including extreme climate events for case study location

Historical climate data for the study sites was sourced from the SILO (Scientific Information for Land Owners) meteorological archives (https://www.longpaddock.qld.gov.au/silo/) with the baseline assumed from 1 January 1980 to 31 December 2018 on a daily time-step. Historical data was used to produce future climate data (max/min 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 climatic extremes, including heatwaves, longer droughts and more extreme rainfall events (Harrison et al., 2016a). The approach used to generate future climate data (1) included mean changes in future climates projected for a region by an ensemble of global climate models, (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), generated climatic projections with increased variability.

Future climate projections were developed using monthly regional climate scaling factors (Table 1) based on Representative Concentration Pathway (RCP) 8.5 for 2030 and 2050 using raw data from GCMs provided in Harris et al. (2019). Changes in potential evapotranspiration and vapour pressure deficit for future climates were calculated using the Penman–Monteith equation (Penman and Keen, 1948; Monteith, 1965) and Teten's formula, respectively (Campbell and Norman, 1998). 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 Climate Change In Australia website (CCIA, 2020).

**Table 1.** Rainfall and temperature monthly change factors, showing fractional change in future temperature and rainfall relative to historical periods for 2030 and 2050. Data sourced from Harris *et al.* (2019) for Representative Concentration Pathways 8.5 (RCP8.5). For example, a value of 1.06 for rainfall in January 2030 suggests that mean monthly average rainfall for the region surrounding the sheep farm is projected to increase by 6% in January for a climate horizon centred on 2030.

| | | Sheep farm | | Beef farm | |
|---|---|---|---|---|---|
| | | Rainfall | Temperature | Rainfall | Temperature |
| 2030 | Jan | 1.06 | 1.04 | 0.99 | 1.05 |
| | Feb | 1.06 | 1.04 | 0.99 | 1.05 |
| | Mar | 0.97 | 1.05 | 0.94 | 1.05 |
| | Apr | 0.97 | 1.05 | 0.94 | 1.05 |
| | May | 0.97 | 1.05 | 0.94 | 1.05 |
| | Jun | 0.95 | 1.08 | 0.93 | 1.06 |
| | Jul | 0.95 | 1.08 | 0.93 | 1.06 |
| | Aug | 0.95 | 1.08 | 0.93 | 1.06 |
| | Sep | 0.92 | 1.07 | 0.89 | 1.06 |
| | Oct | 0.92 | 1.07 | 0.89 | 1.06 |
| | Nov | 0.92 | 1.07 | 0.89 | 1.06 |
| | Dec | 1.06 | 1.04 | 0.99 | 1.05 |
| | **Avg** | 0.97 | 1.06 | 0.94 | 1.06 |
| 2050 | Jan | 1.04 | 1.08 | 0.95 | 1.09 |
| | Feb | 1.04 | 1.08 | 0.95 | 1.09 |
| | Mar | 0.94 | 1.09 | 0.89 | 1.09 |
| | Apr | 0.94 | 1.09 | 0.89 | 1.09 |
| | May | 0.94 | 1.09 | 0.89 | 1.09 |
| | Jun | 0.94 | 1.14 | 0.89 | 1.11 |
| | Jul | 0.94 | 1.14 | 0.89 | 1.11 |
| | Aug | 0.94 | 1.14 | 0.89 | 1.11 |
| | Sep | 0.90 | 1.11 | 0.86 | 1.10 |
| | Oct | 0.90 | 1.11 | 0.86 | 1.10 |
| | Nov | 0.90 | 1.11 | 0.86 | 1.10 |
| | Dec | 1.04 | 1.08 | 0.95 | 1.09 |
| | **Avg** | 0.96 | 1.11 | 0.90 | 1.10 |

## 3.2 A minimum of 10 perspective and costed adaption options identified for each site

Over several workshops, we gleaned RRG thinking on the credibility and practicability of tactical and strategic incremental and systems adaptation and mitigation opportunities in light of quantified impacts of climate change for each case study farm. Table 2 contains a list of adaptations identified during (and refined after) workshops. As part of these discussions, we combined incremental adaptations into distinct themes; 'Low Hanging Fruit' (simple, reversible, easily adoptable interventions), 'Towards Carbon Neutral' (interventions aimed at reducing year on year emissions through sequestration, mitigation, and/or avoidance), 'Income Diversification' (of enterprise mix and climatic exposure of each enterprise) and 'Transformational' (strategic interventions aimed at either making a deep cut in GHG emissions, a step-change in productivity or profitability, or both).

Model inputs were refined iteratively in light of advice from the RRG. Taken together, this process (1) ensured rigour and realism of modelled results, (2) allowed the research team to learn directly from expert practitioners about realistic adaptation, (3) ensured confidence in simulated results by end-users and (4) helped raise ends-user awareness of a diverse and multi-disciplinary array of opportunities for adaptation to the climate crisis.

Details of the methodology of developing 10 perspective and costed adaption options for each site is documented in Section 3.3.

An Honours project was undertaken to assess the impacts of climate change on the productivity of the cow-calf enterprise of the beef farm and the wool enterprise of the sheep farm. This examined incremental adaptations, including changes to livestock production and sensitivity of prices or costs (Appendix 8.3). As part of this, a review of the effect of altered farm management practices (i.e. soil fertility and associated changes in stocking rates) was undertaken for the beef case study farm (Appendix 8.4).

**Table 2.** Preferences (votes) from the Regional Reference Group for adaptation options to be explored in NEXUS. Abbreviations: A = Adapt current farm system, TCN = towards carbon neutral, D = diversification, T = transformational.

| Adaptations | Theme | Votes | Comments |
|---|---|---|---|
| Future climate farm | A | 0 | * See climate impact analysis in this milestone report |
| Future climate farm plus expansion | D | 3 | * Purchasing additional arable agricultural land to remain a viable operation size for future generations<br>* Purchasing/acquiring offset non-arable land (bush block)<br>* Diversification of enterprise (e.g. purchase or establish horticultural enterprise) |
| Sustainable intensification 1 | A | 4 | * Deep-rooted pasture species mixtures (e.g. expand area of farm with lucerne), increase soil carbon at depth<br>* Increase fertiliser inputs (e.g. lime to balance pH, N fertiliser to increase pasture production)<br>* Viability of increasing irrigation capacity |
| Sustainable intensification 2 | A | 1 | * Selling cattle to build ewe and lamb numbers to match feed supply |
| Sustainable extensification | D | 4 | * Intensify 30% of farm, extensify around 70% of the farm<br>* Must account for animal co-benefits associated with shade and shelter<br>* Native covenants applicable in Tasmania – e.g. Bush Heritage, the Nature Conservancy |
| Low-hanging fruit | A | 8 | * Increasing stock vs decreasing stock<br>* Reduce mature cow weight, balancing stocking rate<br>* Sell heavier/sell lighter, sell earlier/sell later in combinations<br>* Less breeders, more purchases vs more breeders, less purchases<br>* Animal genetics for improved growth rate and/or low methane production<br>* Raise dairy beef as part of existing operation<br>* Improve soil fertility (fertiliser, liming for pH adjustment)<br>* Reduce calf and lamb mortality through improved nutrition while cows/ewes are pregnant<br>* Pasture improvement/renovation<br>* Whole farm planning approach – what parts of the farm should be used for production and what should not<br>* Maintain perennial ground cover year-round (add lucerne/legume, add mixed pasture species, add new pasture species adapted to different temps, plant trees)<br>* Is current system optimal with respect to climate change? Can we examine what happens if we convert from an annual system to a perennial system to improve long-term ground cover? |
| Carbon trader | TCN | 4 | * Buy carbon offsets from other communities |

| Adaptations | Theme | Votes | Comments |
|---|---|---|---|
| | | | * Purchase low-value block of land for woody vegetation to offset emissions<br>* Carbon already sequestered on farm. How to make the most of the good practices we have already done?<br>* Plant trees on worst 20%, reduce stocking rates by 10-20%<br>* Increase duration animals are confinement fed<br>* Planting of trees for shade, shelter, emissions reduction<br>* Planting legumes such as lucerne to build soil carbon at depth<br>* Methane-reducing interventions (e.g. supp feeding, vaccines etc) |
| Transformational diversification | D, T | 1 | * Build wind turbines on farm to reduce emissions and diversify income streams (NW Tas)<br>* Establishment of a horticulture enterprise or use solar panels on farm to reduce emissions (Midlands) |
| Transformational digitisation | A, D, T | 2 | * Adopt technology with seasonal climate forecasts<br>* Adopt/purchase satellite imagery for pasture productivity estimates<br>* Invest in GPS collars to improve animal welfare and to improve understanding of intra-paddock grazing variability to improve feed conversion efficiency |
| Social licence to operate | A | 2 | * Animal welfare improvement in response to public concerns<br>* Improve shade shelter effects on animals<br>* Reduce lamb mortality<br>* Reduced GHG emissions<br>* How do we let people know about all the good work we have already done on our farm, e.g. environmental stewardship and animal welfare? |

## 3.3 Greenhouse gas emissions and intensity benchmarking for two case study locations and reporting costed on abatement and sequestration models for each site

### 3.3.1 High rainfall beef production system

The beef farm at Stanley in north-western 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 two 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.), subterranean clover (*Trifolium subterraneum* L.) and lucerne (*Medicago sativa*). The soil type in GrassGro based on the Northcote classification was Uc2.3 (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 (20mm/event on a 14-day interval). Production feeding rules were implemented in GrassGro (Moore et al., 1997) 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 are shown in Table A81.2 of Appendix 8.1.

### 3.3.2 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 3,170 ha and consisted of 49% native grasslands, 48% rainfed developed pastures and 3% centre pivot irrigation (introduced grasses and legumes). The farm also had ~4,600 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 subterranean clover. The land under the centre pivot irrigation was also for dual-purpose wheat that was grazed for four 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 5,300 mature superfine Merino ewes, 7,500 wethers and 5,500 replacement ewes and wethers. The 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 (16 Dec). Wethers were retained for five years before cast for age (14 Oct). All non-replacement ewe and wether lambs were sold 1 Feb. The PLF contained 3,450 Merino ewes from the

SMF and were mated with White Suffolk rams; the 2,950-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 17.4-18.1µm (variation in CFW and micron depended on stock class and age). Maintenance and production feeding rules and grazing rotations are further detailed in Appendix 8.1 (Table A81.3). 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 two years of age and were retained for eight 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). Further details can be found in Appendix 8.1 (Table A81.3).

### 3.3.3 Pasture and livestock production of beef and sheep grazing systems

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. 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). See Appendix 8.1 for additional information related to the methodology of GrassGro to estimate pasture and livestock production for the two case study farms.

### 3.3.4 Estimating soil organic carbon dynamics

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. See Appendix 8.1 for additional information related to the methodology used with Roth-C to estimate soil organic dynamics and Appendix 8.2 for additional information as to how we linked GrassGro and Roth C models to account for soil carbon changes in long-term pastures.

### 3.3.5 Tree growth, carbon in wood and soil carbon between 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. See Appendix 8.1 for additional information related to the methodology used with FullCAM to estimate tree growth, carbon in wood and soil carbon.

### 3.3.6 Estimated on-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; Harrison et al., 2012b) 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). See Appendix 8.1 for additional information relating to the methodology used with SB-GAF to estimate on-farm GHG emissions.

### 3.3.7 Whole-farm economic analysis and risk modelling tool (@Risk)

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). See Appendix 8.1 and 8.2 for additional information relating to the methodology used to estimate whole-farm economics.

### 3.3.8 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. The outcome of this process was the co-design of four distinct adaptation themes where incremental, income and transformational adaptation adaptations suggested by the RRG were individually explored (Table S4) and selectively stacked (Table 3).

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 are shown in Table 3 and Appendix 8.1 (Tables A81.2 and A81.3).

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. Further details are shown in Table 3 and Appendix 8.1 (Tables A81.2 and A81.3).

A third thematic adaptation called "Income Diversification" or ID was co-designed with the RRG in which income is derived from sources other than key farm commodities, through options such as buying another block of land in a different agroclimatic region, leasing land to host a wind farm (GHG offsets owned by wind turbine operator) or diversifying part of the farm area with grapes (climate diversification, reduce the vulnerability to market fluctuations). Further details are shown in Table 3 and Appendix 8.2 (Table A82.4).

The fourth thematic adaptation described as "Carbon Neutral" or CN was created after the modelling and following of the RRG to select the most promising adaptation that could increase productivity and profitability and achieve carbon neutrality to utilise alternative markets such as the carbon market. In addition, alternative pathways to carbon neutrality were designed for each case study (Appendix 8.2 (Fig. A82.4)). A summary of each adaptation theme together with subset incremental adaptations are shown in Table 3. Further details are provided in Appendix 8.2.

**Table 3.** Summarised thematic adaptations co-designed with a Regional Reference Group (RRG). 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. Abbreviations: LHF: Low-hanging fruit. TCN: Towards Carbon Neutral; this theme also included all incremental adaptations for LHF. ID: Income Diversification. TR: Transformational (including the Carbon Neutral (CN) Packages). SR: Stocking Rate. LW: Liveweight per head. FCE: Feed Conversion Efficiency. RD: rooting depth. SSP: Single Superphosphate fertiliser. N: Nitrogen fertiliser. Further details are provided in Appendix 8.2 (Tables A82.2 and A82.3).

| Theme | Incremental, systemic and transformational adaptations stacked into and analysed as holistic adaptation themes |
|---|---|
| LHF | - Removing cattle from the sheep farm and increasing rainfed introduced pasture area to the two sheep flocks<br>- Altered lambing/calving dates to better match seasonal pasture supply<br>- Altered selling dates/SR/LW to better match seasonal pasture supply<br>- Adopting pasture species with 10% improvements in maximum root depth (Cullen et al., 2014)<br>- Increasing soil fertility with SSP and N by 3% (Harrison et al., 2014; all paddocks except the native pastures for the sheep farm)<br>- Increasing FCE 10% in 2030 and 15% in 2050 (Alcock and Hegarty, 2011)<br>- Introduction of Talish clover (*Trifolium tumens)* to a proportion of the sheep farm (Hayes et al., 2019) |
| TCN | - Strategic manipulation of livestock selling dates/SR/LW to better match seasonal pasture supply<br>- Pasture renovation with (and increased farm area of) lucerne pastures<br>- Injecting animals with an enteric $CH_4$ inhibitor vaccine to reduce $CH_4$ by 30% (Reisinger et al., 2021)<br>- Purchase 50 ha of land for the beef farm to establish a tree plantation of Tasmanian Blue Gums to offset livestock GHG emissions<br>- Thickening of 200 ha of existing nature pasture (non-grazed) land for the sheep farm with FullCAM-aligned Environmental Plantings (trees, shrubs and understory species endemic to the region) |
| ID | - Buying an extra farm (750 ha) in a different agroclimatic region by translocating cow-calf systems to Gladstone, NE Tasmania and dedicate the current farm for backgrounding and finishing of weaners/yearlings. The Gladstone region in north-eastern Tasmania is situated some 320 km east of Stanley, the location of the baseline beef production system; as such, Gladstone experiences different climatic patterns to the prevailing westerly winds experienced in Stanley) |

| | |
|---|---|
| | - Diversifying land use with grapes (by repurposing 30 ha land from the sheep farm to grow Pinot Noir and Chardonnay grapes (processed offsite and outside scope of project)<br>- Hosting a wind farm (by leasing land for 12 wind turbines to generate an extra income, no insetting of $CO_2$ from turbines to reduce on-farm GHG emissions was assumed, in line was the business model of the wind turbine company) |
| TR | - Feeding red seaweed (*Asparagopsis taxiformis*) to offset $CH_4$ by 80% (Glasson et al., 2022; Wasson et al., 2022)<br>- Pasture renovation with (and increased farm area of) lucerne pastures<br>- Purchase 50-85ha of land for the beef farm to establish a tree plantation of Tasmanian Blue Gums to offset livestock GHG emissions<br>- Thickening of 200 to 220 ha of existing nature pasture (non-grazed) land for sheep farm with environmental plantings (trees, shrubs and understory species endemic to the region)<br>- Transformational increase in FCE, to 20% in 2030 and 30% in 2050 (Alcock and Hegarty, 2011) |

### 3.3.9 Data analysis

*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 the principles outlined by Gephart et al. (2016). This was undertaken for the Historical, Baselines, LHF, TCN, ID and CN packages. See Appendix 8.1 for additional information.

*Marginal Abatement Cost Curve analysis*

Marginal Abatement Cost Curve (MACC) analyses are frequently used to determine the cost of net GHG emission abatement (Eory et al. 2018; Nur Chairat et al. 2022). We modelled each individual adaptation option that resulted in a reduction in GHG emissions. Options such as altered lambing/calving rate or increased rooting depth were not included as they did not result in a GHG abatement.

*Ease of adoption*

Each adaptation was ranked in terms of ease of adoption, based on feedback from the RRG and cross-disciplinary team expertise. Options coloured red were considered difficult to adopt, such as purchasing a new farm in an alternative location for the beef farm or transformational FCE by 2030 for both farms. In contrast, options coloured green were considered relatively easy to adopt, such as increasing soil fertility or altering calving/lambing dates.

## 3.4 Accompanying prioritised researchable recommendations developed covering beef and sheep enterprises as applicable by region with demonstrated consideration of animal management, animal genetics and landscape management

Prioritised recommendations were developed from the research outcomes of this project, from expertise of the project team and from the RRG. Due to the extensive list of suggestions, we did not have scope to explore all of these suggestions. Further details are given in section 4.3.

## 3.5 Report on 'Involve and Partner' activity/ies and review implementation success, effect on business performance and opportunities or barrier to further uptake

The Involve and Partner (I&P) approach was a biochar supplementation experiment conducted on a commercial farm in northern Tasmania (near Deloraine). Prior to and separate from the NEXUS project, the I&P farmer began implementing a series of pasture renovation activities aimed at increasing soil carbon and have formally registering their activities under the ERF.

Supplementation of a commercial grade biochar 'FeedChar' to approx. 60 Wagyu cross calves (biochar treatment) commenced in May 2022. A second cohort of 60 calves (control treatment) rotationally grazed paddocks of the same farm at the same time to allow a comparison of liveweight gain over the duration of the project. Due diligence has been maintained to ensure that pasture quality and availability remains consistent between treatment groups.

Three workshops undertaken in 2022 and 2023 included processes for documentation of participant knowledge, attitudes, skills and aspirations to commence feeding biochar on their own properties. Follow-up consultation with participants will be undertaken in late 2023 to ascertain longitudinal adoption in not just biochar, but sustainability initiatives more broadly. Interviews with the I&P farm manager were also conducted in order to gather more detailed knowledge of the processes required to integrate biochar supplementation into the I&P farm management.

## 3.6 Report on the human and social capacities and capabilities required to manage the modelled scenarios at farm and industry scale, including strategies to assess industry readiness to respond, and engage producers and farm advisors in building capacity for adaptation and transformation

The human and social capacities and capabilities aspect of the NEXUS project were explored via a range of avenues, totalling five separate 'sub' projects.

### 3.6.1 The Biochar Involve and Partner project

The Biochar I&P Project was run Tasmania wide to explore the technical and social aspects of the biochar usage trial. The exploration involved:

a) In addition to the biochar scientific trial (see Section 3.5 for details), one interview with I&P Manager and one of the other farmers who hosted a workshop.

b) Three workshops where feedback was collected from the participants and permission was gained from many for a 12 month follow up in relation to the biochar usage uptake. Workshops were held across the north of Tasmania at Dunorlan (18th Nov 2022), Ringarooma (1st Dec 2022) and Marrawah (15th Feb 2023).

### 3.6.2 NEXUS regional reference group adaptation and adoption

Producer adaption and adoption for the NEXUS project was explored predominantly through interviews and meeting minutes held with the RRG, but was also supported with our Case Study producers and the I&P producers. A thematic analysis and discourse analysis were used to explore the data via individual RRG members interviews, across seven RRG meetings. Six Tasmanian producers/case study/I&P producers were involved in individual interviews and/or the RRG meetings and contributed to the text that was generated.

*Discourse analysis of interviews and meetings*

Foucaultian Discourse Analysis (Foucault, 1980; Foucault, 1991) accesses embedded sustainable agriculture and climate change adaption 'knowledges' (or understandings) as text based data which incorporates all forms of visual, written and oral text forms. The generation of this diversity of textual data forms the basis of this discourse analysis.

Following a broad thematic analysis focusing on the 'ideas' spoken by producers, a Foucaultian Discourse Analysis was applied to the data generated to explore the social research component of the project. This methodology was used to analyse the data as 'discourse' or 'text'. Through such analysis, the multiple 'truths' that are in circulation concerning the extremes of climate change and responses to these changes, can be explored (Fleming and Vanclay, 2010). This type of analysis determines what the 'rules' of a discourse are. They expose what can be said, what be known and HOW it is known, through the dominant understandings presented when people speak. It can also explore what therefore remains unsaid and unknown, or 'the silences'. This approach allows us to question discourses used so that any 'taken-for-granted' assumptions about the ways in which sustainable agricultural practices and climate change adaptions is known, can be questioned and critiqued.

### 3.6.3 Red Meat Producers Survey

A Red Meat producer survey was run Tasmania-wide. The Tasmanian red meat survey was designed to develop an understanding of future extension priorities and investigate workforce skill development requirements. Survey questions were informed by 13 preliminary scoping interview findings conducted with producers from the Midlands and North-West regions (Appendix 8.6) and have been refined through iterative feedback from the wider NEXUS project team and Tasmanian

RRG members. The survey targeted Tasmanian red meat producer's responses. There was a limited response (n=35) to the survey (Appendix 8.7). Analysis drew on descriptive comparative and multivariate analysis.

Data collection ran from April to October 2022 using the secure web application REDCap (https://www.project-redcap.org/). Respondents covered many of the Tasmania regions and Islands. There were male (21), female (13), other (1) reflecting diversity of interviewees across farms. They were aged between 20-80, although around 67% were over 40. Their farms ran sheep, cattle, or a combination of both, or were one part of a diverse approach to the farming operation.

### 3.6.4 Climate change adaptive capacity survey

The Adaptive Capacity Survey was developed by a team of researchers at TIA and the University of Melbourne (UoM). It was based on RRG individual interviews and RRG meetings held in Tasmania, Victoria, Queensland, and New South Wales. The survey focused on red meat producers and industry service providers and discussions about the effectiveness of the survey were conducts with each RRG in Victoria, Queensland and New South Wales by Nicole Reichelt, and in Tasmania.

In Tasmania, four producers participated in the survey and six in the discussions. The survey analysis was constructed by Nicole Reichelt and applied by Nicoli Barnes for the Tasmanian data using descriptive, comparative and multivariate analysis methods.

### 3.6.5 Red meat consumption patterns survey

A red meat consumption pattern survey was developed by staff at TIA, in partnership with the Institute for Social Change- Tasmania Project, based at UTAS. A descriptive analysis was completed, and two reports were developed from the Fourth General Survey:

- Report 1 - Attitudes towards eating red meat (Report 48)
- Report 2 - Attitudes towards dairy, red meat, and seafood (Report 49)

Data collection ran from April to May in 2021. Of the 3,500 people registered for project, 1,176 responses were gained. The data was analysed using SPSS using descriptive, multivariate and comparative analysis.

## 3.7 Project communications and engagement with regional and transformational reference groups as well as other wider industry stakeholders. This will include details of project presentations at a minimum of 5 industry events or conferences

The Tasmanian RRG met seven times over the duration of the project, either as face-to-face or online due to COVID restrictions. In addition, a range of presentations, webinars, conferences, radio interviews and popular press articles have been delivered by members of the project team.

## 3.8 Submission of a minimum of two scientific journal articles for peer review

Twelve peer-reviewed journal articles have been published or in the peer review process at the time of writing. A list of the journal articles is documented below (Results section), with the full manuscript included in the Supplementary material file.

# 4 Results

## 4.1 Modelled climate change scenarios against 2030 and 2050 horizons, incorporating coverage of climate modelling including extreme climate events for case study location

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

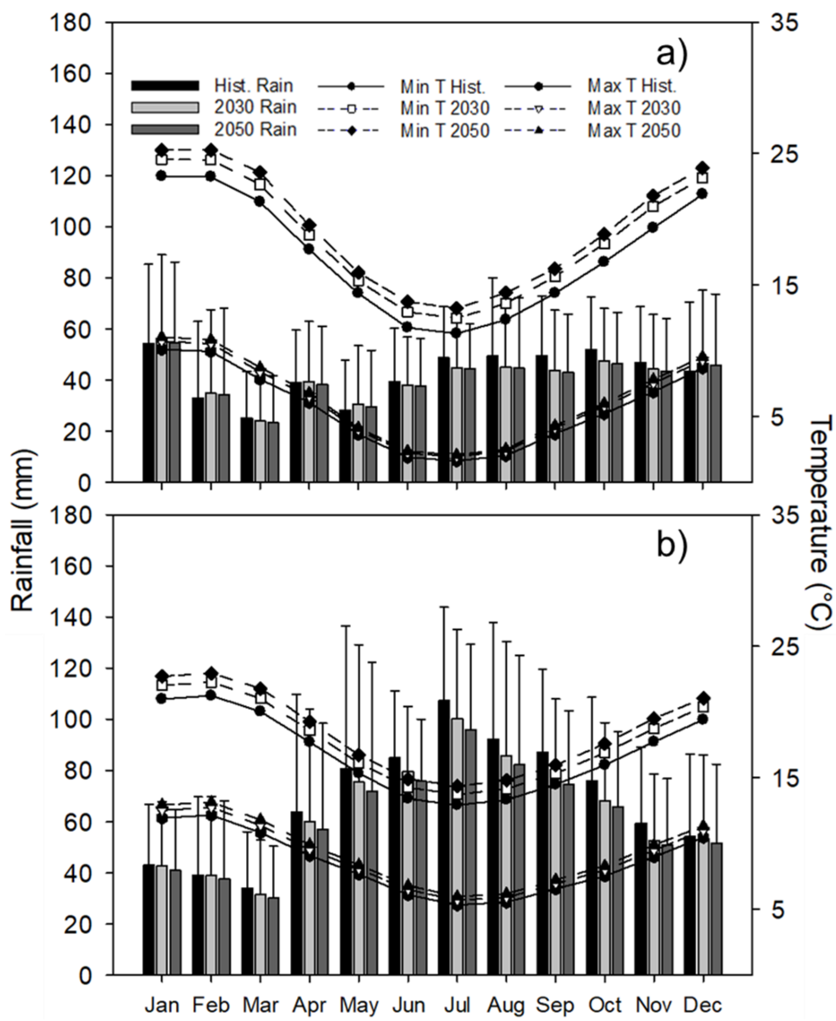


**Fig. 2.** Monthly average rainfall minimum and maximum temperature for the historical, 2030 and 2050 climate horizons for the a) Sheep farm and b) Beef farm. Error bars indicate standard deviation.

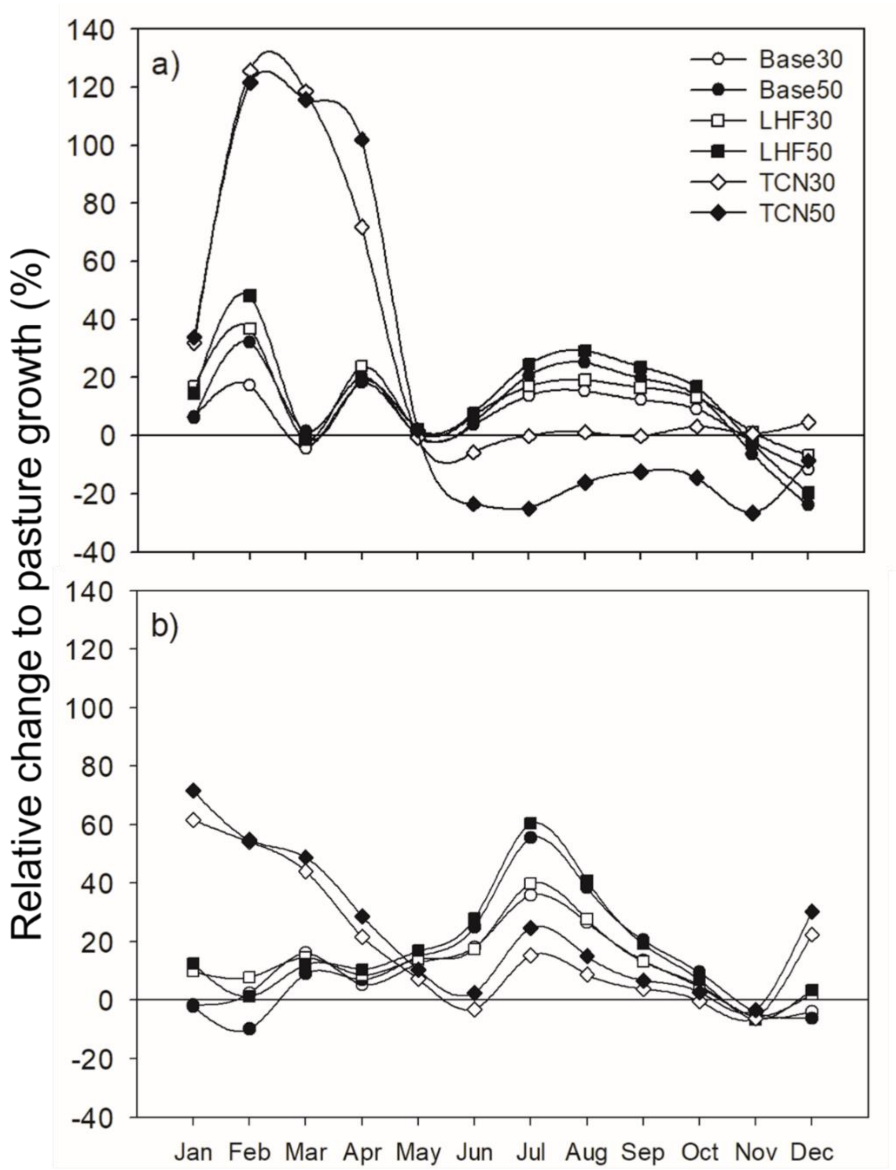


**Fig. 3.** Relative percentage change in monthly pasture growth rates observed in beef farm (a) and sheep farm (b) compared with historical periods. The *dots* represent the percentage differences observed under future climates (2030 and 2050) and interventions Low Hanging Fruit (LHF) and Towards Carbon Neutral (TCN).

## 4.2 Prospective and costed adaption options for each site

### 4.2.1 The nexus between productivity, profitability and net greenhouse gas emission for individual farm interventions

In comparing sheep and beef production systems in 2030 and 2050, we revealed that (1) few individual interventions elicited significant impact on the three dimensions of productivity, most likely annual average profitability (herein profit) and GHG emissions and (2) the impacts of the production system and intervention were greater than the impacts of climate change *per se* (Figs 4, 5).

Interventions targeting livestock enteric methane (methane produced by fermentation in the gut) were most promising for reducing GHG emissions, such as the seaweed feed additive *Asparagopsis taxiformis*, which under the assumed conditions of the analysis could reduce on-farm $CO_2$-eq by 46-72% under future climates (Fig. 4a, 4b, Fig. 5a, 5b, Tables A82.1 - A82.4). However, *Asparagopsis* when used as a feed supplement, identified as one of the costliest singular interventions, reduced profits by $23-25/Mg $CO_2$e mitigated (Fig. 4c, 4d, Fig. 5c, 5d). Interventions that were considered most adoptable by the group of expert practitioners (the RRG) often had the lowest mitigation potential (Figs 4, 5).

Climatic diversification - purchasing a farm in a distinctively different climatic zone - and altering lambing/calving times yielded the greatest improvement in productivity (16-18%), while enterprise diversification (capital investment to enable grapevine/wind turbines enterprises), pasture renovation with deep-rooted legumes and improvements in animal genetic feed-conversion efficiency (FCE) were most conducive to improved profit (17-39%). Interventions that achieved the greatest gains in productivity and profit tended to do little influence to reduce GHG emissions, underlining the challenges inherent in decoupling the tight linkage between productivity and GHG emissions.

Improving FCE - considered akin to good farm management practice by increasing pasture utilisation and liveweight gain per unit utilisation in a sustainable way – would increase profit ($70-250/Mg $CO_2$e mitigation; Fig. 4c, 4d, Fig. 5c, 5d, Tables A82.1 - A82.4), with only modest impacts on productivity (0-6% increase), and on GHG emissions mitigation (-9-15% reduction). Transformational improvement in animal genetic feed conversion efficiencies (TFCE) promises increases in livestock production and farm profits by 8-39% and reducing net GHG emissions by 11-17%, though is aspirational according to the expert group of practitioners because the as yet further livestock genetic science is needed to improve FCE before such genotypes could be widely available (Fig. 6a, 6d, Fig. 7a, 7d).

The modelled climate change scenarios had significant implications for the extent of carbon removal on the case study farms. By 2050, GHG mitigation potential associated with improving soil carbon stocks was reduced by 6-13% for interventions that expanded farm area covered by deep-rooted perennial legumes (in this case lucerne or *Medicago sativa*), and by 20-40% for carbon sequestered by planting native vegetation (Figs 4, 5, Tables A82.1 - A82.4). Planting trees decreased profit per unit $CO_2$ mitigated compared with incorporating lucerne into pastures (Fig. 4c, 4d and Fig. 5c, 5d). This was because lucerne enabled pasture growth and livestock production, whereas trees reduced productive pasture area and livestock carrying capacity.

Biochar was considered to be highly adoptable by the RRG and was proposed as a livestock feed supplement based on anecdotal evidence suggesting that use of biochar (1) improved liveweight gain, (2) reduced enteric methane and (3) enriched organic carbon content of manure. In line with the people-centric nature of this research, we conducted on-farm experiments with free-choice biochar, fed *ad libitum* over 12 months. Little impact of biochar was observed on either liveweight gains or manure organic carbon content (Fig. A82.1). Embedding these nascent results into the modelling frameworks showed that biochar feed supplement would reduce net GHG emissions by 8% and increase profit by 18%, saving \$290 Mg $CO_2e^{-1}$ per year (Fig. 4). However, effects of feeding biochar differed across production systems (cf. Fig. 4 c, d with Fig. 5c, d), with *de minimus* effects of biochar feed supplement on sheep liveweight gains and wool production along with elevated costs of implementation reducing profits by 10% despite an 18% reduction in GHG emissions for both climate horizons (Fig. 5).

To buffer against the possibility of reduced rainfall under future climates, income diversification avenues that were independent of rainfall in the one location were co-designed. These interventions included planting a small irrigated area of grapevines on the sheep farm, hosting wind turbines on the beef farm, and climatic diversification by purchasing a block of land for cattle farming in a distinctively different climatic zone. While wind turbines, developing irrigated grapevines and purchasing another beef cattle farm improved farm profits by 12-18%, 20% and 15% respectively (Figs 4 and 5), effects on productivity and profit varied widely. Buying an extra beef farm in a diverse agro-climatic region improved production by 15% (Fig. 4), but this came with a cost of increased associated GHG emissions (net and emissions intensity, Tables A82.1 - A82.2).

The RRG provided insights into income diversification interventions. For example, purchasing a farm in a diversified climatic zone (north-eastern Tasmania, compared with the beef farm that was located some 400 km away in the north-west of the state) would require additional labour, costs of transporting cattle between regions, sometimes added infrastructure on the new farm, and higher management skills coordinating separate farm enterprises. Still, many farmers do precisely this, profitably. Growing irrigated grapevines requires specialist input, and on-ground evidence such as existing successful grape-growing, to identify suitable microclimates. The option of hosting wind turbines on the property requires proximity to three-phase powerlines (to feed into the main electricity grid) as well as high prevailing windspeeds. These conditions are not usually common or widespread. Despite this however, the sheep case study farmer was pursuing investment in irrigated grapevines, while the beef farmer had signed a lease for a company to lease part of his land for wind turbines.

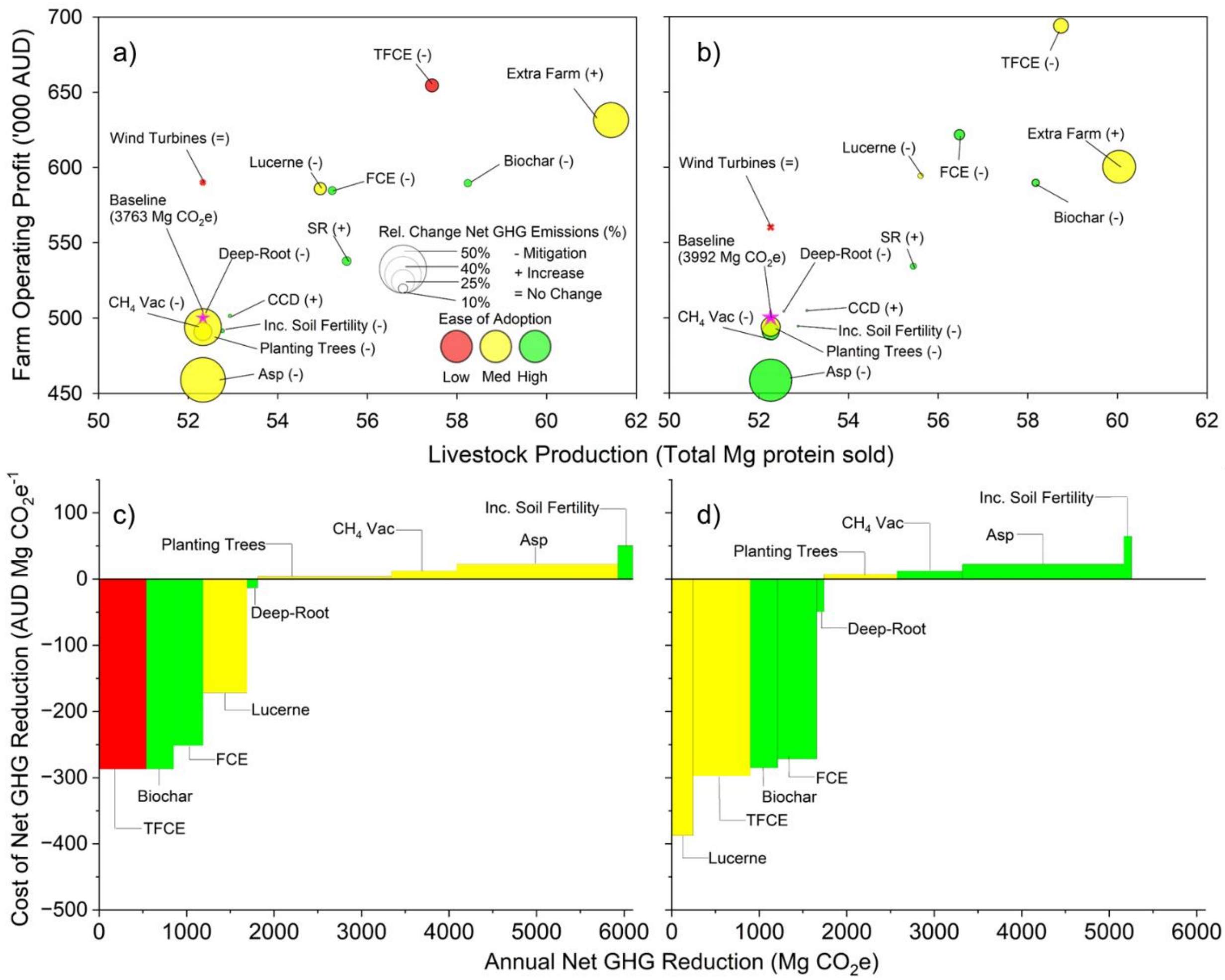


**Fig. 4.** Beef cattle production, total operating profit (EBIT), mitigation potential (a and b) and marginal abatement cost curves (c and d) of multiple thematic adaptations to climate change with variable ease of adoption (colours), codesigned by the Regional Reference Group under 2030 (a and c) and 2050 (b and d) climates. The purple star depicts the baseline scenario. Total emissions for the baseline scenario are declared in parenthesis. Asp: feeding *Asparagopsis taxiformis*. $CH_4$ vac: injecting animals with an enteric $CH_4$ inhibitor vaccine. CCD: changing calving date. Deep-Root: increasing root depth. FCE: improving feed conversion efficiency. SR: increasing stocking rate. TFCE: transformational improvement in feed conversion efficiency.

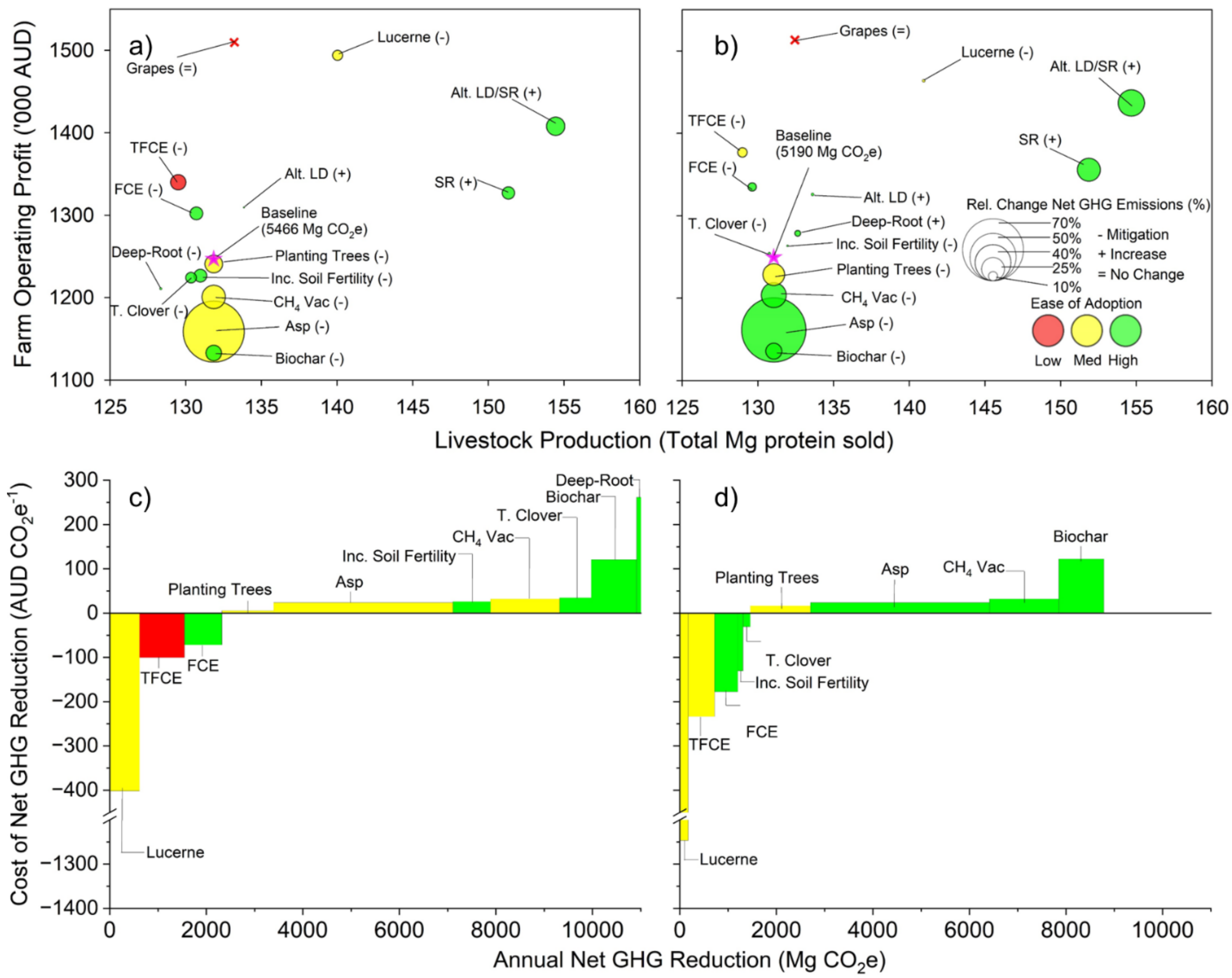


**Fig. 5.** Sheep farm livestock production, total operating profit (EBIT), mitigation potential (a and b) and marginal abatement cost curves (c and d) of multiple thematic climate change adaptation and mitigation options with variable ease of adoption (colours), codesigned by the Regional Reference Group under 2030 (a and c) and 2050 (b and d) climates. The purple star depicts the baseline scenario. Total emissions for the baseline scenario are declared in parenthesis. Alt. LD: altering lambing date. Alt. LD/SR: altering lambing date and increasing stocking rate. Asp: feeding *Asparagopsis taxiformis*. $CH_4$ vac: injecting animals with an enteric $CH_4$ inhibitor vaccine. Deep-Root: increasing root depth. FCE: improving feed conversion efficiency. SR: increasing stocking rate. TFCE: transformational improvement in feed conversion efficiency. T Clover: including Talish clover.

## Contextualised adaptation-mitigation bundles: stacking interventions

We next co-designed and stacked together contextualised bundles of inteventions, each group based on synergies of outcome intended (i.e., interventions were constructed and the outcomes modelled, Figs 6 and 7). Simple, immediately actionable and relatively reversible changes to the farm systems were stacked together into a 'Low Hanging Fruit (LHF)' theme improved annual productivity (15-16%) and increased profit by 19-25% but increased GHG emissions by 6-18% compared with the baseline scenarios under future climates.

A Towards Carbon Neutral (TCN) package was co-designed with the intent of improving productivity and reducing year-on-year GHG emissions. This bundle of interventions combined the LHF package with mitigation interventions (methane inhibition vaccine, planting trees and renovating pastures with deep-rooted legumes). The TCN package respectively increased livestock productivity by 18-20% (beef farm) and by 36-40% (sheep farm) under future climates (Tables A82.5 - A82.8). Despite added costs associated with buying land and planting trees and the costs of a theoretical $CH_4$ vaccine inoculation (Table A82.9), biophysical changes realised from pasture renovation increased profits by 33-37% and 60-68% for the beef and sheep farms, respectively. The TCN package reduced net GHG emissions by 37-69% for the beef farm (Fig. 6) and 29-34% for the sheep farm (Fig. 7), diluting emission intensities by 30-50% (Fig. 8, Tables A82.5 - A82.8). While the TCN package was highly ranked in terms of profit, production and GHG emissions evidenced by equally distributed ternary plots (Fig. 6c, 6f, Fig. 7c, 7f), the incorporation of strategies such as the methane inhibition vaccine (which is not commercially available) and its accompanying social concerns, reduced the adoptability of TCN overall.

Multiple combinations of stacked interventions facilitated profitable transitioning of farm systems to net-zero emissions (Figs 6ad; 7ad). The four carbon neutral packages (CN1-4) were co-designed with consideration to various areas of trees planting, adoption (or not) of livestock genotypes with transformational gains in FCE (TFCE) and/or renovation of pastures with the deep-rooted perennial legume, lucerne. For the beef farm, feeding of *Asparagopsis*, planting trees and TFCE were most promising (CN1 and CN2), facilitating not only carbon neutrality but also increasing productivity by 13% with a possible 30% profit gain under 2050 climates (Fig. 6). For the sheep farm, productivity and profitability gains associated with carbon neutral GHG positions were more likely to be realised with stacking of *Asparagopsis* feed, planting trees and renovating pastures with lucerne, such that CN3 and CN4 increased production and profit by 8% relative to the baselines, respectively (Fig. 7).

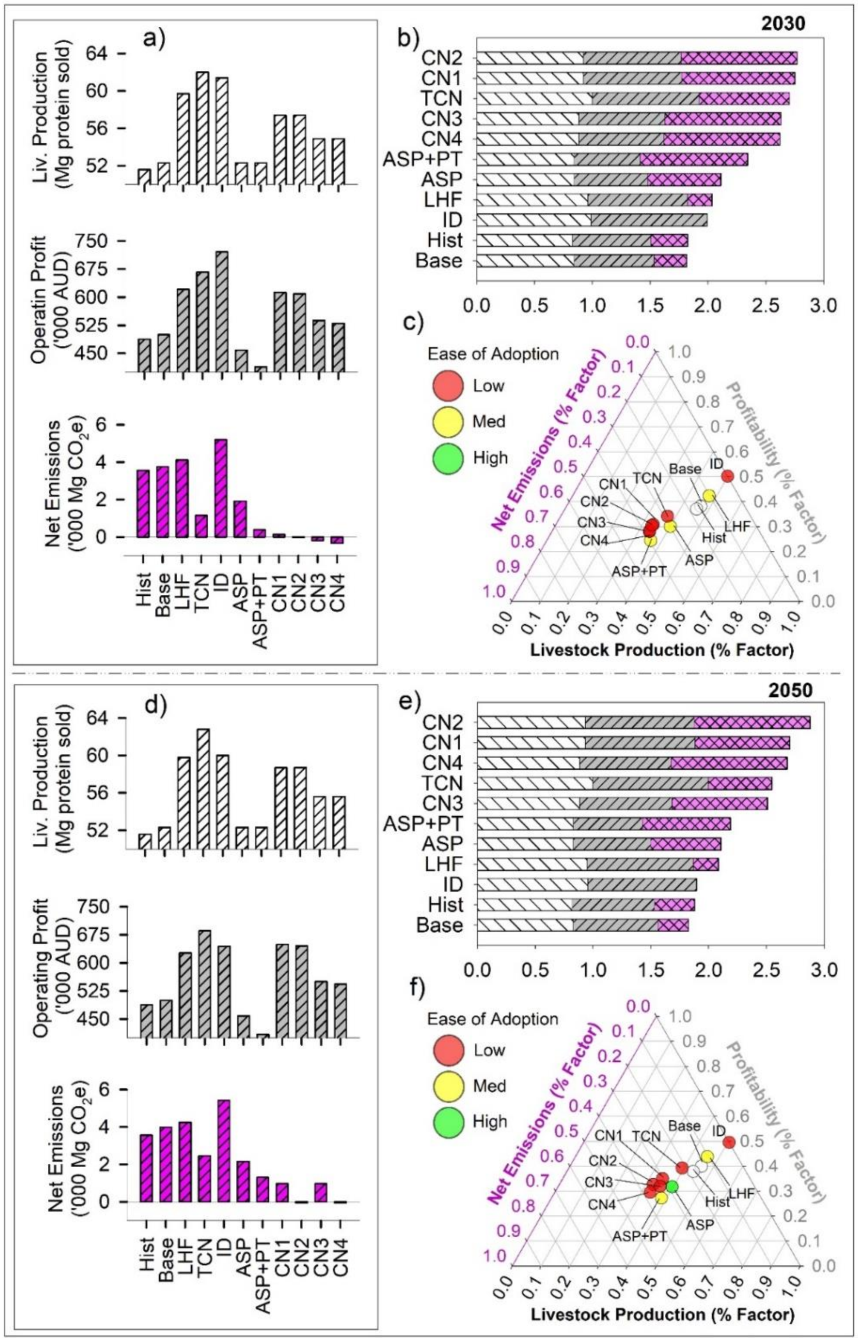


**Fig. 6.** Beef farm multidimensional assessments across climate horizons and thematic adaptations for the beef farm suggested by the Regional Reference Group. Hist: scenarios simulated with historical climates. Base: impact of future climates. LHF: low-hanging fruit packages. TCN: towards carbon neutrality package. ID: income diversification. Asp: *Asparagopsis taxiformis*. Asp+PT: *Asparagopsis taxiformis* + Planting trees 50ha. CN1: carbon neutral package 1 (*Asparagopsis taxiformis* + planting trees 50ha+ transformational feed conversion efficiency. CN2: carbon neutral package 2 (*Asparagopsis taxiformis*+ planting trees 55ha (2030)/ 85ha (2050) + transformational feed conversion efficiency. CN3: carbon neutral package 2 (*Asparagopsis taxiformis* + planting trees 50ha + Lucerne). CN4: carbon neutral package 4 (*Asparagopsis taxiformis* + planting trees 55ha (2030)/ 85ha (2050) + Lucerne).

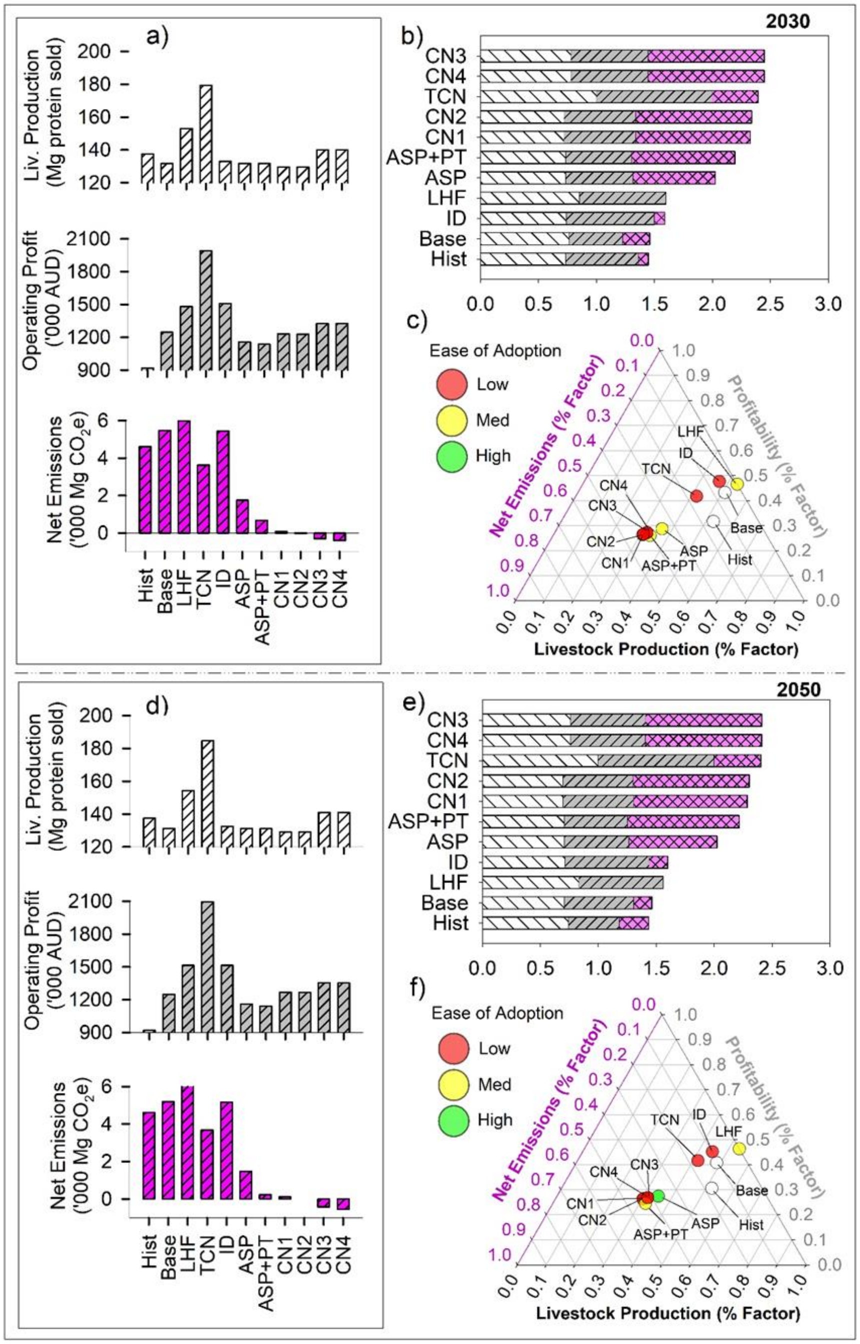


**Fig. 7.** Sheep farm multidimensional assessments across climate horizons and thematic adaptations for the sheep farm suggested by the Regional Reference Group. Hist: scenarios simulated with historical climates. Base: impact of future climates. LHF: low-hanging fruit packages. TCN: towards carbon neutrality package. ID: income diversification. Asp: *Asparagopsis taxiformis*. Asp+PT: *Asparagopsis taxiformis* + Planting trees 200ha. CN1: carbon neutral package 1 (*Asparagopsis taxiformis* + planting trees 200ha+ transformational feed conversion efficiency. CN2: carbon neutral package 2 (*Asparagopsis taxiformis* + planting trees 220ha + transformational feed conversion efficiency. CN3: carbon neutral package 2 (*Asparagopsis taxiformis* + planting trees 200ha + Lucerne). CN4: carbon neutral package 4 (*Asparagopsis taxiformis* + planting trees 220ha + Lucerne).

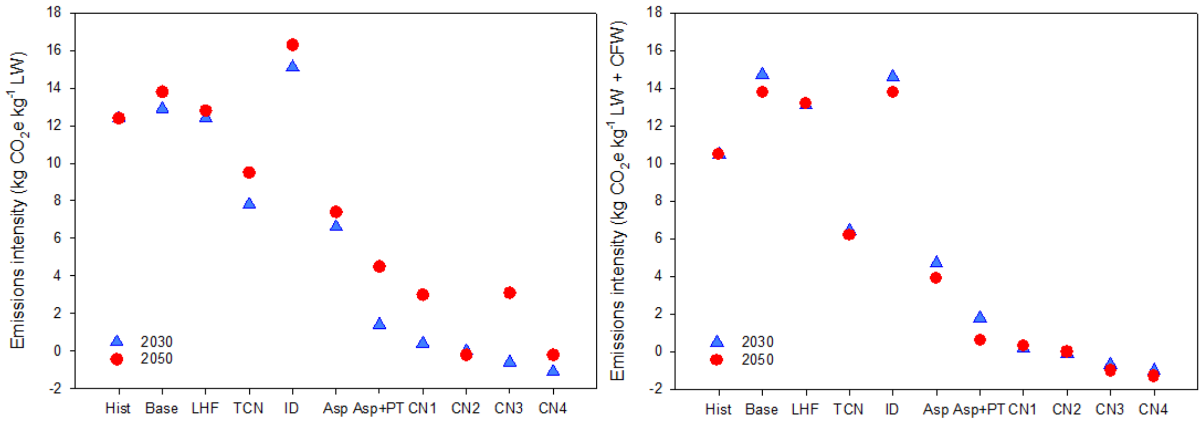


**Fig. 8.** Beef emissions intensity (left) and sheep emissions intensity (right) for 2030 (blue triangles) and 2050 (red circles). Hist: scenarios simulated with historical climates. Base: impact of future climates. LHF: low-hanging fruit packages. TCN: towards carbon neutrality package. ID: income diversification. Asp: *Asparagopsis taxiformis*. Asp+PT: *Asparagopsis taxiformis* + Planting trees. CN1: carbon neutral package 1 (*Asparagopsis taxiformis* + planting trees + transformational feed conversion efficiency. CN2: carbon neutral package 2 (*Asparagopsis taxiformis* + planting trees + transformational feed conversion efficiency. CN3: carbon neutral package 2 (*Asparagopsis taxiformis* + planting trees + Lucerne). CN4: carbon neutral package 4 (*Asparagopsis taxiformis* + planting trees + Lucerne).

### 4.2.2 What is the cost of transitioning a farm business to net zero?

The potential effects of a carbon market existing were analysed in which GHG emissions were taxed and offsets credited, respectively. The case study farmers simply paying the tax on the net $CO_2$e from their farm systems, with no practice changes to reduce GHG emissions, reduced farm profits by 64% and 33% for the beef and sheep farms, respectively (Fig. 9). Using *Asparagopsis* as a feed supplement would reduce operating profit by 7-8%. Paying a carbon tax on net residual GHG emissions would improve profit by 58% (beef farm) or 25% (sheep farm) relative to the baseline farm in which all net GHG emissions were taxed (Fig. 9c, d, g, h). When feeding of *Asparagopsis* was stacked with purchasing an extra farm that was planted with trees (ASP+PT), a further 38-87% net GHG emissions were offset (Fig. 9a, b, e, f). Relative to the baseline farm in which all residual GHG emissions were taxed, ASP+PT improved profits by 34%/68% for the sheep/beef farm.

The CN packages intervention stacked TFCE (CN1 and CN2) or lucerne in the pasture mix (CN3 and CN4) with ASP+PT to reduce GHG emissions, while further reducing the burden of taxes on emissions carbon taxes. For the beef farm, there was little difference in net GHG emissions after implementing TFCE (CN1) and lucerne in the pasture sward (CN3), both with residual GHG emissions of 1,000 Mg $CO_2$e (Fig. 9a, b). Profits after paying the carbon tax were greater for the CN1 package (Fig. 9c) compared with the CN3 package (Fig. 9d), and were three times greater than the baseline farm, even after paying a tax on residual GHG emissions. Additional land for tree plantings was required for the beef farm's CN1 and CN3 packages to become net-zero (CN2 and CN4 packages; Fig. 9a, b). For the sheep farm, the lucerne CN3 package achieved net-zero, with net sequestration of 1,400 Mg $CO_2$e (Fig. 9f) and pre-carbon tax profit of $1,366K (Fig. 9h), which slightly declined if surplus carbon offsets were sold (Fig. 9h).

The RRG highlighted potential difficulties in implementing CN packages (Table A82.10), while the results clearly demonstrate that adoption of mitigation practices were at least three times more profitable for the beef farm and 1.5 times more profitable for the sheep farm, relative to the 'do nothing different scenario', where the two farming systems conducted business as usual and all their net GHG emissions were subjected to carbon taxes.

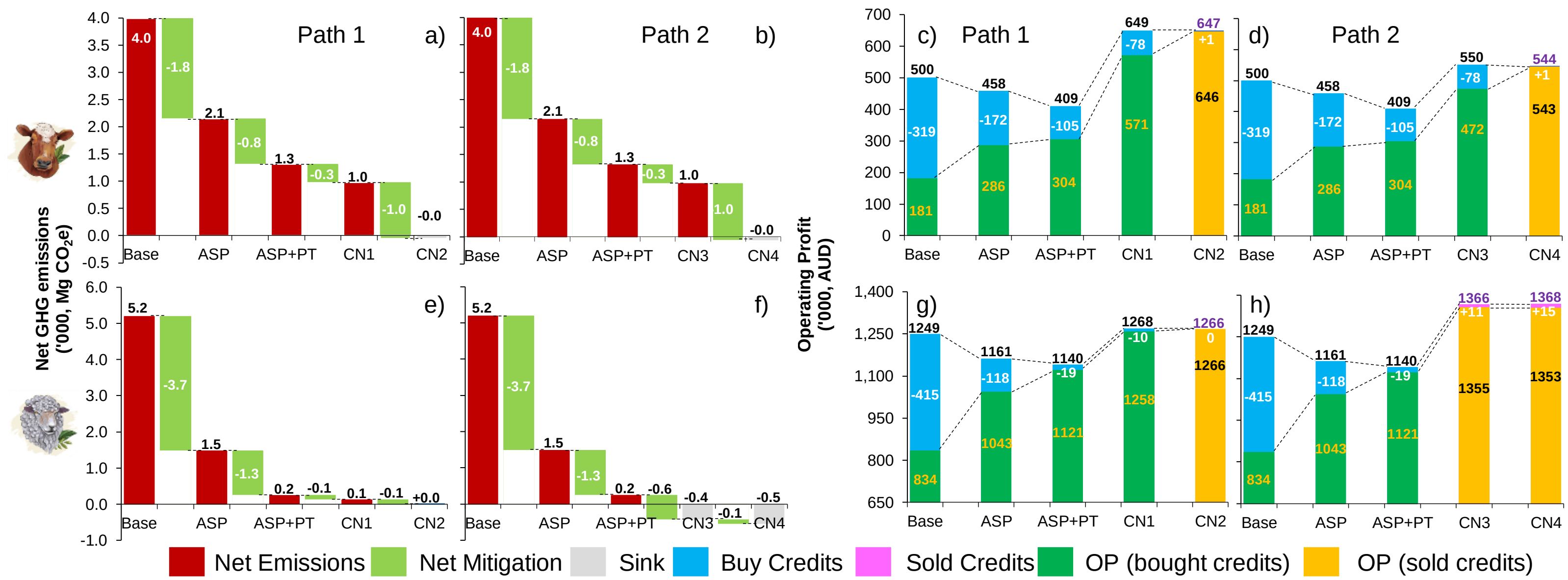


**Fig. 9.** Cost and mitigation associated with two pathways (Path 1, TFCE; Path 2, Lucerne) to net-zero emissions, accounting for pre- and post-carbon taxes and thematic adaptations for a beef farm (a, b, c, d) and sheep farm (e, f, g, h) for a 2050 climate horizon. Base: Baseline climate. Asp: *Asparagopsis taxiformis*. Asp+PT: *Asparagopsis taxiformis* + Planting trees. CN1: carbon neutral package 1 (*Asparagopsis taxiformis* + planting trees (beef farm: 50 ha, sheep farm: 200 ha) + transformational feed conversion efficiency. CN2: carbon neutral package 2 (*Asparagopsis taxiformis* + planting trees (beef farm: 85 ha, sheep farm: 220 ha) + transformational feed conversion efficiency. CN3: carbon neutral package 2 (*Asparagopsis taxiformis* + planting trees (beef farm: 50 ha, sheep farm: 200 ha)+ Lucerne). CN4: carbon neutral package 4 (*Asparagopsis taxiformis* + planting trees (beef farm: 85 ha, sheep farm: 220 ha) + Lucerne).

## 4.3 Accompanying prioritised researchable recommendations developed covering beef and sheep enterprises as applicable by region with demonstrated consideration of animal management, animal genetics and landscape management

Future climates are predicted to have positive livestock and economic outcomes for beef and sheep farms in Tasmania due to effects of warming and $CO_2$ fertilisation, notwithstanding the influence of increasingly variable rainfall quanta and seasonal distribution. However, these improvements will be at the expense of GHG emissions. We explored a range 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, animal genetics, feedbase management and landscape management (planting trees). Each of these LHF options resulted in mixed outcomes, all maintained or increased livestock production, and thus, generally resulted in increased GHG emissions. Improved FCE was showed to maximise livestock production while reduce GHG emissions (model assumed a reduction in enteric $CH_4$ as a result of improved FCE/ residual feed intake) and the most profitable of the individual LHF interventions. Identifying superior animals, especially rams and bulls, and maximising genetic improvement in the herd or flock is imperative to improving livestock production, farm profit and reduce net GHG emissions. However, none of the LHF options explored could be considered a 'silver bullet' with respect of improvements in the overall nexus between production, profit and GHG emissions.

The RRG and project team perceived that the most opportune lever for putting a deep, swift cut in net GHG emissions was that facilitated by reducing enteric $CH_4$ emissions. As such, we explored (1) implementation of a methane inhibition vaccine, assuming a 30% reduction in enteric $CH_4$ emissions, and (2) feeding of *Asparagopsis* as a supplement, assuming an 80% reduction in enteric $CH_4$ emissions. While we note that neither option is commercially available, scenario modelling such as conducted here could inform the viability of proposed commercialisation futures. The findings of the present study could similarly be generically transposed to similar mechanisms purported to reduce enteric $CH_4$, such as 3-nitrooxypropanol (Yu et al., 2021). An important assumption we made with these two interventions was that neither vaccine nor *Asparagopsis* resulted in a change in livestock production due to uncertainty in and lack of peer-reviewed evidence on co-benefits (e.g. productivity gains) and trade-offs (e.g. reduced animal health or fertility) caused by such interventions. We further assumed a low cost of implementation, assuming future economic growth and efficiencies of scale in production. However, when a price was placed on carbon, akin to a future carbon tax, such that farmers would need to purchase carbon credits to negate residual GHG emissions, modelled outcomes for *Asparagopsis* showed the greatest promise (of all interventions examined here) in reducing emissions. Biochar is currently commercially available and is being fed on some commercial farms in Australia. We assumed a modest 10% improvement in liveweight gain, but only for non-replacement animals for the beef case study farm. We also assumed that all three options (vaccine, *Asparagopsis* and biochar) had efficacy for the entire year, as such requiring accompanying labour and infrastructure. If the delivery method of supplementary additives was possible only through feed-lotting - e.g. confinement feeding of ewes over summer/autumn - GHG reduction potential would be considerably lower. Therefore, it is imperative that mode of delivery of proposed enteric $CH_4$ interventions can be easily implemented, facilitates frequent consumption by animals in larger paddocks (e.g. 200 ha), is cost-effective, requires minimal labour, and is scalable.

We explored the benefits of trees on farm in sequestering carbon. For the beef farm, this required the purchase of new land to grow trees, which – in the 20 year period of analysis at least - eroded profit and return on capital. As the marketplace for carbon offsets increases, the cost of buying suitable land for planting trees is also likely to increase. Even with the sheep farm, we modelled woody thickening associated with bushland that is not used for grazing, thus removing the need to purchase new land. However, even this scenario eroded farm profits. These results suggest that income derived from carbon insetting (within the farm business) should be of sufficient magnitude to recoup costs associated with planting and maintenance of tree vegetation on farm.

A significant advantage of systems modelling relative to *in situ* field experimentation is that suitably designed and calibrated systems models can be used to account for longitudinal impacts of management, climate and soil type on long term trajectories in pasture growth, crop yield and/or soil carbon stocks (Ibrahim et al. 2018; Ibrahim et al. 2019; Liu et al. 2020b; Liu et al. 2021; Liu et al. 2023; Farina et al. 2021; Sandor et al. 2020). Relative to the historical climates, future climates will make it more difficult to increase SOC, and in the case of the beef farm, by 2050, the models suggested a reduction in SOC, relative to the historical period centred around the mid-1990s. Interventions such as including deep-rooted lucerne in the pasture sward, resulted in substantial increases in SOC. While the roots were modelled through the full soil profile, the majority of roots still remained in the top 30cm of soil (data not shown) and thus minimal accumulation of SOC at depth. We assumed that around half the sheep farm and almost all of the beef farm required lucerne to be included in the sward (beef farm already has a small proportion of paddocks with lucerne), which may not be achievable on-farm at scale across the Tasmanian red meat industry. Planting lucerne also increased liveweight production, via either selling heavier steers and heifers for the beef farm or retaining prime lambs longer and selling heavier for the sheep farm.

Some of the adaptation options identified by the RRG, though not explored in the current project and thus could be researchable questions for future projects, included:

- Viability of increasing irrigation capacity/capability and which pastures/crops to maximise outcomes,
- Whole farm planning approach - intensifying a proportion of the farm, extensifying the balance,
- Reduce lamb mortality through improved nutrition while the ewes are pregnant,
- Plant trees on the worst 20% of the farm, reduce stocking rates across the whole farm
- Adopt digital technologies to assist with seasonal climate forecasting, pasture productivity and/or GPS collars to improve animal welfare/ pasture management to improve feed conversion efficiency.

## 4.4 Report on 'Involve and Partner' activity/ies and review implementation success, effect on business performance and opportunities or barrier to further uptake

The feeding of biochar to a cohort of animals on the I&P farm is progressing successfully. Results to date have shown little difference in pasture biomass between the two cohort of animals (Fig. 10), and while there has been a divergence in pasture botanical composition over time (Fig. 11), liveweight gain between the control and biochar cohorts has remained similar over the duration of the experiment (Fig. 12). The carbon content of manure samples collected over two timeframes has shown little difference between the two cohorts, indicating potential low intakes of the biochar product (Fig. 13).

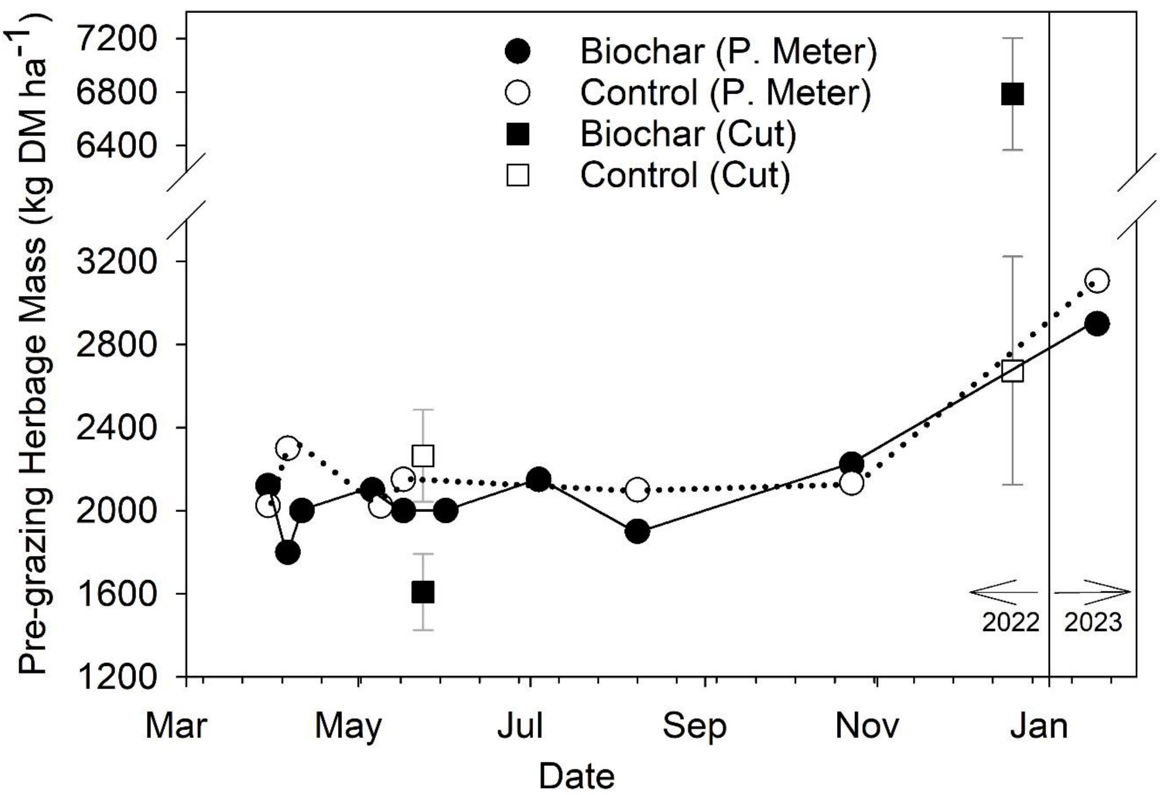


**Fig. 10.** Pre-grazing herbage mass of the control and biochar treatments has been similar over the duration of the experiment. Comparison of plate meter samples and hand cuts indicated little difference in methods for measuring pasture biomass.

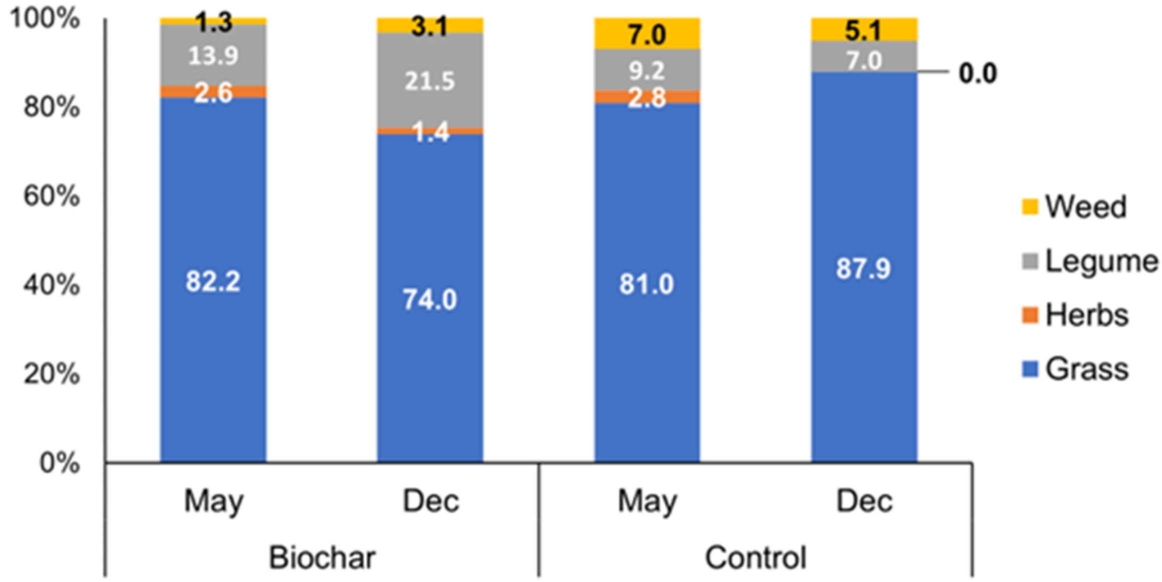


**Fig. 11.** Botanical composition in May and December 2022 of the control and biochar treatment groups.

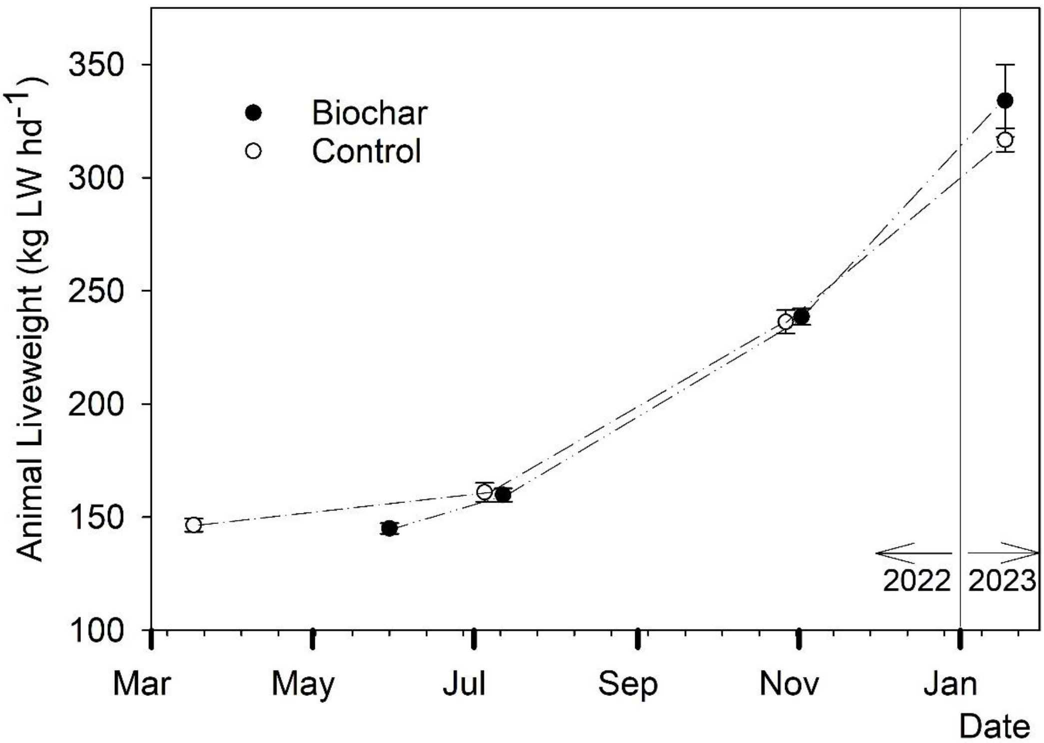


**Fig. 12.** Liveweight of the control and biochar cohorts over the duration of the experiment.

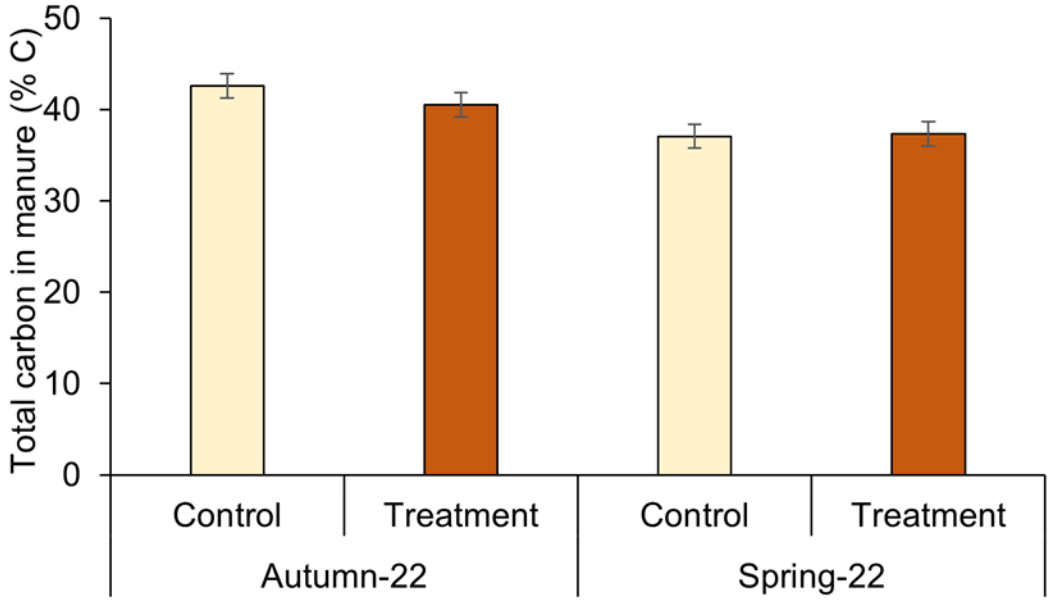


**Fig. 13.** Carbon control in manure for the control and biochar cohorts in autumn and spring 2022.

As part of the 'Involve and Partner' Biochar project, three workshops have been held across the state. See section 4.5.1 for outcomes.

## 4.5 Report on the human and social capacities and capabilities required to manage the modelled scenarios at farm and industry scale, including strategies to assess industry readiness to respond, and engage producers and farm advisors in building capacity for adaptation and transformation

### 4.5.1 The Biochar Involve and Partner project

As part of the 'Involve and Partner' Biochar project, three workshops have been held across the state:

- November 2022 at the I&P farm 'TasAgCo' – Dunorlan (central north Tasmania)
- December 2022 at Stuart and Kylie Nailer's property – Ringarooma (north-east Tasmania)
- February 2023 at Greenham Tasmania's 'Westmore' property, hosted by Aiden Coome – Marrawah (north-west Tasmania)

The purpose of these workshops was to provide an overview of biochar as well as supplementing livestock with biochar, the impacts on GHG emissions, liveweight gain, profit, and the expected outcomes from feeding biochar. A range of speakers presented at the workshops including the supplier of Feedchar to the I&P farm, TIA representatives discussing the results of the trial to date and the producers who hosted the events.

A total of 72 people attended one or more of these workshops, including TIA staff and the supplier of Feedchar for the I&P feeding study. An information package was developed for the workshops, including results and an extensive list of resources (Appendix 8.5). The package also included a feedback survey, devised to gather data around awareness, knowledge and skills related to biochar use, prior and post workshop. Attendees were asked to fill out the feedback survey and the results of the three surveys were collated for reporting purposes.

Overall, 32 people provided feedback after attending one of the three workshops. Of these participants, 23 identified as producers with the remainder identifying as an advisor (3), agribusiness service provider (3), government official (1), supply chain participant (5) or other (2) which included a dairy farm hand and indigenous elder (Fig. 14).

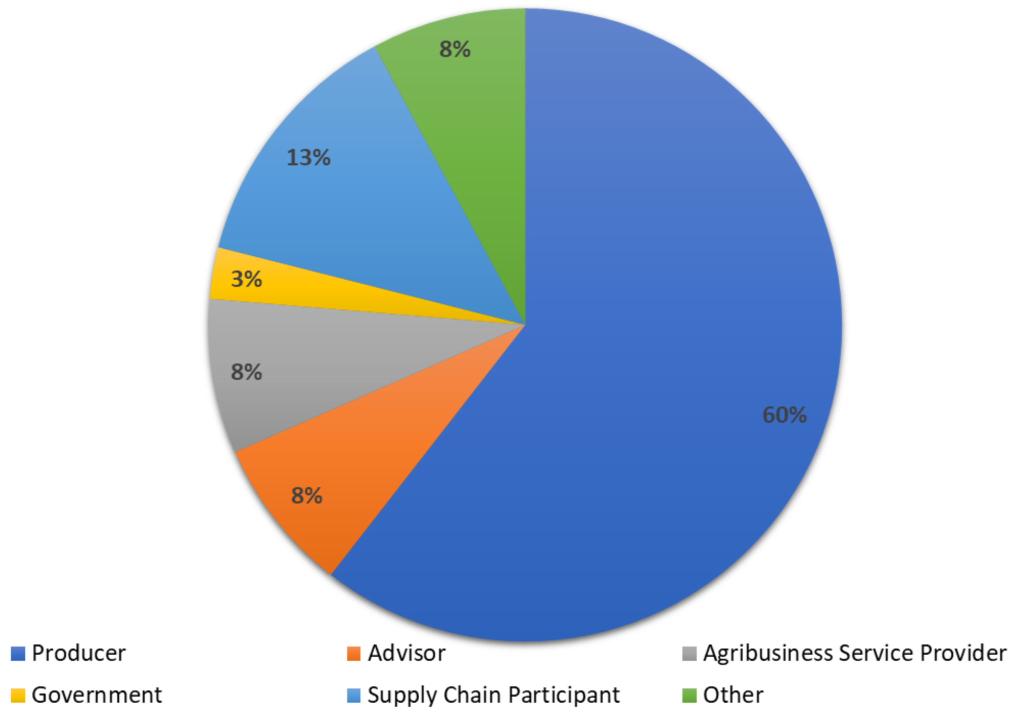


**Fig. 14.** Breakdown of workshop participant involvement in different sectors/industries.

Workshop participants came from a range of production regions across the state with two producers from Flinders Island attending the third workshop, displayed as 'Other' in Fig. 15. There was also a good mix of enterprise/property sizes represented at the workshop. Survey participants were asked to provide an approximate size of their properties as well as the number of cattle and sheep they were running. The property area provided by survey participants from the three workshops totalled 12,747 ha with 20,470 and 19,373 cattle and sheep run on these areas respectively (Table 5). The smallest property size was 2 ha which was running 6 sheep and the largest property size was 4,200 ha which was running 8,000 cattle and 3,000 sheep.

**Table 5.** Total property area, head of cattle and sheep managed by survey participants from the three biochar workshops.

| | Workshop 1 | Workshop 2 | Workshop 3 | Total |
|---|---|---|---|---|
| Property size (ha) | 2,108 | 1,589 | 9,050 | 12,747 |
| Number of cattle | 1,009 | 997 | 18,464 | 20,470 |
| Number of sheep | 9,050 | 3,520 | 6,803 | 19,373 |

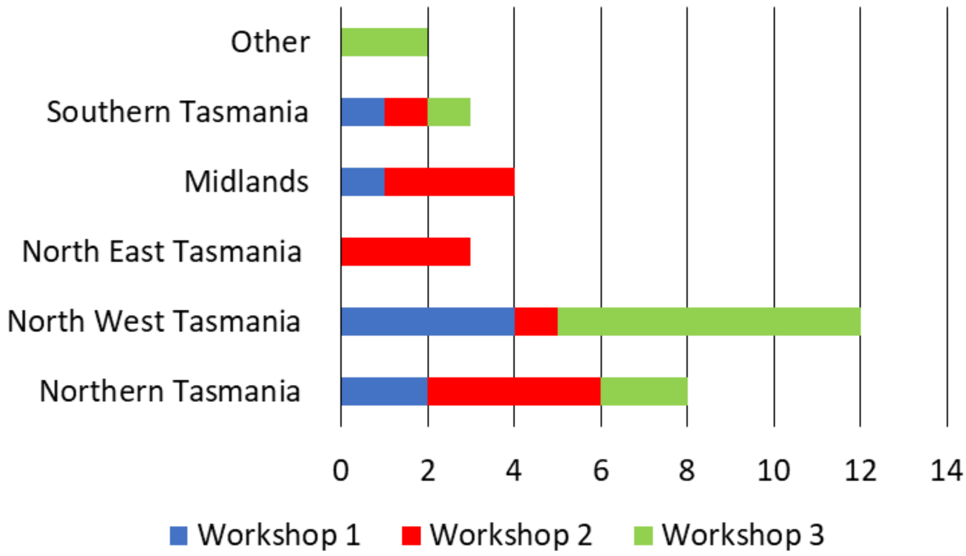


**Fig. 15.** Number of participants from each production region that completed the survey after attending one of the three biochar workshops.

Survey participants were asked to rate their awareness, knowledge and or/skills related to biochar use before and after attending one of the three workshops. Responses indicate that participants gained knowledge by attending one of the three workshops as demonstrated in Fig. 16. Knowledge ratings of 3 and below was higher pre-workshop compared to post-workshop ratings. Additionally, post workshop ratings of 4 and above were higher than pre-workshop ratings. This indicates that the workshops provided a good coverage of information and participants left the workshops feeling that they had gained knowledge.

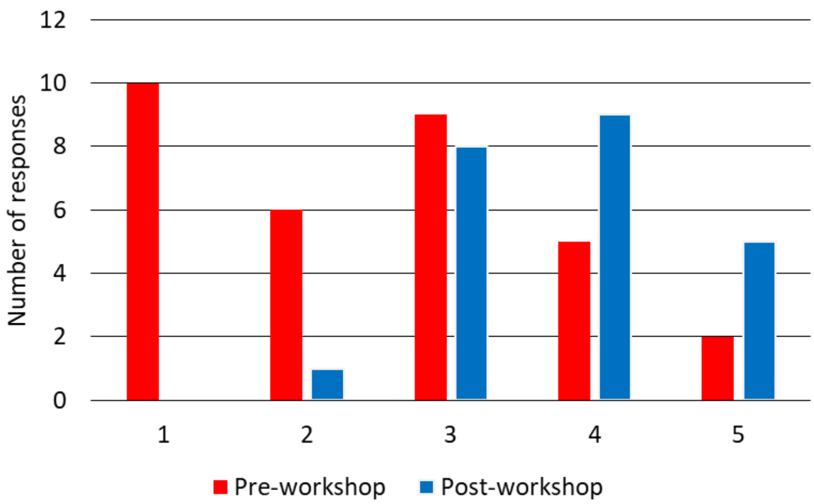


**Fig. 16.** Participant rating of their awareness, knowledge and/or skills related to biochar use before and after the workshops. *(Rating 1-5: 1 = no knowledge, 2 = some knowledge, 3 = some knowledge and limited experience, 4 = adequate knowledge and confidence, 5 = excellent knowledge and confidence).*

The survey participants were asked if they were able to make more informed decisions on topics relating to biochar after attending one of the three workshops. Between 22 and 27 participants felt that they were able to make more informed decisions on the provided topics relating to biochar after attending the workshops (Fig 17). Only one person indicated that they were not comfortable making an informed decision on the forms of biochar available in agriculture.

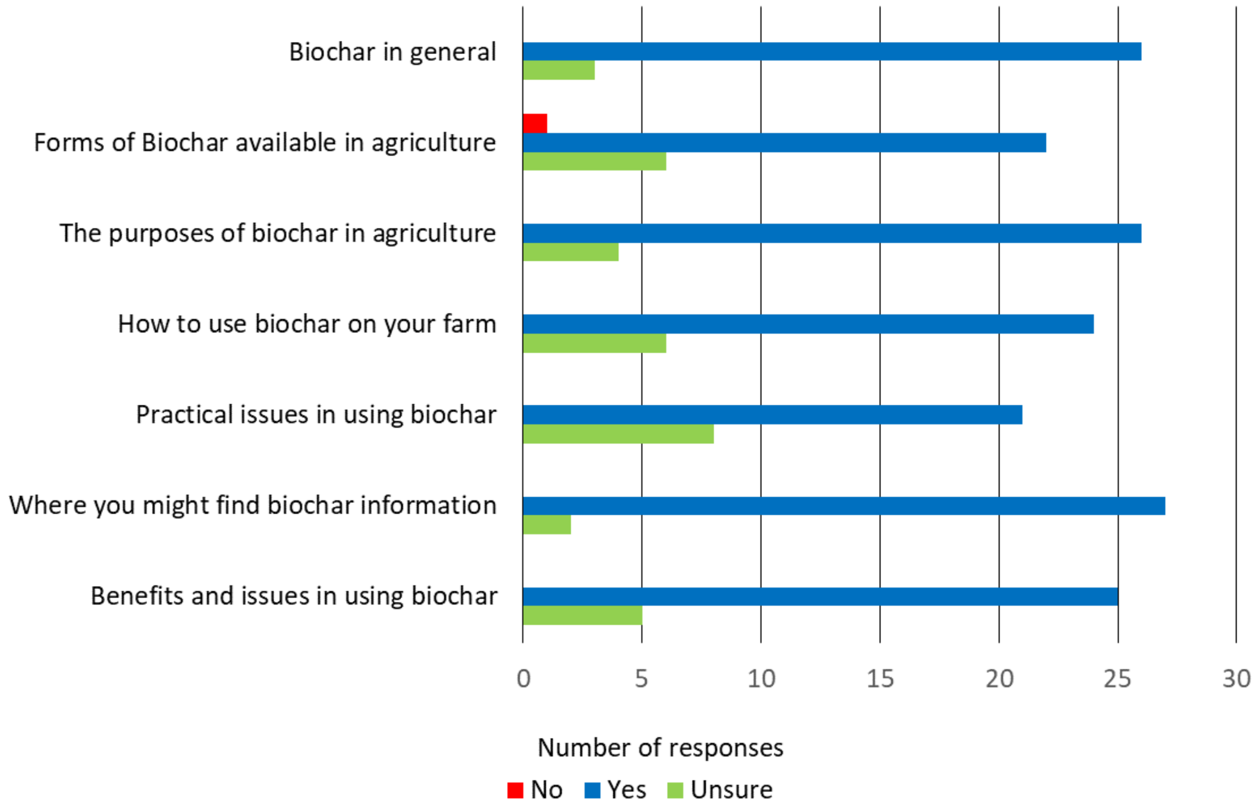


**Fig. 17.** Participants were asked if they were able to make more informed decisions on topics relating to biochar after attending the workshops. A series of topics were provided, and participants gave a yes, no or unsure answer.

After attending one of the field days, 21 participants indicated that they intend to use the biochar as a feed supplement (Fig. 18). The two main reasons for this intention were to improve both animal health and soil carbon (Fig. 19). However, some participants acknowledged that they already feed other supplements, feeding supplement is too impractical and biochar costs too much. This accounted for 9, 12, and 8 participants respectively (Fig. 18).

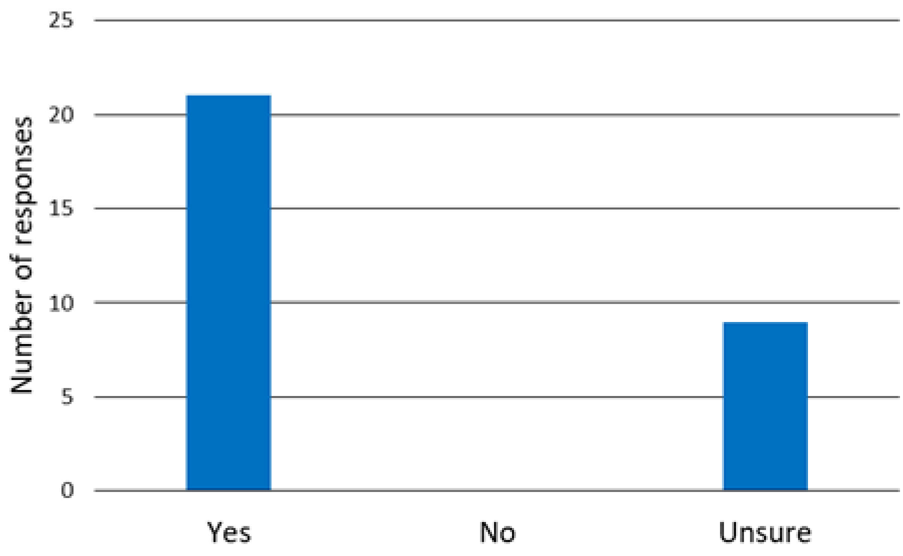


**Fig. 18.** Number of participants who intend to use biochar as a feed supplement or other use after attending the workshop.

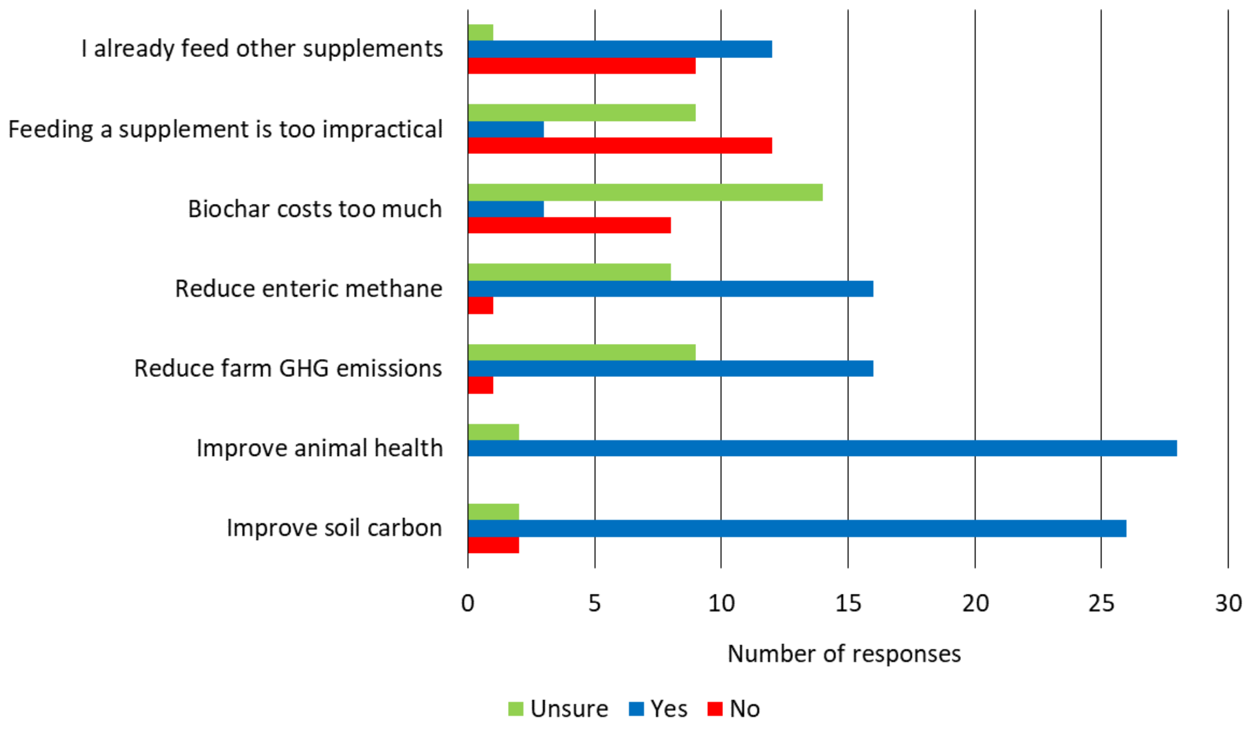


**Fig. 19.** Participants were asked to assess the main reasons for their intention to use biochar after attending the workshop.

At the end of the survey, participants were asked to provide a satisfaction rating for the biochar workshop they attended with 1 = not at all satisfied and 10 = extremely satisfied. Of the 29 responses for this question, 28 participants recorded a satisfaction rating of 8 or higher (Fig. 20). This demonstrates that participants at all three workshops were satisfied with the overall content and running of the workshop series. Workshop participants were also given the opportunity to provide feedback and comments when asked a series of questions in the survey. Table 6 provides a compilation of participant comments from the workshop surveys that were completed. Overall, feedback comments from the survey were positive. However, it can be noted that there were many comments suggesting the need for further research in the area, more specifically looking at advantages to liveweight gain and costs of supplementation. Figs. 21 and 22 were taken at the first and third workshops, respectively.

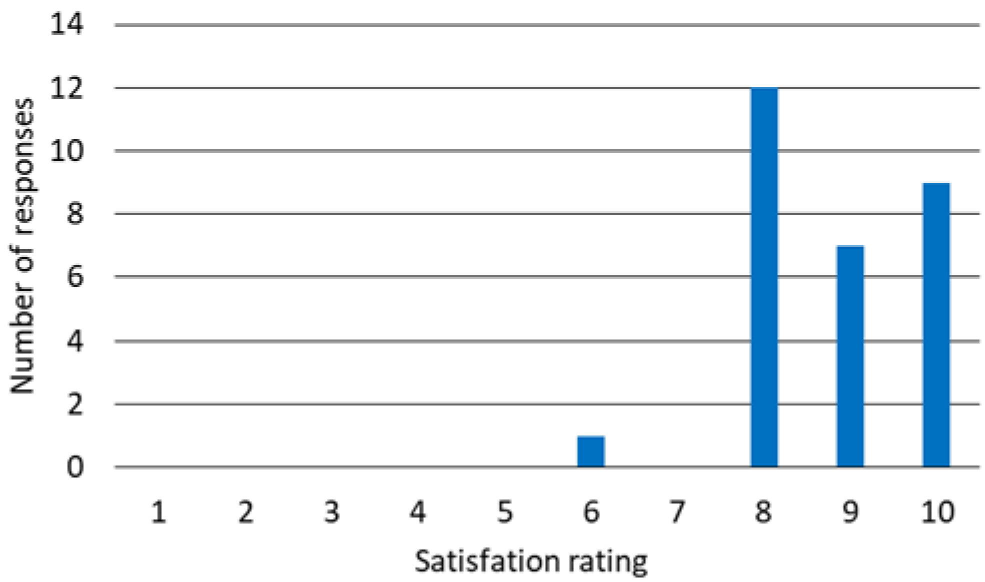


**Fig. 20.** Event satisfaction rating for the biochar workshops. Participants were asked to rate satisfaction out of 10: 1 = not at all satisfied, 10 = extremely satisfied.

**Table 6.** Survey comments from each of the three biochar workshops

| | Comments | | |
|---|---|---|---|
| ***Question*** | ***Workshop 1*** | ***Workshop 2*** | ***Workshop 3*** |
| *Do you intend to use biochar as a feed supplement or other use after today?* | • For calf rearing next year<br>•Didn't know you could<br>•Definitely interested and want to, but need to set up feed bins etc.<br>•To help pasture quality and feed | •Beneficial<br>•Need more research | •Horses<br>•Would like to try<br>•Cost/availability<br>•I have already purchased some<br>•Need to see more evidence of advantages<br>•Fundamentally sounds good. On a large scale not sure. Obviously getting the right product will be very important. |
| *What are the main reasons for your decision for or against the use of biochar after attending the workshop?* | •I am here to learn about it<br>•I don't think the research is there to prove the benefits especially with live weight gains | •Soils (water holding capacity) nutrient access vs chemical inputs vs vet bills<br>•Interested in all the above<br>•Sheep wool grower<br>•Probiotics | •Only have horses. Interested in the bigger picture |
| *Outline what other information or assistance you might need in order to use biochar or recommend* | •One on one assessment as to needs<br>•More research and discussion with Steve (Agspand) if possible<br>•Nutrient-more information on the biochar, cost of biochar, and cost benefit | •Easy to recommend to others<br>•More research-based results and long-term studies. All very anecdotal at this stage<br>•To reduce fly damage to lambs<br>•Different grades of biochar for different applications | •Commenced<br>•Amounts to feed or apply<br>•Would like to see more detailed trial data<br>•Cost Analysis<br>•Keep abreast of biochar information as it develops<br>•Recognise a good quality product |
| *Event satisfaction - What should be continued/changed?* | •Good variety of speakers and topics<br>•It was great. So informative. I had attended biochar workshops for making biochar and using on soil but had no idea the value of feeding it to stock | •Show more measured results. Compare to other research findings | •More workshops. Would like the opportunity to spread the word as the burning is important to country<br>•More time sharing/less talking at |

**Fig. 21.** Attendees at the first workshop held on the Involve and Partner project farm, inspecting a mob of Wagyu cross cattle being fed biochar (November 2022).

**Fig. 22.** Attendees at the third biochar workshop in Marrawah had the opportunity to have a brief farm tour of the Greenham Tasmania 'Westmore' property. Here, attendees inspect a mob of Wagyu cross cattle that had previously been supplemented with feed char (February 2023).

Of the 32 respondents providing feedback, 30 supplied contact details for follow up phone interviews to be conducted the end of the I&P project to ascertain the impact of the workshops over time and whether biochar has become a part of farm management practice or, for advisers, a recommended practice. The phone interviews will occur in October/November and be reported on in the final I&P project report.

### 4.5.2 NEXUS Producers Adaptation and Adoption

*1) Biochar Project*

*Introduction*

Reporting to the social aspects of the I&P Biochar project has been done here separately to the other adaption/adoption reporting as it was far more targeted and the data reported only concerns one case, with supporting information gathered from the Biochar workshops. From this data five themes were identified and discussed below. These included:

- Forms of biochar
- Feeding mechanisms
- Biochar feeding responses
- Time and Efficiency Imperative
- Observed Effects/Impacts

*Forms of Biochar*

> "Not sure how others will get biochar into cattle when they're on pasture …. maybe the troughs like we do, to access whenever they like" (I&P Farm Manager)

Statements such as these indicate that both the form of the biochar and the method of delivery (see below) are aspects to be considered for using biochar. Biochar generally comes as a powder that can be fed straight to livestock. In this form it can also be mixed into feed pellets, mixed through other feed e.g., silage, and as licks. Other suggestions mentioned about the forms and distribution of biochar include:

- Feedlots use a total mixed ration feeder which might also suit distribution in dairies.
- Weather pro bags that are mineralised could also mix in biochar. These, however, might break down in weather and are very expensive.
- Preference by the farmer was for something like lick blocks. These were not good for the trial as the uptake of the biochar could not be measured but could be considered in different contexts
- Lick blocks can also have other 'needs' added to the block and the livestock "would come […] have more reason to eat [the biochar]". Suggested additions to such a lick block would include for example, copper, selenium, magnesium, cobalt (deficient in Tasmanian soils), molybdenum and dolomite and biochar could then be gained inadvertently with these other needs.

However, the manufacturer attached to the research suggested that this was not really feasible as the uptake of biochar would probably not be sufficient and the number of lick blocks required would make it cost prohibitive.

- It was indicated that adding salt or molasses was not desirable to attract biochar uptake, which is a suggested strategy.

  "It feels a bit like I'm forcing them to eat the biochar by feeding salt."

  "It makes most sense to have as a mineralised lick block to decrease salt intake."
- Adding the biochar to grain was also suggested however this could raise consumer issues and be problematic to existing programs such as that offered by major Tasmanian abattoirs' programs which promote their products being 'grass fed'. Another suggestion for consideration would be adding to grain free pellets.

*Feeding Mechanisms - Trough vs Feeder*

To feed out the biochar, both troughs and a feeder were trialled. Both methods had the added advantage that when they were filled the cattle looked interested and investigated, encouraging them to eat the biochar.

*Troughs* – These were moved from paddock to paddock with 3 joined together and dragged (sled) with a quadbike. Doing this meant that there was some loss/waste of the biochar either via cattle or in moving the troughs to a new paddock

"At the moment I lose about 1 litre per day"

The trough option also meant that the biochar could get wet (a significant issue in Tasmania in the north-west). When biochar gets wet it sets. "Think about straw, like they're not gonna eat wet straw…can't see why they would want to eat the wet char. So, if we can keep it dry….". The farmer reported that he had to "fluff it up about once a month", BUT he also indicated that it was easy to measure out for trial. The troughs were also much cheaper than the feeder.

*Feeder* – During the first months of the trial the troughs were replaced by a *feeder* on a trailer. This meant it could still be easily moved from paddock to paddock with the quadbike.

"It's on wheels rather than sled so easier over rocks and won't flip."

Consumption could still be easily measured for the trial via a window on the side of the feeder and it was difficult for the calves to waste as there was a) no loss out of trough and b) the calves h to work to get it out. The feeders also kept the biochar dry (although it still needed 'fluffing'), however feeders are an expensive option (approximately $5,000 each).

*Biochar feeding response*

During the biochar trial it was noted that there was not a consistent uptake of biochar. This observation was supported by other biochar users at the Biochar Workshops. At different times of the year, and with different feed available, the cattle would eat more or stop eating the biochar according to need.

The biochar farmer noted stages that the calves went through in the uptake of the biochar.

- Stage 1 - “calves loved it at first, couldn’t eat enough”
  During this stage the farmer added salt to encourage eating (100L biochar:20L salt) then weaned them off the salt

- Stage 2 – “The calves dropped off feeding”
  It was noted that this was when pasture growth began to decline in winter

- Stage 3 - “then they pretty much went completely off it and they didn’t want anything to do with it.”
  The calves stopped eating when biochar got wet and cold and not very appetising compared to “straight out of the bin its soft and fluffy, lots of air in it”. This also coincided with feeding straw. Other biochar users also noted that their cattle tend to eat biochar when there was a lot of green feed and suggested that the biochar became an alternate source of carbon when it was not available. This generally coincided with spring and not with winter when feed such as silage and hay were used as a supplement.

*Time and Efficiency Imperative*

As the following quotes indicate, the use of biochar was another job to fit into an already busy day for producers. Therefore, time and efficiency were paramount in considering its use.

> “Everything we do, we try to minimize the number of times you’re handling something and the amount of time it takes.”
>
> “Makes sense to eat where you store.”
>
> “It’s not a big deal, but if I’m under the pump …. there’s another hour a day …. and it’s another task …. another thing.”

The biochar farm manager described the ‘ease of use’ process of using both the troughs and the feeder making the feeder more time and energy efficient.

*Troughs* = Biochar comes in bulker bag > into Jackie bin > truck to pick up bin to fill buckets > 20 litre buckets (for measuring) onto bike trailer > take biochar to troughs > fill and record amounts on phone > move to new paddock when calves are moved

*Feeder* = Biochar comes in bulker bag > tractor pours into feeder > already measured as per bag weight > measure as per level each week for % consumed > hitch to bike to move to new paddock

The feeder was able to reduce the hours required to feed, especially in winter (Tasmanian winters have very short daylight hours). The feeder reduced the need for the manual labour required for bucketing the biochar into troughs daily. The feeder could be filled via bulker bag, once.

*Observed Effects/Impacts*

Producers who had used biochar also observed certain impacts on their cattle when they commenced the use of biochar. All these effects/impacts seem to be indicators of 'good' health but would need to be further explored. The producers suggested that the biochar works to:

- Settle manure to a yoghurt consistency when calves are on green feed

- Possibly helped with clearing up ringworm lesions – hair coming through the lesions, but the lesions came back (maybe when biochar feeding slowed?)

- Cattle got their winter coat early, before the control mob and it was shiny for longer

- The percentage of 'dark cutters' at the abattoir was reduced, representing a cost saving to the abattoir business.

While the biochar trial has yet to demonstrate significant results in terms of liveweight gain and soil carbon, the social research suggests that there are areas such as biochar's impact on animal health and meat quality that would be useful further explorations.

*2) NEXUS Regional Reference Group Adaption and Adoption*

Discussions of adaption and adoption with the RRG included both the technical manifestations (what happened) and the temporal knowledge (the thinking and knowledge around what happened) required for the NEXUS adaption options explored (low hanging fruit, income diversification and transformational options) to be implemented. It should be noted here that while specific questions were asked of all three of the NEXUS adaptions modelled and discussed, the RRG usually responded with generalities. Their focus was on an overall uptake of a range of adaptions rather than 'specifics'. This was possibly due to the limited time they had to convey their knowledge. However, the RRG producers also identified at other times, that the context specific nature of each of their own farm environments meant that they were cautious about being too specific of the needs in contexts different to their own. Their responses were therefore limited concerning specific adaptions. We include some of the more specific ideas below (Table 7), but the focus here will be on the more general temporal knowledges concerning what the producers discourse exposed concerning producer thinking and how this understanding might be used in adaption/adoption activity in general.

*Temporal knowledges vs technical manifestations*

Overall, the RRG producer discourse was underpinned by four distinct understandings:

1. The need for 'real' solutions
2. Stewardship of the land and people
3. Complexity of issues
4. Viable change

Approaches to the Nexus adaptions appeared to be informed by a balance of these four understandings.

*1. The need for 'real' solutions*

The RRG spoke of the need for 'real' solutions: their sense of 'real' incorporated the notion of what one producer called 'winning big'. If they were going to enter into a solution (which included everything from the Low Hanging Fruit option of planting legumes to a Transformational option of wind turbines) they wanted it to demonstrate a worth that went beyond financial gains. Solutions must be:

* A win/win for both the producers and their land/environment and meant that any solution must be low or no impact on the environment,
* Balanced between risk/finance/production levels/practicalities of seasonal impacts. All these aspects needed to be considered,
* Based on beneficial partnerships and alliances – preferably within their communities for locally based solutions. One example given was the difference between the two available large abattoirs in Tasmania. They saw JBS as trying to "grind farmers down", verses seeing Greenhams, as a local opportunity, developed between local business and local farmers. Greenhams were seen as a part of the solution as they had set up a specific market for each red meat product they market and supported producers in their efforts to produce for those markets.

*2. Stewardship of land and people*

The RRG's understanding of stewardship encompassed understandings of sustainability, legacy, and the uniqueness of the Tasmanian context.

Sustainability, as currently understood, was almost spoken of as a 'compromise' to environmental approaches in livestock farming, rather than one of the 'real' solutions spoken of above. For sustainability to occur, producers spoke of the need to recognize issues of food security – both internal and external to Tasmania; the need for reducing human impact and "tread lightly" on their land and the use of conservation practices. In terms of climate change, the RRG did not believe Tasmania was in trouble yet, but still needed to look to the future.

The RRG was made up of both young and very experienced producers. Both expressed a profound sense of being able to either pass on or receive a legacy through the family farm. There was also an acknowledgement of the importance of generational knowledge from the past as well as future focused knowledge being blended for the most impact. The older generation were preparing for "generational rollover" and were excited by the younger generations ability to bring a "modern approach". A conservationist approach for one of the RRG had always been a focus for his family since his great grandfather. "It's just been the thing that the family [does]. […] it's a better family farm for the kids". This focus had been passed on and was now valued by the next generation.

The uniqueness of Tasmania also provided the RRG with options that they believed were not available in other parts of Australia. "We can make claims others can't" in relation to Tasmania's clean/green credentials, biosecurity, food bowl status, and being "GM free", antibiotic free, 100% grass fed. This built the profile for a "rare product" that could then be marketed and was an important understanding that the RRG were not willing to compromise. The RRG producers translated this into working on their farms so as not to jeopardise their ability to make these claims.

The notion of stewardship therefore impacted on what the RRG producers would support and recommend in relation to the NEXUS adaptions.

### *3. Complexity of Climate Change Issues*

All of the RRG members identified the extreme complexity of climate change and farming responses. While each of the producers had shown a willingness to engage in the research space, they also had concerns. They spoke of the knowledge required to respond to climate change as being extremely diverse, vast, and often contradictory, inconsistent or incomplete. As one producer asked,

> "What is the 'truth'?"

The 'truth' was seen as hard to determine so therefore questions about how to act on information, which may or may not be reliable, was a concern. Most of the RRG did their own research and used avenues such as local producer groups to talk through issues and to invite speakers who they trusted. However, they also identified that the limited resources and a lack of knowledgeable consultancy were problematic, and the idea of a one size fits all approach was unworkable. "Every farm is unique – soil, rainfall, climate, tree cover, biodiversity. General universal practices are OK but then it's got to be individual". Their belief in working together and wanting to support each other in acting for climate change was also tempered by the question of when it was appropriate to act individually verses acting communally so that individual contexts and needs were being met.

As many of the RRG were proactive, rather than reactive, in their thinking and farm management, this quest for the 'truth' made them swing between "where do I start?" and an optimistic approach to being able to take every opportunity to move their thinking and their farming forward in relation to their climate change responses. This could be seen with new ideas being explored and in their volunteering for the LLP NEXUS and Legume activities. Many of the RRG were also conducting other research trials and their own trials, which sat alongside these projects. This allowed them to work out for themselves in their own context what 'the truth' was and to sort through the issues that arose for best practice.

The hunt for reliable knowledge was hindered by a lack of trust in those giving the information. In what we have termed 'knowledge hoarding', producers had experienced some knowledge holders who had had the opportunity to pull together much of the information/research around climate change responses. However, these people were seen to be almost holding this knowledge for ransom in order to make a profit out of it or selling off their knowledge at a cost that was prohibitive for most farmers.

One of the issues that some of the RRG had not expected was that their 'forward thinking' around sustainable practice would trigger a negative social response.

> "Facebook doesn't help. It's too easy for someone to take a picture of a dead lamb and decide all farmers are murdering their lambs. You know, that sort of thing."

Issues such as animal welfare, public misconceptions of 'transformational' action on their farms and the negative use of social media had an unexpected and often negative impact on them.

*4. Viable change*

For the RRG, change was an essential part of their farm management. They were prepared to take significant risks to respond to climate change. Financial and other risk taking (e.g. locking up a paddock for a trial, experimenting with pasture species, and many of the LHF options) was not a concern for them as they approached change as a 'when' rather than 'if' proposition. The size of their farms and financial security probably played a large part in this confidence, that might not be available to others.

Industry response was a concern for them. The cost of advice and their lack of confidence in it, the 'knowledge hoarding' they had experienced, the greed of the multinational companies they were forced to engage with all contributed to their distrust of industry to do the 'right thing' in general. Examples given were of fertiliser companies that were seen to have hugely negative impacts on the farming industry in relation to issues such as soil health, but had instead continued to increase prices and a reliance on chemical use rather than responding to climate change; the Nutrien buy up of Roberts, Harcourts and Tas Irrigation, limiting access to competition; and while many of the agronomy advisory services were respected, there were questions about the lack of experienced employees that these services were able to employ.

> "Consultants are different, all sorts of different people with different skills"

> "they're so short…. I'm sure they'd like to access some better skilled people"

However, the RRG had also been discerning about who they relied on for information and were including researchers as well as industry for advice.

Costing for change was important. The RRG spoke of the Low Hanging Fruit options being able to be "done tomorrow", but that an environmental cost should also be included in the financial calculations of options being explored. They identified that there would always be a cost burden associated with change but identified that when the market allowed producers to be in profit, they could take advantage of trialing the riskier options for climate change.

The RRG identified many of the skills they required to operate in a changing context which focused on "think quicker and adapt faster". Many were about knowledge gathering, however others that were important were:

* Business skills – they identified that while producers might have excellent farming skills this did not necessarily translate into having good business skills and that farming required both,
* Partnering up – developing relationships that allowed opportunities to be taken to partner "with people you like", particularly with those who bring another set of skills to the partnership,
* Being Proactive – the RRG spoke of "opportunity hunting", "searching out solutions", being on the "front foot", "act[ing] before being forced", "trial with support", "watch what the 'best' or 'smart operators' do", "have a go and then help others". All these statements indicated the RRG being ready and willing to respond to climate change in forward thinking ways and bringing others along with them,
* Fail well – in the same way as the RRG spoke of "winning big" they also were prepared to 'fail well'. They always planned to succeed but were willing to take the risk of failure to learn. 'Failure' was not perceived a bad thing but as a part of taking a calculated risk. Their notion of "short term pain for long term gain" was instrumental in this. Being prepared to fail was important for growth both personally and as a producer, "you need one failure a year to know that you are actually doing what you need to be doing". These 'failures' came with provisos – they must be tempered against financial loss, and they must be learned from. They suggested that people start small with risk taking.

*Knowledge gathering skills included:*

* Watching nature and asking "Why?" at deeper and deeper levels and "Is it really advantageous?". For example, asking "why are there no longer lady bugs eating other pests and diseases?" and then looking to the pesticides being used. Low trace elements in livestock might mean they are no longer in the soil. "It's a long game…. And you gotta continue to question why. Just because your grandfather did it, or your father…. do you do it?",
* Listen to our kids,
* International connections – Many saw other countries as being far ahead of Australia and could therefore be drawn on for advice,
* Accessing researchers,
* Taking part in trials,
* Watch the successful for practical advice, habits, experience and poor operators for what not to do – "although they are probably say the same thing of me",
* Social media – with discernment,

* Read,
* Classes, field days, University, producer groups, Facebook groups (from Victoria and US),
* Based around productivity,
* Revel in the changes seen and “being satisfied with what you are doing…. That’s pretty cool!”,
* Include farmers in the design of education programs,
* Mentors,
* Taking advantage of ZOOM for more participation.

*Adaption Specifics*

Table 7 contains statements from RRG members related to the adaptation/mitigation options explored in NEXUS. Note that we did not always receive responses for each part of each adaptation (e.g. irrigation, earlier finishing, land purchase and planting trees have limited responses).

**Table 7.** NEXUS Regional Reference Group responses related specifically to some of the adaptations. Note that biochar use was described separately (see above).

| | Low Hanging Fruit | | | Income Diversification | | |
|---|---|---|---|---|---|---|
| **Factors** | **Pasture renovation – with legumes and regenerative pastures** | **Irrigation** | **Earlier finishing** | **Wind turbines** | **Land purchase** | **Planting trees** |
| Purpose | ▪ Nitrogen fixing,<br>▪ Providing a summer crop<br>▪ Continual food ie increasing 'multiple species' within multi species pasture | | ▪ Requires increasing liveweight gain<br>▪ Greater productivity and pasture management required | | | |
| Benefits | | ▪ We are missing the point about irrigation – if we build soil carbon, soil moisture, soil holding capacity etc, then irrigation becomes unnecessary and damaging | | ▪ The farm location is in a place with a lot of wind, is isolated from the nearby town<br>▪ Benefits of the turbines are to both the town and farmer with development and greater opportunities to grow the local community through employment and bring families into the community rather than just retirees. | | |

| | Low Hanging Fruit | | | Income Diversification | | |
|---|---|---|---|---|---|---|
| **Factors** | **Pasture renovation – with legumes and regenerative pastures** | **Irrigation** | **Earlier finishing** | **Wind turbines** | **Land purchase** | **Planting trees** |
| Issues/Blocks to Change or Adaption | ▪ Lack of spring feed compared to rye grass<br>▪ Consultants/agronomists seem to have been fixated on what is quick growing/short establishment (e.g. rye) for money gain<br>▪ Ag industry often ultra conservative<br>▪ Regen definitions are up in the air but seems to be about having lots of mixed pastures<br>▪ have irrigation but won't use this year<br>▪ Some natural grass, some brassica over mix and other large selection of chicory, plantain, crimson clover, fenugreek, radish, | | | ▪ Suggestions that producers should do the LHF and then look at the diversifications that could be done as a group (e.g. the wind farm)<br>▪ The wind farm "for most farmers out there, it's not going to be possible." Only 1-2% able to potentially have this option. "What happens to helping the other 98% of farmers?"<br>▪ Social Issues - "People in town seem to think we could build [the turbines] in their backyard"<br>▪ "People not understanding that wind is east west and the town is south so | | |

| | **Low Hanging Fruit** | | | **Income Diversification** | | |
|---|---|---|---|---|---|---|
| **Factors** | **Pasture renovation – with legumes and regenerative pastures** | **Irrigation** | **Earlier finishing** | **Wind turbines** | **Land purchase** | **Planting trees** |
| | sunflower, Siberian millet, oats, rye, rape maize, lucerne, clover, linseed<br>▪ The mix means they are active at different times of the year<br>▪ Cattle get a bit of everything in rotation.<br>▪ Watch cattle trying to work out how to eat a sunflower. They have a bit of fun. It's good for them and they get a varied diet<br>▪ Minimal to no synthetic fertilizer used<br>▪ Calcium and chicken manure used<br>▪ Over 60% of farm renovated and will keep going | | | noise can't travel. You show the evidence but they don't get it. Just haven't got a perception of distance and noise and sound and wind"<br>▪ Retiree outsider driven opposition is preventing opportunity for town development to<br>○ "Get more families to come and live in [the community] to do maintenance or build turbines… then their kids turn up and their wives look for a job"<br>○ They're turning [the community] | | |

| | Low Hanging Fruit | | | Income Diversification | | |
|---|---|---|---|---|---|---|
| **Factors** | **Pasture renovation – with legumes and regenerative pastures** | **Irrigation** | **Earlier finishing** | **Wind turbines** | **Land purchase** | **Planting trees** |
| | ▪ Get silage out of it as well | | | into a retirement village and everybody wants the restaurants open, but there's no one to work in them. So you know it's not working the way they're doing it."<br>▪ Being accused of "all sorts of things" on Facebook/phone calls. But we have heaps of support from town"<br>▪ Complaints about the damaged skyline by people building their mansions on the top of a hill. The turbines will only | | |

| | Low Hanging Fruit | | | Income Diversification | | |
|---|---|---|---|---|---|---|
| **Factors** | **Pasture renovation – with legumes and regenerative pastures** | **Irrigation** | **Earlier finishing** | **Wind turbines** | **Land purchase** | **Planting trees** |
| | | | | be there 25 years. Their houses will be there forever | | |
| Use and Ease of Use | ▪ Long time to establish | | | ▪ Not a typical property as there is no bushland so therefore have to look for other ways to stack CN options | ▪ Gut feeling additional land would be better close to farm. | |
| Economics | ▪ Expensive to establish, especially if planting fails<br>▪ Profitability is questionable<br>▪ More funding from government bodies is required to support specific areas (e.g. harnessing the industry)<br>▪ Farmers can set the agenda forcing companies to respond. i.e., no customers = no | | | ▪ Less than 10 ha to produce a lot of electricity and livestock can still access the grass around them<br>▪ The turbines have a 25 year lifespan and then are taken away | | |

| | **Low Hanging Fruit** | | | **Income Diversification** | | |
|---|---|---|---|---|---|---|
| **Factors** | **Pasture renovation – with legumes and regenerative pastures** | **Irrigation** | **Earlier finishing** | **Wind turbines** | **Land purchase** | **Planting trees** |
| | profit = companies fall over | | | | | |
| Skills for Adaption | ▪ Increased education for farmers<br>▪ HOW TO: Awareness of<br>○ establishment of pastures<br>○ grazing,<br>○ persistence,<br>○ long term benefits beyond feed (e.g. nitrogen fixing) rather than short term money grab | | | ▪ Opportunity arose via someone who had put in a turbine, had the knowledge and nowhere to go with it. So took the opportunity | | |
| Ideas for moving forward | ▪ Independent trials that also develop large/commercial scaling up of solutions<br>▪ Mapping of legumes across all Aust regions (Farm App) as people need this advice<br>• Like LIST | | | | | |

| | Low Hanging Fruit | | | Income Diversification | | |
|---|---|---|---|---|---|---|
| **Factors** | **Pasture renovation – with legumes and regenerative pastures** | **Irrigation** | **Earlier finishing** | **Wind turbines** | **Land purchase** | **Planting trees** |
| | • Distinguish between red/white clover<br>▪ Government enacted restrictions per hectare for synthetic N use (P as well?) e.g. NZ has done this<br>▪ Free education for all farmers re-legume adaption in pastures<br>▪ Use current innovation – e.g. genetically add the active ingredient for methane reduction (bromoform) from asparagopsis to legumes<br>▪ Funding to facilitate more 'Nexus, Legume" type projects<br>▪ Put more in | | | | | |

| | Low Hanging Fruit | | | Income Diversification | | |
|---|---|---|---|---|---|---|
| **Factors** | **Pasture renovation – with legumes and regenerative pastures** | **Irrigation** | **Earlier finishing** | **Wind turbines** | **Land purchase** | **Planting trees** |
| | ▪ Companies need to get involved for commercialisation | | | | | |
| Understandings Impacting Decisions | ▪ Profitability/Low cost options<br>▪ Practicality of broad change/Ease of use<br>▪ Consequences for future generations<br>▪ Sustainable growth | | | | | |
| Governance/ Policy | ▪ Can we trust their decisions – would like to think so and can work collaboratively with industry/companies to make commercialisation happen | | | ▪ Planning process required to help address social issues | | ▪ Bush has restrictions and bureaucracy means that farmers won't fence e.g. land along the river has an endangered gum species which can't be taken out to make straight fence lines for protection of bush from cattle. Increases material and costs and loss of productive land. "Removing 10% of trees he could have protected the lot. |

| | **Low Hanging Fruit** | | | **Income Diversification** | | |
|---|---|---|---|---|---|---|
| **Factors** | **Pasture renovation – with legumes and regenerative pastures** | **Irrigation** | **Earlier finishing** | **Wind turbines** | **Land purchase** | **Planting trees** |
| | | | | | | So now he hasn't fenced it, so the cattle are in there all the time. It just doesn't make sense. [..] But you know, I guess common sense isn't so common" |
| Ethical Issues | | | | ▪ More negativity than expected but from a small minority<br>▪ We live here we aren't going to damage the place<br>▪ Environment first if they come up with a good reason not to "I'm happy to listen to it …. But no one's come up with anything other than 'I don't want to be able to see it. They fully support renewable energy | | |

| | Low Hanging Fruit | | | Income Diversification | | |
|---|---|---|---|---|---|---|
| **Factors** | **Pasture renovation – with legumes and regenerative pastures** | **Irrigation** | **Earlier finishing** | **Wind turbines** | **Land purchase** | **Planting trees** |
| | | | | but we just don't want to see it." | | |

### 4.5.3 Red Meat Producers Survey

The Red Meat Producers Survey was based on producer scoping interviews and other requirements of the two LLP projects- NEXUS and Legumes projects (see Appendix 8.7). The information from those interviews and project requirement included questions concerning:

- Information seeking skills
- Succession planning
- Employment – paid/unpaid family, non-family
    - Recruitment
    - Turn over
    - Workforce constraints
- Climate change perspectives
- Pasture
    - Feed supply and feed demand
    - Feral and native browsing
    - Irrigation

For this report, those questions concerning red meat production have been the focus.

Responses to the survey were limited (n=36) but does give a broad snapshot of red meat farming across Tasmania with responses coming from most regions. A ratio of approximately 2:1 males/females responded. Farm sizes ranged from hobby farms to very large farms of 24,000 Ha.

*Red Meat Farms*

Overall 34% of farms produce beef, 26% of farms produced lamb and 40% produced both beef and lamb. In combination, 75% of farms were producing beef and 66% of farms were producing lamb.

The farms producing lamb were either just breeding ewes for lambs (50%) or a doing a combination of breeding and trading (50%). There were no enterprises that only traded lamb. The size of the farm determined the numbers of lambs being bred and/or traded. This was different for beef where 6% of beef producers were finishing beef only. However, there was still a majority of producers who were either breeding (68.5%) and/or finishing (60%).

*Red Meat Production*

Most farm's red meat production was over 50% of the whole farm operation. Those farms whose production was less than this were either hobby farms or very large farms where diversification was possible on a large scale and other production was available at scale e.g. cropping.

*Red Meat Production Plans*

No red meat producers were planning to reduce their production in the next 5-10 years and almost (70%) were planning to increase their production.

*Climate Change Perspectives*

There appeared to only minimal climate change 'deniers' (6%). The remaining red meat producers agreed that the climate was changing and they were responding in a variety of ways. Some (11%) did not feel they needed to change their management. One was from the North-West where climate change has minimal impact in the current conditions. Another two were from the Midlands and had irrigation already installed to help deal with the possible impacts of drought. Examples of responses gleaned from the Red Meat Producers Survey, related to climate change, are presented in Appendix 8.8.

Producers wanted more information on how the climate was changing in order to better respond. Some producers were not sure of how to respond. However, 60% were beginning to adapt their farming practices. Comment was made that support to do this was needed as there was too much conflicting information. Other comments also supported the idea of climate change. One presented a slightly alternative understanding that still spoke of their willingness to adjust their practice

> "The climate evolves in cycles so adapting to those cycles and having an idea of where the cycle currently sits is the greatest help to managing or mitigating those variances".

The other was very concerned about getting the right kind of advice to best adapt support the comment from above.

> "I believe the climate is changing … a lot and that it is vital for me, my business, food production and the planet, to change how I do things. But getting honest, practical, reliable advice is difficult to find and I fear, expensive".

*Feed*

Most red meat producers were confident in managing their feed supply and demand with 50% of producers ranking their ability at 75% or more. Farmers with less confidence were often those that ran hobby, small and small/medium sized farms. This could indicate that these farms had tighter restrictions on available feed. It may also have indicated a lack of confidence due to less experience as producers. However, we did not ask about years of experience to quantify if this might be the pattern.

Most farmers, even those indicating their confidence at over 90%, would like to improve their knowledge and skills in balancing their feed supply/demand. Written responses included statements such as

- 'always up for more training',
- 'I would like to increase my knowledge and skills…',
- 'I have room to improve and would like to increase knowledge and skills.'

One of the very large farms has managers that make decisions about feed supply/demand so wanted training for their staff. In relation to training, one farmer acknowledged that he both struggled with 'learning difficulties' and had little time to do training as he was a small/medium sized farmer where he was the only worker. He would prefer if he could get support face-to-face and one-on-one.

*Pastures*

Pasture swards on farms were a combination of improved and native pastures, at 88.5% of respondents, with the balance 11% of farms had fully improved pastures. Most of the fully improved pastures were on hobby farms where this would be easier to implement and manage. Many farms appeared to have sections of possible 'unusable' land (e.g. creeks, slopes, treed areas) in their farm enterprise mix as the percentages given did not equate to a full 100% of the land owned.

*Pasture Measurement*

Almost 60% of producers did no pasture measurement or used only one type of measure – predominantly pasture cover/pasture availability measure. At the other extreme, five (14%) of the producers used all four of the measures listed (i.e. ground cover, pasture composition, pasture growth rates, and pasture cover/pasture availability) while 18% used a combination of two or three of the measures. The most commonly used measures were pasture cover and availability, and pasture composition.

*Impact of feral and native browsing*

Feral and native browsing was identified as an issue across all the respondents' regions, however ranking this impact was diverse. Most respondents said browsing had a 60% or greater impact on their pastures, with 37% believing the issue to be greater than 81%. Most felt that this impact would be maintained into the future with the impacts limiting production.

*Irrigation*

About half the producers irrigated pasture on their farms. Most of these were from very large farms in the Northern and Southern Midlands area. Small farms that were irrigating had mostly improved pasture on their properties.

The farms with irrigation had lower percentages of red meat production (less than 50% of the total farm production) and irrigation was used for other production such as cropping. Of the farms with irrigation, 43% used their infrastructure to irrigate for feed. These were located in the Midlands on very large farms.

Areas of irrigation varied from 10-1,500 ha with predominantly centre pivots and linear travel irrigators being used on larger farms and hard hoses on small and medium sized properties.

*Climate Change Adaptions*

Respondents were asked what changes due to climate change they had made in the *previous 10 years* and what change they would be likely to make *in the next 10 years*. One option was increasing the extent of deep rooted legumes in perennial pasture. Adjusting stocking rates, working on soil fertility, and planting trees were the prominent choices that farmers had been working on over the previous 10 years. Diversifying the farming system and planting deep rooted legumes had also been done but was not as popular a choice previously.

However, as can be seen in the table below, increasing the extent of deep rooted legumes in perennial pastures was the top choice for change to occur in the next 10 years as being likely or very likely. This was followed by adjusting seasonal stocking rates, improving soil fertility with PKS fertilisers, and planting trees for environmental purposes.

As noted in Table 8, less acceptable options were buying arable land in different climates, developing a new enterprise for income diversification and irrigation.

Despite carbon offsets being an integral part of climate change adaptation, 90% of respondents indicated that they were either very unlikely, unlikely or neutral towards buying offsets to reduce their farm's carbon footprint (Table 8). The higher likelihood to undertake other options on-farm indicates that on-farm change practice is the preferred method to reduce on-farm GHG emissions, and thus credits may be a last resort. Biophysical modelling in this project would support this, in terms of it being more profitable to undertake as many adaptation and mitigation options on farm before purchasing offsets for any residual GHG emissions.

**Table 8.** Preferences for adaptation to climate change from the Red Meat Producers Survey (35 participants).

| Adaptation options | Response rate to Likely or Very Likely |
|---|---|
| Planting deep rooted legumes | 80% |
| Adjusting stocking rate to feed supply | 77% |
| Tree planting | 71% |
| Increasing soil fertility | 65% |
| Irrigation | 56% |
| Buying additional arable land to expand farm | 44% |
| New farm enterprise | 37% |
| Dairy beef | 17% |
| Purchasing carbon offsets | 90% very unlikely, unlikely, neutral |

### 4.5.4 Red Meat Consumption Patterns Survey

A red meat consumption pattern survey was developed by staff at TIA in partnership with the Institute for Social Change- Tasmania Project (Lester et al., 2021a, Lester et al., 2021b). The survey was emailed to around 3,500 Tasmanians who are registered to be involved in The Tasmania Project. A total of 1,176 full responses were collected, with two reports generated from the survey results (Lester et al., 2021; see Appendices 9.9 and 9.10 for full reports).

Around two-thirds of respondents were female, the majority were 45+ years of age, and two-thirds were highly educated with a Bachelor's degree or higher, around half of the respondents were residents in the Greater Hobart area, with the proportion of respondents relatively equally split between the three household income brackets (~40% had annual salaries < $60K/annum, 28% of respondent income was $60K-$100K, and 32% of respondents' household income was > $100K/annum).

*Sourcing food*

While the major supermarkets still appears to hold the greatest market share for these consumers (89%), there appears to be a growing trend for people to grow their own food (56%) or source it from more specialty shops (30%), the local fruit and vegetable shop (50%) or and directly from producers at markets (30%) or farm gate/wharf (18%; Fig. 23).

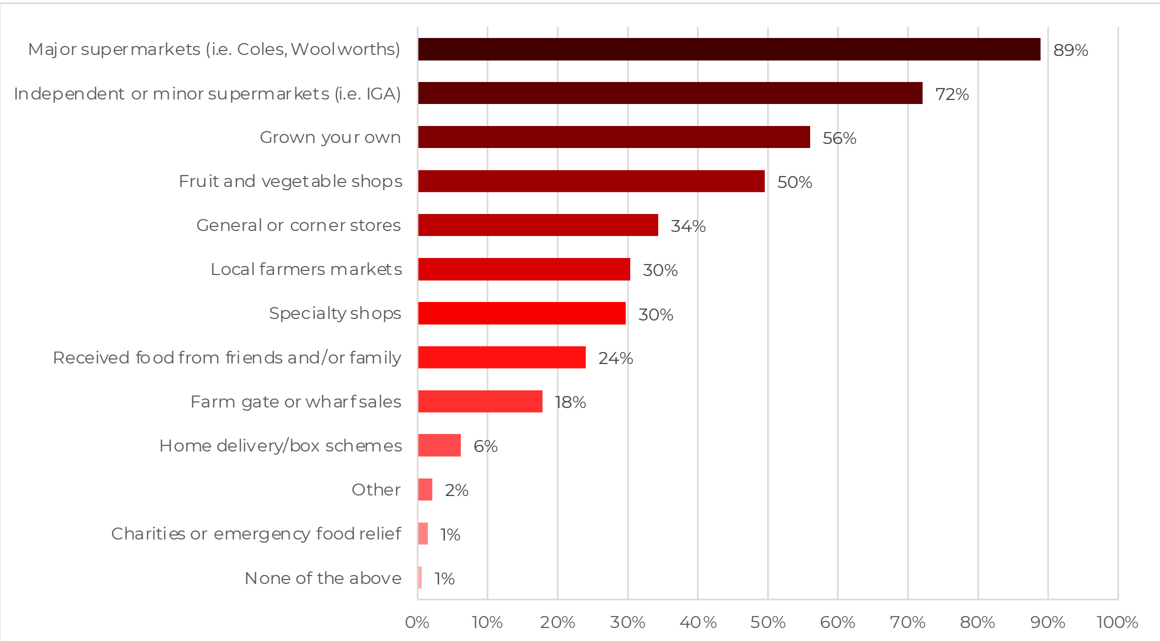


**Fig. 23.** In the last 30 days, where have you sourced you food from?

*Eating red meat*

The survey participants identified that the majority of them (82%) do eat red meat as one part of a varied diet, however, 18% do not eat red meat at all (Fig. 24). In addition, 95% of respondents include dairy in their diet, while 77% include seafood in their diet (Fig. 24). Other data showed that:

- males are more likely to eat red meat than females (89% vs 79%),
- Over 65's consume more red meat that younger people (84% vs 67-82%),
- The higher the level of education the less red meat eaten,
- Launceston and other parts of Tasmania consume more red meat than those in Greater Hobart,
- People with children are more likely to consume red meat,
- Higher income households are more likely to eat red meat,
- People are eating less red meat than they used to but still see it as a valuable source of nutrition

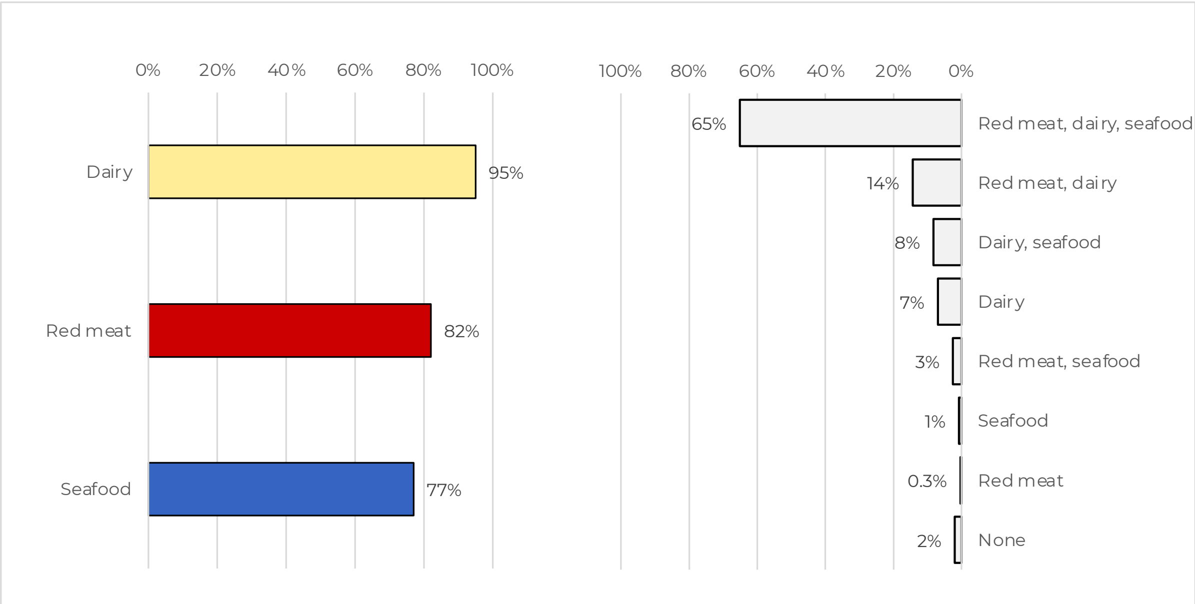


**Fig. 24.** Respondents' consumption of red meat, dairy and seafood (left) and various combinations of food types (right).

*Tasmanian attitudes to eating red meat*

Tasmanians are eating less red meat than they used to but still see red meat as a valuable source of nutrition (Fig. 25).

Tasmanians would like their livestock food products come from farms that prioritise animal health and welfare (78%), environmental stewardship and land care (69%), this is particularly true of women (63%) more so than men (51%). Tasmanians also want their red meat to come from Tasmanian farms (79%) and are concerned that farmers receive a fair price for their produce (81%; Fig. 25).

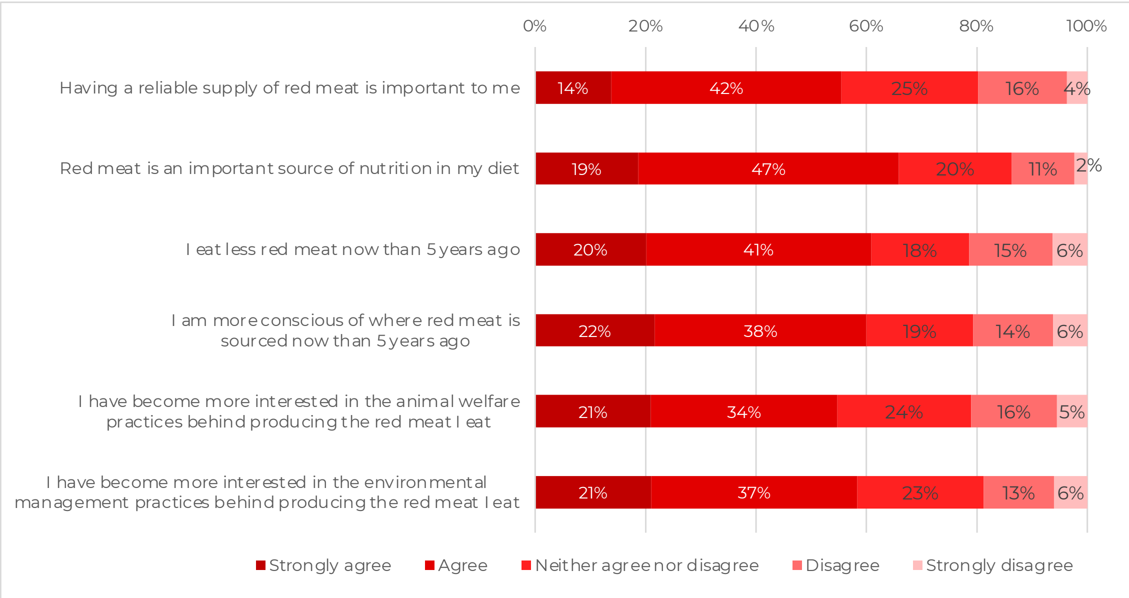


**Fig. 25.** Respondent attitudes towards the production and consumption of red meat.

## 4.6 Communications and engagement with regional and transformational reference groups as well as other wider industry stakeholders. This will include details of project presentations at a minimum of 5 industry events or conferences

The Tasmanian Regional Reference Group (RRG) met seven times over the project, with two face-to-face meetings in 2020 (including a visit to one of the case study farms at Campbell Town), two meetings in 2021 (online meetings due to COVID restrictions), two meetings in 2022 (Face-to-face meeting, including a visit to the other case study farm at Stanley, and an online meeting), and a final project meeting in March 2023.

A range of field days (Fig. 26), workshops, webinars, conferences, radio interviews and popular press articles have been delivered by members of the project team (see Appendix 8.11 for details). Direct engagement, defined as people we interacted with at workshops, field days, webinars, conferences etc, total over 3,920. Assuming that only 1% of newspaper or radio listeners either red or listened to NEXUS content, indirect engagement was conservatively estimated at almost 169,000 people.

The impact of NEXUS participatory engagement is estimated be to very significant. Using conservative statistics for the number of animals, farm size and farm gate profit in Australia, the collective modelling, social research and industry engagement in NEXUS is estimated to have resulted in 333,000 tonnes $CO_2$e removals via improvement in pasture production over 227,000 hectares, improving cumulative farm gate revenue by $11.7M (for details, see Appendix 8.12).

Examples of NEXUS presentations include industry events or conferences, with some of the more attended events including:

August 2021: Presentation at the South Australia Ag Excellence Forum & Awards “Pathways to carbon neutrality on farms”

September 2021: Presentation at the Farmers for Climate Action Conference, Launceston, Tasmania, “Pathways to carbon neutrality on farms” and poster presentations

June 2022: 8$^{th}$ International Greenhouse Gas & Animal Agriculture Conference, Florida, USA. An abstract and presentation of “The productivity-profitability-carbon nexus of livestock systems under increasingly variable climates” and “Overview of greenhouse gas emissions mitigation and climate change adaptation pathways being explored in NEXUS project”

June 2022: Agriculture and Agri-Food Canada, presenting background to climate change, GHG emissions, results of NEXUS towards carbon neutral and low hanging fruit adaption options

June 2022: Western Australia Climate-Smart Fellowship, presenting impacts of extreme climatic events on agriculture, options for reducing emissions, co-benefits and trade-offs of emissions mitigation

July 2022: Tasmanian Red Meat Updates 2022 Conference, promoting the NEXUS project

August 2022: Tasmanian AgFest 2022 field days, presentation of the NEXUS project

<u>November 2022-February 2023:</u> Involve and Partner project workshops


**Fig. 26.** Field day at the sheep case study farm in November 2021 where discussions on the NEXUS project and local climate projections helped inform discussions on the day around the role of perennial legumes in a drier and more variable climate.

## 4.7 Submission of a minimum of two scientific journal articles for peer review

A total of 12 peer reviewed articles have either been submitted, accepted and/or published during the NEXUS project. Each paper has been included in the Appendices (see Supplementary journal articles for papers 3-12 listed below).

1. Bilotto F, Christie-Whitehead KM, Malcolm B, Harrison MT (2023) Carbon, cash, cattle and the climate crisis. *Sustainability Science* (published online; Appendix 8.1)

2. Bilotto F, Christie-Whitehead KM, Malcolm B, Harrison MT (2023) Incremental/Income Diversification/Transformational adaptations (under review with One Earth journal; Appendix 8.2).

3. 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. *Global Change Biology* **27**, 5726-5761.

4. Bilotto F, Harrison MT, Christie KM (2022) The Productivity-profitability-carbon nexus of livestock systems under increasingly variable climates. *Proceedings of the 8th International Greenhouse Gases and Animal Agriculture Conference*. June 5-9, Orlando, Florida, USA

5. Cullen BR, Harrison MT, Mayberry D, Cobon D, An-Vo D-A, Christie KM, Bilotto F, Talukder S, Perry L, Eckard RJ, Davison TM (2022) NEXUS Project: Pathways for greenhouse gas mitigation and climate change adaptations for Australian livestock industries. *Proceedings of the 8th International Greenhouse Gases and Animal Agriculture Conference*. June 5-9, Orlando, Florida, USA.

6. Kabir J, Bilotto F, Christie-Whitehead KM, Harrison MT (2023) Pasture growth and soil organic carbon sequestration in sheep and beef farms under the historical and future extreme events in Tasmania: An analysis of impact and adaptation potential (in draft).

7. Bilotto F, Vibart R, Mackay A, Costall D, Harrison MT (2022) Towards an integrated phosphorus, carbon and nitrogen cycling model for topographically diverse grasslands. *Nutrient Cycling in Agroecosystems* **124**, 153-172.

8. Cullen BR, Harrison MT, Mayberry D, Cobon DH, Davison TM, Eckard RJ (2021) Climate change impacts and adaption strategies for pasture-based industries: Australian perspective. *Resilient Pastures- Grassland Research and Practice Series* **17**, 139-148.

9. Cullen BR, Ayre M, Reichelt N, Nettle RA, Hayman G, Armstrong DP, Beillin R, Harrison MT (2021) Climate change adaptation for livestock production in southern Australia: transdisciplinary approaches for integrated solutions. *Animal Frontiers* **11**, 30-39.

10. Henry B, Dalal R, Harrison MT, Keating B (2022) Creating frameworks to foster soil carbon sequestration. *Burleigh Dodds Series in Agricultural Science*).

11. Albanito F, McBey D, Harrison M, Smith P, Ehrhardt F, Bhati A, Bellocchi G, Brilli L, Carozzi M, Christie K, Doltra J, Dorich C, Doro L, Grace P, Grant B, Léonard J, Liebig M, Ludeman C, Martin R,

Meier E, Meyer R, De Antoni Migliorati M, Myrgiotis V, Recous S, Sándor R, Snow V, Soussana J-F, Smith WN, Fitton N (2022) How modelers model: the overlooked social and human dimensions in model intercomparison studies. *Environmental Science & Technology* **56**, 13485-13498.

12. He Q, Liu DL, Wang B, Li L, Cowie A, Simmons S, Zhou H, Tian Q, Li S, Li Y, Liu K, Yan H, Harrison MT, Feng P, Waters C, Li GD, de Voil P, Yu Q (2022) Identifying effective agricultural management practices for climate change adaptation and mitigation: A win-win strategy in South-Eastern Australia. *Agricultural Systems* **203**, 103527.

# 5 Discussion

## 5.1 Adaptations for an increasingly variable climate

Overall, our work showed little impacts on climate change on Tasmania out to 2050: while rainfall signals were uncertain, it was clear that temperature and evaporative demand would continue to rise. Our work calls for collaboration between institutions, disciplines and sectors to ensure that proposed adaptation/mitigation interventions are legitimate, credible and salient. While we modelled economic and biophysical outcomes of co-designed adaptations, further assessment of practicality and economic and environmental risk was called for by our regional reference group (RRG). We have shown that to empower local communities to adapt, it is essential that proponents engage a range of stakeholders directly or indirectly affected by the climate crisis. 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 (ie. the 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 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 production, increasing net farm GHG emissions and net emissions intensity, but also reducing the need for purchased supplementary feed. Collectively these factors increased farm profitability. 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 (NDCs; 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 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 lucerne 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 while 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 (Appendices 9.3 to 9.6). The increased availability of pasture and the reduced dependence on external inputs improved economic indicators and enabled more effective adaptation climate change (Figs. 6 and 7). However, our findings suggest that warmer future climates may affect 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 not be sufficient to prevent global temperature changes; 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 & Livestock Australia's Carbon Neutral 2030 Initiative) currently call for net-zero emissions by specified time horizons of 2050 or 2030, respectively, and rightly include interim targets to ensure longitudinal progress.

Our Towards Carbon Neutral (TCN) intervention package resulted in deep cuts in emissions in a profitable and sustainable way. The TCN intervention 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. The one exception was with the 2050 TCN beef farm. However, livestock production was the highest of all scenarios explored, indicating that seasonal feed supply better matched herd demand for the 2050 TCN farm, decreasing need for supplementary feed by more than half (Appendix 8.1), resulting in maximising profitability to cope best with long-term shifts in temperature and rainfall 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). From social perspective, the low ease of adoption of planting trees can be explained by the extra knowledge the required to identify the type of tree species to plant, the sowing date, the forestry management (regular watering and fertilisation) to achieve the adequate roots anchoring as well as financial limitations. In addition, future climates may contrain nations' ability to rely on soil carbon sequestration in their NDCs (Vermeulen et al., 2019). However, there comes a point in time when annual accumulation of carbon in trees deminishes and thus other avenues are required to avoid, reduce or offset GHG emissions.

By 2050, the enteric $CH_4$ vaccine was more effective in reducing net GHG emissions, with consistent reductions 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 led to the planting of native species endemic to the region (Environmental plantings in FullCAM), thus reducing carbon sequestration potential. For both sites, inclusion of deep rooted lucerne into the pasture sward increased pasture production and carrying capacity (e.g. lambs retained longer with the sheep farm) but had minimal effect on net GHG emissions. This suggests that any aspiration to mitigate farm level emissions must first consider the individual potential of each option, secondly consider the extent to which incremental adaptations can be stacked together for mutual (potentially multiplicative) benefit, and thirdly 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 showed 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).

The most important insight of the present study was the Carbon Neutral (CN) packages, in that they simultaneously increased farm productivity and profitability while offsetting GHG emissions in both case studies. This result is particularly noteworthy given that the Parliament of Australia in 2022 has updated the country's NDCs and has pledged to cut carbon emissions by 43% in 2030 below 2005 levels and to net zero by 2050, including land use, land use change and forestry (LULUCF) net emissions (Australian Government, 2022). This national, long-term strategy provides a timeframe for the implementation of actions articulated by operational innovation networks for the promotion of transformational adaptations already suggested by RRG. Despite delivery of Asparagopsis to the animal as an additive was the most promising adaptation to build CN packages upon, there is currently no large-scale commercial cultivation of such additive (Reisinger et al., 2021). Long-term projections by 2040 indicate a potential for creating a $1.5 billion seaweed industry in Australia with 9,000 jobs, a 10% national GHG emissions reduction per year with significant contribution to *UN Sustainable Development Goals* (SDG 2, 3, 8, 10, 12, 13 and 14; Kelly, 2020). It will require an urgent high and long-term investment to increase its worldwide scalability in livestock systems by improving the cost-efectiveness, formulation and delivery of this $CH_4$ inhibitor. We assumed a high 80% efficacy rate in reducing enteric $CH_4$ emissions, which has been achieved under research conditions (Glasson et al., 2022; Wasson et al., 2022) but is unproven at commercial scale. Moreover, the lack of ecosystem-level studies as a potential invasive specie introduction, concerns regarding potential carcinogenic compounds (halogenated methane analogue) and ozone-depleting effects could bury the social-license and future adoption of Asparagopsis as a ruminant feed ingredient (Vijn et al., 2020; Glasson et al., 2022).

The incorporation of transformational improvement in FCE (TFCE) into a carbon neutral package (CN1 and CN2) demontrated a further improvement in animal performance in the beef farm and in both case studies subtantially decreased costs of production (supplementary feed reduction of 50 to 88%), and increasing EBIT by 10-39% by 2050 (Figs. 3 and 4). Sinergically, the lower pasture intakes due to animal genetic improvement may also reduce 12-17% $CH_4$ emissions and increase residual biomass with higher plant C inputs and SOC stocks. Despite these interesting emergent economic and environmental complementarities, the benefits from genetic improvement can only be observed after 10-20 years of sustained investment (Arthur et al., 2005; Alford et al., 2006), compromising its ease of adoption. In addition, the genetic improvement in animal feed efficiency is a complex multifaceted trait with moderate heritability under control of multiple biological processes and environmental conditions (Kenny et al., 2018; Taussat et al., 2020) which requires of an holistic farm management.

The RRG were supportive of greater inclusion of legumes (e.g. Lucerne) within existing grass pastures; favour was also given to combining legume management and with timely and cost-effective delivery of *Asparagopsis* to the herd or flock (CN3 and CN4 packages). In line with our findings, Sturludóttir, et al. (2014) demonstrated that mixing grasses with legume improved herbage yield, dry matter digestibility and crude protein in pastures from Northern Europe and Canada, but also reduced the invasion of weeds compared to monocultures. The nitrogen yield advantage from grass-legume mixtures supported by symbiotic $N_2$ fixation (Suter et al., 2015), given the closely linkage between C and N cycles in grazing systems (Wang et al., 2016; Bilotto et al. 2021) and the higher subsoil C inputs, rhizodeposition and subsequent microbial stabilization in deep-rooted legumes, are the main mechanisms involved in the increase of SOC stocks in long-term pastures (Peixoto et al., 2022). It must be noted that the large gas and stable foam formation from the predominant forage legumes in temperate grazing systems, such as lucerne with high soluble protein content, may cause ruminant bloat and ocasionally animal deaths (estimated annual losses >NZ$200M in Australia and New Zealand and US$80M in the USA (Hancock et al., 2014). Therefore, the mitigation of bloat risks in ruminats will require training and professional advice on legume management to adapt livestock to shifts in the farm-feedbase.

While both carbon neutral packages achieved net zero emissions for both farms, potential mitigation or adaptation is not the only factor in determining whether 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 reducing enteric $CH_4$ kg $DMI^{-1}$. 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; Christie et al. 2020) 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; Liu et al. 2021), 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, and likely to maintain social licence, such vaccines do not exist commercially at the time of writing and may be some time away (Reisinger et al. 2021). However, there are alternatives, such as 3-nitrooxypropanol (3NOP), which has been shown to achieve a similar $CH_4$ reduction potential to that of a vaccine modelled here (Yu et al., 2021), and thus the GHG reduction potential presented in this paper could be applicable to any mechanism that achieves a 30% reduction in enteric $CH_4$. 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. In addition, planting trees 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 NDCs, forests need 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 available (Wise et al. 2019).

## 5.2 Involve and Partner activities: on-farm experimentation and discussions with biochar as a feed supplement

The on-farm research component of the I&P Biochar project will not conclude until after the larger NEXUS project has concluded. The three planned field days have been undertaken, with a total of 72 attendees across all three days, with 32 of these providing feedback pre-and post-workshop. Survey results from the three biochar workshops demonstrate an increase in participant knowledge post workshop. The survey rating system showed that many participants had excellent knowledge and confidence post workshop, indicating that the content of the workshops provided relevant information and impacted the intended audience. Participants felt they were able to make more informed decisions on topics relating to biochar and most responses provided a positive rating of eight or higher for overall satisfaction. We identified that two of the main motivations behind planning to implement of biochar supplementation was to improve animal health and soil carbon. However, general comments provided in the survey indicate underlying concerns regarding the adoption of biochar supplementation. Participants indicated a desire to see further research in biochar supplementation, more specifically in liveweight gains and costing associated with supplementation. One comment was made regarding implementation in a large-scale system, demonstrating that there may be producer concerns regarding the ease of which biochar is supplemented. This sentiment was evident when discussing with workshop attendees on the day of the workshops.

The survey results demonstrated an industry interest for further research in the area so producers have a clear indication of the weight gain benefits, costing and intakes required to achieve maximum performance when supplementing biochar. Our modelling in NEXUS has shown that biochar is likely to have a modest impact on liveweight gain (0-11%), a reasonable effect on profits (-7% to +12%) but overall a relatively small impact on soil carbon sequestration and therefore net GHG emissions. It must be noted that the rate of biochar addition in the modelling component of NEXUS may be lower than what could occur on farm, and we assumed no change in enteric $CH_4$ emissions with the modelling of biochar. However, adoptability was prioritised by farmers as very high, so it is plausible that small mitigation in GHG emissions (per unit farm) could occur across many farms, which would be conducive to impact at scale. We content that further work is required on the types of biochar (derivative materials, e.g. wood, crop residues etc), as this derivative product may have a significant impact on liveweight gain and therefore productivity associated with biochar. Follow-up phone calls to attendees of the three workshops will be undertaken towards the end of the I&P project (late 2023) to ascertain any practice change occurring as a result of attending these workshops.

## 5.3 Human and social capacities and capabilities required to adapt to a changing climate and mitigate global warming

The social research conducted here covered a broad cross section of ideas, understandings and issues; some linked across the entire project, others were standalone. These ideas encompassed the topics of biochar use through the I&P; interviews with the Nexus and Legumes RRG concerning the adaptions and adoptions explored in the project; and surveys that were run Tasmania wide aimed at drawing out both consumer and producer understandings of the red meat industry.

*Biochar supplementation: potential enteric methane mitigation, animal health, enrichment of soil carbon?*

The biochar workshops we conducted attracted attention across the livestock industry with government, industry and producer participants involved. More workshops have been requested in the south of Tasmania, beyond the project. Most producers wanted to at least trial the use of biochar and there is appetite for more workshops.

The attractiveness of the use of biochar was influenced primarily by its ease of use and how efficiently it could be fed out to livestock. Efficiency and time would possibly be important across all the proposed adaptions. If adaptions are not ‘easy’ to do and take more time and energy on top of already heavy workloads, then they are unlikely to happen. It was also obvious that the use of a feeder, despite its cost, was preferred over the troughs due to the need for efficiency.

One of the more pressing requests from the workshops was for more research on biochar. However, there is significant research available. For example, a google search of biochar shows over 100,000 research articles published since 2015, with over 27,000 being published in the last year. This suggests that rather than lack of research, it is more likely that to be an issue of both access to the research and/or its accessibility or ease of collation and interpretation that is the cause of concern.

Within in the biochar component of the project, ongoing research in the area of the health benefits to livestock seems to be indicated. While liveweight and carbon sequestration were the target of the overall research, there was significant comment from users and workshop participants that suggested there were health benefits for livestock. However, this was not targeted and could be a beneficial direction for future research. Another area of research would also be into livestock seasonal feeding responses. As was noted in the I&P trial and the workshops, there were different times of the year when biochar was being heavily taken up by cattle and other times when this did not occur. An exploration of when and why livestock access biochar is therefore suggested.

*Adaptions and Adoption*

Rather than speaking specifically to each of the Tasmanian Nexus adaptions, the RRG producers spoke mostly in generalities, particularly about the need to recognise the unique contexts of each Tasmanian farm, where climate varies significantly within a small distance. However, two adaptions stood out as being those that they did speak about, indicating that these were important to the group in a broadly general way. The first was the use of the income diversification strategy of putting in wind turbines as it seemed innovative, had a sustainable focus and had little impact on the land while still being able to be farmed. However this and many of the adaptions are seen to be inaccessible to most farmers and would only benefit corporate or large scale farming and therefore would not be taken up by many of the small/medium producers who could not afford to take on the added financial burden of these larger scale adaptions.

The second was the low hanging fruit option of planting deep rooted legumes and multi-species pastures as a way to both improve pastures for drought conditions and sequester carbon. Planting legumes was also the most supported option for the next 10 years from respondents to the Red Meat Producers survey, suggesting that this is a priority area. This option was being taken up by many of the RRG with other trials being implemented across Tasmania.

Respect for the knowledge across generations was important. Learning from the past and combining this knowledge with knowledge from the present was seen as vital to successfully moving into the future. This revolved around the importance placed on legacy (what is to be left behind) and in providing stewardship for the land that needs to support farming families into the future.

The complexity of climate change responses and the information surrounding them was central to discussions with the RRG. Simple, one off and one-size-fits-all responses (i.e. the ‘silver bullets’) are seen to either not be available or not appropriate to the Tasmanian context. As responding to climate change in the agricultural context is only just beginning to scratch the surface as to options, their impacts and their contextual appropriateness needs to be explored. Uptake of adaptions therefore needs to be carefully managed to prevent further possible damage. However, it is recommended that the ‘fail well’ principals from the RRG are considered.

One of the least preferred options in the red meat producers survey was carbon credits, despite use of purchasing carbon credits (or Australian Carbon Credit Units, ACCUs) being central to addressing climate change within the project transformation options. Lack of trust in this type of system needs to be addressed so that carbon credit system can be evaluated with integrity and legitimacy.

There was a clear sense from the RRG that because they are learning, they also had a responsibility to pass that on what they were discovering and this was seen in their willingness to partner with TIA within and externally to the project. The RRG took a positive view of risk and risk taking especially while they have the financial opportunity. There was a level of profit they were willing to work with. However, many farmers would not be in this position to take advantage of this. The RRG producers also had a high level of technical understanding and so they easily engage with the science of climate change and how it relates to farming and could respond to it through their own explorations. Their knowledge gathering skills as well as other supporting skills were an advantage in allowing them to be proactive in their response to climate change.

*Red Meat Consumer Survey*

The good news for Tasmanian red meat producers is that consumers want Tasmanian meat. Their preference is for meat that is produced locally by producers who focus on animal welfare and environmental stewardship and conservation. This means that those producers who do take sustainable approaches to climate change are likely to be supported by consumers.

# 6 Conclusions and key messages

We revealed the serendipitous finding in which climate change to 2030 (and to a lesser extent, 2050) in Australia's southern-most State of Tasmania will have beneficial impacts on pasture growth and liveweight produced, reducing the need for supplementary feed and improving farm gate profit (under the baseline scenario where contemporary management continues *ceteris paribus*).

While these results foreshadow an optimistic outlook for the Tasmanian livestock sector, we caution that much more work is needed to develop profitable, inclusive and sustainable pathways for reducing greenhouse gas emissions due to the tight coupling between livestock productivity and GHG emissions. This is even more critical given the increased availability of irrigation infrastructure and water in Tasmania likely in the decades to come; as irrigation water becomes available for land that has long been historically rainfed, water use and agricultural productivity will climb, increasing area-based methane and nitrous oxide emissions as cropping intensity and stocking rates are ramped up. These findings are consistent with previous assessments across the dairy, red meat and cropping sectors (Christie et al. 2020; Harrison et al. 2019; Liu et al. 2020b; Liu et al. 2023; Phelan et al. 2018; Rawnsley et al. 2019; Sandor et al. 2020; Taylor et al. 2016).

While GHG emissions will rise with increased productivity, the warming climate will contribute further $CO_2$ efflux through reduced soil carbon sequestration. Our prognostics indicate that soil carbon sequestration will decline by 55-133% by 2050 under *ceteris paribus* management. We documented a 2-3% increase in livestock pasture consumption under future climates together with -0.14-0.21 t $C^{-1}$ $ha^{-1}$ $yr^{-1}$ losses by 2050 increased net GHG emissions by 6-12%.

While we modelled two case study farms in the first case, these conclusions are generically applicable to all agricultural production systems and agro-ecological zones in which productivity per unit land area or area-based production is increasing, for example due to arable agriculture land use expansion, increased application rates or fertiliser or irrigation. As well, the transdisciplinary participatory approach developed here is generically applicable to other locations and production systems.

Several key messages emerged from the NEXUS project:

1. Changes caused by interventions to the farming system (e.g. due to feed supplements and tree planting) were much greater than the impact of climate change out to 2050.
2. There were few triple-win interventions allowing GHG emissions mitigation, improved productivity and improved profitability under future climates. In this context the most promising interventions included transformational feed conversion efficiency (TFCE, a 30% gain in FCE by 2050), feed conversion efficiency (FCE, 15% improvement in FCE by 2050), and renovating grass pastures with lucerne to improve both energetic content per hectare and soil carbon stocks. We note that the influence of deep-rooted legumes on soil carbon stocks (and by extension, net farm GHG) was small due to the exponential decline in root mass with increasing depth.
3. Purchasing an extra farm in a new climatic zone diversified climatic exposure and significantly raised profit and production, but was considered by the RRG as more difficult to implement due to geographical separation and additional labour requirements to concurrently manage separate operations.

4. Altering lambing time had a significant impact on productivity and profit, although altering calving time for beef production system (high rainfall zone) had less impact.
5. Use of *Asparagopsis taxiformis* (seaweed) as a livestock feed supplement had the greatest impact of all interventions on GHG emissions, but also came with the greatest negative impact on farm profit. Due to the absence of analytical peer-reviewed measurements, we did not include changes in productivity (positive or negative) associated with feeding of *Asparagopsis* in the modelling. This aspect could be addressed in future.
6. Biochar as a livestock feed supplement had significant potential for the beef production system, but was counterproductive and costly for the sheep production system.
7. Tactical changes in stocking rates in response to seasonal changes in pasture supply under the warming climate resulted in modest improvements in productivity and profitability.
8. New tree plantations or thickening of existing tree groves had high carbon removal potential (less than *Asparagopsis* as a feed supplement) but disadvantaged both productivity and profit, again noting that no co-benefit of woody vegetation for livestock production was assumed.
9. With regards to stacked interventions, the LHF adaptation theme had the greatest impact on pasture production in late winter/early spring, transiently improving baseline growth rates by 30-60%. In contrast, the TCN adaptation improved pasture growth rates by 60-120% in late summer/early autumn, particularly for the beef production system.
10. Several forms of new knowledge and/or skills were identified as important in adapting to a changing climate or GHG emissions abatement. These included (1) new business skills, (2) partnerships and collaboration with learned people, (3) being proactive in developing a strategy for the farm system while acknowledging that in some years, change may not be possible, and (4) failing well: learning from mistakes and refining management going forwards was perceived as positive and necessary in adapting to future changes in climates, markets and consumer attitudes.
11. Several social, environmental and institutional factors were shown to influence adoption, even when an adaptation could be profitable and reduce GHG emissions. Broadly these factors included (1) the need for ‘real’ solutions that were economically and environmentally beneficial, (2) impact on stewardship of the land and people, including intergenerational sustainability (3) ability to dissect complexity, particularly that pertaining to climate change and (4) level of trust that could be placed in information purporting viable change; information derived from large corporate institutions (real estate, fertiliser manufacturers to abattoirs) was often perceived as conflicted with commercial interests and/or not fully transparent, and (5) agility of adaptation, with many stakeholders commenting on the need to ‘think fast and adapt quicker’.
12. A survey of livestock producers across Australia revealed that more than 94% of people believed in climate change and suggested that more action must be taken to help address this challenge. Pasture management, improving legume content and better controlling feral animal browsing of pastures were common adaptations farm managers had previously actioned to adapt to climatic variability or change.
13. An extensive survey of 1,176 Tasmanians revealed that 85% of people regularly consume red meat, with 95% of people frequently consuming dairy. Around 89% and 79% of males and females regularly ate red meat; people with higher education ate less red meat; people who were older, had children, or had higher salary consumed more red meat in general. Consumer

preference was stronger for livestock products derived from farms that prioritised animal health and welfare, environmental stewardship, and low-emissions premium products.

In reviewing outcomes of the TCN intervention, the RRG called for quantification of economic costs associated with transitioning farm systems to net zero emissions. In addressing this question, we found that the cost of purchasing carbon credits to offset all farm emissions was greatest (33-64% of farm profits), while stacking together three synergistic interventions (planting trees for carbon, reducing enteric methane with *Asparagopsis* as a feed supplement and adopting animal genotypes with higher feed conversion efficiency) not only resulted in net-zero emissions, but also raised profit by 2-30%. The cost of attaining carbon neutrality was thus likely to be low (or negative) if several beneficial interventions were imposed simultaneously. However, implementation of multiple farming systems changes often called for new knowledge, skills and labour, as outlined above. These results reflect the important trade-off between impact on GHG emissions, productivity and profitability with adoptability: systems with transformative impact were often less adoptable, similar to conclusions promulgated by others (James and Harrison 2016).

Deployment of a nascent GHG mitigation opportunity on a northern Tasmanian farm following MLA guidelines for 'Involve and Partner' (I&P) activities was conducted using biochar as a livestock feed supplement. Use  was suggested for further investigation based on anecdotal evidence that biochar feed supplement could improve liveweight gain and animal health, reduce enteric methane and improve soil carbon through enrichment of organic carbon in manure. We conducted workshops both on the I&P farm as well as two other farms who had adopted biochar feeding at an earlier stage, the latter allowing insight into longitudinal farmer learning with regards to use of biochar. At the time of writing, our evaluation indicated little difference between the liveweight gain and manure organic carbon content of the control and biochar treatments, although the I&P experiment will continue until late 2023. Feedback from workshops indicated that participants were overall very pleased with the information they received, and, notwithstanding results from the I&P experiment *per se*, the majority of participants documented an intent to use biochar as a feed supplement for reasons related to animal health, soil carbon and long-term sustainability.

Based on our research, development, extension and end-user feedback, a number of future research priorities emerged. High priority opportunities included:

1. **Quantification of co-benefits and trade-offs** associated with various interventions, e.g., potential livestock productivity co-benefits associated with planting shelter belts or renovating pastures with lucerne, or with feeding of *Asparagopsis*, as interventions that improved liveweight gain generally resulted in improved profitability. Trade-offs evaluate downside risk associated with change, e.g., losses in pasture area elicited by tree planting, or additional labour needed to manage an additional paddock that is geographically isolated from an existing farm.
2. **Stacking of synergistic combinations of GHG mitigation options:** Overlaying combinations ("stacking") of two or three beneficial adaptations that combined mitigation, sequestration, avoidance and adaptation (e.g. planting trees, renovating pastures with lucerne, feeding *Asparagopsis* and improving animal feed conversion efficiency) often resulted in the greatest benefit in terms of production, GHG emissions and profitability. However, difficulties in adoption increased with the number of stacked interventions due to additional skills, knowledge, labour and capital needed to implement more complex stacked interventions. Aspirations of Australia's

nascent 'Integrated Farm Management' greenhouse gas Emissions Reduction Fund (ERF) policy align well with the benefits obtained by stacking adaptations.

3. **Economic costs of transitioning to net-zero:** due to the varied and multidimensional pathways with which GHG emissions could be reduced, further research is needed on the costs of pathways for modifying farming systems to attain net-zero emissions.
4. **Reducing downside risk associated with climates and markets** by improving the agility of adaptation through trusted knowledge sources offering well-grounded solutions (agronomic, environmental, social) including academics, including knowledge of when (and when not) to change the *modus operandi*.
5. **Enterprise climatic diversification:** purchasing an additional farm or field in a different climatic zone to the current farm to diversify climatic exposure and risk.
6. **Animal genetics:** genetic and husbandry approaches for transformational improvement in feed conversion efficiency, including implications of such at the whole farm scale across climatic zones.
7. **Feed supplements:** GHG and economic implications of the type of biochar feed supplement (e.g., whether the derivative product from wood or crop residues) and *Asparagopsis* on the consumption, animal health and liveweight responses.
8. **The carbon-natural capital nexus:** approaches for improving natural capital (e.g. biodiversity) and carbon sequestration at the farm and landscape scales.
9. **Feedbase:** productive digestible legumes that can be incorporated into existing pastures to improve pasture available energy per hectare.
10. **Transdisciplinary approaches:** application of the approach developed here – across disciplines and institutions (refining economic and biophysical modelling with social research and stakeholder discussions) - could be generically scaled to any agricultural system, agro-ecological zone or problem. Such approaches are urgently needed with nascent research items above to ensure that proposed solutions are credible, legitimate and fit-for-purpose.

The impact of NEXUS engagement (accounting for direct interactions only) is estimated be to very significant. Over the course of NEXUS, more than 3,920 people were *directly* engaged in workshops, on-farm demonstrations, webinar discussions and polls, or conferences, while *indirect* engagement is conservatively estimated at 169,000 people. The estimated cumulative impact of the modelling, social research and industry engagement includes removal of 333,000 tonnes $CO_2$-eq from the atmosphere via improvement in pasture and livestock production over 227,000 hectares, improving farm gate revenue by more than $11.7M. Global spatial extent and/or longitudinal impact is likely to be greater, as neither the impact of scientific publications nor information legacy post-project has been accounted for in these estimates. Overall, these values indicate significant potential for further impact through the development of new skills, technologies and practices that allow decoupling of the often tight relationship between livestock productivity and GHG emissions. The need for and application of new knowledge will become increasingly crucial as the global climate changes and anthropogenic demand for premium quality low-emissions Australian livestock product burgeons in the decades to come.

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# 8 Appendices

## Appendix 8.1: Carbon, cash, cattle and the climate crisis

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*Franco Bilotto[1,2], Karen Michelle Christie-Whitehead[3], Bill Malcolm[4], Matthew Tom Harrison[1*]*

[1] *Tasmanian Institute of Agriculture, University of Tasmania, Newnham, Launceston, TAS 7248, Australia*

[2] *AgResearch, Grasslands Research Centre, Tennent Drive, Private Bag 11008, Palmerston North 4442, New Zealand*

[3] *Tasmanian Institute of Agriculture, University of Tasmania, Burnie, TAS, 7320, Australia*

[4] *Faculty of Veterinary and Agricultural Sciences, The University of Melbourne, Parkville, VIC 3010, Australia*

*Corresponding author: matthew.harrison@utas.edu.au

### 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 the one hand (Liu et al. 2020), 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; Sandor 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 2018-19 from 25M cattle and 74M sheep (MLA 2022). In the absence of adaptation to climate change, livestock production and profitability across in many regions will decline, driven largely by a truncated pasture growth duration and concerningly common compounding and cascading extreme weather events (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; Henry et al. 2022). 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 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; Langworthy et al. 2018; Ibrahim et al. 2019; 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 spatio-temporal 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 section). 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. 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 A81.2 and A81.3). 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 costs and profitability were modelled stochastically using the @Risk model (Palisade Corporation 2012) to account for market volatility (Fig. A81.1). 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 section).

### 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. A81.1). 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 A81.1) 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 CCIA (2020).

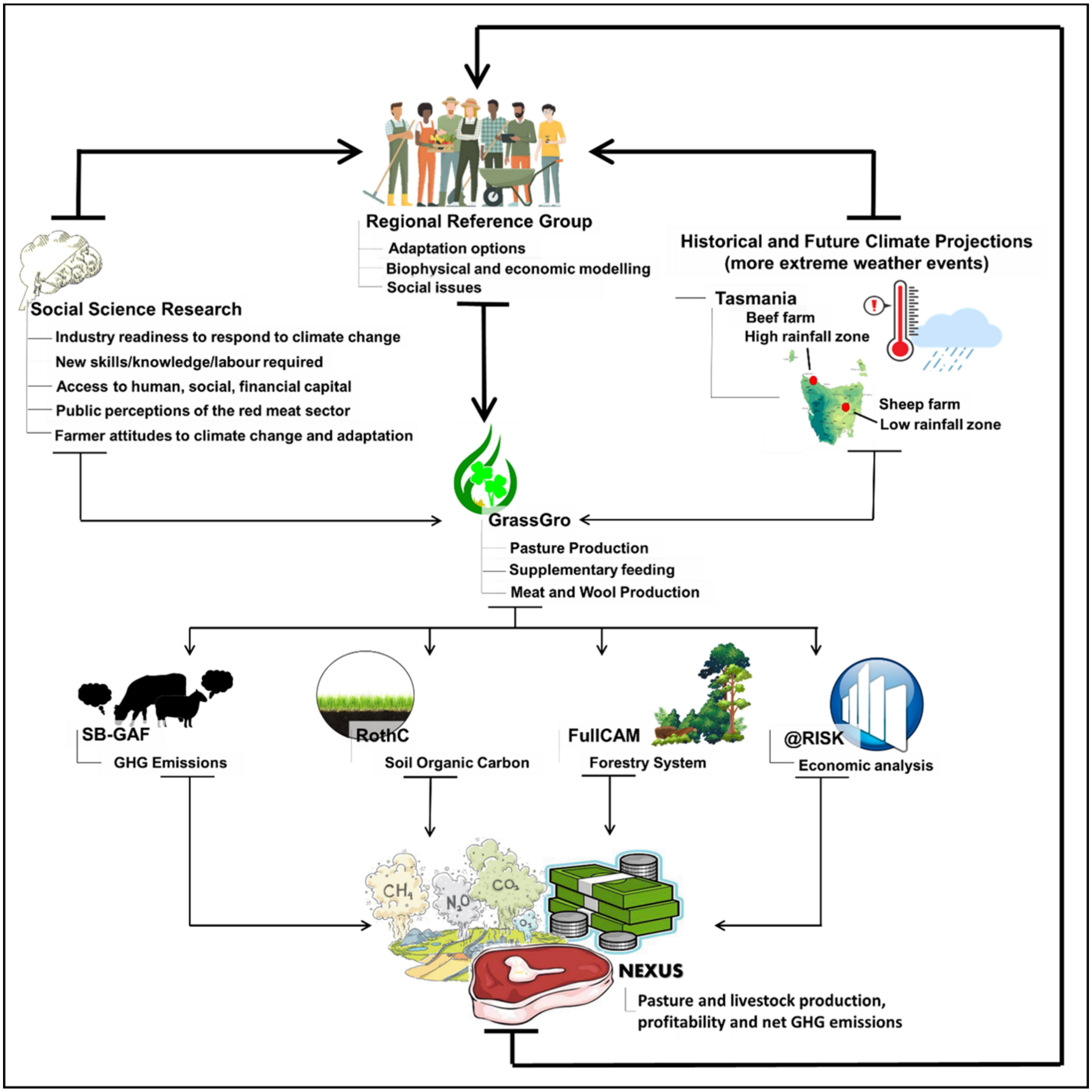


**Fig. 1**. **Transdisciplinary approach pioneered in the present paper ('NEXUS project')** including modelling frameworks used to examine the nexus between productivity, profitability, GHG emissions and social factors under historical and future climate scenarios that included more frequent extreme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

### 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 six years of data to allow for model stabilisation), with results data centered on 2030 (2022 to 2041) and 2050 (2042 to 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 ends-user 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 A81.2 and A81.3).

### 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 carry-over effects from one 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 two 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.), subterranean clover (*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 (20mm/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 Table A81.2.

### 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 3,170 ha and consisted of 49% native grasslands, 48% rainfed developed pastures and 3% centre pivot irrigation (introduced grasses and legumes). The farm also had ~4,600 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 subterranean clover. The land under the centre pivot irrigation was also for dual-purpose wheat that was grazed for four 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 5,300 mature superfine Merino ewes, 7,500 wethers and 5,500 replacement ewes and wethers. The 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 (16 Dec). Wethers were retained for five years before cast for age (14 Oct). All non-replacement ewe and wether lambs were sold 1 Feb. The PLF contained 3,450 Merino ewes from the SMF and were mated with White Suffolk rams; the 2,950-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 17.4-18.1µm (variation in CFW and micron depended on stock class and age). Maintenance and production feeding rules and grazing rotations are further detailed in Table A81.3. 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 two years of age and were retained for eight 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). Further details can be found in Table A81.3

## 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 was 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; Christie et al. 2020; Rawnsley et al. 2019); $CO_2$ 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 the 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 A81.4 to A81.7). 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 $CO_2$e above baseline GHG emissions was taxed at \$60-\$100/t $CO_2$e, following Stiglitz et al. (2017). The farmer shares of the total carbon tax paid was 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 $kg^{-1}$ $CO_2$e), total greenhouse gas emissions (t $CO_2$e) and net farm emissions (t $CO_2$e).

### 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 Table 1, Tables A81.2 and A81.3). 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 Tables A81.2 and A81.3.

**Table 1. Summarised thematic adaptations co-designed with a Regional Reference Group (RRG).** 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. Abbreviations: 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. Further details are provided in Tables A81.2 and A81.3.

| 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. |
| | - | 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 |
| | - | 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) |

## 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. A81.1), 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.

A81.2). However, the lower rainfall and higher temperatures (Fig. A81.1) decreased pasture production in late spring, with than produced in 2050 falling below historical herbage growth rates (Fig. A81.2).

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 (Table 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.** Hist = historical, Base = baseline farm with no adaptation, LHF = Low Hanging Fruit and TCN = Towards Carbon Neutral.

| Variables | Scenarios | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Hist** | **Base30** | **Base50** | **LHF30** | **LHF50** | **TCN30** | **TCN50** |
| **Livestock System** | | | | | | | |
| Stocking Rate (DSE $ha^{-1}$ $yr^{-1}$) | 24.2 | 24.4 | 24.4 | 25.3 | 25.2 | 25.8 | 25.6 |
| Farm Liveweight Production (t LW $yr^{-1}$) | 287 | 291 | 290 | 332 | 332 | 344 | 349 |
| Protein Production (t protein $yr^{-1}$) | 52 | 52 | 52 | 60 | 60 | 62 | 63 |
| Pasture Production (t DM $ha^{-1}$ $yr^{-1}$) | 20.0 | 20.5 | 20.3 | 21.5 | 21.2 | 22.6 | 19.8 |
| Supplementary Feeding (t DM $ha^{-1}$ $yr^{-1}$) | 0.80 | 0.78 | 0.79 | 0.67 | 0.67 | 0.30 | 0.29 |
| Total livestock GHG emissions (t $CO_2$e) | 3,864 | 3,881 | 3,892 | 4,364 | 4,364 | 4,496 | 4,619 |
| Methane Vaccine (t $CO_2$e $ha^{-1}$ $yr^{-1}$, $CH_4$ reduction) | - | - | - | - | - | 1.53 | 1.55 |
| Initial SOC stocks (t C $ha^{-1}$, 1m depth) | 235 | 240 | 241 | 240 | 243 | 240 | 249 |
| Final SOC stocks (t C $ha^{-1}$, 1m depth) | 238 | 241 | 241 | 243 | 244 | 249 | 254 |
| SOC change (t C $ha^{-1}$ $yr^{-1}$) | 0.14 | 0.06 | -0.05 | 0.12 | 0.06 | 0.45 | 0.21 |
| SOC change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | 0.53 | 0.21 | -0.18 | 0.44 | 0.20 | 1.65 | 0.77 |
| **Forestry system** | | | | | | | |
| Site C change (t C $ha^{-1}$ $yr^{-1}$) | - | - | - | - | - | 8.3 | 4.6 |
| Site C change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | - | - | - | - | - | 30.5 | 16.7 |
| Site C change x 50 ha (t $CO_2$e $yr^{-1}$) | - | - | - | - | - | 1,527 | 836 |
| Net farm emissions (t $CO_2$e) | 3,563 | 3,762 | 3,992 | 4,114 | 4,250 | 1,161 | 2,462 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ LW produced) | 12.4 | 12.9 | 13.8 | 12.4 | 12.8 | 7.8 | 9.5 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ 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 |

**Table 3. Long-term average historical, 2030 and 2050 biophysical, environmental and economic outcomes for the low rainfall sheep production system.** Hist = historical, Base = baseline farm with no adaptation, LHF = Low Hanging Fruit and TCN = Towards Carbon Neutral.

| Variables | Scenarios | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Hist** | **Base30** | **Base50** | **LHF30** | **LHF50** | **TCN30** | **TCN50** |
| **Livestock System** | | | | | | | |
| Stocking Rate (DSE $ha^{-1}$ $yr^{-1}$) | 9.0 | 9.1 | 9.1 | 9.1 | 9.1 | 10.0 | 10.4 |
| Farm Liveweight Production (t LW $yr^{-1}$) | 371 | 384 | 387 | 371 | 380 | 476 | 495 |
| Farm Wool Production (t CFA $yr^{-1}$) | 70 | 70 | 70 | 86 | 86 | 95 | 95 |
| Protein Production (t protein $yr^{-1}$) | 137 | 139 | 139 | 152 | 154 | 181 | 184 |
| Pasture Production (t DM $ha^{-1}$ $yr^{-1}$) | 7.2 | 7.7 | 7.8 | 7.8 | 8.0 | 8.2 | 8.6 |
| Supplementary Feeding (t DM $ha^{-1}$ $yr^{-1}$) | 0.32 | 0.30 | 0.28 | 0.12 | 0.12 | 0.08 | 0.06 |
| Total livestock GHG emissions (t $CO_2$e) | 7,037 | 7,094 | 7,081 | 7,666 | 7,676 | 8,479 | 8,650 |
| Methane Vaccine (t $CO_2$e $ha^{-1}$ $yr^{-1}$, $CH_4$ reduction) | - | - | - | - | - | 0.62 | 0.63 |
| Initial SOC stocks (t C $ha^{-1}$, 1m depth) | 175 | 183 | 185 | 183 | 185 | 183 | 186 |
| Final SOC stocks (t C $ha^{-1}$, 1m depth) | 179 | 185 | 187 | 185 | 188 | 186 | 189 |
| SOC change (t C $ha^{-1}$ $yr^{-1}$) | 0.21 | 0.12 | 0.11 | 0.15 | 0.13 | 0.16 | 0.15 |
| SOC change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | 0.77 | 0.42 | 0.42 | 0.53 | 0.48 | 0.57 | 0.55 |
| **Forestry system** | | | | | | | |
| Site C change (t C $ha^{-1}$ $yr^{-1}$) | - | - | - | - | - | 1.5 | 1.7 |
| Site C change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | - | - | - | - | - | 5.4 | 6.2 |
| Site C change x 200 ha (t $CO_2$e $yr^{-1}$) | - | - | - | - | - | 1,071 | 1,247 |
| Net farm emissions (t $CO_2$e) | 4,612 | 5,753 | 5,762 | 5,980 | 6,144 | 3,623 | 3,680 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ LW produced) | 6.0 | 7.4 | 7.4 | 7.0 | 7.2 | 4.7 | 4.8 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ CFW produced) | 33.5 | 41.1 | 41.1 | 39.1 | 39.8 | 20.0 | 19.8 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ protein) | 33.8 | 41.5 | 41.4 | 39.2 | 39.9 | 20.1 | 20.0 |
| Net cash flow-pre-carbon tax/income (‘000 AU$, mean 5 years) | 937.4 | 1,122 | 1,147 | 1,223 | 1,188 | 1,311 | 1,330 |
| Net cash flow-post-carbon tax/income (‘000 AU$, mean 5 years) | | | | 1,215 | 1,177 | 1,377 | 1,399 |

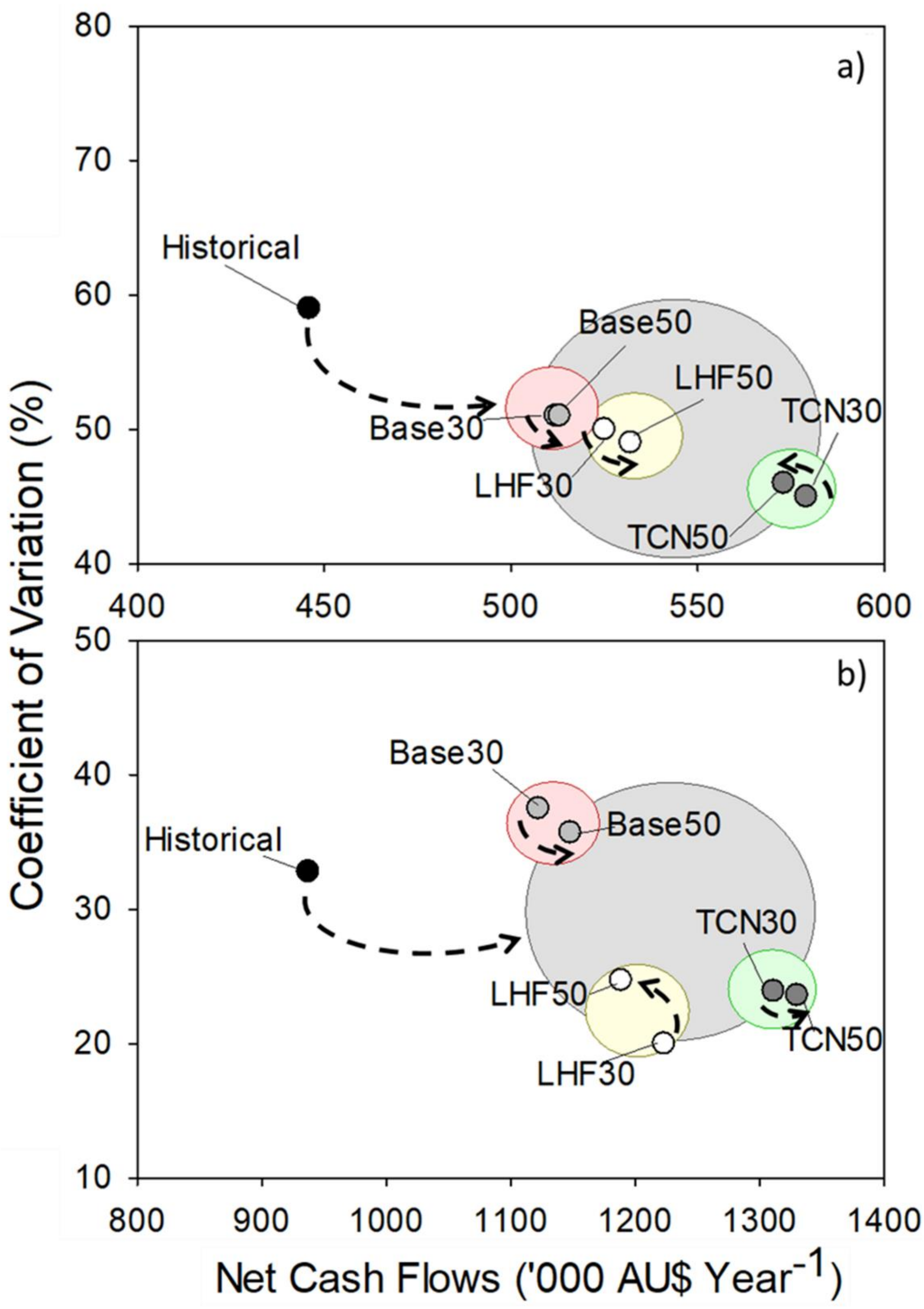


**Fig. 2. Mean and coefficient of variation of net cash flow (NCF) for the beef farm (a) and sheep farm (b).** Black, white, grey and dark grey circles represent the historical period, future climates (2030 and 2050, red bubbles), Low Hanging Fruit (LHF, yellow bubbles) and Towards Carbon Neutral (TCN, 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.

## 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 2030/50 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).

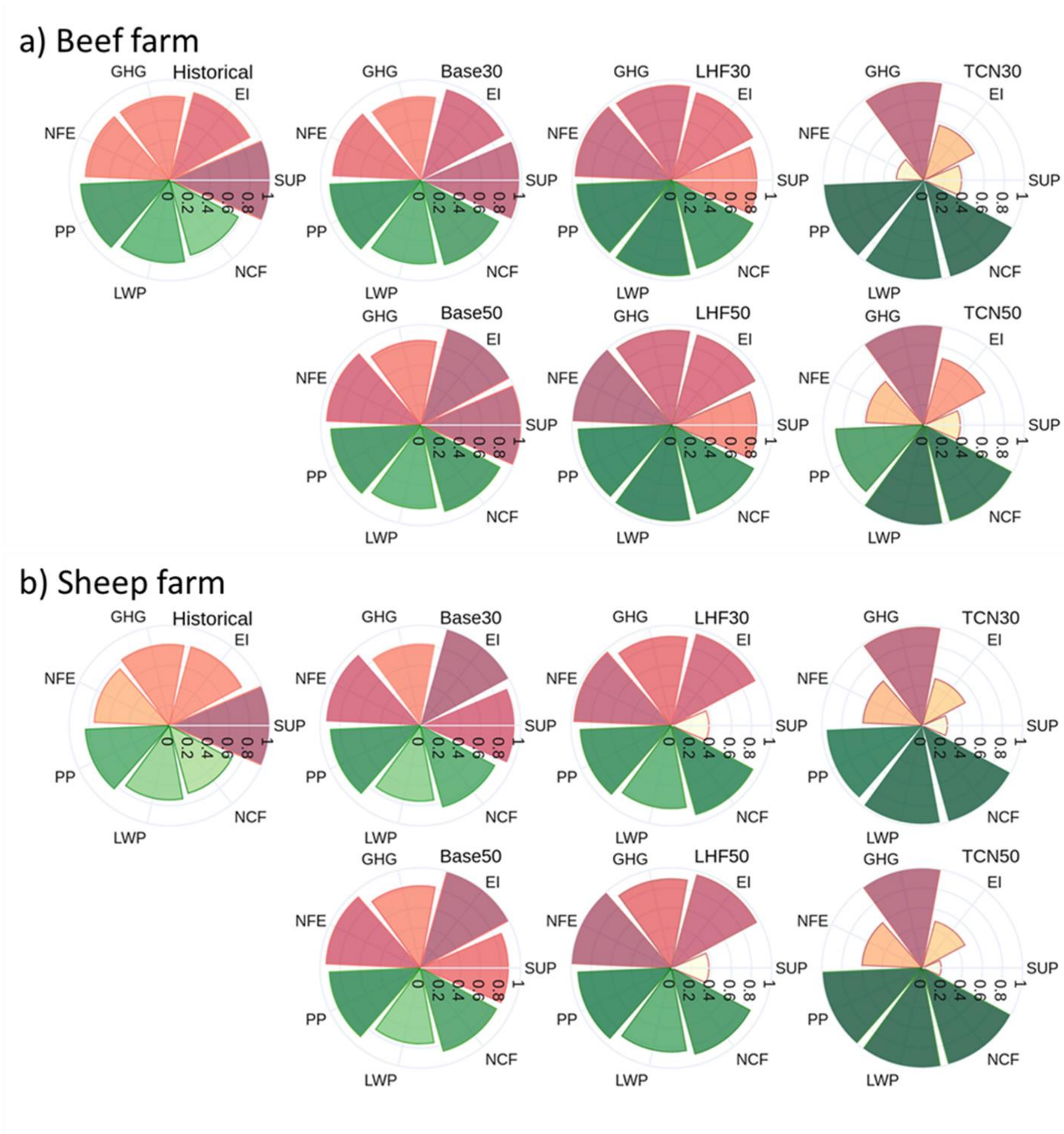


**Fig. 3. Relative change in production, profit and GHG emissions in 2030 and 2050 for the beef and sheep farms relative to the historical period**. Changes are computed relative to the ceiling of the same metric across all other time horizons and adaptations. SUP: supplementary feeding (kg DM $ha^{-1}$), 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 $kg^{-1}$ $CO_2e$), GHG: total greenhouse gas emissions (t $CO_2e$), NFE: net farm emissions (t $CO_2e$). Green segments: positive outcomes. Red segments: negative outcomes. Darker colours indicate values close to 1 and lighter colours indicate values close to 0.

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 $CO_2$e $ha^{-1}$ $year^{-1}$ with the 2050 baseline to +0.20 t $CO_2$e $ha^{-1}$ $year^{-1}$ 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 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).

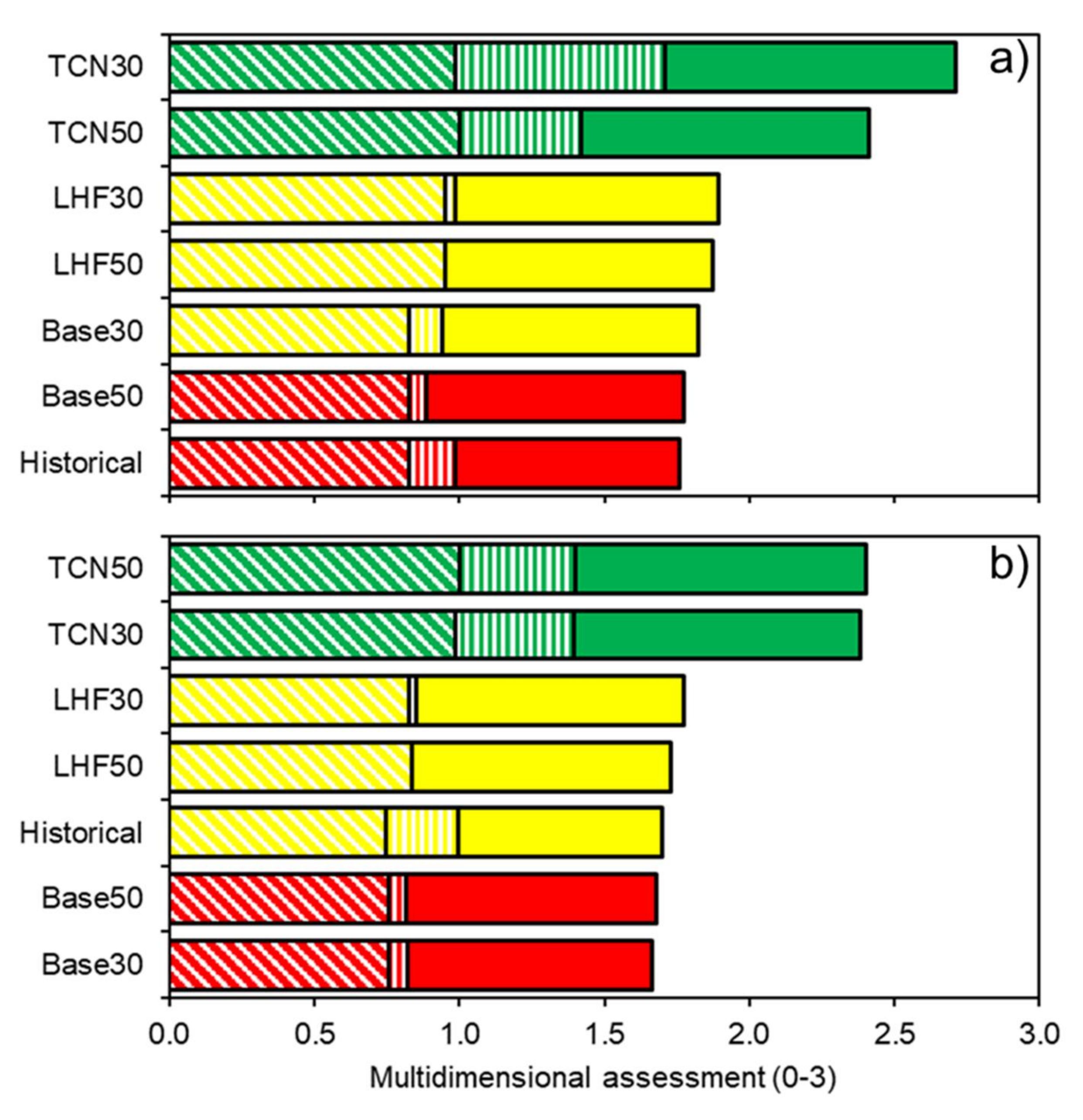


**Fig. 4.** Normalised multidimensional assessment across climate horizons and thematic adaptations for the beef farm (a) and sheep farm (b). Bars depict the sum of normalised biophysical, economic, and environmental metrics: liveweight production (diagonal stripes), inverse net farm emissions (1 - normalised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

## 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%), 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 ($1,500 ha$^{-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).

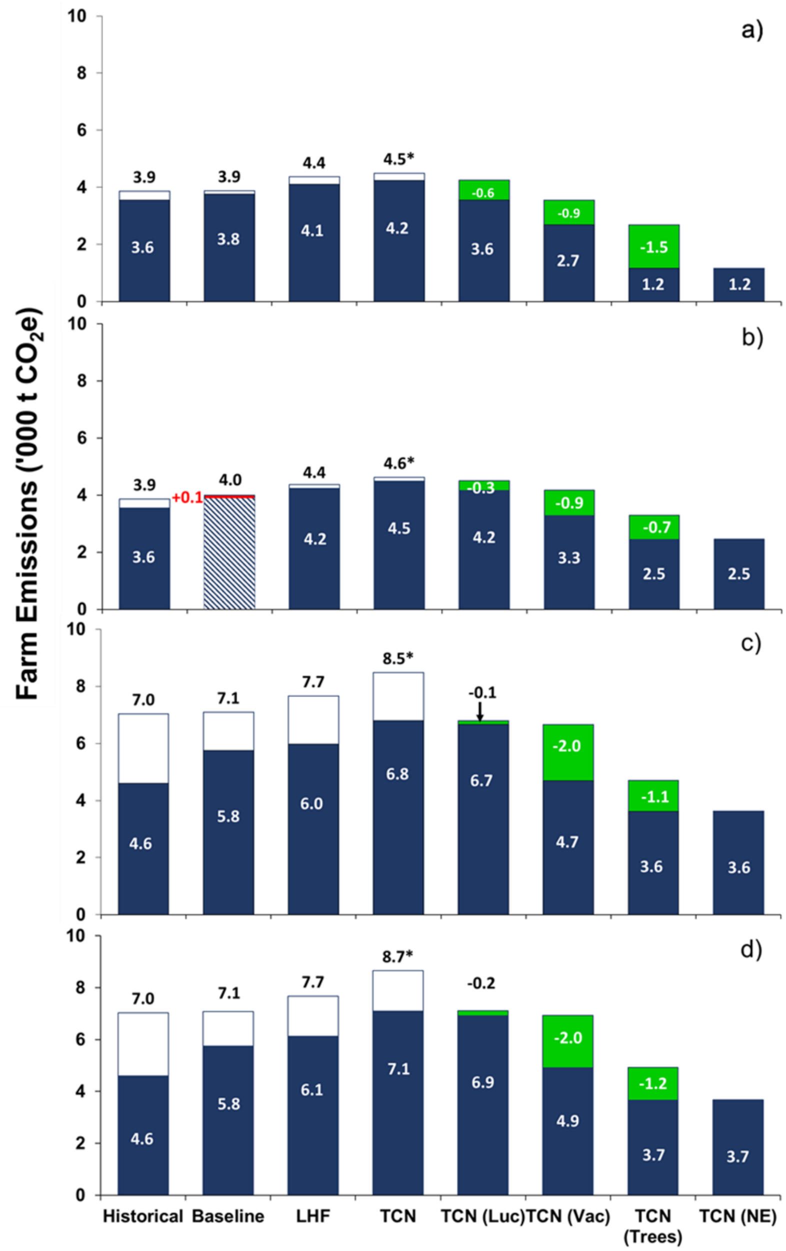


**Fig. 5.** Disaggregation of incremental adaptations stacked together to form the thematic TCN adaptation. Net GHG emissions (blue bars), total GHG emissions (white plus blue bars) and GHG abatement generated by incremental constituents of TCN (green bars) for the beef (a and b) and sheep farms (c and 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.

## 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 directly or indirectly affected by the climate crisis. 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 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, five-year mean NCF variability of the sheep farm increased from a historical value of 33% to 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 climate change (Fig. 2). However, warmer future climates may affect the SOC sequestration, which play 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 & 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. 2020), 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 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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## Author contributions

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## Competing interests

The authors declare no competing interests.

## Data availability

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

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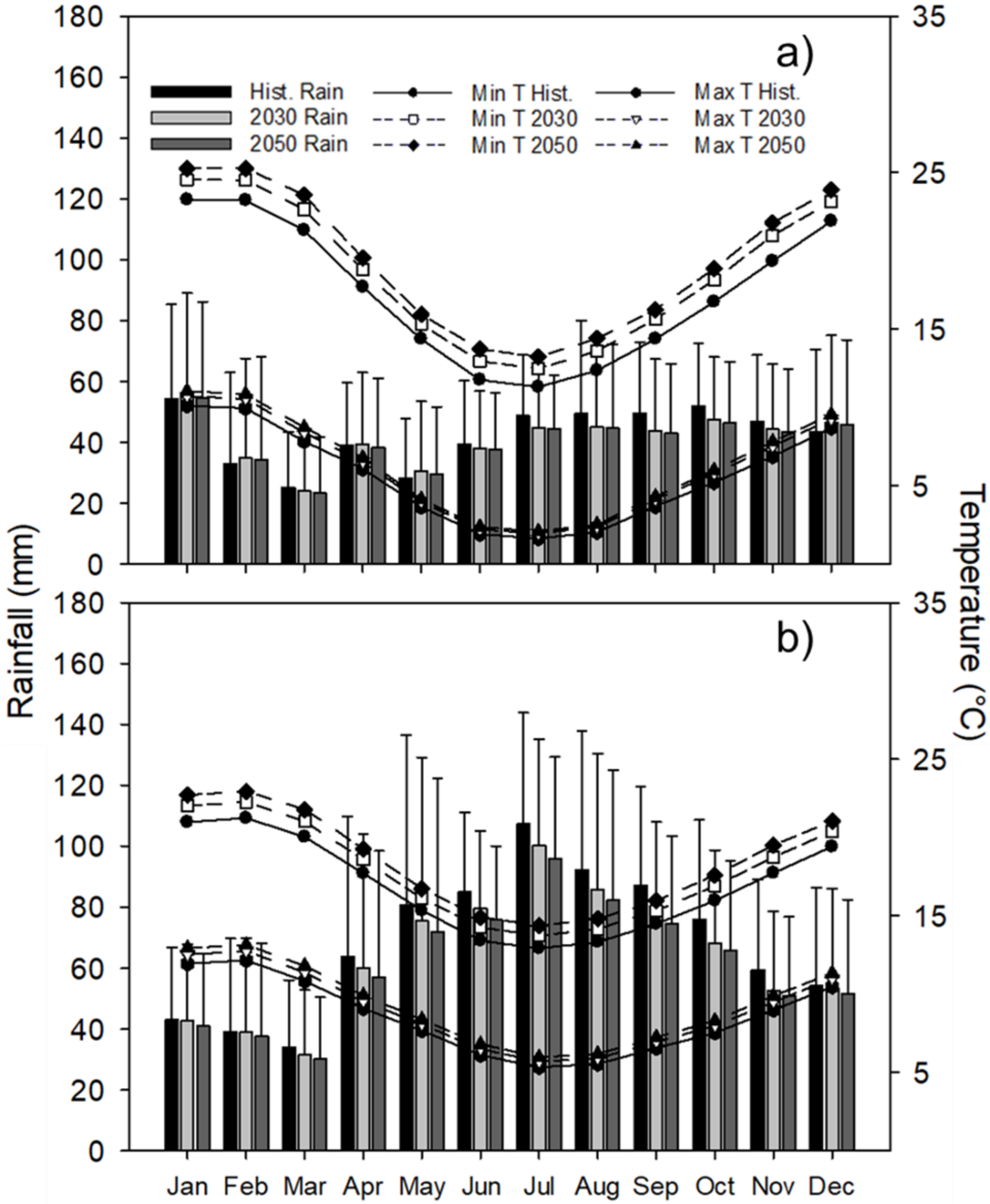


**Fig. A81.1.** Monthly average rainfall minimum and maximum temperature for the historical, 2030 and 2050 climate horizons for the a) Sheep farm and b) Beef farm. Error bars indicate standard deviation.

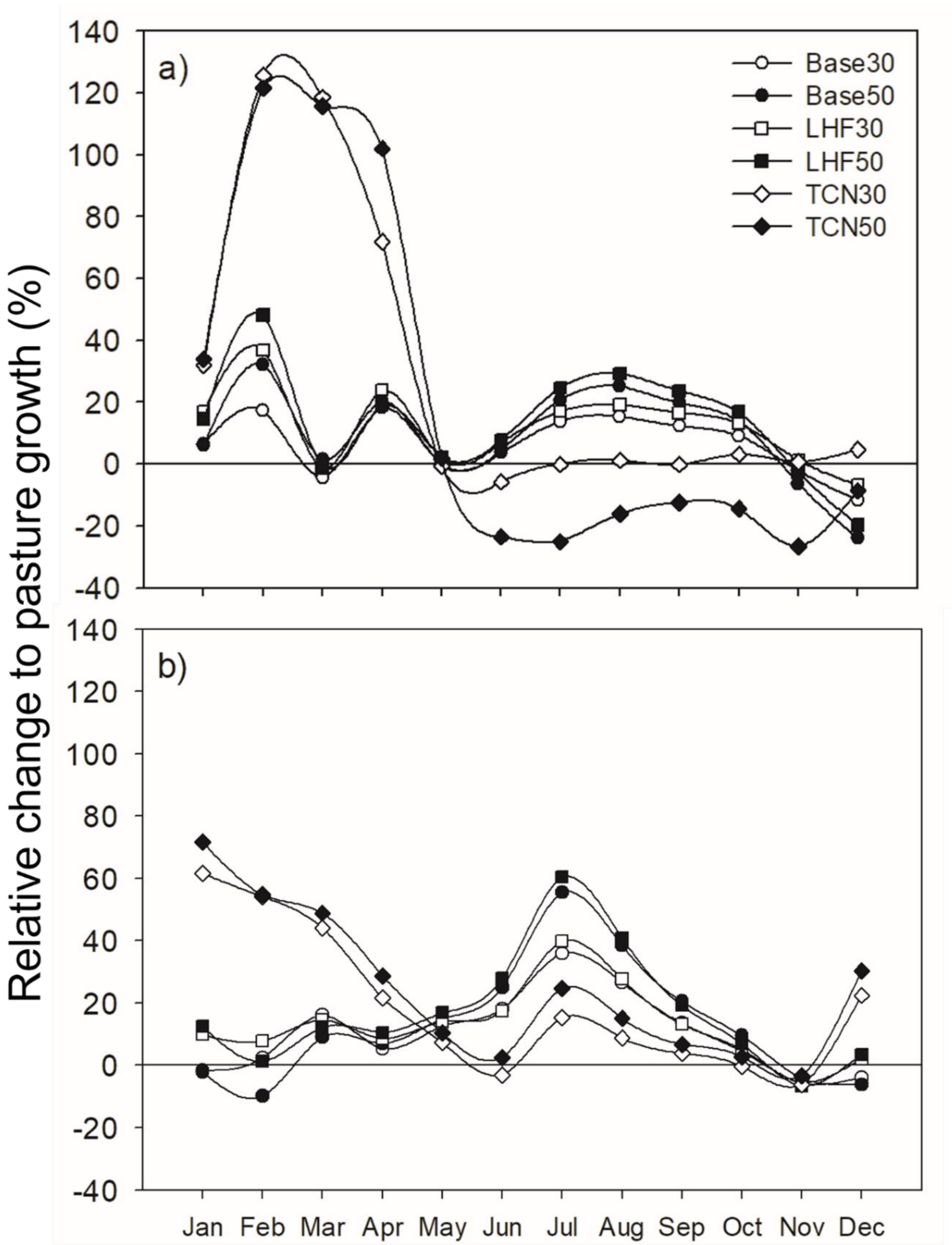


**Fig. A81.2.** Relative percentage change in monthly pasture growth rates observed in beef farm (a) and sheep farm (b) compared with historical periods. The dots represent the percentage differences observed under future climates (2030 and 2050) and planned farm interventions (LHF and TCN).

**Table A81.1.** Monthly change factors showing fractional change in temperate and rainfall for 2030 and 2050 relative to historical monthly average values. Calculated using raw data from Harris et al. (2019) for Representative Concentration Pathways 8.5 (RCP8.5)

| | | Sheep farm | | Beef farm | |
|---|---|---|---|---|---|
| | | Rainfall | Temperature | Rainfall | Temperature |
| 2030 | Jan | 1.06 | 1.04 | 0.99 | 1.05 |
| | Feb | 1.06 | 1.04 | 0.99 | 1.05 |
| | Mar | 0.97 | 1.05 | 0.94 | 1.05 |
| | Apr | 0.97 | 1.05 | 0.94 | 1.05 |
| | May | 0.97 | 1.05 | 0.94 | 1.05 |
| | Jun | 0.95 | 1.08 | 0.93 | 1.06 |
| | Jul | 0.95 | 1.08 | 0.93 | 1.06 |
| | Aug | 0.95 | 1.08 | 0.93 | 1.06 |
| | Sep | 0.92 | 1.07 | 0.89 | 1.06 |
| | Oct | 0.92 | 1.07 | 0.89 | 1.06 |
| | Nov | 0.92 | 1.07 | 0.89 | 1.06 |
| | Dec | 1.06 | 1.04 | 0.99 | 1.05 |
| | **Avg** | 0.97 | 1.06 | 0.94 | 1.06 |
| 2050 | Jan | 1.04 | 1.08 | 0.95 | 1.09 |
| | Feb | 1.04 | 1.08 | 0.95 | 1.09 |
| | Mar | 0.94 | 1.09 | 0.89 | 1.09 |
| | Apr | 0.94 | 1.09 | 0.89 | 1.09 |
| | May | 0.94 | 1.09 | 0.89 | 1.09 |
| | Jun | 0.94 | 1.14 | 0.89 | 1.11 |
| | Jul | 0.94 | 1.14 | 0.89 | 1.11 |
| | Aug | 0.94 | 1.14 | 0.89 | 1.11 |
| | Sep | 0.90 | 1.11 | 0.86 | 1.10 |
| | Oct | 0.90 | 1.11 | 0.86 | 1.10 |
| | Nov | 0.90 | 1.11 | 0.86 | 1.10 |
| | Dec | 1.04 | 1.08 | 0.95 | 1.09 |
| | **Avg** | 0.96 | 1.11 | 0.90 | 1.10 |

**Table A81.2.** Beef farm treatments modelled. Summary of parameters and biophysical variables considered such as flock structure and dynamics, livestock, pasture and soil management, including key input factors and assumptions for each thematic adaptation which comprised multiple stacked incremental adaptations suggested by the Regional Reference Group.

| *Herd* | Variable | Historical/future climate | LFH | TCN |
|---|---|---|---|---|
| ***Main herd*** <br><br> **(Cow-calf and home-bred young stock herd)** | Area grazed | • 402ha | • 402ha | • 452ha (402ha grazable and 50ha Tasmanian Blue Gums) |
| | Livestock numbers | • Stocking rate of 1.1 cows/ha | • Stocking rate of 1.2 cows/ha (increased by 10% to utilise additional pasture production) | • Stocking rate of 1.2 cows/ha (increased by 10% to utilise additional pasture production) |
| | Livestock management | • Breed: Angus <br> • Average liveweight at the start of the analysis: <br> -Cows 580 kg LW/head <br> -Weaners 240 kg LW/head <br> -Yearlings 425 kg LW/head steers and 400 kg LW/head heifers <br> -2-3 years old 650 kg LW/head steers and 625 kg LW/head heifers <br> -Calves 50 kg LW/head <br> • Self-replacing herd, replace 11 Feb <br> • Culled cows sold on 10 Feb (6-7 yrs) <br> • Sell excess heifers 30 Sep (26 months) or at 600 kg target LW <br> • Sell steers 15 Sep (25 months) or at 650 kg target LW | • Breed: Angus <br> • Average liveweight at the start of the analysis: <br> • -Cows 580 kg LW/head <br> • -Weaners 240 kg LW/head <br> • -Yearlings 425 kg LW/head steers and 400 kg LW/head heifers <br> • -2-3 years old 650 kg LW/head steers and 625 kg LW/head heifers <br> • -Calves 68 kg LW/head <br> • Self-replacing herd, replace 11 Feb <br> • Culled cows sold on 10 Feb (6-7 yrs) <br> • Sell excess heifers 8 Oct (27 months) or at 600 kg target LW <br> • Sell steers 8 Oct (27 months) or at 650 kg target LW | • As per LFH |

| | | | |
|---|---|---|---|
| | • Mate 23 Oct, Calving 2 Aug, wean 7 Feb (27 wks)<br>• Age of first joining 1-2 years<br>• 1 bull per 25 cows (kept for 4 years)<br>• Maint. feed females, when thinnest CS2.5<br>• Maint. feed weaners in paddock when thinnest CS3<br>• Maint. feed 100% hay (DM 85%, ME 11.5 MJ/kg DM, CP 20%)<br>• Production feeding rule- feedlot cows every year in feedlot and feed 5.5 kg/head to oldest cows from 1 Jul to 31 Jul<br>• Feed steers in a paddock from 1 Feb to reach 515 kg LW/head on 31 Aug<br>• Feed heifers in a paddock from 1 Feb to reach 505 kg LW/head on 15 Sep | • Mate 8 Oct, Calving 18 Jul, wean 7 Feb (29 wks)<br>• Age of first joining 1-2 years<br>• 1 bull per 25 cows (kept for 4 years)<br>• Maint. feed females, when thinnest CS2.5<br>• Maint. feed weaners in paddock when thinnest CS3<br>• Maint. feed 100% hay (DM 85%, ME 11.5 MJ/kg DM, CP 20%)<br>• Production feeding rule- feedlot cows every year in feedlot and feed 5.5 kg/head to oldest cows from 1 Jul to 31 Jul<br>• Feed steers in a paddock from 1 Feb to reach 535 kg LW/head on 31 Aug<br>• Feed heifers in a paddock from 1 Feb to reach 520 kg LW/head on 15 Sep | |
| Livestock genetics | • Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33<br>• Conception rate 95%<br>• Analysis of historical mortality rate from GrassGro 0.5% | • Alter FCE in GrassGro by increasing factors by 10%, for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.55, 0.022, 0.0385 and 0.363 (Alcock and Hegarty 2011)<br>• Conception rate 95%<br>• Analysis of historical mortality rate from GrassGro 0.5% | • Alter enteric $CH_4$ in SB-GAF by 30% to reflect an intervention to reduce emissions |
| Pasture types | • Paddock 1 (8ha), Irrigated Perennial Ryegrass (720mm RD), Cocksfoot (850 mm RD) and White Clover (500mm RD) | • Increasing rooting depth of grasses/legumes by 10% (except lucerne- retained this | • Add Lucerne (semi winter active) as deep-rooted |

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| | | for LFH + Towards Carbon Neutral (TCN) modelling), | species, mix with Perennial Ryegrass |
| | • Paddock 2 (20ha), Irrigated Lucerne-semi winter active (1200mm RD), Perennial Ryegrass (720mm RD) | • Paddock 1 (8ha), Irrigated Perennial Ryegrass (792mm RD), Cocksfoot (935 mm RD) and White Clover (550mm RD) | • Paddock 1 (8ha), Irrigated lucerne (semi winter active, 1200mm RD) and Perennial Ryegrass (792mm RD) |
| | • Paddock 3 (187ha), Rainfed Perennial Ryegrass (720mm RD), Cocksfoot (850 mm RD) and Sub-Clover – Seaton Park (600mm RD) | • Paddock 2 (20ha), Irrigated Lucerne-semi winter active (1200mm RD), Perennial Ryegrass (792mm RD) | • Paddock 2 (20ha), Irrigated lucerne (semi winter active, 1200mm RD) and Perennial Ryegrass (792mm RD) |
| | • Paddock 4 (187ha), Rainfed Perennial Ryegrass (750mm RD) and White Clover (500mm RD) | • Paddock 3 (187ha), Rainfed Perennial Ryegrass (792mm RD), Cocksfoot (935 mm RD) and Sub-Clover – Seaton Park (660mm RD) | • Paddock 3 (187ha), Rainfed lucerne (semi winter active, 1200mm RD) and Perennial Ryegrass (792mm RD) |
| | | • Paddock 4 (187ha), Rainfed Perennial Ryegrass (825mm RD) and White Clover (550mm RD) | • Paddock 4 (187ha), Rainfed lucerne (semi winter active, 1200mm RD) and Perennial Ryegrass (792mm RD) |
| Pasture management (note rooting depth in pasture type) | • Irrigate paddock 1 and 2 between 21 Nov and 31 Mar, applying 20mm and fill to 0.95 | • Increased rooting depth by 10%, | • Rooting depth of Lucerne is 1200mm |
| | • Cut paddocks 3 and 4 (whenever DM yield exceeds 5000kg/ha between 2 Sep-14 Dec). Proportion gathered 90%. Cutting height 125mm. Don't cut when DM/ha is below 800 kg/ha | • All other aspects as per historical (checking similar irrigation water applied to historical) | • Increased rooting depth by 10%, |
| | | • Alter fertiliser (urea and SSP) to reflect change in pasture growth, additional clover requiring less N | • All other aspects as per historical (checking similar irrigation water applied to historical)<br>• Alter fertiliser (urea and SSP) to reflect change in pasture growth, additional clover requiring less N |

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| Grazing management | • Cows- From 1 Jul to 30 Jun graze paddocks 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>• Heifer Weaners- From 1 Jul to 30 Jun graze paddocks 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>• Heifer Yearlings- From 1 Jul to 30 Jun graze paddocks 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>• Heifers 2-3 years old- From 1 Jul to 30 Jun graze paddocks 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>• Steers Weaners- From 1 Jul to 30 Jun graze paddocks 1, 2, 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>• Steers Yearlings- From 1 Jul to 30 Jun graze paddocks 2, 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>• Steers 2-3 years old - From 1 Jul to 30 Jun graze paddocks 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day | • As per Historical | • As per LFH |
| Soils | • All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Uc2.3 classification (Northcote 1979)<br>• Paddocks 1 and 2 FS 0.87<br>• Paddocks 3 and 4 FS 0.85 | • Increase soil fertility 3% increase<br>• Paddocks 1 and 2 FS 0.90<br>• Paddocks 3 and 4 FS 0.88 | • As per LFH |
| Tree plantings | • No environmental plantings beyond currently on farm | • No environmental plantings above what currently on farm | • Extra 50ha for environmental plantings in FullCAM |

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| ***Purchased weaner herd*** | Area grazed | • 127ha | • 127ha | • 127ha |
| | Livestock numbers | • Stocking rate of 1.8 steers/ha | • Stocking rate as per Historical | • As per LFH |
| | Livestock management | • Breed: Angus<br>• Average liveweight at the start of the analysis:<br>-Weaners 225 kg LW/head<br>-Yearlings 425 kg LW/head<br>-2-3 years old 650 kg LW/head<br>-3-4 years old 700 kg LW/head<br>• Purchased 1 Feb at 6 mths of age and sold on 15 Sep (25 mths) or at 633 kg LW/head<br>• Maint. feed mature males and weaners in paddock when thinnest CS2.5.<br>• Maint. feed 100% hay (DM 85%, ME 11.5 MJ/kg DM, CP 20%)<br>• Feed steers in a paddock from 1 Feb to reach 500 kg LW/head on 1 Sep | • As per Historical | • As per LFH |
| | Livestock genetics | • Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33 | • Alter FCE in GrassGro by increasing factors by 10%, for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.55, 0.022, 0.0385 and 0.363 (Alcock and Hegarty 2011) | • Alter enteric $CH_4$ in SB-GAF by 30% to reflect an intervention to reduce emissions |
| | Pasture types | • Paddock 1 (32ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD)<br>• Paddock 2 (32ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD) | • Increasing rooting depth of grasses/legumes by 10% (except lucerne- retained this for LFH + Towards Carbon Neutral (TCN) modelling),<br>• Paddock 1 (32ha), Rainfed Perennial Ryegrass (792mm RD) and White Clover (550mm RD) | • Add Lucerne (semi winter active) as deep-rooted species, mix with Perennial Ryegrass<br>• Paddock 1 (32ha), Lucerne (semi winter active, 1200mm RD) and Perennial Ryegrass (792mm RD) |

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| | • Paddock 3 (31.5ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD)<br><br>• Paddock 4 (31.5ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD) | • Paddock 2 (32ha), Rainfed Perennial Ryegrass (792mm RD) and White Clover (550mm RD)<br>• Paddock 3 (31.5ha), Rainfed Perennial Ryegrass (792mm RD) and White Clover (550mm RD)<br>• Paddock 4 (31.5ha), Rainfed Perennial Ryegrass (792mm RD) and White Clover (550mm RD) | • Paddock 2 (32ha), Lucerne (semi winter active, 1200mm RD) and Perennial Ryegrass (792mm RD)<br>• Paddock 3 (31.5ha), Lucerne (semi winter active, 1200mm RD) and Perennial Ryegrass (792mm RD)<br>• Paddock 4 (31.5ha), Lucerne (semi winter active, 1200mm RD) and Perennial Ryegrass (792mm RD) |
| Pasture management | • Reset pasture species as necessary 1 Feb<br><br>• Cut paddocks 1 (Years: 1 and 4), 2 (Years: 1 and 2), 3 (Years: 2 and 3) and 4 (Years: 3 and 5) (whenever DM yield exceeds 5000kg/ha between 2 Sep-14 Dec). Proportion gathered 90%. Cutting height 125mm. Don't cut when DM/ha is below 800 kg/ha | • Increased rooting depth by 10%,<br>• Reset pasture species as necessary 1 Feb<br><br>• Cut paddocks 1 (Years: 1 and 4), 2 (Years: 1 and 2), 3 (Years: 2 and 3) and 4 (Years: 3 and 5) (whenever DM yield exceeds 5000kg/ha between 2 Sep-14 Dec). Proportion gathered 90%. Cutting height 125mm. Don't cut when DM/ha is below 800 kg/ha | • Rooting depth of Lucerne is 1200mm<br>• Increased rooting depth by 10%,<br><br>• Reset pasture species as necessary 1 Feb<br><br>• Cut paddocks 1 (Years: 1 and 4), 2 (Years: 1 and 2), 3 (Years: 2 and 3) and 4 (Years: 3 and 5) (whenever DM yield exceeds 5000kg/ha between 2 Sep-14 Dec). Proportion gathered 90%. Cutting height 125mm. Don't |

| | | | | |
|---|---|---|---|---|
| | | | | cut when DM/ha is below 800 kg/ha |
| | Grazing management | • Weaners, Yearlings and 2-3 years old- From 1 Jan to 31 Dec graze paddocks 1, 2, 3 and 4, withhold 14 days, check every 7 days and move when weight gain margin is > 0.01 kg/day | • As per Historical<br>• Alter fertiliser (urea and SSP) to reflect change in pasture growth, additional clover requiring less N | • As per LFH |
| | Soils | • All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Uc2.3 classification (Northcote 1979)<br>• All paddocks FS 0.85 | • All paddocks now 0.88 (3% increase) | • As per LFH |
| | Tree plantings | • No environmental plantings above what currently on farm | • No environmental plantings above what currently on farm | • No environmental plantings above what currently on farm |
| ***Purchased yearlings with agisted heifers*** | Area grazed | • 40ha | • 40ha | • 40ha |
| | Livestock numbers | • Stocking rate of 3.9 steers/ha | • Stocking Rate as per Historical | • As per LFH |
| | Livestock management | • Breed: Angus<br>• Purchased 1 Feb at 16 mths of age (375 kg LW/head) and sold on 15 Sep (28 mths) or at 545 kg LW/head<br>• Maint. feed steers in paddock when thinnest CS2.<br>• Maint. feed 100% hay (DM 85%, ME 11.5 MJ/kg DM, CP 20%) | • As per Historical | • As per LFH |

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|---|---|---|---|
| | • Feed steers in a paddock from 1 Feb to reach 350 kg LW/head on 1 Sep | | |
| Livestock genetics | • Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33 | • Alter FCE in GrassGro by increasing factors by 10%, for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.55, 0.022, 0.0385 and 0.363 (Alcock and Hegarty 2011) | • Alter enteric $CH_4$ in SB-GAF by 30% to reflect an intervention to reduce emissions |
| Pasture types | • Paddock 1 (20ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD)<br>• Paddock 2 (20ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD) | • Increasing rooting depth of grasses/legumes by 10% (except lucerne- retained this for LFH + Towards Carbon Neutral (TCN) modelling),<br>• Paddock 1 (20ha), Rainfed Perennial Ryegrass (792mm RD) and White Clover (550mm RD)<br>• Paddock 2 (20ha), Rainfed Perennial Ryegrass (792mm RD) and White Clover (550mm RD) | • Add Lucerne (semi winter active) as deep-rooted species, mix with Perennial Ryegrass<br>• Paddock 1 (20ha), Lucerne (semi winter active, 1200mm RD) and Perennial Ryegrass (792mm RD)<br>• Paddock 2 (20ha), Lucerne (semi winter active, 1200mm RD) and Perennial Ryegrass (792mm RD) |
| Pasture management | • No hay cutting | • As per Historical<br>• Alter fertiliser (urea and SSP) to reflect change in pasture growth, additional clover requiring less N | • As per LFH |
| Grazing management | • Steers (Yearling and 2-3 years old)- From 1 Jan to 31 Dec graze paddocks 1 and 2, withhold 14 days, check every 7 days and move when weight gain margin is > 0.01 kg/day | • As per Historical | • As per LFH |
| Soils | • All paddocks soil texture defined from Atlas in GrassGro, corresponding to a | • All paddocks now 0.84 (3% increase) | • As per LFH |

| | | | |
|---|---|---|---|
| | Northcote Uc2.3 classification (Northcote 1979)<br>• Paddock 1 and 2 FS 0.82 | | |
| Tree plantings | • No environmental plantings above what currently on farm | • No environmental plantings above what currently on farm | • No environmental plantings above what currently on farm |

**Table A81.3.** Sheep farm treatments modelled. Summary of parameters and biophysical variables considered such as flock structure and dynamics, livestock, pasture and soil management, including key input factors and assumptions for each thematic adaptation which comprised multiple stacked incremental adaptations suggested by the Regional Reference Group.

| *Flock/herd* | Variable | Historical/future climate | LFH | TCN |
|---|---|---|---|---|
| ***Wool flock*** | Area grazed | • 2,545 ha | • 2,777 ha (i.e. 2,545 ha + 232 ha from cattle) to retain the same proportion of land to wool vs prime lamb flock as per historical | • Grazing platform as per LFH<br>• Assumed 200ha of trees planted to environmental plantings but through thickening of existing non-grazed areas so same as LFH |
| | Livestock numbers | • Stocking rate of 2.8 ewes and 2.7 wethers/ha | • Increased stocking rate to 3.3 ewes and 3.2 wethers/ha | • Increased stocking rate to 3.4 ewes and 3.3 wethers/ha |
| | Livestock management | • Self-replacing Merino flock, replace 1 Sep<br>• CFA ewes sold 31 Aug (4-5 yrs) into lamb flock<br>• CFA wethers 14 Oct (5-6 yrs)<br>• Mate 22 Apr, lamb 18 Sep, wean 31 Jan (19 wks) and sell excess 1 Feb (19 wks)<br>• Shearing 20 Jul<br>• Maint. feed ewes, wethers and weaners in paddock when thinnest CS2.5<br>• Maint. feed weaners in paddock when thinnest CS3<br>• Maint. feed 78% wheat, 22% hay (ME 12.3 MJ, CP 12%)<br>• Production feeding rule- feedlot ewes every year in feedlot and feed | • Self-replacing Merino flock, replace 18 Aug<br>• CFA ewes sold 17 Aug (4-5 yrs) into lamb flock<br>• CFA wethers still sold 14 Oct (5-6 yrs)<br>• Mate 8 Apr, lamb 4 Sep, wean 17 Jan (19 wks) and sell excess 10 Feb as preliminary modelling results suggest feed available until then<br>• Shearing 6 Jul<br>• Maint. and production feeding as per historical | • As per LFH with respect to mature animals<br>• Mating and weaning as per LFH<br>• Sell excess lambs 28 Feb (25 weeks)<br>• Shearing as per LFH<br>• Maint. and production feed ewes, wethers and weaners as per LFH |

| | | | |
|---|---|---|---|
| | 0.52 kg/head from 15 Jan to 15 Apr, same quality as maint. feeding<br>• No other production rule for weaner lambs or wethers | | |
| Livestock genetics | • Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33<br>• Conception rate 88% singles, 0% twins and 0% triplets<br>• Analysis of historical mortality rate from GrassGro 16.2% | • Alter FCE in GG by increasing factors by 10% in parameter editor, now 0.55, 0.022, 0.0385 and 0.363 (Alcock and Hegarty 2011)<br>• Retain same conception rate as per historical<br>• Lamb mortality to remain below the historical 16.2% | • Alter enteric $CH_4$ in SB-GAF by 30% to reflect an intervention to reduce emissions |
| Pasture types | • Paddock 1 (800ha), rainfed Phalaris (750mm RD) and sub clover (500mm RD)<br>• Paddock 2 (1,553ha), rainfed Danthonia and Microlaena<br>• Paddock 3 (64ha), rainfed Phalaris seed crop (750mm RD)<br>• Paddock 4 (30ha), rainfed Phalaris (750mm RD) and sub-clover (440mm RD, lower rooting depth of subterranean clover to other paddocks due to soil conditions)<br>• Paddock 5 (67ha), irrigated lucerne (900mm RD)<br>• Paddock 6 (31ha), irrigated ARG as wheat (520mm RD) | • Extra 232 ha rainfed pastures<br>• Paddock 1 now 750ha, rainfed Phalaris and sub clover<br>• Paddock 4 now 312 ha, rainfed Phalaris and sub-clover plus Talish clover (alteration of white clover in the GG parameter editor)<br>• Paddocks 2, 3, 5 and 6 remain as per historical | • Add rainfed lucerne (semi winter active) to Paddock 1 (550ha)<br>• Add rainfed lucerne (semi winter active) to Paddock 4 (312ha)<br>• New paddock 7 which replicates paddock 1 in terms of species present(200ha)<br>• Paddocks 2, 3, 5 and 6 reman as per historical |

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|---|---|---|---|
| Pasture management (note rooting depth in pasture type) | • Irrigate paddock 5 and 6 between 1 Sep and 31 Mar, applying 18mm and fill to 0.95<br>• Reset pasture species as necessary on 5 Apr<br>• Cut paddock 5 (irrigated lucerne) 10 Nov | • Increased rooting depth by 10%, Phalaris to 825mm, subterranean clover to 550/485 mm, across relevant paddocks<br>• All other aspects as per historical (checking similar irrigation water applied to historical) | • Rooting depth of new lucerne is 1200 mm<br>• All other aspects as per historical |
| Grazing management | • Ewes- 15 Jan to 30 Jun graze paddocks 1 and 3, withhold 14 days, check every 7 days and move when weight gain margin is > 0.02 kg/day<br>• Ewes- 1 Jul to 14 Jan graze paddock 1, without 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Wethers- 15 Jan to 14 Mar graze paddocks 1 and 3, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Wethers- 15 Mar to 30 Jun graze paddocks 1,2 and 3, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Wethers- 1 Jul to 15 Sep graze paddocks 1 and 2, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Wethers- 16 Sep to 14 Jan graze paddock 1, withhold 14 days, check | • Ewes- 15 Jan to 30 Jun as per historical<br>• Ewes- 1 Jul to 14 Jan graze paddocks 1 and 3, withhold 14 days, check every 7 days and move when weight gain margin is > 0.02 kg/day<br>• Wethers- as per historical<br>• Ewe and wether weaners as per historical | • Ewes- 15 Jan to 30 Jun graze paddocks 1, 3, 4 and 7, withhold 14 days, check every 7 days and move when weight gain margin is > 0.02 kg/day<br>• Ewes- 1 Jul to 14 Jan graze paddocks 1, 4 and 7, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Wethers- 15 Jan to 14 Mar graze paddocks 1, 3, 4 and 7, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Wethers- 15 Mar to 30 Jun graze paddocks 1,2, 3, 4 and 7, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Wethers- 1 Jul to 15 Sep graze paddocks 1, 2, 4 and 7, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Wethers- 16 Sep to 14 Jan graze paddocks 1, 4 and 7, withhold 14 days, check every |

| | | |
|---|---|---|
| | every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Ewe and wether weaners- 1 Jan to 14 Jan graze paddocks 1, 4 and 5, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Ewe and wether weaners- 15 Jan to 30 Apr graze paddocks 1,3, 4 and 5, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Ewe and wether weaners- 1 May to 31 May graze paddocks 1, 3, 4, 5 and 6, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Ewe and wether weaners- 1 Jun to 30 Jun graze paddocks 1, 3, 4 and 6, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Ewe and wether weaners- 1 Jul to 31 Aug graze paddocks 1, 4 and 6, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Ewe and wether weaners- 1 Sep to 31 Dec graze paddocks 1 and 4, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day | 4 days and move when weight gain margin is > 0.02 kg/day<br>• Ewe and wether weaners- 1 Jan to 14 Jan graze paddocks 1, 4, 5 and 7, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Ewe and wether weaners- 15 Jan to 30 Apr graze paddocks 1,3, 4, 5 and 7, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Ewe and wether weaners- 1 May to 31 May graze paddocks 1, 3, 4, 5, 6 and 7, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Ewe and wether weaners- 1 Jun to 30 Jun graze paddocks 1, 3, 4, 6 and 7, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• Ewe and wether weaners- 1 Jul to 31 Aug graze paddocks 1, 4, 6 and 7, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>• weaners- 1 Sep to 31 Dec graze paddocks 1, 4 and 7, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day |

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| | Soils | • All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Dy5.61 classification (Northcote 1979)<br>• Paddocks 1, 3-6 FS 0.84<br>• Paddock 2 FS 0.80 (natives can't be fertilised, species altered, area changed etc) | • Paddocks 1, 3-6 FS increase soil fertility to 0.87 (3% increase)<br>• Paddock 2 (natives) as per historical | • As per LFH |
| | Tree plantings | • No environmental plantings beyond currently on farm | • No environmental plantings above what currently on farm | • 200ha environmental plantings in FullCAM |
| ***Prime lamb flock*** | Area grazed | • 360 ha | • 393 ha (360 ha + 33 ha from cattle) | • Assumed 200ha of trees but through thickening of existing non-grazed areas so no change here |
| | Livestock numbers | • Stocking rate of 9.6 ewes/ha | • Stocking rate as per historical | • As per LFH |
| | Livestock management | • Purchased 1 Sep (from wool flock) at 24 mths of age<br>• Mate 11 Apr, lamb 7 Sep, wean 15 Dec (14 wks), sell lambs 15 Dec at 27kg<br>• Shearing 20 Jul<br>• CFA 16 Dec (3-4 yrs)<br>• Maint. feed ewes in paddock when thinnest CS2.5- rerun historical, 2030 and 2050 with CS 2.5<br>• Maint. feed weaners in paddock when thinnest CS3 | • Purchased 18 Aug (from wool flock) at 24 mths of age<br>• Mate 14 days sooner so 28 Mar, lamb 24 Aug, wean 20 Dec (17 wks) as feed remained until then<br>• Shearing 6 Jul<br>• CFA ewes remains the same as lambs still taken through to 20 Dec (3-4 yrs)<br>• Maint. and production feeding as per historical | • Purchases, mating, lambing, weaning, shearing and sale of CFA ewes as per LFH<br>• Retain lambs until 1st Apr (32 weeks)<br>• Maint/ feeding as per historical<br>• No longer require any production feeding for ewes |

| | | | |
|---|---|---|---|
| | • Maint. feed 78% wheat, 22% hay (ME 12.3 MJ, CP 12%)<br>• Production feeding rule- feedlot ewes every year in feedlot and feed 0.52 kg/head from 15 Jan to 15 Apr, same quality as maint. feeding<br>• No production feeding rule for lambs | | |
| Livestock genetics | • Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33 | • Alter FCE in GG by increasing by 10% in parameter editor, now 0.55, 0.022, 0.0385 and 0.363 (Alcock and Hegarty 2011) | • Alter enteric $CH_4$ in SB-GAF by 30% to reflect an intervention to reduce emissions |
| | • Conception rate 91% singles, 2% twins and 0% triplets<br>• Analysis of historical mortality rate from GrassGro 8.5% | • Retain same conception rate as per historical<br>• Lamb mortality remains below the historical 8.5% | • As per LFH for conception rate |
| Pasture types | • Paddock 1 (120ha), rainfed Phalaris (750mm RD) and subterranean clover (500mm RD) | • Extra 33ha rainfed pasture from cattle | |
| | • Paddock 2 and 3 a repeat of paddock 1 | • All paddocks 131ha with Phalaris and sub-clover<br>• Paddock 2 also includes perennial Talish clover (600mm rooting depth in GG, adapted from white clover in parameter editor) | |
| Pasture management | • Reset pasture species as necessary 5 Apr (mimic sub-clover germination if required) | • Increased rooting depth by 10%, Phalaris to 825mm, subterranean clover to 550mm, Talish cover to 660mm | • Introduced rainfed lucerne to either paddock 1 or 3 as we retain Talish clover on paddock 2 |
| | • Cut one paddock per year 16 Dec, rotating between the three paddocks so always have 2 for grazing | • Alter fertiliser (urea and SSP) to reflect change in pasture growth, additional clover requiring less N<br>• Balance as per historical | • Alter fertiliser (urea and SSP) to reflect change in pasture growth, additional clover requiring less N |

| | | | | |
|---|---|---|---|---|
| | Grazing management | • All sheep- 1 Jan to 31 Dec graze paddocks 1, 2 and 3, withhold 14 days, check every 4 days and move when weight gain margin is > 0.025 kg/day | • As per historical | • As per historical |
| | Soils | • All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Dy5.61 classification (Northcote 1979)<br>• Paddocks 1,2 &3 FS 0.85 | • Paddocks 1,2 &3 FS now 0.88 (3% increase) | • As per LFH |
| | Tree plantings | • No environmental plantings above what currently on farm | • No environmental plantings above what currently on farm | • See tree plantings for wool flock |
| ***Cattle herd*** | Area grazed | • 265ha | | |
| | Livestock numbers | • Stocking rate of 1.5 cows/ha (~ 337 cows, 55 replacement heifers per age group, 145 steers and 90 non-replacement heifers) | | |
| | Livestock management | • Self-replacing Hereford herd 1 Apr<br>• CFA cows 31 Mar (7-8 yrs)<br>• Mate 20 Nov, wean 31 Mar, sell excess heifers 1 Apr at 31 weeks or 220 kg, sell steers 28 Feb at 18 months or 460 kg<br>• Maint. feed cows in paddock when thinnest CS3<br>• Maint. feed weaners in paddock when thinnest CS2.5<br>• Maint. feed 100% hay (ME 11.0 MJ, CP 14%)<br>• Production feeding rule- feed steers in paddock from 1 Apr to reach 460 kg 28 Feb | | |

| | | |
|---|---|---|
| | • Production feeding rule- feed heifers in paddock from 1 Sep to reach 250 kg 31 Mar<br>• Production feed same quality hay as per maint. Feeding | |
| Livestock genetics | • Default within GrassGro<br>• Conception rate of 92% at CS3 | |
| Pasture types | • Paddock 1 (132.5ha), rainfed Phalaris (750mm RD) and subterranean clover (500mm RD)<br>• Paddock 2 same as paddock 1 | |
| Pasture management | • Reset pasture species as necessary 5 Apr (mimic sub-clover germination if required)<br>• No hay cutting | |
| Grazing management | • All cattle- 1 Jan to 31 Dec graze paddocks 1 and 2, withhold 14 days, check every 7 days and move when weight gain margin is > 0.01 kg/day | |
| Soils | • All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Dy5.61 classification (Northcote 1979)<br>• Paddock 1 & 2 FS 0.85 | |
| Tree plantings | • No environmental plantings above what currently on farm | |

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**Table A81.4.** Fitted parameters for capital costs, annual farm variable costs, and TCN costs distribution for both cases of study (beef and sheep farm)

| Variables | Beef farm | Sheep farm |
|---|---|---|
| **Capital costs (Year 1)** | | |
| Land | 13,237,500 | 10,000,000 |
| Livestock | 3,941,860 | 1,645,477 |
| Machinery | 1,113,425 | 400,000 |
| Water | 32,350 | - |
| **Annual Farm Variable costs** (exc. supp feed) | 635,230 | 161,049 |
| Annual Supplementary feed | 100,000 | 7,248 |
| Annual Farm Cash Overhead costs | 516,480 | 239,700 |
| **TCN options** | | |
| (Lucerne, trees, methane vaccine) | | |
| Tree Establishment ($ ha$^{-1}$) | 1500 | 1500 |
| Tree maintenance p.a. ($ ha$^{-1}$) | 30 | 30 |
| Vaccine per head ($ hd$^{-1}$) | Uniform<br>Mean= 10<br>Max= 15<br>Min= 5 | Uniform<br>Mean= 6.5<br>Max= 10<br>Min= 3 |
| Lucerne establishment cost ($ ha$^{-1}$) | 200 | 200 |
| Extra annual fertiliser maintenance ($ ha$^{-1}$) | 50 | 50 |
| Land purchase cost ($ ha$^{-1}$) | 10,000 | - |

**Table A81.5.** Fitted parameters and market price distributions for beef cattle (c kg$^{-1}$ dressed weight)

| Units | 1 Y.O Heifers (PTIC) | Mixed age cows (PTIC) | Steers | MSA steers | Surplus heifers and feeder heifers | Cull cows |
|---|---|---|---|---|---|---|
| Probability Distribution | Pert | Pert | Pert | Pert | Log-normal | Pert |
| Min | 300 | 300 | 300 | 300 | - | 300 |
| Max | 900 | 700 | 900 | 850 | - | 700 |
| M. Likely | 530 | 500 | 530 | 500 | - | 500 |
| Mean | - | - | - | - | 500 | - |
| Std. Deviation | - | - | - | - | 350 | - |

**Table A81.6.** Fitted parameters and market price distributions for wool production (c kg$^{-1}$ Clean Fleece Weight)

| Units | Lambs (16 um) | Ewes (18 um) | Wethers (18 um) | Merino Ram (18 um) |
|---|---|---|---|---|
| Probability Distribution | Pert | Pert | Pert | Pert |
| Min | 1400 | 1385 | 1385 | 1385 |
| Max | 2500 | 2300 | 2300 | 2300 |
| M. Likely | 1700 | 1636 | 1636 | 1636 |

**Table A81.7.** Fitted parameters and market price distributions for sheep meat (\$ $kg^{-1}$ dressed weight)

| Units | Lambs at 6 months | Prime lambs | Wethers | Rams | Cull ewes |
|---|---|---|---|---|---|
| Probability Distribution | Pert[a] | Pert | Pert | Pert | Pert |
| Min | 3.00 | 3.40 | 1.50 | 1.50 | 1.50 |
| Max | 8.00 | 8.00 | 5.93 | 5.93 | 5.93 |
| M. Likely | 5.40 | 5.70 | 3.45 | 3.45 | 3.45 |

[a] Family of continuous probability distributions defined

# Appendix 8.2: Costs of transitioning to net-zero emissions under future climates

Draft paper submitted to One Earth journal

*Franco Bilotto[1,2], Karen Michelle Christie-Whitehead[3], Bill Malcolm[4], Nicoli Barnes[3], Brendan Cullen[4], Margaret Ayre[4], Matthew Tom Harrison[1 5*]*

[1] *Tasmanian Institute of Agriculture, University of Tasmania, Newnham, Launceston, TAS 7248, Australia*

[2] *AgResearch, Grasslands Research Centre, Tennent Drive, Private Bag 11008, Palmerston North 4442, New Zealand*

[3] *Tasmanian Institute of Agriculture, University of Tasmania, Burnie, TAS, 7320, Australia*

[4] *Faculty of Veterinary and Agricultural Sciences, The University of Melbourne, Parkville, VIC 3010, Australia*

[5] *Lead contact*

*Corresponding author: matthew.harrison@utas.edu.au

## Graphical abstract


## Highlights

- Carbon farming proponents are challenged by social and ethical license to operate
- We co-developed pathways to net-zero for livestock farms under future climates
- Costs of transitioning to net-zero vary widely; in some cases were profitable
- Transformational solutions will require recognition of agri-environmental stewardship

## eTOC blurb

Balancing land use priorities for agri-food production, conversation and carbon sequestration is becoming increasingly challenging. We co-developed multiple pathways to net-zero emissions while also accounting for the changing climate. Seaweed (*Asparagopsis*) feed supplement and planting trees offered the greatest mitigation potential; purchasing carbon credits was the most expensive option. Costs associated with transitioning to net-zero varied widely (-64% to +30%). Transformation may be realised by solutions that simultaneously improve productivity, profitability, carbon sequestration and social and ethical license to operate.

## Science for society

Land managers are faced with the trilemma of agri-food production, greenhouse gas (GHG) abatement and natural resource conservation while maintaining social and ethical license to operate. Working with regional industry practitioners, we co-designed and modelled multiple climate change adaptation and GHG mitigation pathways for transitioning livestock farming systems to net-zero emissions under future climates. Interventions that improved livestock production and profit generally also increased net GHG emissions. Conversely, interventions eliciting GHG emissions abatement did not necessarily reduce status quo production and profit. Stacking together multiple synergistic interventions that enable carbon sequestration, environmental stewardship, livestock production-co-benefit, mitigation and improved social and ethical licence to operate could be perceived as transformative. In this way, suitably combined bundles of interventions can enable profitable pathways to net-zero emissions.

## Summary

Land managers are challenged with balancing priorities for agri-food production, greenhouse gas (GHG) abatement, natural conservation, social and economic license to operate. We co-designed pathways for transitioning farming systems to net-zero emissions under future climates. Few interventions enhanced productivity and profitability while also reducing GHG emissions. Seaweed (*Asparagopsis*) feed supplement and planting trees enabled the greatest mitigation (67-95%), while enterprise diversification (installation of wind turbines) and improved feed-conversion efficiency (FCE) were most conducive to improved profitability (17-39%). Mitigation efficacy was hampered by adoptability. Serendiptiously, the least socially acceptable option – business as usual and purchasing carbon credits to offset emissions – were also the most costly options. In contrast, stacking synergistic interventions enabling enteric methane mitigation, improved FCE and carbon removals entirely negated net emissions in a profitable way. We conclude that costs of transitioning to net-zero vary widely (-64% to +30%), depending on whether interventions are stacked and/or elicit productivity co-benefits.

## Keywords

Climate emergency, Net-Zero 2050, Nationally Determined Contribution, Carbon Storage, Soil Carbon, Food Security, Environmental Stewardship, Social license to operate, adoptability

## Introduction

Increasing atmospheric greenhouse gases concentrations (GHG) evokes global warming, intensifying the global water cycle and increasing the risk of extreme events[1,2]. During the last four decades, the frequency of natural disasters borne by extreme events has almost quadrupled, causing the equivalent of US$280B in crop and livestock production losses[3]. However, regional variation in the effects of climate change, including seasonal and regional patterns of precipitation may - in some cases - realise benefits, such as reduced frequencies of extreme cold[4] and reduced waterlogging in arable landscapes[5].

Carefully conceived adaptations may enable food systems transformation, but often only if due consideration is given to a wide range of socioeconomic, institutional and cultural factors in the co-design process[6,7]. As a corollary, few *bona fide* examples of food systems transformations exist, perhaps because research has traditionally progressed in a reductionist fashion, with primarily unidisciplinary and isolated foci instead of multidisciplinary system approach. Research designed to address only one GHG emissions reduction intervention has given rise to a phenomenon called 'Carbon Myopia', representing studies in which singular interventions are evaluated and rated based primarily on carbon removals or GHG emissions avoidance[8]. Effects of, or interactions caused by, such interventions on or with extraneous social factors, such as prosperity, productivity, risk, environmental stewardship and social license, are often downplayed or ignored completely, even though such collectively factors determine the whether an intervention will be sustainable, and ultimately, successful[8,9]. Compared with unidisciplinary approaches however, multi- and transdisciplinary work (cross discipline and cross institutional, respectively) tends to be more difficult to lead, and more costly in time and money to execute, and hence the majority of GHG emissions mitigation research continues to progress in siloed pockets[8-10].

The bulk of past climate change adaptation and mitigation work for the livestock sector has however been premised primarily upon biophysical lenses. Such studies have examined, for example, (1) evaluation of GHG emissions of cropping and livestock systems[11], (2) comparisons of GHG emissions from model ensembles[12], (3) and the influence of genotype by management by environment combinations on GHG emissions and productivity[13-16]. Much less work for sheep and beef systems has focused on how interventions aimed at adaptation and/or mitigation influence productivity, profitability and GHG emissions, although similar efforts for other sectors (such as dairy and grains) indicate that conclusions drawn differ considerably when economics are also taken into account[17,18]. While land managers have multiple potential opportunities to reduce GHG emissions (e.g. through carbon removals, GHG emissions avoidance, or GHG emissions mitigation), scientific literature that develops, contrasts and identifies economic pathways to carbon neutral farming systems is scarce. Here, our aim is to (1) co-develop a range of management, genetic, environmental, livestock and landscape interventions for both adapting livestock systems while reducing GHG emissions and (2) analytically cost (economically and biophysically) a range of plausible pathways to net-zero emissions and (3) balance these with the needs of stakeholders within the 'reality' of a working farm and industry co-designing interventions with a 'regional reference group' (RRG) of industry experts and practitioners to ensure relevance, credibility and legitimacy of our proposed adaptation/mitigation interventions[10]. We calibrated our models and social research using two real farms in southern Australia, refining analytical methods based on feedback from the RRG. We then explored the impact of singular and stacked (bundled) interventions on productivity, profitability, GHG emissions and adoptability[19]. Stacked interventions were categorised into groups based on similarity of intent, including 'Low Hanging Fruit' (simple, reversible, immediate changes that could be made to the farm system), 'Towards Carbon Neutral' (interventions primarily designed to reduce GHG emissions), 'Income Diversification' (enabling revenue generation from enterprises other than livestock to reduce dependence on rainfall as a primary source of income) and 'Transformational Adaptations' (long-term, innovative, restructuring, cross-sectoral, potential economic, social and environmental high risks). While we exemplify our methods from two case study farms, the approach could be generically adapted to any location, production system or transdisciplinary problem.

## Results

## The nexus between productivity, profitability and net greenhouse gas emissions

In comparing sheep and beef production systems in 2030 and 2050, we revealed that (1) few individual interventions elicited significant impact on the three dimensions of productivity, most likely annual average profitability (herein profit) and GHG emissions and (2) the impacts of the production system and intervention were greater than the impacts of climate change *per se* (Figs 1, 2).

Interventions targeting livestock enteric methane (methane produced by fermentation in the gut) were most promising for reducing GHG emissions, such as the seaweed feed additive *Asparagopsis taxiformis*, which under the assumed conditions of the analysis could reduce on-farm $CO_2$-eq by 46-72% under future climates (Fig. 1a, 1b, Fig. 2a, 2b, Tables A82.1 - A82.4). However, *Asparagopsis* when used as a feed supplement, identified as one of the costliest singular interventions, reduced profits by $23-25/Mg $CO_2$e mitigated (Fig. 1c, 1d, Fig. 2c, 2d). Interventions that were considered most adoptable by the group of expert practitioners (the RRG) often had the lowest mitigation potential (Figs 1, 2).

Climatic diversification - purchasing a farm in a distinctively different climatic zone - and altering lambing/calving times yielded the greatest improvement in productivity (16-18%), while enterprise diversification (capital investment to enable grapevine/wind turbines enterprises), pasture renovation with deep-rooted legumes and improvements in animal genetic feed-conversion efficiency (FCE) were most conducive to improved profit (17-39%). Interventions that achieved the greatest gains in productivity and profit tended to do little influence to reduce GHG emissions, underlining the challenges inherent in decoupling the tight linkage between productivity and GHG emissions.

Improving FCE - considered akin to good farm management practice by increasing pasture utilisation and liveweight gain per unit utilisation in a sustainable way – would increase profit ($70-250/Mg $CO_2$e mitigation; Fig. 1c, 1d, Fig. 2c, 2d, Tables A82.1 - A82.4), with only modest impacts on productivity (0-6% increase), and on GHG emissions mitigation (-9-15% reduction). Transformational improvement in animal genetic feed conversion efficiencies (TFCE) promises increases in livestock production and farm profits by 8-39% and reducing net GHG emissions by 11-17%, though is aspirational according to the expert group of practitioners because the as yet further livestock genetic science is needed to improve FCE before such genotypes could be widely available (Fig. 3a, 3d, Fig. 4a, 4d).

The modelled climate change scenarios had significant implications for the extent of carbon removal on the case study farms. By 2050, GHG mitigation potential associated with improving soil carbon stocks was reduced by 6-13% for interventions that expanded farm area covered by deep-rooted perennial legumes (in this case lucerne or *Medicago sativa*), and by 20-40% for carbon sequestered by planting native vegetation (Figs 1, 2, Tables A82.1 - A82.4). Planting trees decreased profit per unit $CO_2$ mitigated compared with incorporating lucerne into pastures (Fig. 1c, 1d and Fig. 2c, 2d). This was because lucerne enabled pasture growth and livestock production, whereas trees reduced productive pasture area and livestock carrying capacity.

Biochar was considered to be highly adoptable by the RRG and was proposed as a livestock feed supplement based on anecdotal evidence suggesting that use of biochar (1) improved liveweight gain, (2) reduced enteric methane and (3) enriched organic carbon content of manure. In line with the people-centric nature of this research, we conducted on-farm experiments with free-choice biochar, fed *ad libitum* over 12 months. Little impact of biochar was observed on either liveweight gains or manure organic carbon content (Fig. A82.1). Embedding these nascent results into the modelling frameworks showed that biochar feed supplement would reduce net GHG emissions by 8% and increase profit by 18%, saving \$290 Mg $CO_2e^{-1}$ per year (Fig. 1). However, effects of feeding biochar differed across production systems (cf. Fig. 1 c, d with Fig. 2c, d), with *de minimus* effects of biochar feed supplement on sheep liveweight gains and wool production along with elevated costs of implementation reducing profits by 10% despite an 18% reduction in GHG emissions for both climate horizons (Fig. 2).

To buffer against the possibility of reduced rainfall under future climates, income diversification avenues that were independent of rainfall in the one location were co-designed. These interventions included planting a small, irrigated area of grapevines on the sheep farm, hosting wind turbines on the beef farm, and climatic diversification by purchasing a block of land for cattle farming in a distinctively different climatic zone. While wind turbines, developing irrigated grapevines and purchasing another beef cattle farm improved farm profits by 12-18%, 20% and 15% respectively (Figs 1 and 2), effects on productivity and profit varied widely. Buying an extra beef farm in a diverse agro-climatic region improved production by 15% (Fig. 1), but this came with a cost of increased associated GHG emissions (net and emissions intensity, Tables A82.1 - A82.2).

The RRG provided insights into income diversification interventions. For example, purchasing a farm in a diversified climatic zone (north-eastern Tasmania, compared with the beef farm that was located some 400 km away in the north-west of the state) would require additional labour, costs of transporting cattle between regions, sometimes added infrastructure on the new farm, and higher management skills coordinating separate farm enterprises. Still, many farmers do precisely this, profitably. Growing irrigated grapevines requires specialist input, and on-ground evidence such as existing successful grape-growing, to identify suitable microclimates. The option of hosting wind turbines on the property requires proximity to three-phase powerlines (to feed into the main electricity grid) as well as high prevailing windspeeds. These conditions are not usually common or widespread. Despite this however, the sheep case study farmer was pursuing investment in irrigated grapevines, while the beef farmer had signed a lease for a company to lease part of his land for wind turbines.

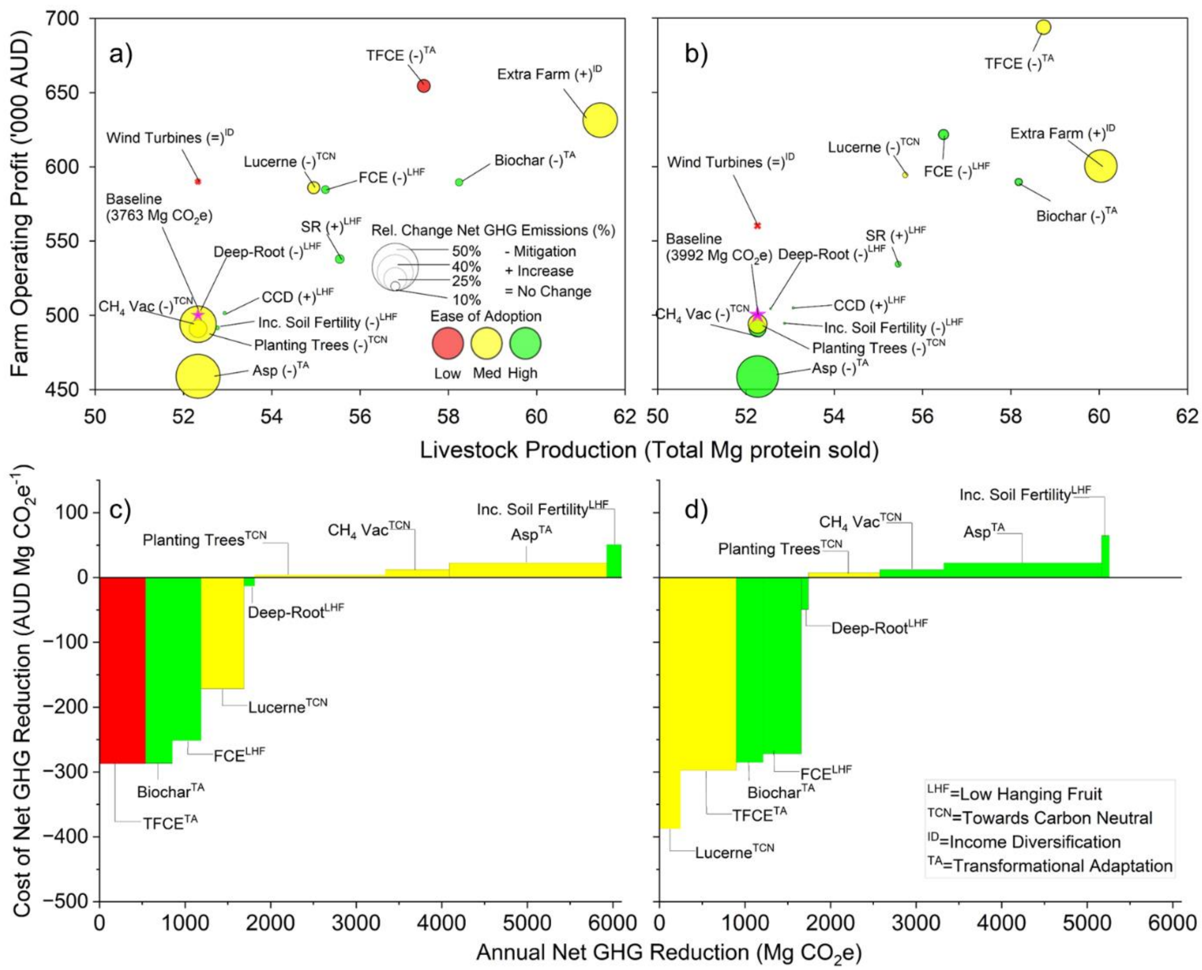


**Fig. 1.** Production, operating profit, adoptability, mitigation potential (a and b) and marginal abatement cost curves (c and d) of multiple thematic adaptation/mitigation intervention/s for a beef farming system. Interventions were co-designed with a Regional Reference Group of expert practitioners for 2030 (a and c) and 2050 (b and d) climates. Purple star depicts the baseline scenario. Total emissions for the baseline scenario shown in parenthesis in (a) and (b). Asp: *Asparagopsis taxiformis* as a feed supplement; CH4 vac: injecting animals with an enteric CH4 inhibitor vaccine; CCD: changing calving date; Deep-Root: increasing pasture sward root depth with perennial legume renovation; FCE: increasing livestock feed conversion efficiency; SR: increasing stocking rate; TFCE: transformational increases in livestock feed conversion efficiency.

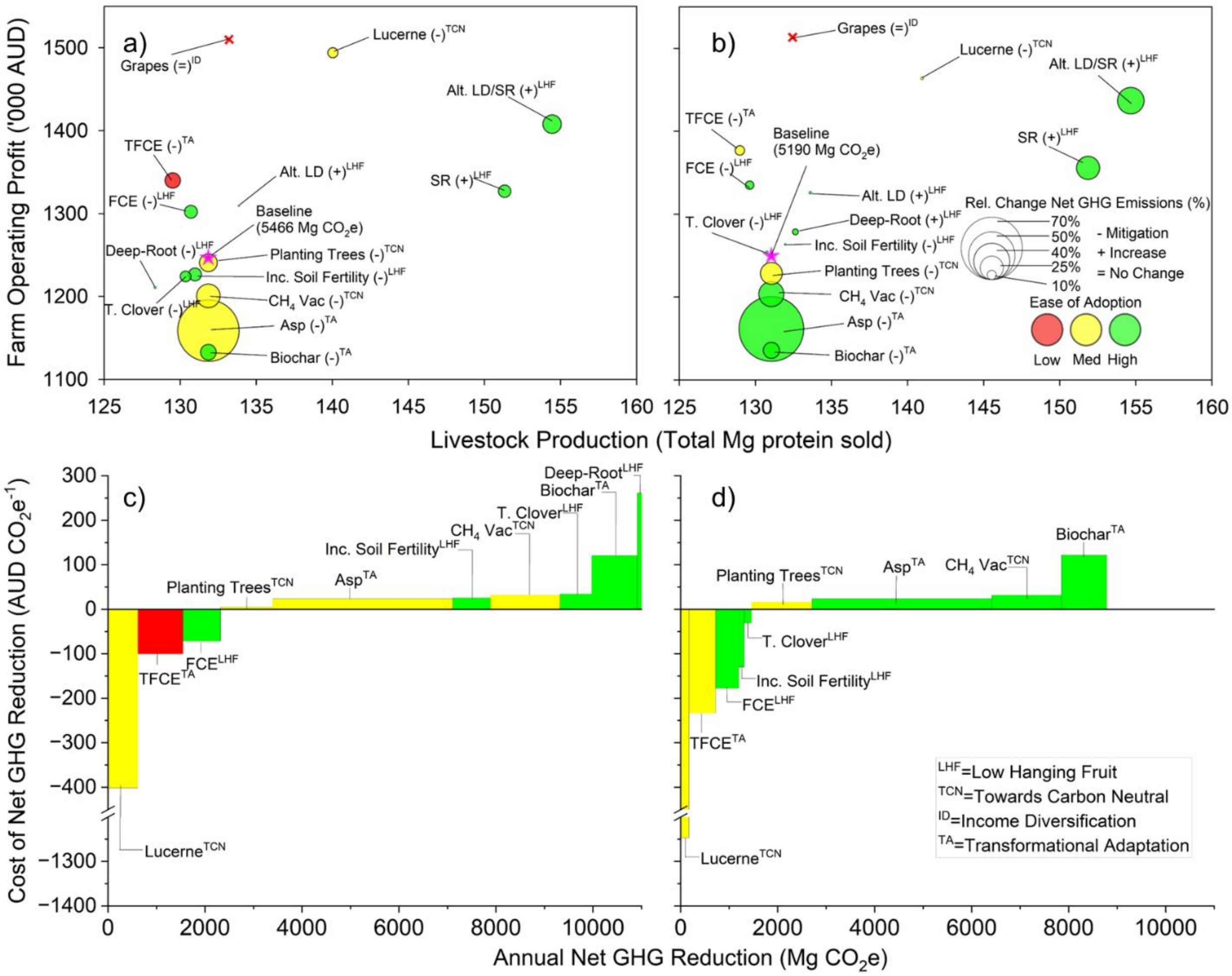


**Fig. 2.** Production, operating profit, adoptability, mitigation potential (a and b) and marginal abatement cost curves (c and d) of multiple thematic adaptation/mitigation intervention/s for a sheep farming system. Interventions were co-designed with a Regional Reference Group of expert practitioners for 2030 (a and c) and 2050 (b and d) climates. Purple star depicts the baseline scenario. Total emissions for the baseline scenario shown in parenthesis in (a) and (b). Asp: *Asparagopsis taxiformis* as a feed supplement; CH4 vac: injecting animals with an enteric CH4 inhibitor vaccine; CCD: changing calving date; Deep-Root: increasing pasture sward root depth with perennial legume renovation; FCE: increasing livestock feed conversion efficiency; SR: increasing stocking rate; TFCE: transformational increases in livestock feed conversion efficiency.

## Contextualised adaptation-mitigation bundles: stacking interventions

We next co-designed and stacked together contextualised bundles of inteventions, each group based on synergies of outcome intended (i.e., interventions were constructed and the outcomes modelled, Figs 3 and 4). Simple, immediately actionable and relatively reversible changes to the farm systems were stacked together into a 'Low Hanging Fruit (LHF)' theme improved annual productivity (15-16%) and increased profit by 19-25% but increased GHG emissions by 6-18% compared with the baseline scenarios under future climates.

A Towards Carbon Neutral (TCN) package was co-designed with the intent of improving productivity and reducing year-on-year GHG emissions. This bundle of interventions combined the LHF package with mitigation interventions (methane inhibition vaccine, planting trees and renovating pastures with deep-rooted legumes). The TCN package respectively increased livestock productivity by 18-20% (beef farm) and by 36-40% (sheep farm) under future climates (Tables A82.5 - A82.8). Despite added costs associated with buying land and planting trees and the costs of a theoretical $CH_4$ vaccine inoculation (Table A82.9), biophysical changes realised from pasture renovation increased profits by 33-37% and 60-68% for the beef and sheep farms, respectively. The TCN package reduced net GHG emissions by 37-69% for the beef farm (Fig. 3) and 29-34% for the sheep farm (Fig. 4), diluting emission intensities by 30-50% (Tables A82.5 - A82.8). While the TCN package was highly ranked in terms of profit, production and GHG emissions evidenced by equally distributed ternary plots (Fig. 3c, 3f, Fig. 4c, 4f), the incorporation of strategies such as the methane inhibition vaccine (which is not commercially available) and its accompanying social concerns, reduced the adoptability of TCN overall.

Multiple combinations of stacked interventions facilitated profitable transitioning of farm systems to net-zero emissions (Figs 3ad; 4ad). The four carbon neutral packages (CN1-4) were co-designed with consideration to various areas of trees planting, adoption (or not) of livestock genotypes with transformational gains in FCE (TFCE) and/or renovation of pastures with the deep-rooted perennial legume, lucerne. For the beef farm, feeding of *Asparagopsis*, planting trees and TFCE were most promising (CN1 and CN2), facilitating not only carbon neutrality but also increasing productivity by 13% with a possible 30% profit gain under 2050 climates (Fig. 3). For the sheep farm, productivity and profitability gains associated with carbon neutral GHG positions were more likely to be realised with stacking of *Asparagopsis* feed, planting trees and renovating pastures with lucerne, such that CN3 and CN4 increased production and profit by 8% relative to the baselines, respectively (Fig. 4).

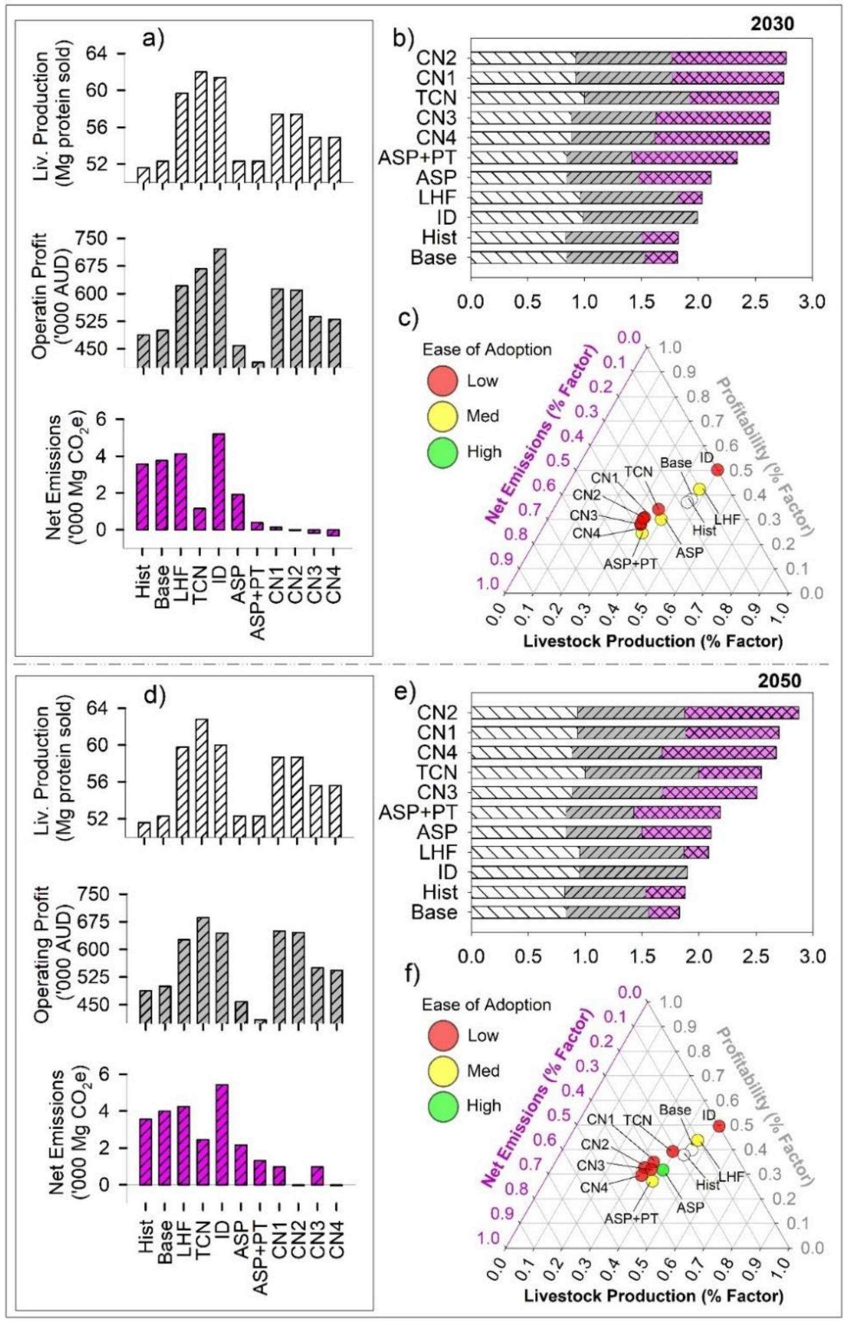


**Fig. 3.** Multidimensional assessment of co-designed thematic adaptations for a beef case study farm under 2030 and 2050 climate horizons. Hist: historical climates; Base: existing farming system under future climates; LHF: low-hanging fruit package; TCN: towards carbon neutral package; ID: income diversification; Asp: *Asparagopsis taxiformis* as a feed supplement; Asp + PT, Asp + planting 50 ha trees; TFCE, adopting livestock genotypes with transformational feed conversion efficiency; CN1: carbon neutral package 1 (Asp + TFCE + planting 50 ha trees), CN2: carbon neutral package 2 (Asp + TFCE + 55 ha trees 2030 and 85 ha trees 2050), CN3: carbon neutral package 3 (Asp + renovating pastures with lucerne + planting 50 ha trees); CN4: carbon neutral package 4 (Asp + renovating pastures with lucerne + 55 ha trees 2030 and 85 ha trees 2050).

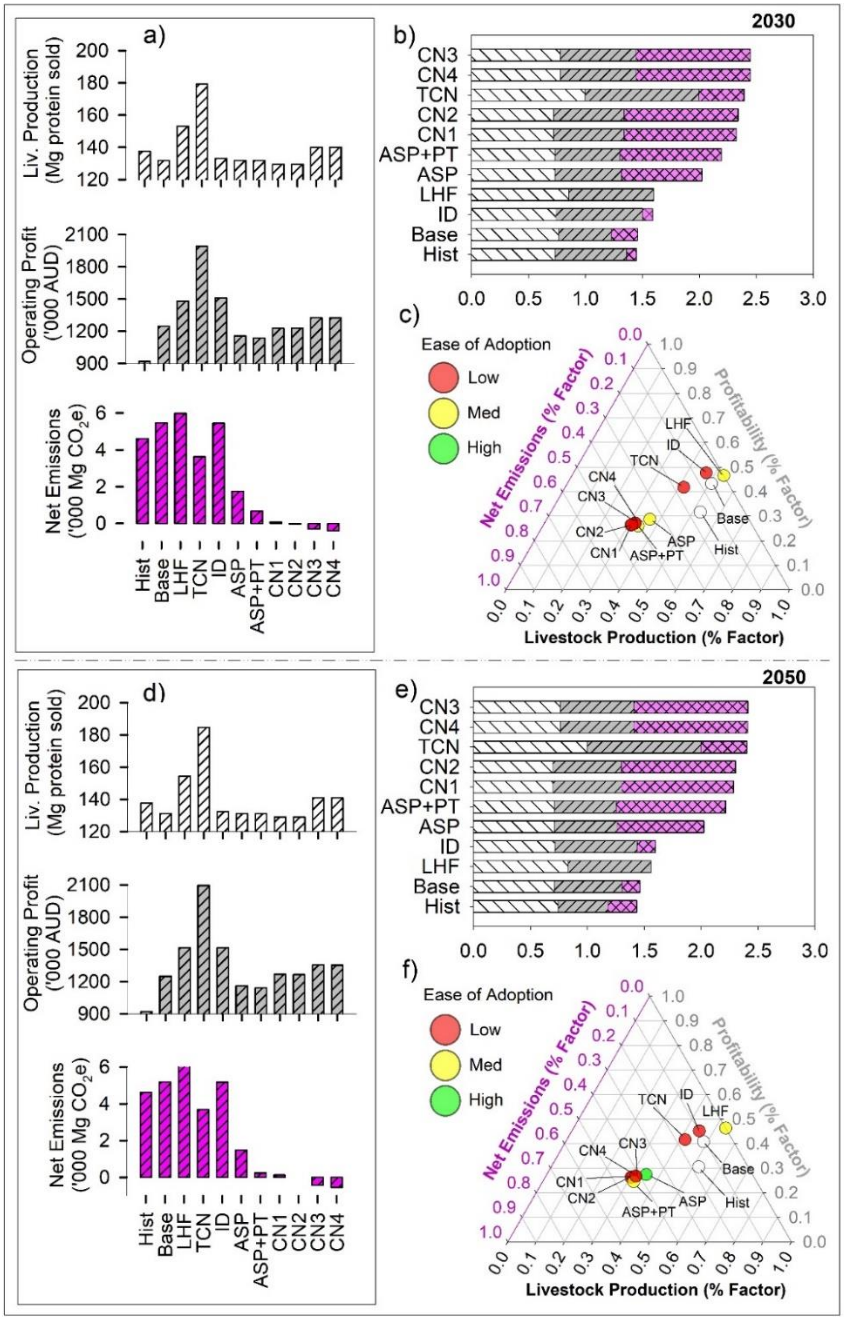


**Fig. 4.** Multidimensional assessment of co-designed thematic adaptations for a sheep case study farm under 2030 and 2050 climate horizons. Hist: historical climates; Base: existing farming system under future climates; LHF: low-hanging fruit package; TCN: towards carbon neutral package; ID: income diversification; Asp: *Asparagopsis taxiformis* as a feed supplement; TFCE, adopting livestock genotypes with transformational feed conversion efficiency; Asp + PT, Asp + planting 200 ha trees; CN1: carbon neutral package 1 (Asp + TFCE + planting 200 ha trees), CN2: carbon neutral package 2 (Asp + TFCE + 220 ha trees), CN3: carbon neutral package 3 (Asp + renovating pastures with lucerne + planting 200 ha trees); CN4: carbon neutral package 4 (Asp+ renovating pastures with lucerne + 220 ha trees).

## Costs of transitioning to net-zero emissions under future climates

The potential effects of a carbon market existing were analysed in which GHG emissions were taxed and offsets credited, respectively. The case study farmers simply paying the tax on the net $CO_2$e from their farm systems, with no practice changes to reduce GHG emissions, reduced farm profits by 64% and 33% for the beef and sheep farms, respectively (Fig. 5). Using *Asparagopsis* as a feed supplement would reduce operating profit by 7-8%. Paying a carbon tax on net residual GHG emissions would improve profit by 58% (beef farm) or 25% (sheep farm) relative to the baseline farm in which all net GHG emissions were taxed (Fig. 5c, d, g, h). When feeding of *Asparagopsis* was stacked with purchasing an extra farm that was planted with trees (ASP+PT), a further 38-87% net GHG emissions were offset (Fig. 5a, b, e, f). Relative to the baseline farm in which all residual GHG emissions were taxed, ASP+PT improved profits by 34%/68% for the sheep/beef farm.

The CN packages intervention stacked TFCE (CN1 and CN2) or lucerne in the pasture mix (CN3 and CN4) with ASP+PT to reduce GHG emissions, while further reducing the burden of taxes on emissions carbon taxes. For the beef farm, there was little difference in net GHG emissions after implementing TFCE (CN1) and lucerne in the pasture sward (CN3), both with residual GHG emissions of 1,000 Mg $CO_2$e (Fig. 5a, b). Profits after paying the carbon tax were greater for the CN1 package (Fig. 5c) compared with the CN3 package (Fig. 5d), and were three times greater than the baseline farm, even after paying a tax on residual GHG emissions. Additional land for tree plantings was required for the beef farm's CN1 and CN3 packages to become net-zero (CN2 and CN4 packages; Fig. 5a, b). For the sheep farm, the lucerne CN3 package achieved net-zero, with net sequestration of 1,400 Mg $CO_2$e (Fig. 5f) and pre-carbon tax profit of $1,366K (Fig. 5h), which slightly declined if surplus carbon offsets were sold (Fig. 5h).

The RRG highlighted potential difficulties in implementing CN packages (Table A82.10), while the results clearly demonstrate that adoption of mitigation practices were at least three times more profitable for the beef farm and 1.5 times more profitable for the sheep farm, relative to the 'do nothing different scenario', where the two farming systems conducted business as usual and all their net GHG emissions were subjected to carbon taxes.

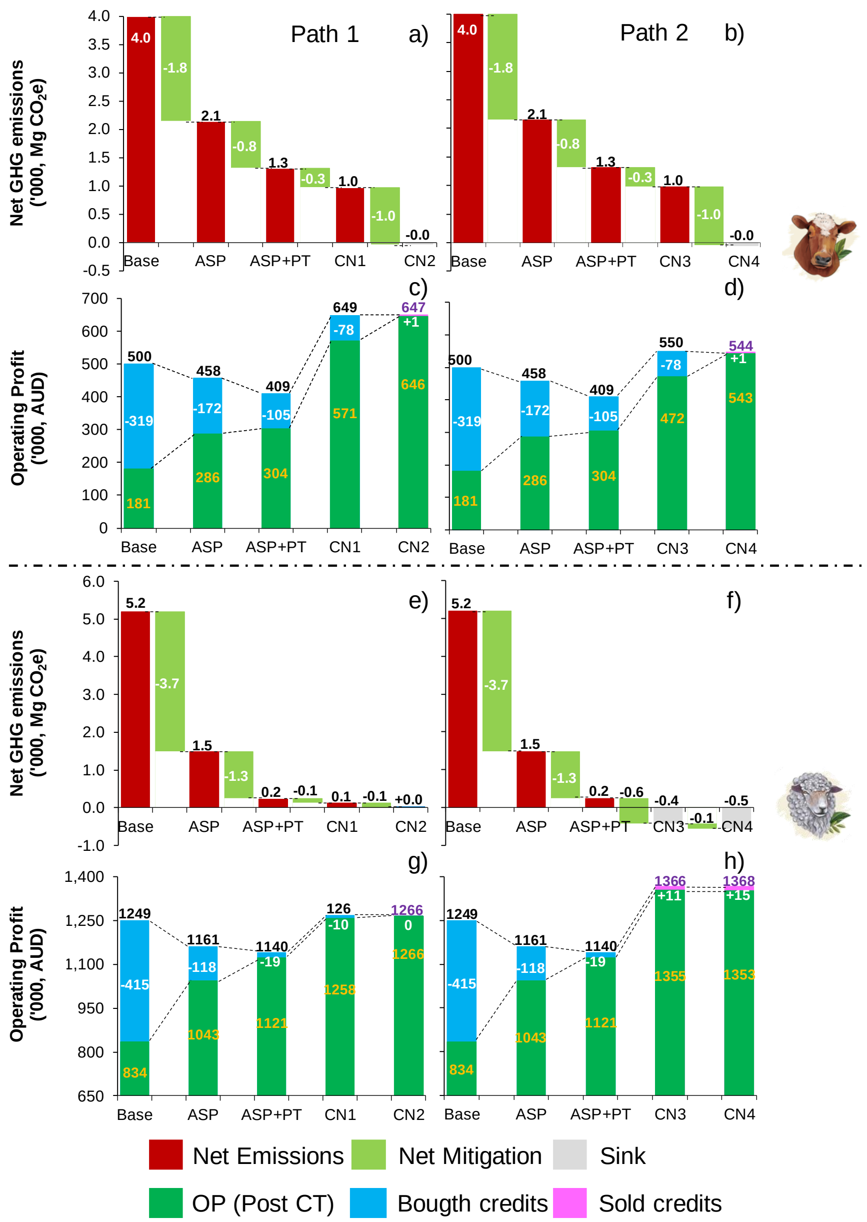


**Fig. 5.** Pathways to carbon neutrality (red and light green bars) with associated costs of pre-carbon taxes (blue) and post-carbon taxation (dark green and pink bars) across climate horizons and thematic adaptations for the beef farm (a, b, c and d) and sheep farm (e, f, g and h). Pathways 1 and 2 reflect net-zero farming systems attained by improving animal genetics (CN1 and CN2) or renovating pasture swards with lucerne (CN3 and CN4); Base: 2050 climates; ASP: *Asparagopsis taxiformis* as livestock feed supplement; Asp+PT: *Asparagopsis taxiformis* + planting trees (50 ha); CN1: carbon neutral package 1 [*Asparagopsis taxiformis* + planting trees 50 ha (beef farm) or 200 ha (sheep farm) + transformational feed conversion efficiency]; CN2: carbon neutral package 2 [*Asparagopsis taxiformis* + planting trees 85 ha (beef farm) or 220 ha (sheep farm) + transformational feed conversion efficiency]; CN3: carbon neutral package 3 [*Asparagopsis taxiformis* + planting trees 50 ha (beef farm) or 200 ha (sheep farm) + Lucerne]; CN4: carbon neutral package 4 [*Asparagopsis taxiformis* + planting trees 85 ha (beef farm) or 220 ha (sheep farm) + Lucerne]; OP: operating profit.

## Discussion

### A new framework for co-designing bundles of mitigation-adaptation interventions

This reseach was conducted using co-design framework that embodied the best available science for effective climate action, along with the critically important engagement of farmers and other interested parties. The aim was to analyse potential implications for farm systems that could flow from the key outcomes of the COP27[20] being achieved. The people-centric framework meant engaging end-users who would be directly or indirectly affected by the climate crisis and policies responding to it, to develop fit-for-purpose farm interventions and thematic innovation bundles[8,21]. The flexible design of this framework, using integrated, interchangeable and numerical and social systems thinking is adaptable to explore sustainability indicators associated with multuple analogous production systems, locations or climatic horizons. This co-design framework and research builds end-user awareness, knowledge and confidence to increase chances of adoption, which also engenders social license for landholders to operate stemming from public recognition of producers agri-environmental stewardship[22].

### The cost of transitioning farm systems to net-zero emissions

The findings from the modelled analyses of case study farms suggest that if the future climates eventuated, and the social cost of GHG emissions was to be brought home to the farmer emitters of GHG emissions, profitable individual and combined options exist for the farmers to change their systems and reduce their emissions whilst maintaining and even increasing their profits in the future compared with the current profit of their farm businesses. Eventually, the most socially unacceptable option – continuing business as usual and purchasing carbon credits to offset net farm emissions – was also the most costly option. Furthermore, relying on carbon credits to offset a GHG emissions may be perceived as transferring responsibility to someone else. From an ethical standpoint, producers must take ownership of their carbon emissions and strive to reduce them within their own operations.

For the case study farms analysed, stacking together interventions enable improved pasture growth and some added soil carbon sequestration (e.g. renovation with lucerne, and ignoring additionality), and adopting future animal genotypes that are able to gain more weight on the same amount of feed (FCE, TFCE), along with planting small areas of trees relative to farm size (50-220 ha in this case and subject to permanence considerations), in combination, went some considerable way towards negating all farm emissions. When interventions to reduce GHG emissions delivered a productivity co-benefit – such as improved metabolisible energy supply per unit area with legumes, or shade and shelter provided by trees – on the case study farms there both carbon neutrality as well as 8% gains in productivity and profit were possible under future climates. As ever, these positive findings are tempered by the limits of the analyses, practical barriers to adoption, development and acquisition of new knowledge required to develop some of the technologies needed and to implement changes in farm practices, and, ultimately by consumer needs and expectations and the public policies that will be implemented. These extraneous factors may influence adoptability, as shown by feedback from the RRG on some of the mitigation/adaptation bundles here (e.g. purchasing and extra farm or leasing part of the land to wind turbine companies to generate electricity).

The need of the case study farms to buy carbon credits to offset their farm GHG was reduced as additional interventions were combined, especially when such interventions catalysed improved animal performance (CN packages, Fig. 5). The results reiterated the enduring imperative faced by livestock producers to adapt profitably to the changing climatic, technical and economic circumstances in which they farm so as to avoid, reduce and remove GHG emissions (e.g., through interventions such as enteric $CH_4$ vaccines, feed additives such as *Asparagopsis*, breeding low $CH_4$ emitting animals, nitrification inhibitors, balancing dietary energy to protein[8]), as well as, if possible and profitable, offset farm emissions through revegetation and with increasing SOC. Depending on cost, purchasing additional land with the explicit objective of planting trees to offset livestock emissions and feeding a $CH_4$ inhibitor such as *Asparagopsis* in combination with TFCE (CN1 and CN2) or lucerne (CN3 and CN4) in the pasture mix showed a promising avenue for improving profit while also achieving carbon neutrality. As the need for non-agricultural industries to also offset their GHG emissions increases, the price of arable land is likely to increase in line with public pressure to maintain or improve institututional and organisational carbon removals[23]. As a corollary, carbon insetting (practices to reduce GHG within the value chain) may become higher priority, feasible and profitable for some land managers selling carbon credits, rather than seeking new arable land elsewhere. The CN packages examined with and without emission trading schemes were more profitable than the baselines business-as usual scenarios where existing and emerging technologies could deliver the necessary abatement to reach net zero by 2050, opening the door to new markets spurred by increasing consumer preferences for low carbon products[24].

Flexibity in systems and management is key to responding to change in timely and effectively ways, while adopting. Tactical and strategic whole farm management plans therefore need to dynamically include new available technologies, practices, and market and climatic trends[25]. To be effective in Nationally-Determined Contributions, forests require a minimum level of 'permanence' (e.g. 25-100 years, depending on carbon market) [26], potentially consuming arable zones that go a long way towards fulfilling the growing global need for protein, fibre and starch.

An *en masse* land-use conversion from commodity-based production to that designed for ecosystems services may have perverse outcomes, such as diminished food security or increase poverty; phenomena exacerbated by a burgeoning global population. Countries or regions that prioritise carbon and/or environmental outcomes may invoke carbon leakage[27], wherein commodity-based production shifts to other regions or nations, potentially causing land clearing (e.g., substantial release of GHG emissions in developing nations in South America), and thus the atmosphere perceived more GHG emissions that would have occurred had the original land not been locked up for carbon or biodiversity purposes.

**Simple changes to systems raise productivity and profitability but further practices are required to reduce emissions to net-zero**

An important insight from this study, and the case study farms analysed, was that CN packages may simultaneously increase farm profitability while offsetting GHG emissions. Under the assumed level of performance, feeding livestock with the modelled use of *Asparagopsis* was a promising adaptation, decreasing enteric $CH_4$ emissions by 80% (46-72% reduction in total net GHG emissions on farm). However, there is much uncertainty about how *Asparagopsis* will perform. The rates of enteric $CH_4$ mitigation assumed in this analysis were relatively high, though lower than some published results[28], the $CH_4$ mitigation quantum remains to be observed in practice. Some projections for 2040 suggest a $1.5 billion seaweed industry in Australia, creating 9,000 jobs and up to 10% national GHG emissions reduction per year, making a substantial contribution to the UN Sustainable Development Goals[29]. Apart from farm level challenges of feeding *Asparagopsis* and a potential solution for reducing $CH_4$ emissions important questions remain about its impact on health and the environment. For example, are the species of seaweed used for $CH_4$ mitigation invasive, and what implications could this have for local ecosystems? When fed to animals, could bromoform, a potent $CH_4$ inhibitor derived from seaweed, have negative effects on consumer health? And what are the potential environmental consequences of scaling up the manufacture of synthetic bromoform, given its impact on ozone depletion? These

questions highlight the need for further research and careful consideration of the benefits and risks associated with using seaweed as a means of reducing greenhouse gas emissions[28,30].
Stacking the transformational FCE (TFCE) into CN packages (CN1, CN2) increased animal performance in the beef farm and decreased costs of production (i.e. 50-88% reduction in supplementary feeding), improving profits (Figs 3, 4). However, reduced wool production associated with TFCE eroded overall livestock production for the sheep farm, similar to results seen by others[31]. On the other hand, lower pasture intakes may reduce enteric $CH_4$ emissions and increase residual biomass and litter fall, potentially improving SOC stocks. Despite these prospective emergent economic and environmental complementarities, benefits elicited from genetic improvement have historically only been observed after 10-20 years of sustained investment[32,33].

The expert group of practitioners involved in the research were keen on including legumes (e.g., lucerne and Talish clover) into existing grass pastures (CN3 and CN4 packages). Sturludóttir, *et al*. [34] further demonstrated the well-established reality that mixing grasses with legumes improved herbage yield, dry matter digestibility and crude protein in pastures from Northern Europe and Canada, while reducing the invasion of weeds compared to monocultures. The nitrogen yield advantage from grass-legume mixtures supported by symbiotic $N_2$ fixation[35], given the close linkage between C and N cycling in grazing systems[36], are in effect also mechanisms increasing SOC stocks[37-39]. However, excessive proportions of legumes within swards come with animal welfare concerns, with excessive soluble protein and nitrate contents linked to ruminant bloat and even animal deaths, particularly for cattle but less so for sheep[40].

## Concluding remarks

The unique insights arising from this research include:

1. Singular interventions elicit little improvements in productivity and profitability or GHG emissions;
2. Under future climate conditions, feeding *Asparagopsis* and planting trees had the greatest emissions benefits, but also came with the greatest costs;
3. Spatial and climatic diversification (purchasing an extra farm block in a different climatic zone) as well as hypothetical transformational improvements in animal feed-conversion efficiency (TFCE) promise to deliver the greatest benefits for productivity and profitability;

4. Stacking of interventions explicitly aimed at (1) reducing enteric methane, (2) carbon removals and (3) improving productivity were often the most profitable and productive, while also having the least GHG emissions;
5. Continuing business as usual and purchasing carbon credits to negate all farm GHG emissions was a more costly option than using suites of interventions;
6. Appropriately contextualised bundles of interventions to local conditions like planting trees, renovating pastures with deep rooted legumes and adopting high FCE animal genotypes not only have the potential to reduce farm business GHG emissions to net zero, but also improved profitability and productivity gains;
7. Genuinely *transformational* solutions will be combinations and permutations of changes in individual farm systems that reduce GHG emissions, maintain and improve future productivity and profit, strengthen social license to operate through public recognition of producers' agri-environmental stewardship.

## Experimental procedures

### Resource availability

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Matthew Tom Harrison (matthew.harrison@utas.edu.au).

**Materials availability**

This study did not generate new unique materials.

**Data and code availability**

All the source data used in this paper are derived from the cited references or databases. The data supporting the findings for this study are provided in the supplementary information (supplementary tables and figures). The methods applied are fully described in the manuscript or expanded in supplementary information. The majority of aggregate data is available in the supplementary information; raw data will be made available by the lead contact upon request.

### Study overview

Farming systems were co-designed using integrated, cross-disciplinary framework[10]. A Regional Reference Group (RRG) of experts and industry practitioners was involved in the co-design of biophysical, environmental, and economic interventions (Fig. 6). Co-designed interventions (singularly and in combination) were further examined using a social science lens, including assessment of adoption barriers, social license to operate, and new skills needed to adopt them. This co-design framework was used to quantify and stack individual whole farm adaptations on top of the baseline farm system, each intervention iteratively refined by discussing results with the RRG over several cycles[10].

To showcase this approach, farm systems across two regions of Tasmania, Australia, were selected to be modelled: a sheep production system (hereafter 'sheep farm') in the low rainfall zone in central Tasmania and a beef production system (hereafter 'beef farm') in the relatively high rainfall zone of northwestern Tasmania. Individual interventions aimed at income diversification and/or transformational were suggested by the RRG. Transformational adaptations were considered to be longer-term, higher risk interventions with some degree of irreversibility. These adaptations were stacked together in a mutually synergistic way based on commonality of intended outcomes. Incremental adaptations were defined as those that do not significantly alter the *status quo*. Income diversification interventions were designed such that new income streams would be derived that were independent of rainfall in the location of the current farm system, as rainfall was perceived to be a climatic index that would change under future climates, and these livestock systems relied primarily on pasture produced from rainfall. Income diversification was thus classified as those interventions affording either climatic diversification or enterprise diversification. A multitude of approaches and software packages were used to simulate farm systems (Fig. 6). Future climate projections[22] accounted for increased frequency and severity of extreme weather events. The whole-farm model GrassGro® (version 3.3.10[41]) was used to simulate daily pasture and livestock production and was driven by historical and future climate horizons. Soil organic carbon sequestration were simulated using RothC model (version 26.3 in Microsoft Excel format[42]) with GrassGro outputs, while FullCAM (version 4.1.6[43]) was invoked to estimate tree carbon sequestration. Net farm GHG emissions were calculated using Sheep Beef-Greenhouse Accounting Framework (SB-GAF version 1.4[44]) using outputs from GrassGro®, RothC and FullCAM. The @Risk model[45] was used to account for market volatility using a partial budgeting approach (i.e. Earnings Before Interest and Taxes and herein referred to as operating profit or most likely annual profitability) to compare the costs and income benefits of incremental, income diversification and transformational adaptions faced by a farm business.

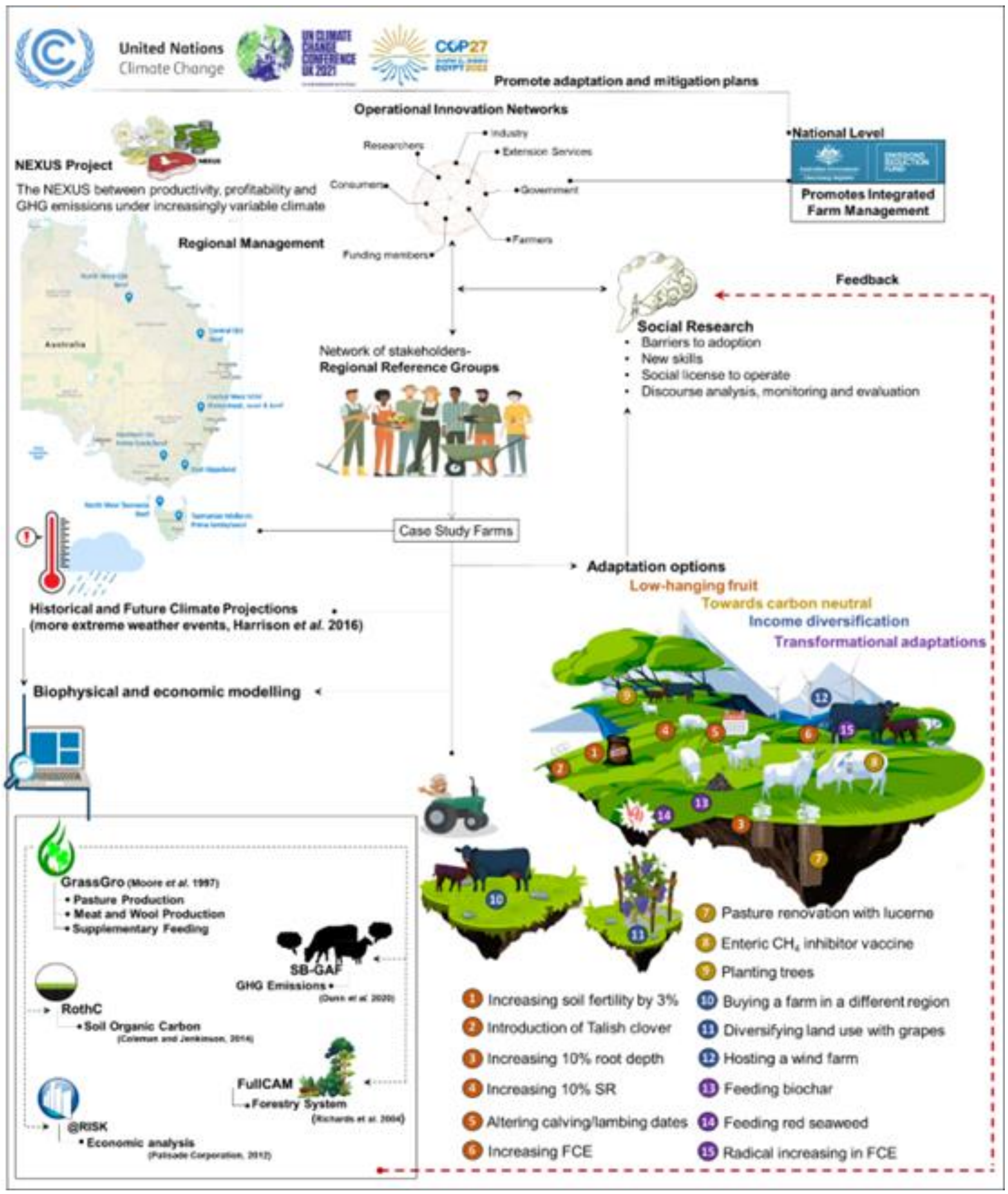

**Fig. 6.** Co-design climate change adaptation-mitigation framework for quantifying and examining relationship between productivity, profitability, GHG emissions, social acceptability and adoptability under historical and future climates. Orange, light brown, blue and purple circles represent Low-Hanging Fruit (LHF), Towards Carbon Neutral (TCN), Income Diversification (ID) and Transformational adaptation-mitigation themes, respectively.

## Historical and future climates

The beef farm was located at Stanley in the cool temperate zone of north-western Tasmania (40° 43' 41''S 145° 15' 43''E), while the sheep farm was located in the Midlands, west of Campbell Town (41°56'30"S 147°25'02"E). Stanley and Campbell Town have long-term mean and standard deviation annual rainfall of 807 ± 139 mm and 499 ± 103 mm, respectively, with 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. A82.2). Daily historical climate data for the baseline period of 1 January 1980 to 31 December 2018 was sourced from SILO meteorological archives (http://www.longpaddock.qld.au/silo). Data from SILO was used to generate future climate data following Harrison *et al.* [22] using a stochastic approach to account for changes in climatic extremes, including heatwaves, droughts and extreme rainfall events[22]. Future climate projections were downscaled from global circulation models (GCMs) to regional and farm-scale[46]. To generate future climate data, (1) we estimated mean changes in future climates projected for a region based on ensembles of global climate models (GCMs), (2) accounted for historical climate characteristics (obviated by raw GCM data) and (3) generated climatic projections with increased variability. Future climate projections for 2030 and 2050 were developed using monthly regional climate scaling factors (Table A82.14) from GCMs provided by Harris *et al.* [46] based on Representative Concentration Pathway (RCP) 8.5. Atmospheric $CO_2$ concentrations were set at 350 ppm, 450 ppm and 530 ppm for the historical, 2030 and 2050 climate scenarios, respectively[47].

## People-Centred Design: the Regional Reference Group (RRG)

During an iterative process with a RRG, we sense-checked model assumptions and results. Model outputs discussed with the RRG included pasture growth rates, stocking rates, livestock production, wool production, supplementary feeding, costs, income, depreciation, net cash flows, and wealth. When RRG consensus was reached for results for each historical period (1986 to 2005), several biophysical and economic models were run for 26-year periods (first six years of data discarded to allow for model initialisation) centered on 2030 (2022 to 2041) and 2050 (2042 to 2061). Over several workshops, we gleaned RRG thinking and feedback on incremental, systems and transformational adaptation and mitigation opportunities in light of qualified holistic impacts of climate change. Assuming the recommendations from the RRG, we explored individual adaptations to understand their potential effects on productivity, profitability and offsetting of GHG emissions and acceptability within the industry. Sequentially, several adaptations were combined into four distinct themes; '*Low Hanging Fruit*', '*Towards Carbon Neutral*', '*Income Diversification*' and '*Carbon Neutral*'; outcomes from these themes were compared with the baseline scenario (detailed Fig. 5 and Table 1). Based on RRG advice, we refined model parameters to reflect feasibility and magnitude of variables simulated for each theme of adaptation. This process (1) ensured that model results were realistic, (2) provided the research team with nascent knowledge relating to opportunities for adaptation and mitigation of climate change from expert practitioners, (3) engender end-user confidence in the analytical process and results and (4), provided end-users with credible, legitimate and fit-for-purpose adaptation/mitigation modelled interventions. Detailed information about the baselines and adaptation process is below and in the supplementary information (Tables A82.15 – A82.18, Fig. A82.3).

## Pasture and livestock production

The model GrassGro® enables simulation of ruminant grazing enterprises of southern Australia by combining biophysical (climate, soils, pastures and livestock), farm management (soil fertility, paddock size and layout, pasture grazing rotations, stocking rate and animal management) and economic data (gross margin). GrassGro® has been used to explore the effects of climate, soil, pasture, herd/flock management and adaptation for predicted climate change impacts on livestock productivity and profitability[48] in pasture-based industries across Australia[17,49], North America and Northern China[50,51]. GrassGro® computes soil moisture, pasture production, pasture quality [Crude Protein (%CP) and Dry Matter Digestibility (%DMD)] on a daily basis for each pasture species, paddock and farm. Other variables calculated by the model include sward characteristics, pasture cover, pasture persistence, pasture availability, pasture intake, feed supplement requirements, liveweight change, and feed carry-over effects from year to year. We initialised and parameterized GrassGro® using baseline information collated from each case study farmer.

## High rainfall beef production system

The beef farm ran a self-replacing cow and calf operations on a land area of 569 ha. This enterprise comprised 367 mature cows calving in late winter (1 Aug with 95% weaning rate, first calving at two years of age) assuming a typical replacement rate of around 20% each year (74 heifers). Home-bred non-replacement heifers and steers were sold at 25 months (1 Sep) at approx. 550 and 600 kg, respectively. An additional 115 of weaners were purchased at 6 months of age (1 Feb) at approx. 200 kg liveweight (LW) and were sold at 25 months (1 Sep) at approx. 600 kg LW. A group of 155 steers was also purchased at 16 months of age (1 Feb) at approx. 375 kg LW each year and sold at 28 months (31 Jan) at approx. 545 kg LW. Before being cast for age on 10 Feb, mature cows were retained for five lactations. Pasture species mainly comprised perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) but also cocksfoot (*Dactylis glomerata* L.), subclover (*Trifolium subterraneum* L.) and lucerne (*Medicago sativa*). According to the Northcote classification[52], the soil type defined in GrassGro was Uc2.3. In addition, 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 (20mm/event on a 14-day interval) to replicate long-term average irrigation water applied. To either maintain LW (cows) or achieve target LWs (all other stock), production feeding rules were implemented in GrassGro using hay (dry matter digestibility (DMD) of 77% and crude protein (CP) of 20%)). While all stock grazed rainfed pastures, home-bred steers were also given access to irrigated pastures throughout the year. Further information can be found in the Supplementary Material (Table A82.15).

## Low-rainfall sheep production system

The sheep farm ran a self-replacing Merino superfine wool, prime lamb and, secondary, a beef cattle enterprise grazing 3,170 ha and consisted of 49% native grasslands, 48% rainfed developed pastures and 3% centre pivot irrigation (introduced grasses and legumes). A total of 4,600 ha of native woodlands were also present on the farm that were not subjected to grazing. According to the Northcote classification[52], the soil type defined in GrassGro was Dy5.61. The modelled rainfed pastures were composed of pure stands of phalaris (*Phalaris aquatica* L.) or phalaris-subclover mixtures. One paddock of lucerne was used for grazing and hay production and another paddock of dual-purpose wheat (*Triticum aestivum* L.) was grazed for four months prior to grain production. Both of these 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 when soil water deficit reached 50%.

The sheep farm ran 24,750 animals, grouped in two flocks: a self-replacing Merino flock (SMF) and a prime lamb flock (PLF). The SMF comprised three groups: 5,300 mature superfine Merino ewes, 7,500 wethers and 5,500 replacement ewes and wethers. The SMF ewes were first lambed at 2 years of age and retained for three lambings before entering the PLF for two more annual births before being cast at 7 years old (16 Dec). Before wethers were cast for age (14 Oct), the animals were retained for five years. The non-replacement wether lambs and ewes were sold 1 Feb. A total of 3,450 Merino ewes were mated with White Suffolk rams in the PLF; the 2,950-lamb progeny were sold in mid-December at 27 kg LW. The sheep (except prime lambs) were all shorn on 20 Jul, clean fleece weight (CFW) were 3.3-4.1 kg with fibre diameters of 17.4-18.1µm (variation in CFW and micron depended on stock class and age). Further details are provided on maintenance and production feeding rules, as well as grazing rotations in Supplementary Material (Table A82.14). The beef cattle herd consisted of 340 mature cows and 60 replacement heifers per age group. Two-year-old mature cows calved (30 Aug) and were retained for eight years before being cast for age. After weaning date (1 Apr), steers (150 head) were sold at 18 months of age (28 Feb at ~ 460 kg LW) while non-replacement heifers (90 head) were sold at 200 kg LW.

## Net farm greenhouse gas emissions

The Sheep-Beef Greenhouse Accounting Framework (SB-GAF version 1.4[44]), which incorporates Intergovernmental Panel on Climate Change methodology and is detailed in the Australian National Greenhouse Gas Inventory, was used to calculate net farm greenhouse gas emissions. Use of outputs from biophysical models[22,48] as SB-GAF inputs has been previously shown to be reliable for beef[53] and sheep enterprises[54]. Twenty-year seasonal mean data from GrassGro was used as input data for SB-GAF. To convert $CH_4$ and $N_2O$ into carbon dioxide equivalents ($CO_2e$), SB-GAF assumes 100-year global warming potentials ($GWP_{100}$) of 28 and 265, respectively. Greenhouse gas outputs were calculated as net farm emissions (Mg $CO_2e$/annum) and emissions intensity (Mg $CO_2e$/Mg product). Greenhouse gas emissions considered included $CH_4$ from livestock enteric fermentation and manure; $N_2O$ from nitrogenous (N) fertiliser, waste management, urinary deposition and indirect N emissions via nitrate leaching and ammonia volatilisation; $CO_2$ 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. According to Wiedemann *et al*.[55], the allocation of emissions between meat and wool was based on protein mass ratio.

## Soil organic carbon in grazed pastures

The Rothamsted Carbon model (RothC; version 26.3 in Microsoft Excel format[42]) was used to simulate dynamic soil organic carbon (SOC). RothC has been used globally to model the impacts of climate and management on SOC stocks[56]. RothC simulations are driven by historical and projected monthly means of temperature, rainfall and pan evaporation (see *Historical and future climate data*). Monthly average GrassGro outputs were input into RothC including dung and litter. Root residue C inputs were derived from GrassGro outputs considering litter, 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) and dung excreted by animals. Further details about the link between GrassGro and RothC can be found in *Supplementary Material* (*see subsection 'Linking GrassGro and RothC model to account for soil carbon changes in long-term pastures'*). Soil types primarily consisted of clay loam Red Ferrosols on the beef farm[57], and Dermosols on the slopes adjacent to native vegetation and Vertosols on the river flats on the sheep farm[58]. Soil clay contents in the 0-30 cm and 30-100 cm layers were derived from the TERN-ANU Landscape Data Visualiser (https://maps.tern.org.au/#/) and historical SOC was sourced from regional sources[57]. RothC simulates 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) [42]. RPM, HUM and IOM fractions were comparable to historical data for the three soil types across the two farms[57]. Allocations across SOC pools given by Hoyle *et al*. [59] for initial fractions of DPM, BIOF and BIOS were adopted here (1%, 2% and 0.2% of initial SOC stocks, respectively) and IOM fraction was similar to that reported by Falloon *et al*. [60]. Soil carbon decomposition rates at 30 cm were derived following Jenkinson and Coleman[61], except for the decomposition rate for RPM, which was set to 0.17 following Richards and Evans[43], similar to the 0.15 reported by Cotching[57], 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[61]; 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. To account for the C enrichment of manure by feeding biochar, a sub-model was incorporated to RothC (*see more detail in supplementary materials subsection 'Accounting for carbon changes in soil by enrichment of manure with biochar', Fig. A82.14*).

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

We invoked the FullCAM model (version 4.1.6[43]) 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 (*Eucalyptus globulus* L.) 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. The parameters assumed to simulate SOC changes for grapes were further explained in *Supplementary Material* (*see subsection 'Diversifying land use with grapes on a sheep farm'*).

## Economic analyses

In concert with GrassGro outputs, we used the @Risk Software[45] 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[62]. 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 A82.9, A82.11 – A82.13). 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 operating profit (Earnings Before Interest and Taxes), as well as measures of return on capital. To attribute a cost for carbon offsetting, we computed operating profit plus a carbon 'tax', in which each tonne of $CO_2$e was taxed at \$60-\$100/Mg $CO_2$e, following Stiglitz *et al*. [63]. Any carbon sequestration beyond net farm GHG emissions were 'credited' at 35% that of a carbon tax[64].

## 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*. [65], liveweight production, net operating profit (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).

### Incremental, systemic, transformational adaptations and contextualised stacking of thematic interventions

The outcome of the co-design process was distinct adaptation/mitigation themes that were analysed individually, or as combined interventions 'stacked' together (Table A82.17; Table 1). The "Low-Hanging Fruit" (LHF) intervention 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 (Tables 1 and A82.17). 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: "Towards Carbon Neutral" or TCN. Incremental adaptations 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 third thematic adaptation "Income Diversification" (ID) was co-designed with the RRG in which income is derived from sources other than the current livestock farm system through options such as buying another block of land in a different agroclimatic region (climate diversification), leasing land to host a wind turbine farm or diversifying part of the farm area with grapes (climate diversification, reduce the vulnerability to market fluctuations). The fourth thematic adaptation/mitigation bundle, described as "Carbon Neutral" or CN, was created after co-designing pathways designed to reach net zero emissions (Fig. A82.3). A summary of each adaptation theme together with subset incremental adaptations are shown in Table 1 (further details provided in Tables A82.15 – A82.18, Fig. A82.3).

**Table 1. Summarised thematic adaptations co-designed with a Regional Reference Group (RRG).** 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. Abbreviations: LHF: Low-Hanging Fruit. TCN: Towards Carbon Neutral; this theme also included all incremental adaptations for LHF. ID: Income Diversification. CN. Carbon Neutral Package. SR: Stocking Rate. LW: Liveweight per head. FCE: Feed Conversion Efficiency. RD: Rooting Depth. SSP: Single Superphosphate fertiliser. N: Nitrogen fertiliser. Further details are provided in Tables A82.15 – A82.18.

| **Theme** | **Incremental, systemic and transformational adaptations stacked into holistic adaptation themes** |
|---|---|
| LHF | - Altered lambing/calving dates to better match seasonal pasture supply<br>- Altered selling dates/SR/LW to better match seasonal pasture supply<br>- Adopting pasture species with 10% improvements in maximum root depth[66]<br>- Increasing soil fertility with SSP and N by 3% [Harrison *et al.*[67]; all paddocks except the native pastures for the sheep farm]<br>- Increasing FCE by 10% in 2030 and 15% in 2050, relative to baseline[68]<br>- Introduction of Talish clover (*Trifolium tumens)* to a proportion of the sheep farm[69]<br>- 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<br>- Pasture renovation with (and increased farm area of) lucerne pastures<br>- Injecting animals with an enteric $CH_4$ inhibitor vaccine to reduce $CH_4$ by 30%[70] |

| | |
|---|---|
| | - Purchase 50 ha of land for the beef farm to establish a tree plantation of Tasmanian Blue Gums to offset livestock GHG emissions<br>- 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) |
| ID | - Buying an extra farm in a different agroclimatic region (by translocating cow calf systems to Gladstone, NE Tasmania to dedicate the current farm for backgrounding and finishing of weaners)<br>- Diversifying land use with grapes by repurposing 30ha from the sheep farm to grow Pinot Noir and Chardonnay grapes (processed offsite and outside scope of the current project)<br>- Hosting a wind farm (by leasing land for 12 wind turbines to generate an extra income, no insetting of $CO_2$ from turbines to reduce on-farm GHG emissions, in line with the business model of the wind turbine company) |
| CN | - Feeding red seaweed (*Asparagopsis taxiformis*) to offset $CH_4$ by 80%[71]<br>- Pasture renovation with (and increased farm area of) lucerne pastures<br>- Purchase 55 to 85 ha of land for the beef farm to establish a tree plantation of Tasmanian Blue Gums to offset livestock GHG emissions<br>- Thickening of 200 to 220 ha of existing nature pasture (non-grazed) land for sheep farm with environmental plantings (trees, shrubs and understory species endemic to the region)<br>- Transformational increase in FCE, to 20% in 2030 and 30% in 2050, relative to baseline[68] |

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## Author contributions

F.B., K.M.C-W., B.M., B.C., M.A., M.T.M. conceiving and/or designing the project or output. F.B., K.M.C-W., N.B., M.T.M. acquired research data where the acquisition has required significant intellectual judgement, planning, design or output. F.B., K.M.C-W., N.B., M.T.M. contributing knowledge, where justified, including indigenous knowledge. F.B., K.M.C-W., B.M., N.B., M.T.M. analysing and/or interpreting research data. F.B., K.M.C-W., B.M., N.B., M.A., M.T.M. Drafting significant parts of research output/s or critically revising output/s to contribute to interpretation.

## Declaration of interests

The authors declare no competing interests.

## Inclusion and diversity

We support inclusive, diverse, and equitable conduct of research.

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## Supplementary material to Appendix 8.2

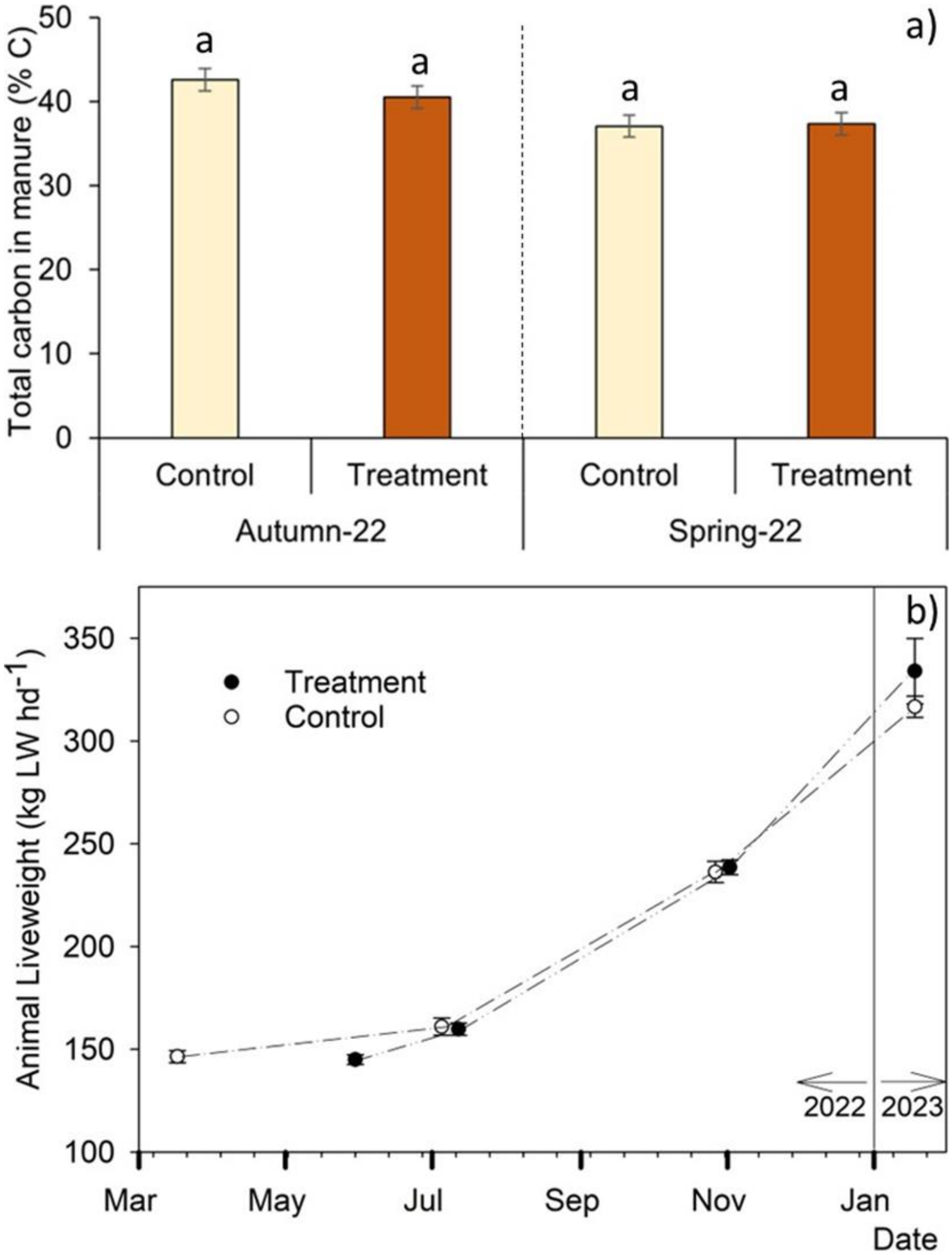


**Fig. A82.1.** Biophysical results from on-farm experiments with free-choice biochar, Tasmania, Australia. a) Mean total carbon content of manure samples collected over two timeframes from grazing steers fed with biochar *ad libitum* (Treatment, n=8) and no biochar (Control, n=8) in autumn and summer 2022. The t-test showed no significant differences between the two cohorts ($p$>0.05). b) Mean animal liveweight from grazing steers fed with biochar ad libitum (Treatment, n=75) and no biochar (Control, n=75). Error bars depict standard error.

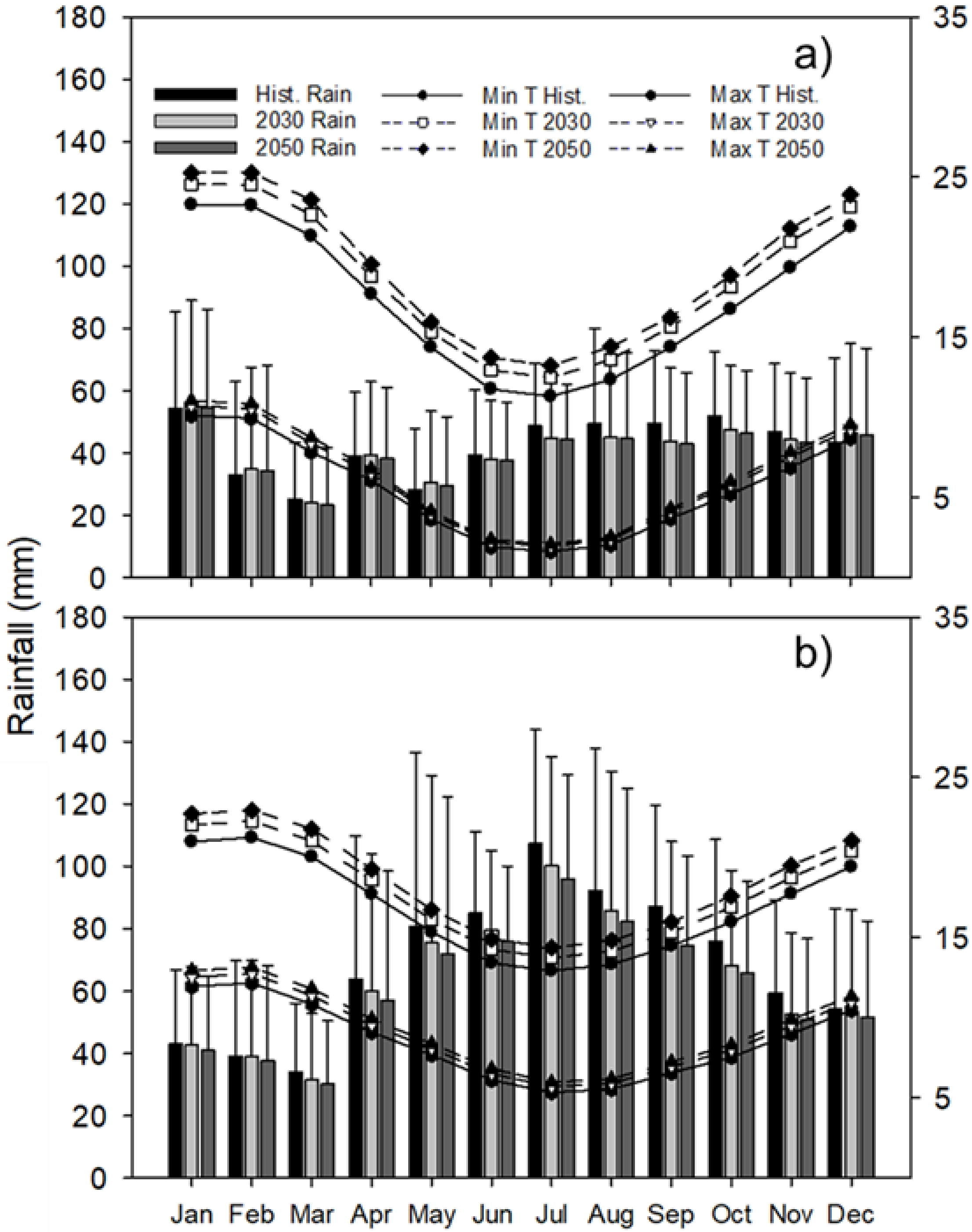


**Fig. A82.2.** Monthly average rainfall minimum and maximum temperature for the historical. 2030 and 2050 climate horizons for the a) Sheep farm and b) Beef farm. Erro bars indicate standard deviation.

**Pathways to Carbon Neutrality in livestock systems**

Considering the national long-term strategy to reach Carbon Neutrality by 2050, we articulated and packed co-designed adaptation options in Carbon Neutral bules using transformational adaptations suggested by RRG. Initially, we included *Asparagopsis* as ingredient in the ruminant diet as the most promising option to offset GHG emissions. Then, we gradually expanded the land to an extra paddock with trees (beef farm) or replaced marginal vegetation with native trees (sheep farm) to generate Carbon Neutral packages (CN) assuming a larger investment on animal feed conversion efficiency (TFCE) (CN1 and CN2, Fig. S3a) or mixing lucerne with grasses (CN3 and CN4, Fig. S3b).

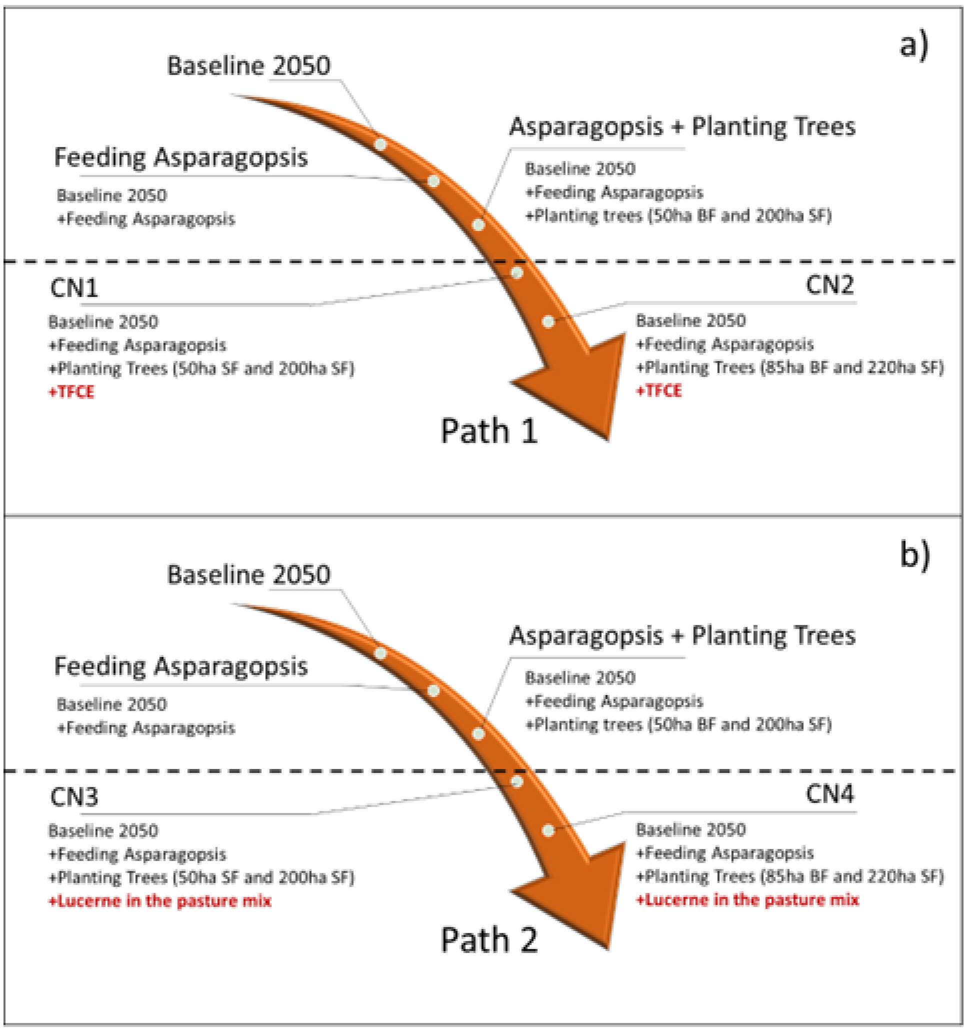


**Fig. A82.3.** Co-designed pathways to achieve Carbon Neutrality in the case studies analysed under 2050 climates. a) Description of pathway 1 by including transformational feed conversion efficiency, and b) pathway 2 by mixing lucerne with grasses. BF: beef farm. SF: sheep farm.

**Linking GrassGro and RothC to account for soil carbon changes in long-term pastures**

The Rothamsted Carbon model (RothC) version 26.3[10] was used to simulate dynamic soil organic carbon. RothC has been used extensively to model the impacts of climate and management on SOC stocks around the world[11]. RothC is driven by monthly means of temperature, rainfall and pan evaporation. Monthly average GrassGro outputs were input into RothC including dung (ManureC) and litter (senescent leaves, stems and roots = Plant residueC + RootC). Root residue C inputs (RootC) were derived considering the allocation of net primary production (ANP) between plant components [percentage allocated to leaves (Leaf%), stems (Stem%) and seeds (Seed%)] active root length density and proportion of root by layer (0-30 cm and 30-100 cm depth).

Cumulative monthly pasture litter (litter C, kg DM month$^{-1}$) was converted to C mass applying a conversion factor of 0.36. The DM fraction was 90% organic matter containing 40% of C[12].

$$LitterC\ (kg\ C\ ha^{-1}\ month^{-1}) = [Plant\ residueC\ (kg\ C\ ha^{-1}\ month^{-1}) + RootC(kg\ C\ ha^{-1}\ month^{-1})] \times\ 0.9\ \times\ 0.4$$

Some work allocated only 50% plant residueC and 50% RootC turned over annually and available for soil organic formation[13]. However, if 50% over the remaining 50% in a period of 20-40 years, it does not make difference in the long-term. On the other hand, if LitterC is fully available to the soil organic formation the decomposition rates will impact the C pools instantly. We followed the latter comprehensive and conservative approach to guarantee precise C accumulation rates. For short-term rotations, we recommend using 50% turnover rate for LitterC.

The cumulative monthly plant residueC was estimated subtracting cumulative pasture intake and haymaking or silage making (mainly in Spring-Summer) over cumulative aboveground net primary production (ANPP) as follows:

$$\begin{aligned} Plant\ residueC\ (kg\ C\ ha^{-1}\ month^{-1}) &= [ANPP\ (kg\ DM\ ha^{-1}\ month^{-1}) - Pasture\ Intake\ (kg\ DM\ ha^{-1}\ month^{-1}) \\ &\quad - Haymaking\ or\ Silage\ (kg\ DM\ ha^{-1}\ month^{-1})\ ] \times\ 0.9\ \times\ 0.4 \end{aligned}$$

The cumulative monthly RootC was calculated indirectly by using the allocated percentage of assimilates to leaf (Leaf%), stem (Stem%) and seed (Seed%) or a given time *i*:

$$\begin{aligned} If\ ANPP > 0, RootC(kg\ C\ ha^{-1}\ month^{-1}) &= [\frac{ANPP\ (kg\ DM\ ha^{-1}\ month^{-1})}{Leaf\%_i + Stem\%_i + Seed\%_i} - ANPP\ (kg\ DM\ ha^{-1}\ month^{-1})] \times\ 0.9\ \times\ 0.4 \end{aligned}$$

$$If\ ANPP\ \leq 0, RootC(kg\ C\ ha^{-1}\ month^{-1}) = 0$$

The monthly accumulated amount of RootC (kg C ha$^{-1}$) at 30 cm and 100 cm depth was based on the proportion of active root by layer.

In addition, the cumulative monthly ManureC was estimated as the indigestible fraction of the pasture intake ($DMD_{Pi}$)or supplements supplied ($DMD_{Si}$) (mainly in Autumn-Winter) for a given time *i* as was returned as dung to the soil C pool as follows:

$$ManureC\ (kg\ C\ ha^{-1}\ ha^{-1}\ month^{-1}) = [Pasture\ Intake\ (kg\ DM\ ha^{-1}\ month^{-1}) \times (1 - DMD_{Pi}) + Supplements\ (kg\ DM\ ha^{-1}\ month^{-1}) \times (1 - DMD_{Si})] \times\ 0.9\ \times\ 0.4$$

**Accounting for carbon changes in soil by enrichment of manure with biochar**

Based on the recent literature, we used RothC with a sub-model for biochar decomposition[14,15].

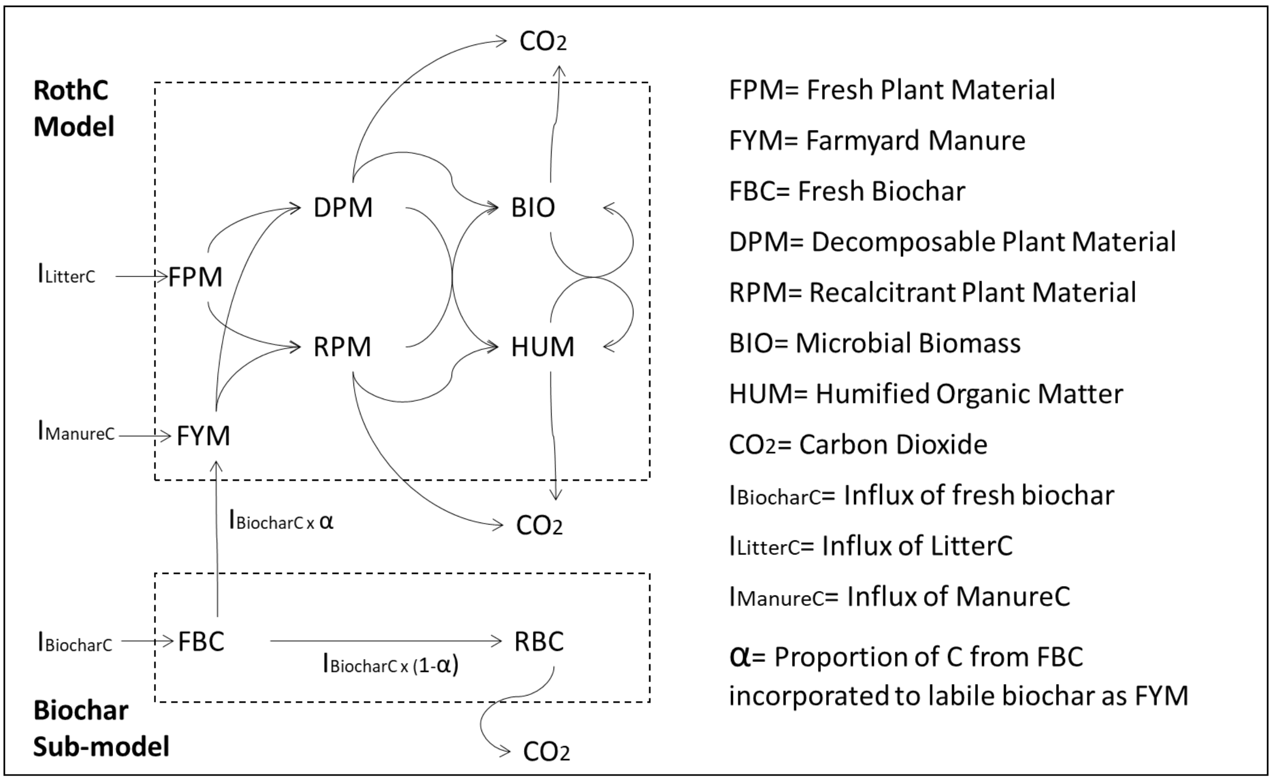


**Fig. A82.4.** Modelling soil organic changes from manure C enrichment with biochar. The biochar sub-model was adapted from Lefebvre et al.[14] to RothC for the decomposition of fresh biochar combined with influxes of fresh manure and litter.

Given the novel use of biochar as an ingredient in the ruminant diet (pasture intake + supplements), we targeted total biochar intake rates between 0.5-1.0% (DM basis) from experiments developed under Australian grazing conditions[16]. Assuming that almost 100% of the biochar supplied is excreted as dung with an average carbon concentration of 65% (reference), we can estimate a cumulative monthly influx C excreted from biochar ($I_{BiocharC}$) as:

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

Here, a proportion, α, of the C in $I_{BiocharC}$ is treated as farmyard manure and added to FYM pool in RothC as labile biochar. The remaining fraction of $I_{BiocharC}$ is simulated as recalcitrant material (RBC) and it decomposes very slowly releasing $CO_2$. Given the work recently developed by Lefebvre et al. (2020); Pulcher et al. (2022), we assumed a constant rate of 3% for α added to FYM pool per year ($I_{BiocharC}$ x 0.03) and 97% as RBC [$I_{BiocharC}$ x (1-0.03)]. For simplicity, the RCB fraction decomposes at a decay rate (*dC*RCB) of 11.9% over 100 years (mean residence time=840 years)[14]:

$$dC\mathrm{RCB} = RCB \times \frac{0.1189}{100}$$

$$RCB_{i+1} = \left[I_{BiocharC_i} \times (1 - 0.03)\right] - dC\mathrm{RCB}_i + \mathrm{RCB}_i$$

**Diversifying land use with grapes on a sheep farm**

The RRG defined 30ha of vineyards on the sheep farm to cultivate and harvest Chardonnay and Pinot Noir (it represents <1% of the total grazable area of the farm). We assume that the animal stock over these 30ha was absorbed into the remaining farm so no reduction in livestock emissions. Annual inputs included an extra 150 kWh $ha^{-1}$, 60 litres of diesel $ha^{-1}$, 35 kg N $ha^{-1}$, 0.6 kg SSP $ha^{-1}$, and 10 litres herbicide $ha^{-1}$ [17-19]. Grape GHG emissions were estimated using SB-GAF and were comparative to other studies[20-21]. Carbon stored in above-ground vines was estimating based on 3,075 vines $ha^{-1}$ (typical planting spacing for the region) and 0.187 kg C $ha^{-1}$ [22]. Changes in below-ground C accumulation in rootstock was assumed to be zero due to unavailable data, while changes in SOC remained the same as per the whole farm due to highly variable results in the literature[17,23-26].

**Table A82.1. Long-term biophysical, environmental, and economic outcomes averages for individual incremental, systemic and transformational adaptations comprised in LHF, TCN, ID and CN packages in the high rainfall beef production system under 2030 climates.** Hist: historical, B30: baseline farm with no adaptation in 2030, F: increasing soil fertility by 3%, DR: increasing rooting depth by 10%, SR: increasing stocking rate by 10%, CCD: changing calving date, FCE: increasing feed conversion efficiency by 10%, Luc: pasture renovation with lucerne, $CH_4$ Vac: enteric $CH_4$ inhibitor vaccine, Planting trees: buying an extra paddock for trees, Extra Farm: buying an extra farm in a different agroclimatic region, Wind: hosting a wind farm by leasing land, Bioc: feeding biochar, Asp: feeding *Asparagopsis taxiformis*, TFCE: increasing feed conversion efficiency by 20%.

| Variables | Scenarios | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hist | B30 | F | DR | SR | CCD | FCE | Luc | $CH_4$ Vac | Planting Trees | Extra Farm | Wind | Bioc | Asp | TFCE |
| **Livestock System** | | | | | | | | | | | | | | | |
| Stocking Rate (DSE $ha^{-1}$ $yr^{-1}$) | 24.2 | 24.4 | 24.5 | 24.3 | 25.9 | 24.8 | 23.3 | 25.1 | 24.4 | 24.4 | 12.6 | 24.4 | 24.4 | 24.4 | 22.2 |
| Farm Liveweight Production (t LW $yr^{-1}$) | 287 | 291 | 293 | 291 | 309 | 294 | 307 | 305 | 291 | 291 | 341.3 | 291 | 324 | 291 | 319 |
| Protein Production (t protein $yr^{-1}$) | 52 | 52 | 53 | 52 | 56 | 53 | 55 | 55 | 52 | 52 | 61 | 52 | 58 | 52 | 57 |
| Pasture Production (t DM $ha^{-1}$ $yr^{-1}$) | 20.0 | 20.5 | 21.3 | 20.9 | 20.2 | 20.3 | 20.4 | 21.8 | 20.5 | 20.5 | 12.3 | 20.5 | 20.5 | 20.5 | 20.4 |
| Supplementary Feeding (t DM $ha^{-1}$ $yr^{-1}$) | 0.80 | 0.78 | 0.73 | 0.78 | 0.86 | 0.83 | 0.61 | 0.32 | 0.78 | 0.78 | 0.56 | 0.78 | 0.78 | 0.78 | 0.46 |
| Total livestock GHG emissions (t $CO_2$e) | 3,864 | 3,881 | 3,976 | 3,889 | 4,078 | 3,974 | 3,638 | 4,035 | 3,138 | 3,881 | 5,691 | 3,881 | 3,652 | 2,041 | 3,435 |
| **Soil organic carbon** | | | | | | | | | | | | | | | |
| Initial SOC stocks (t C $ha^{-1}$, 1m depth) | 235 | 240 | 240 | 240 | 240 | 240 | 240 | 240 | 240 | 240 | 161 | 240 | 240 | 240 | 240 |
| Final SOC stocks (t C $ha^{-1}$, 1m depth) | 238 | 241 | 244 | 243 | 240 | 241 | 242 | 248 | 241 | 241 | 163 | 241 | 242 | 241 | 242 |
| SOC change (t C $ha^{-1}$ $yr^{-1}$) | 0.14 | 0.06 | 0.18 | 0.12 | -0.03 | 0.03 | 0.10 | 0.37 | 0.06 | 0.06 | 0.11 | 0.06 | 0.10 | 0.06 | 0.10 |
| SOC change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | 0.53 | 0.21 | 0.67 | 0.44 | -0.10 | -0.12 | 0.37 | 1.36 | 0.21 | 0.21 | 0.39 | 0.21 | 0.35 | 0.21 | 0.37 |
| Total SOC change (t $CO_2$e $yr^{-1}$) | 301 | 119 | 383 | 252 | -58 | 78 | 211 | 773 | 119 | 119 | 523 | 119 | 201 | 119 | 211 |
| **Forestry system** | | | | | | | | | | | | | | | |
| Site C change (t C $ha^{-1}$ $yr^{-1}$) | - | - | - | - | - | - | - | - | - | 8.3 | - | - | - | - | - |
| Site C change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | - | - | - | - | - | - | - | - | - | 30.5 | - | - | - | - | - |
| Total site C change (t $CO_2$e $yr^{-1}$) | - | - | - | - | - | - | - | - | - | 1,527 | - | - | - | - | - |
| **Net GHG emissions** | | | | | | | | | | | | | | | |
| Net farm emissions (t $CO_2$e) | 3,563 | 3,762 | 3,593 | 3,637 | 4,135 | 3,904 | 3,426 | 3,262 | 3,018 | 2,236 | 5,168 | 3,762 | 3,451 | 1,921 | 3,225 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ LW produced) | 12.4 | 12.9 | 12.3 | 12.5 | 13.4 | 13.3 | 11.2 | 10.7 | 10.4 | 7.7 | 15.1 | 12.9 | 10.6 | 6.6 | 10.1 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ protein) | 69 | 72 | 68 | 70 | 74 | 74 | 62 | 59 | 58 | 43 | 83 | 72 | 60 | 37 | 57 |
| **Economics** | | | | | | | | | | | | | | | |

| Variables | Scenarios | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Hist** | **B30** | **F** | **DR** | **SR** | **CCD** | **FCE** | **Luc** | **$CH_4$ Vac** | **Planting Trees** | **Extra Farm** | **Wind** | **Bioc** | **Asp** | **TFCE** |
| Earnings before interests and taxes ('000 AU$) | 487 | 500 | 491 | 502 | 538 | 501 | 585 | 586 | 491 | 494 | 631 | 590 | 589 | 459 | 655 |
| Return on Capital (RoC, %) | 4.04 | 4.15 | 4.08 | 4.16 | 4.43 | 4.15 | 4.88 | 4.85 | 4.07 | 3.93 | 3.58 | 4.89 | 4.89 | 3.81 | 5.49 |

**Table A82.2. Long-term biophysical, environmental, and economic outcomes averages for individual incremental, systemic and transformational adaptations comprised in LHF, TCN, ID and CN packages in the high rainfall beef production system under 2050 climates.** Hist: historical, B50: baseline farm with no adaptation in 2050, F: increasing soil fertility by 3%, DR: increasing rooting depth by 10%, SR: increasing stocking rate by 15%, CCD: changing calving date, FCE: increasing feed conversion efficiency by 15%, Luc: pasture renovation with lucerne, $CH_4$ Vac: enteric $CH_4$ inhibitor vaccine, Planting trees: buying an extra paddock for trees, Extra Farm: buying an extra farm in a different agroclimatic region, Wind: hosting a wind farm by leasing land, Bioc: feeding biochar, Asp: feeding *Asparagopsis taxiformis*, TFCE: increasing feed conversion efficiency by 30%

| Variable | Scenario | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hist | B50 | F | DR | SR | CCD | FCE | Luc | $CH_4$ Vac | Planting Trees | Extra Farm | Wind | Bioc | Asp | TFCE |
| **Livestock System** | | | | | | | | | | | | | | | |
| Stocking Rate (DSE $ha^{-1}$ $yr^{-1}$) | 24.2 | 24.4 | 24.5 | 24.4 | 25.9 | 24.9 | 22.6 | 25.0 | 24.4 | 24.4 | 12.3 | 24.4 | 24.4 | 24.4 | 21.6 |
| Farm Liveweight Production (t LW $yr^{-1}$) | 287 | 290 | 294 | 292 | 308 | 295 | 314 | 309 | 290 | 290 | 333.6 | 290 | 323 | 290 | 326 |
| Protein Production (t protein $yr^{-1}$) | 52 | 52 | 53 | 53 | 56 | 53 | 57 | 56 | 52 | 52 | 60 | 52 | 58 | 52 | 59 |
| Pasture Production (t DM $ha^{-1}$ $yr^{-1}$) | 20.0 | 20.3 | 21.1 | 20.6 | 20.0 | 20.3 | 20.2 | 19.2 | 20.3 | 20.3 | 12.0 | 20.3 | 20.3 | 20.3 | 20.3 |
| Supplementary Feeding (t DM $ha^{-1}$ $yr^{-1}$) | 0.80 | 0.79 | 0.74 | 0.80 | 0.89 | 0.84 | 0.54 | 0.35 | 0.79 | 0.79 | 0.59 | 0.79 | 0.79 | 0.79 | 0.39 |
| Total livestock GHG emissions (t $CO_2$e) | 3,864 | 3,890 | 3,981 | 3,888 | 4,073 | 3,979 | 3,525 | 4,136 | 3,144 | 3,890 | 5,635 | 3,890 | 3,659 | 2,045 | 3,397 |
| **Soil organic carbon** | | | | | | | | | | | | | | | |
| Initial SOC stocks (t C $ha^{-1}$, 1m depth) | 235 | 241 | 244 | 243 | 240 | 241 | 242 | 248 | 241 | 241 | 163 | 241 | 242 | 241 | 242 |
| Final SOC stocks (t C $ha^{-1}$, 1m depth) | 238 | 241 | 245 | 242 | 238 | 240 | 242 | 251 | 241 | 241 | 164 | 241 | 242 | 241 | 243 |
| SOC change (t C $ha^{-1}$ $yr^{-1}$) | 0.14 | -0.05 | 0.04 | -0.01 | -0.10 | -0.05 | -0.01 | 0.19 | -0.05 | -0.05 | 0.04 | -0.05 | -0.00 | -0.05 | 0.03 |
| SOC change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | 0.53 | -0.18 | 0.14 | -0.04 | -0.35 | -0.19 | -0.03 | 0.68 | -0.18 | -0.18 | 0.15 | -0.18 | -0.03 | -0.18 | 0.10 |
| Total SOC change (t $CO_2$e $yr^{-1}$) | 301 | -102 | 80 | -23 | -196 | -110 | -20 | 387 | -102 | -102 | 204 | -102 | -19 | -102 | 58 |
| **Forestry system** | | | | | | | | | | | | | | | |
| Site C change (t C $ha^{-1}$ $yr^{-1}$) | - | - | - | - | - | - | - | - | - | 4.6 | - | - | - | - | - |
| Site C change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | - | - | - | - | - | - | - | - | - | 16.7 | - | - | - | - | - |
| Total site C change (t $CO_2$e $yr^{-1}$) | - | - | - | - | - | - | - | - | - | 836 | - | - | - | - | - |
| **Net GHG emissions** | | | | | | | | | | | | | | | |
| Net farm emissions (t $CO_2$e) | 3,563 | 3,992 | 3,902 | 3,910 | 4,269 | 4,088 | 3,545 | 3,749 | 3,246 | 3,156 | 5,431 | 3,992 | 3,678 | 2,147 | 3,340 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ LW produced) | 12.4 | 13.8 | 13.3 | 13.4 | 13.9 | 13.9 | 11.3 | 12.1 | 11.2 | 10.9 | 16.3 | 13.8 | 11.4 | 7.4 | 10.2 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ protein) | 69 | 76 | 74 | 74 | 76 | 77 | 62 | 67 | 62 | 61 | 91 | 76 | 63 | 41 | 57 |
| **Economics** | | | | | | | | | | | | | | | |

| Variable | Scenario | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hist | B50 | F | DR | SR | CCD | FCE | Luc | $CH_4$ Vac | Planting Trees | Extra Farm | Wind | Bioc | Asp | TFCE |
| Earnings before interests and taxes ('000 AU$) | 487 | 500 | 494 | 504 | 534 | 505 | 622 | 594 | 491 | 494 | 600 | 560 | 589 | 458 | 694 |
| Return on Capital (RoC, %) | 4.04 | 4.15 | 4.10 | 4.18 | 4.40 | 4.18 | 5.19 | 4.92 | 4.07 | 3.93 | 3.40 | 4.64 | 4.89 | 3.80 | 5.84 |

**Table A82.3. Long-term biophysical, environmental, and economic outcomes averages for individual incremental, systemic and transformational adaptations comprised in LHF, TCN, ID and CN packages in the medium rainfall sheep production system under 2030 climates.** Hist: historical, B30: baseline farm with no adaptation except removal of cattle, DR: increasing rooting depth by 10%, F: increasing soil fertility by 3%, FCE: increasing feed conversion efficiency by 10%, TC: Talish clover, LD: Altered lambing date, SR: increased stocking rate, LD/SR: altered lambing date and increased stocking rate, Luc: pasture renovation with lucerne, $CH_4$ Vac: enteric $CH_4$ inhibitor vaccine, Planting trees: thickening of non-grazing land with 200 ha of trees, ID: income diversification with vineyard, Bioc: feeding biochar, Asp: feeding *Asparagopsis taxiformis*, TFCE: increasing feed conversion efficiency by 20%.

| Variable | Scenario | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hist | B50 | DR | F | FCE | TC | LD | SR | LD/SR | Luc | $CH_4$ Vac | Trees | ID | Bioc | Asp | TFCE |
| **Livestock System** | | | | | | | | | | | | | | | | |
| Stocking Rate (DSE $ha^{-1}$ $yr^{-1}$) | 9.0 | 8.0 | 8.0 | 8.0 | 7.6 | 8.0 | 8.1 | 9.3 | 9.5 | 8.4 | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 | 7.3 |
| Farm Liveweight Production (t LW $yr^{-1}$) | 370.0 | 293.6 | 295.1 | 294.9 | 306.9 | 292.6 | 309.6 | 336.0 | 354.4 | 322.1 | 293.6 | 293.6 | 293.6 | 293.6 | 293.6 | 319.5 |
| Farm Wool Production (t CFW $yr^{-1}$) | 71.0 | 79.0 | 75.2 | 77.9 | 75.5 | 77.7 | 78.1 | 90.8 | 90.7 | 82.1 | 79.0 | 79.0 | 79.0 | 79.0 | 79.0 | 72.0 |
| Farm Livestock Production (t LW + CFW $yr^{-1}$) | 441.0 | 372.6 | 370.3 | 372.8 | 382.4 | 370.3 | 387.7 | 426.9 | 445.1 | 404.1 | 372.6 | 372.6 | 372.6 | 372.6 | 372.6 | 391.5 |
| Protein Production (t protein $yr^{-1}$) | 137.6 | 131.9 | 128.4 | 131.0 | 130.7 | 130.3 | 133.8 | 151.3 | 154.4 | 140.0 | 131.9 | 131.9 | 133.3 | 131.9 | 131.9 | 129.5 |
| Pasture Production (t DM $ha^{-1}$ $yr^{-1}$) | 7.2 | 7.7 | 7.8 | 7.9 | 7.7 | 7.7 | 7.5 | 7.6 | 7.7 | 8.3 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 |
| Supplementary Feeding (t DM $ha^{-1}$ $yr^{-1}$) | 0.3 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.0 | 0.1 | 0.1 | 0.1 | 0.11 | 0.11 | 0.1 |
| Total livestock GHG emissions (t $CO_2$e) | 7,037 | 6,375 | 6,371 | 6,413 | 6,065 | 6,350 | 6,505 | 7,278 | 7,454 | 6,804 | 4,944 | 6,375 | 6,375 | 5,911 | 2,662 | 5,834 |
| **Soil organic carbon** | | | | | | | | | | | | | | | | |
| Initial SOC stocks (t C $ha^{-1}$, 1m depth) | 175.0 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 |
| Final SOC stocks (t C $ha^{-1}$, 1m depth) | 179.2 | 184.1 | 184.3 | 185.5 | 184.9 | 185.1 | 184.1 | 184.3 | 184.0 | 185.9 | 184.1 | 184.1 | 184.1 | 184.9 | 184.1 | 184.7 |
| SOC change (t C $ha^{-1}$ $yr^{-1}$) | 0.21 | 0.08 | 0.09 | 0.15 | 0.12 | 0.13 | 0.08 | 0.09 | 0.07 | 0.17 | 0.08 | 0.08 | 0.08 | 0.12 | 0.08 | 0.11 |
| SOC change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | 0.77 | 0.29 | 0.33 | 0.54 | 0.43 | 0.48 | 0.30 | 0.33 | 0.27 | 0.62 | 0.29 | 0.29 | 0.29 | 0.44 | 0.29 | 0.41 |
| SOC change (t $CO_2$e $yr^{-1}$) | 2,425 | 910 | 1,043 | 1,724 | 1,375 | 1,537 | 950 | 1,049 | 8,64 | 1,954 | 910 | 910 | 910 | 1,388 | 910 | 1,298 |
| **Forestry/horticulture system** | | | | | | | | | | | | | | | | |
| Site C change (t C $ha^{-1}$ $yr^{-1}$) | | | | | | | | | | | | 1.5 | 0.6 | | | |

| Variable | Scenario | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Hist** | **B50** | **DR** | **F** | **FCE** | **TC** | **LD** | **SR** | **LD/SR** | **Luc** | **$CH_4$ Vac** | **Trees** | **ID** | **Bioc** | **Asp** | **TFCE** |
| Site C change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | | | | | | | | | | | | 5.4 | 2.1 | | | |
| Farm Grape Production (t fresh fruit $yr^{-1}$) | | | | | | | | | | | | | 300 | | | |
| Grapes GHG emissions (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | | | | | | | | | | | | | 1.1 | | | |
| Total site C change (t $CO_2$e $yr^{-1}$) | | | | | | | | | | | | 1,073 | 29 | | | |
| **Net GHG emissions** | | | | | | | | | | | | | | | | |
| Net farm emissions (t $CO_2$e) | 4,612 | 5,466 | 5,328 | 4,688 | 4,690 | 4,813 | 5,555 | 6,229 | 6,591 | 4,850 | 4,034 | 4,393 | 5,436 | | 1,752 | 4,535 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ LW produced) | 6.0 | 7.5 | 7.5 | 6.4 | 6.5 | 6.6 | 7.5 | 7.4 | 7.7 | 6.2 | 5.5 | 6.0 | 7.5 | | 2.4 | 6.3 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ CFW produced) | 33.5 | 41.5 | 41.5 | 35.8 | 35.9 | 36.9 | 41.5 | 41.2 | 42.7 | 34.6 | 30.6 | 33.3 | 41.5 | | 13.3 | 35.0 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ fruit produced) | | | | | | | | | | | | | -0.01 | | | |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ LW + CFW produced) | 10.5 | 14.7 | 14.4 | 12.6 | 12.3 | 13.0 | 14.3 | 14.6 | 14.8 | 12.0 | 10.8 | 11.8 | 14.6 | | 4.7 | 11.6 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ protein) | 33.5 | 41.5 | 41.5 | 35.8 | 35.9 | 36.9 | 41.5 | 41.2 | 42.7 | 34.6 | 30.6 | 33.3 | 40.8 | | 13.3 | 35.0 |
| **Economics** | | | | | | | | | | | | | | | | |
| Earnings before interests and taxes ('000 AU$) | 919 | 1,246 | 1,210 | 1,226 | 1,302 | 1,224 | 1,309 | 1,327 | 1,408 | 1,494 | 1,200 | 1,240 | 1,510 | 1,132 | 1,158 | 1,340 |
| Return on Capital (RoC, %) | 5.11 | 6.93 | 6.73 | 6.82 | 7.24 | 6.81 | 7.28 | 7.26 | 7.70 | 8.05 | 6.68 | 6.78 | 8.40 | 6.30 | 6.44 | 7.45 |

**Table A82.4. Long-term biophysical, environmental, and economic outcomes averages for individual incremental, systemic and transformational adaptations comprised in LHF, TCN, ID and CN packages in the medium rainfall sheep production system under 2050 climates.** Hist: historical, B50: baseline farm with no adaptation except removing cattle, DR: increasing rooting depth by 10%, F: increasing soil fertility by 3%, FCE: increasing feed conversion efficiency by 15%, TC: Talish clover, LD: Altered lambing date, SR: increased stocking rate, LD/SR: altered lambing date and increased stocking rate, Luc: pasture renovation with lucerne, $CH_4$ Vac: enteric $CH_4$ inhibitor vaccine, Planting trees: thickening of non-grazing land with 200 ha of trees, ID: income diversification with vineyard, Bioc: feeding biochar, Asp: feeding *Asparagopsis taxiformis*, TFCE: increasing feed conversion efficiency by 30%.

| Variable | Scenario | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hist | B50 | DR | F | FCE | TC | LD | SR | LD/SR | Luc | $CH_4$ Vac | Trees | ID | Bioc | Asp | TFCE |
| **Livestock System** | | | | | | | | | | | | | | | | |
| Stocking Rate (DSE $ha^{-1}$ $yr^{-1}$) | 9.0 | 8.0 | 8.0 | 8.0 | 7.4 | 8.0 | 8.2 | 9.3 | 9.5 | 8.4 | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 | 7.0 |
| Farm Liveweight Production (t LW $yr^{-1}$) | 370.0 | 297.2 | 299.0 | 299.7 | 317.0 | 297.6 | 314.4 | 341.8 | 360.0 | 328.6 | 297.2 | 297.2 | 297.2 | 297.2 | 297.2 | 334.4 |
| Farm Wool Production (t CFW $yr^{-1}$) | 71.0 | 77.6 | 78.8 | 78.0 | 72.6 | 77.2 | 77.0 | 90.4 | 89.9 | 81.8 | 77.6 | 77.6 | 77.6 | 77.6 | 77.6 | 68.8 |
| Farm Livestock Production (t LW + CFW $yr^{-1}$) | 441.0 | 374.8 | 377.8 | 377.7 | 389.5 | 374.8 | 391.4 | 432.1 | 449.9 | 410.5 | 374.8 | 374.8 | 374.8 | 374.8 | 374.8 | 403.2 |
| Protein Production (t protein $yr^{-1}$) | 137.6 | 131.1 | 132.6 | 132.0 | 129.6 | 130.8 | 133.6 | 151.9 | 154.7 | 141.0 | 131.1 | 131.1 | 132.5 | 131.1 | 131.1 | 129.0 |
| Pasture Production (t DM $ha^{-1}$ $yr^{-1}$) | 7.2 | 7.9 | 8.0 | 8.0 | 7.8 | 7.9 | 7.9 | 7.8 | 7.8 | 8.6 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.8 |
| Supplementary Feeding (t DM $ha^{-1}$ $yr^{-1}$) | 0.3 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.0 | 0.1 | 0.1 | 0.1 | 0.12 | 0.12 | 0.1 |
| Total livestock GHG emissions (t $CO_2$e) | 7,037 | 6,332 | 6,375 | 6,407 | 5,929 | 6,330 | 6,471 | 7,263 | 7,425 | 6,944 | 4,897 | 6,332 | 6,332 | 5,868 | 2,622 | 5,637 |
| **Soil organic carbon** | | | | | | | | | | | | | | | | |
| Initial SOC stocks (t C $ha^{-1}$, 1m depth) | 175.0 | 184.1 | 184.3 | 185.5 | 184.9 | 185.1 | 184.1 | 184.3 | 184.0 | 185.8 | 184.1 | 184.1 | 184.1 | 184.1 | 184.1 | 184.7 |
| Final SOC stocks (t C $ha^{-1}$, 1m depth) | 179.2 | 186.0 | 185.8 | 187.7 | 187.0 | 187.4 | 186.0 | 185.6 | 185.2 | 189.2 | 186.0 | 186.0 | 186.0 | 186.8 | 186.0 | 186.4 |
| SOC change (t C $ha^{-1}$ $yr^{-1}$) | 0.21 | 0.10 | 0.07 | 0.11 | 0.11 | 0.11 | 0.10 | 0.06 | 0.06 | 0.17 | 0.10 | 0.10 | 0.10 | 0.14 | 0.10 | 0.09 |
| SOC change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | 0.77 | 0.36 | 0.27 | 0.42 | 0.39 | 0.41 | 0.35 | 0.23 | 0.22 | 0.61 | 0.36 | 0.36 | 0.36 | 0.51 | 0.36 | 0.31 |
| SOC change (t $CO_2$e $yr^{-1}$) | 2,425 | 1,142 | 851 | 1,323 | 1,221 | 1,291 | 1,114 | 734 | 705 | 1,926 | 1,142 | 1,142 | 1,142 | 1,610 | 1,142 | 993 |
| **Forestry/horticulture system** | | | | | | | | | | | | | | | | |
| Site C change (t C $ha^{-1}$ $yr^{-1}$) | - | - | - | - | - | - | - | - | - | - | - | - | 0.6 | - | - | - |
| Site C change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | - | - | - | - | - | - | - | - | - | - | - | - | 2.1 | - | - | - |
| Farm Grape Production (t fresh fruit $yr^{-1}$) | - | - | - | - | - | - | - | - | - | - | - | - | 300 | - | - | - |
| Grapes GHG emissions (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | - | - | - | - | - | - | - | - | - | - | - | - | 1.1 | - | - | - |
| Total site C change (t $CO_2$e $yr^{-1}$) | - | - | - | - | - | - | - | - | - | - | - | - | 29 | - | - | - |
| **Net GHG emissions** | | | | | | | | | | | | | | | | |
| Net farm emissions (t $CO_2$e) | 4,612 | 5,190 | 5524 | 5083 | 4708 | 5039 | 5357 | 6529 | 6720 | 5018 | 3755 | 3943 | 5,160 | 4,258 | 1,480 | 4,644 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ LW produced) | 6.0 | 7.1 | 7.5 | 6.9 | 6.5 | 6.9 | 7.2 | 7.7 | 7.8 | 6.4 | 5.2 | 5.4 | 7.1 | 5.8 | 2.0 | 6.5 |
| Net emission intensity | 33.5 | 39.6 | 41.6 | 38.5 | 36.3 | 38.5 | 40.1 | 43.0 | 43.4 | 35.6 | 28.7 | 30.1 | 39.6 | 32.5 | 11.3 | 36.0 |

| Variable | Scenario | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hist | B50 | DR | F | FCE | TC | LD | SR | LD/SR | Luc | $CH_4$ Vac | Trees | ID | Bioc | Asp | TFCE |
| (kg $CO_2$e kg$^{-1}$ CFW produced) | | | | | | | | | | | | | | | | |
| Net emission intensity (kg $CO_2$e kg$^{-1}$ fruit produced) | - | - | - | - | - | - | - | - | - | - | - | - | -0.01 | - | - | - |
| Net emission intensity (kg $CO_2$e kg$^{-1}$ LW + CFW produced) | 10.5 | 13.8 | 14.6 | 13.5 | 12.1 | 13.4 | 13.7 | 15.1 | 14.9 | 12.2 | 10.0 | 10.5 | 13.8 | 11.4 | 3.9 | 11.5 |
| Net emission intensity (kg $CO_2$e kg$^{-1}$ protein) | 33.5 | 39.6 | 41.6 | 38.5 | 36.3 | 38.5 | 40.1 | 43.0 | 43.4 | 35.6 | 28.7 | 30.1 | 39.0 | 32.5 | 11.3 | 36.0 |
| **Economics** | | | | | | | | | | | | | | | | |
| Earnings before interests and taxes ('000 AU$) | 919 | 1,249 | 1,278 | 1,263 | 1,335 | 1,254 | 1,326 | 1,356 | 1,437 | 1,464 | 1,203 | 1,228 | 1,513 | 1,135 | 1,161 | 1,377 |
| Return on Capital (RoC, %) | 5.11 | 6.95 | 7.11 | 7.02 | 7.42 | 6.97 | 7.37 | 7.41 | 7.85 | 7.88 | 6.69 | 6.72 | 8.42 | 6.31 | 6.46 | 7.65 |

**Table A82.5. Long-term biophysical, environmental, and economic outcomes averages for co-designed pathways to achieve Carbon Neutrality in the high rainfall beef production system under 2030 climates.** Hist: historical, Base: baseline farm with no adaptation, LHF: Low Hanging Fruit and TCN: Towards Carbon Neutral. Hist: scenarios simulated with historical climates. Base: impact of future climates. LHF: low-hanging fruit packages. TCN: towards carbon neutrality package. ID: income diversification. Asp: *Asparagopsis taxiformis*. Asp+PT: *Asparagopsis taxiformis* + Planting trees 50ha. CN1: carbon neutral package 1 (*Asparagopsis taxiformis*+ planting trees 50ha+ transformational feed conversion efficiency. CN2: carbon neutral package 2 (*Asparagopsis taxiformis*+ planting trees 85ha + transformational feed conversion efficiency. CN3: carbon neutral package 2 (*Asparagopsis taxiformis*+ planting trees 50ha + Lucerne). CN4: carbon neutral package 4 (*Asparagopsis taxiformis*+ planting trees 85ha + Lucerne).

| Variables | Scenario | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Hist** | **Base30** | **LHF** | **TCN** | **ID** | **Asp** | **Asp+PT** | **CN1** | **CN2** | **CN3** | **CN4** |
| **Livestock System** | | | | | | | | | | | |
| Stocking Rate (DSE $ha^{-1}$ $yr^{-1}$) | 24.2 | 24.4 | 25.3 | 25.8 | 12.6 | 24.4 | 24.4 | 22.2 | 22.2 | 25.1 | 25.1 |
| Farm Liveweight Production (t LW $yr^{-1}$) | 287 | 291 | 332 | 344 | 341.3 | 291 | 291 | 319 | 319 | 305 | 305 |
| Protein Production (t protein $yr^{-1}$) | 52 | 52 | 60 | 62 | 61 | 52 | 52 | 57 | 57 | 55 | 55 |
| Pasture Production (t DM $ha^{-1}$ $yr^{-1}$) | 20.0 | 20.5 | 21.5 | 22.6 | 12.3 | 20.5 | 20.5 | 20.4 | 20.4 | 21.8 | 21.8 |
| Supplementary Feeding (t DM $ha^{-1}$ $yr^{-1}$) | 0.80 | 0.78 | 0.67 | 0.30 | 0.56 | 0.78 | 0.78 | 0.46 | 0.46 | 0.32 | 0.32 |
| Total livestock GHG emissions (t $CO_2$e) | 3,864 | 3,881 | 4,364 | 3,627 | 5,691 | 2,041 | 2,041 | 1,877 | 1,877 | 2,120 | 2,120 |
| **Soil organic carbon** | | | | | | | | | | | |
| Initial SOC stocks (t C $ha^{-1}$, 1m depth) | 235 | 240 | 240 | 240 | 161 | 240 | 240 | 240 | 240 | 240 | 240 |
| Final SOC stocks (t C $ha^{-1}$, 1m depth) | 238 | 241 | 243 | 249 | 163 | 241 | 241 | 242 | 242 | 248 | 248 |
| SOC change (t C $ha^{-1}$ $yr^{-1}$) | 0.14 | 0.06 | 0.12 | 0.45 | 0.11 | 0.06 | 0.06 | 0.10 | 0.10 | 0.37 | 0.37 |
| SOC change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | 0.53 | 0.21 | 0.44 | 1.65 | 0.39 | 0.21 | 0.21 | 0.37 | 0.37 | 1.36 | 1.36 |
| SOC change (t $CO_2$e $yr^{-1}$) | 301 | 119 | 250 | 945 | 523 | 119 | 119 | 211 | 211 | 774 | 774 |
| **Forestry system** | | | | | | | | | | | |
| Site C change (t C $ha^{-1}$ $yr^{-1}$) | - | - | - | 8.3 | - | - | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 |
| Site C change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | - | - | - | 30.5 | - | - | 30.5 | 30.5 | 30.5 | 30.5 | 30.5 |
| Total site C change (t $CO_2$e $yr^{-1}$) | - | - | - | 1,527 | - | - | 1,527 | 1,527 | 1,678 | 1,527 | 1,678 |
| **Net GHG emissions** | | | | | | | | | | | |
| Net farm emissions (t $CO_2$e) | 3,563 | 3,762 | 4,114 | 1,155 | 5,168 | 1,921 | 396 | 139 | -13 | -180 | -331 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ LW produced) | 12.4 | 12.9 | 12.4 | 7.8 | 15.1 | 6.6 | 1.4 | 0.4 | -0.0 | -0.6 | -1.1 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ protein) | 69 | 72 | 69 | 43 | 83 | 37 | 7.6 | 2.4 | -0.2 | -3.3 | -6.0 |

| **Variables** | **Scenario** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Hist** | **Base30** | **LHF** | **TCN** | **ID** | **Asp** | **Asp+PT** | **CN1** | **CN2** | **CN3** | **CN4** |
| **Economics** | | | | | | | | | | | |
| Earnings before interests and taxes (‘000 AU$) | 487 | 500 | 621 | 667 | 721 | 459 | 414 | 613 | 609 | 537 | 530 |
| Return on Capital (RoC, %) | 4.04 | 4.15 | 5.13 | 5.50 | 4.09 | 3.81 | 3.30 | 4.91 | 4.77 | 4.25 | 4.09 |

**Table A82.6. Long-term biophysical, environmental, and economic outcomes averages for co-designed pathways to achieve Carbon Neutrality in the high rainfall beef production system under 2050 climates.** Hist: historical, Base: baseline farm with no adaptation, LHF: Low Hanging Fruit and TCN: Towards Carbon Neutral. Hist: scenarios simulated with historical climates. Base: impact of future climates. LHF: low-hanging fruit packages. TCN: towards carbon neutrality package. ID: income diversification. Asp: *Asparagopsis taxiformis*. Asp+PT: *Asparagopsis taxiformis* + Planting trees 50ha. CN1: carbon neutral package 1 (*Asparagopsis taxiformis*+ planting trees 50ha+ transformational feed conversion efficiency. CN2: carbon neutral package 2 (*Asparagopsis taxiformis*+ planting trees 85ha + transformational feed conversion efficiency. CN3: carbon neutral package 2 (*Asparagopsis taxiformis*+ planting trees 50ha + Lucerne). CN4: carbon neutral package 4 (*Asparagopsis taxiformis*+ planting trees 85ha + Lucerne).

| Variables | Scenario | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hist | Base50 | LHF | TCN | ID | Asp | Asp+PT | CN1 | CN2 | CN3 | CN4 |
| **Livestock System** | | | | | | | | | | | |
| Stocking Rate (DSE $ha^{-1}$ $yr^{-1}$) | 24.2 | 24.4 | 25.2 | 25.6 | 12.3 | 24.4 | 24.4 | 21.6 | 21.6 | 25.0 | 25.0 |
| Farm Liveweight Production (t LW $yr^{-1}$) | 287 | 290 | 332 | 349 | 333.6 | 290 | 290 | 326 | 326 | 309 | 309 |
| Protein Production (t protein $yr^{-1}$) | 52 | 52 | 60 | 63 | 60 | 52 | 52 | 59 | 59 | 56 | 56 |
| Pasture Production (t DM $ha^{-1}$ $yr^{-1}$) | 20.0 | 20.3 | 21.2 | 19.8 | 12.0 | 20.3 | 20.3 | 20.3 | 20.3 | 19.2 | 19.2 |
| Supplementary Feeding (t DM $ha^{-1}$ $yr^{-1}$) | 0.80 | 0.79 | 0.67 | 0.29 | 0.59 | 0.79 | 0.79 | 0.39 | 0.39 | 0.35 | 0.35 |
| Total livestock GHG emissions (t $CO_2$e) | 3,864 | 3,890 | 4,364 | 3,736 | 5,635 | 2,045 | 2,045 | 1,869 | 1,869 | 2,196 | 2,196 |
| **Soil organic carbon** | | | | | | | | | | | |
| Initial SOC stocks (t C $ha^{-1}$, 1m depth) | 235 | 241 | 243 | 249 | 163 | 241 | 241 | 242 | 242 | 248 | 248 |
| Final SOC stocks (t C $ha^{-1}$, 1m depth) | 238 | 241 | 244 | 254 | 164 | 241 | 241 | 243 | 243 | 251 | 251 |
| SOC change (t C $ha^{-1}$ $yr^{-1}$) | 0.14 | -0.05 | 0.06 | 0.21 | 0.04 | -0.05 | -0.05 | 0.03 | 0.03 | 0.19 | 0.19 |
| SOC change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | 0.53 | -0.18 | 0.20 | 0.77 | 0.15 | -0.18 | -0.18 | 0.10 | 0.10 | 0.68 | 0.68 |
| Total SOC change (t $CO_2$e $yr^{-1}$) | 301 | -102 | 115 | 438 | 204 | -102 | -102 | 58 | 58 | 387 | 387 |
| **Forestry system** | | | | | | | | | | | |
| Site C change (t C $ha^{-1}$ $yr^{-1}$) | - | - | - | 4.6 | - | - | 4.6 | 4.6 | 6.0 | 4.6 | 6.0 |
| Site C change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | - | - | - | 16.7 | - | - | 16.7 | 16.7 | 22.0 | 16.7 | 22.0 |
| Total site C change (t $CO_2$e $yr^{-1}$) | - | - | - | 836 | - | - | 836 | 836 | 1,861 | 836 | 1,861 |
| **Net GHG emissions** | | | | | | | | | | | |
| Net farm emissions (t $CO_2$e) | 3,563 | 3,992 | 4,250 | 2,462 | 5,431 | 2,147 | 1,312 | 976 | -50 | 973 | -52 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ LW produced) | 12.4 | 13.8 | 12.8 | 9.5 | 16.3 | 7.4 | 4.5 | 3.0 | -0.2 | 3.1 | -0.2 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ protein) | 69 | 76 | 71 | 53 | 91 | 41 | 25 | 16.5 | -0.8 | 17.4 | -0.9 |
| **Economics** | | | | | | | | | | | |
| Earnings before interests and taxes | 487 | 500 | 627 | 686 | 644 | 458 | 409 | 649 | 646 | 550 | 543 |

| Variables | Scenario | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hist | Base50 | LHF | TCN | ID | Asp | Asp+PT | CN1 | CN2 | CN3 | CN4 |
| ('000 AU$) | | | | | | | | | | | |
| Return on Capital (RoC, %) | 4.04 | 4.15 | 5.18 | 5.66 | 3.65 | 3.80 | 3.26 | 5.22 | 5.10 | 4.35 | 4.20 |

**Table A82.7. Long-term biophysical, environmental, and economic outcomes averages for co-designed pathways to achieve Carbon Neutrality in the medium rainfall sheep production system under 2030 climates.** Hist: historical, Base: baseline farm with no adaptation except removal of cattle, LHF: Low Hanging Fruit and TCN: Towards Carbon Neutral. Hist: scenarios simulated with historical climates. Base: impact of future climates. LHF: low-hanging fruit packages. TCN: towards carbon neutrality package. ID: income diversification with vineyard. Asp: *Asparagopsis taxiformis*. Asp+PT: *Asparagopsis taxiformis* + Planting trees 200ha. CN1: carbon neutral package 1 (*Asparagopsis taxiformis*+ planting trees 200ha+ transformational feed conversion efficiency. CN2: carbon neutral package 2 (*Asparagopsis taxiformis*+ planting trees 220ha + transformational feed conversion efficiency. CN3: carbon neutral package 2 (*Asparagopsis taxiformis*+ planting trees 200ha + Lucerne). CN4: carbon neutral package 4 (*Asparagopsis taxiformis*+ planting trees 220ha + Lucerne).

| Variable | Scenario | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hist | Base30 | LHF | TCN | ID | Asp | Asp+PT | CN1 | CN2 | CN3 | CN4 |
| **Livestock System** | | | | | | | | | | | |
| Stocking Rate (DSE $ha^{-1}$ $yr^{-1}$) | 9.0 | 8.0 | 9.1 | 10.0 | 8.0 | 8.0 | 7.3 | 8.0 | 7.3 | 7.3 | 8.4 |
| Farm Liveweight Production (t LW $yr^{-1}$) | 370.0 | 293.6 | 369.8 | 475.5 | 293.6 | 293.6 | 319.5 | 293.6 | 319.5 | 319.5 | 322.1 |
| Farm Wool Production (t CFW $yr^{-1}$) | 71.0 | 79.0 | 86.5 | 93.7 | 79.0 | 79.0 | 72.0 | 79.0 | 72.0 | 72.0 | 82.1 |
| Farm Livestock Production (t LW + CFW $yr^{-1}$) | 441.0 | 372.6 | 456.3 | 569.2 | 372.6 | 372.6 | 372.6 | 391.5 | 391.5 | 404.1 | 404.1 |
| Protein Production (t protein $yr^{-1}$) | 137.6 | 131.9 | 153.1 | 179.3 | 133.3 | 131.9 | 129.5 | 131.9 | 129.5 | 129.5 | 140.0 |
| Pasture Production (t DM $ha^{-1}$ $yr^{-1}$) | 7.2 | 7.7 | 7.8 | 8.2 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 | 8.3 |
| Supplementary Feeding (t DM $ha^{-1}$ $yr^{-1}$) | 0.3 | 0.1 | 0.1 | 0.1 | 0.1 | 0.11 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 |
| Total livestock GHG emissions (t $CO_2$e) | 7,037 | 6,375 | 7,666 | 6,510 | 6,375 | 2,662 | 5,834 | 2,662 | 2,455 | 2,455 | 2,797 |
| **Soil organic carbon** | | | | | | | | | | | |
| Initial SOC stocks (t C $ha^{-1}$, 1m depth) | 175.0 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 | 182.5 |
| Final SOC stocks (t C $ha^{-1}$, 1m depth) | 179.2 | 184.1 | 185.4 | 185.6 | 184.1 | 184.1 | 184.7 | 184.1 | 184.7 | 184.7 | 186.0 |
| SOC change (t C $ha^{-1}$ $yr^{-1}$) | 0.21 | 0.08 | 0.15 | 0.16 | 0.08 | 0.08 | 0.11 | 0.08 | 0.11 | 0.11 | 0.17 |
| SOC change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | 0.77 | 0.29 | 0.53 | 0.57 | 0.29 | 0.29 | 0.41 | 0.29 | 0.41 | 0.41 | 0.64 |
| SOC change (t $CO_2$e $yr^{-1}$) | 2,425 | 910 | 1,686 | 1,815 | 910 | 910 | 910 | 1,298 | 1,298 | 2,020 | 2,020 |
| **Forestry/horticulture system** | | | | | | | | | | | |
| Site C change (t C $ha^{-1}$ $yr^{-1}$) | - | - | - | 1.5 | 0.6 | - | - | 1.5 | 1.5 | 1.5 | 1.5 |
| Site C change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | - | - | - | 5.4 | 2.1 | | | 5.4 | 5.4 | 5.4 | 5.4 |
| Farm Grape Production (t fresh fruit $yr^{-1}$) | - | - | - | - | 300 | - | - | - | - | - | - |
| Grapes GHG emissions (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | - | - | - | - | 1.1 | - | - | - | - | - | - |
| Total site C change (t $CO_2$e $yr^{-1}$) | - | - | - | 1,073 | 29 | - | - | 1,073 | 1,180 | 1,073 | 1,180 |
| **Net GHG emissions** | | | | | | | | | | | |
| Net farm emissions (t $CO_2$e) | 4,612 | 5,466 | 5,980 | 3,623 | 5,436 | 1,752 | 680 | 83 | -24 | -296 | -403 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ LW produced) | 6.0 | 7.5 | 7.0 | 3.6 | 7.5 | 2.4 | 0.9 | 0.0 | -0.03 | -0.4 | -0.5 |

| **Variable** | **Scenario** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Hist** | **Base30** | **LHF** | **TCN** | **ID** | **Asp** | **Asp+PT** | **CN1** | **CN2** | **CN3** | **CN4** |
| Net emission intensity (kg $CO_2e$ $kg^{-1}$ CFW produced) | 33.5 | 41.5 | 39.1 | 20.2 | 41.5 | 13.3 | 5.2 | 0.1 | -0.2 | -2.1 | -2.9 |
| Net emission intensity (kg $CO_2e$ $kg^{-1}$ fruit produced) | | | | | -0.01 | | | | | | |
| Net emission intensity (kg $CO_2e$ $kg^{-1}$ LW + CFW produced) | 10.5 | 14.7 | 13.1 | 6.4 | 14.6 | 4.7 | 1.8 | 0.2 | -0.1 | -0.7 | -1.0 |
| Net emission intensity (kg $CO_2e$ $kg^{-1}$ protein) | 33.5 | 41.5 | 39.1 | 20.2 | 40.8 | 13.3 | 0.2 | 0.0 | -0.0 | -0.1 | -0.1 |
| **Economics** | | | | | | | | | | | |
| Earnings before interests and taxes (‘000 AU$) | 919 | 1,246 | 1,481 | 1,991 | 1,510 | 1,158 | 1,137 | 1,231 | 1,228 | 1,327 | 1,325 |
| Return on Capital (RoC, %) | 5.11 | 6.93 | 8.10 | 10.34 | 8.40 | 6.44 | 6.22 | 6.73 | 6.71 | 7.03 | 7.01 |

**Table A82.8. Long-term biophysical, environmental, and economic outcomes averages for co-designed pathways to achieve Carbon Neutrality in the medium rainfall sheep production system under 2050 climates.** Hist: historical, Base: baseline farm with no adaptation except removal of cattle, LHF: Low Hanging Fruit and TCN: Towards Carbon Neutral. Hist: scenarios simulated with historical climates. Base: impact of future climates. LHF: low-hanging fruit packages. TCN: towards carbon neutrality package. ID: income diversification with vineyard. Asp: *Asparagopsis taxiformis*. Asp+PT: *Asparagopsis taxiformis* + Planting trees 200ha. CN1: carbon neutral package 1 (*Asparagopsis taxiformis*+ planting trees 200ha+ transformational feed conversion efficiency. CN2: carbon neutral package 2 (*Asparagopsis taxiformis*+ planting trees 220ha + transformational feed conversion efficiency. CN3: carbon neutral package 2 (*Asparagopsis taxiformis*+ planting trees 200ha + Lucerne). CN4: carbon neutral package 4 (*Asparagopsis taxiformis*+ planting trees 220ha + Lucerne).

| Variable | Scenario | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hist | Base30 | LHF | TCN | ID | Asp | Asp+PT | CN1 | CN2 | CN3 | CN4 |
| **Livestock System** | | | | | | | | | | | |
| Stocking Rate (DSE $ha^{-1}$ $yr^{-1}$) | 9.0 | 8.0 | 9.1 | 10.4 | 8.0 | 8.0 | 8.0 | 7.0 | 7.0 | 8.4 | 8.4 |
| Farm Liveweight Production (t LW $yr^{-1}$) | 370.0 | 297.2 | 379.5 | 493.0 | 297.2 | 297.2 | 297.2 | 334.4 | 334.4 | 328.6 | 328.6 |
| Farm Wool Production (t CFW $yr^{-1}$) | 71.0 | 77.6 | 86.0 | 96.0 | 77.6 | 77.6 | 77.6 | 68.8 | 68.8 | 81.8 | 81.8 |
| Farm Livestock Production (t LW + CFW $yr^{-1}$) | 441.0 | 374.8 | 465.6 | 589.0 | 374.8 | 374.8 | 374.8 | 403.2 | 403.2 | 410.5 | 410.5 |
| Protein Production (t protein $yr^{-1}$) | 137.6 | 131.1 | 154.4 | 184.7 | 132.5 | 131.1 | 131.1 | 129.0 | 129.0 | 141.0 | 141.0 |
| Pasture Production (t DM $ha^{-1}$ $yr^{-1}$) | 7.2 | 7.9 | 8.0 | 8.6 | 7.9 | 7.9 | 7.9 | 7.8 | 7.8 | 8.6 | 8.6 |
| Supplementary Feeding (t DM $ha^{-1}$ $yr^{-1}$) | 0.3 | 0.1 | 0.1 | 0.1 | 0.1 | 0.12 | 0.12 | 0.1 | 0.1 | 0.0 | 0.0 |
| Total livestock GHG emissions (t $CO_2$e) | 7,037 | 6,332 | 7,676 | 6,647 | 6,332 | 2,622 | 2,622 | 2,366 | 2,366 | 2,862 | 2,862 |
| **Soil organic carbon** | | | | | | | | | | | |
| Initial SOC stocks (t C $ha^{-1}$, 1m depth) | 175.0 | 184.1 | 185.4 | 185.6 | 184.1 | 184.1 | 184.1 | 184.7 | 184.7 | 185.8 | 185.8 |
| Final SOC stocks (t C $ha^{-1}$, 1m depth) | 179.2 | 186.0 | 188.0 | 188.6 | 186.0 | 186.0 | 186.0 | 186.4 | 186.4 | 189.4 | 189.4 |
| SOC change (t C $ha^{-1}$ $yr^{-1}$) | 0.21 | 0.10 | 0.13 | 0.15 | 0.10 | 0.10 | 0.10 | 0.09 | 0.09 | 0.17 | 0.17 |
| SOC change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | 0.77 | 0.36 | 0.48 | 0.54 | 0.36 | 0.36 | 0.36 | 0.31 | 0.31 | 0.64 | 0.64 |
| SOC change (t $CO_2$e $yr^{-1}$) | 2,425 | 1,142 | 1,531 | 1,719 | 1,142 | 1,142 | 1,142 | 993 | 993 | 2,032 | 2,032 |
| **Forestry/horticulture system** | | | | | | | | | | | |
| Site C change (t C $ha^{-1}$ $yr^{-1}$) | - | - | - | 1.7 | 0.6 | - | - | 1.5 | 1.5 | 1.5 | 1.5 |
| Site C change (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | - | - | - | 6.2 | 2.1 | | | 5.4 | 5.4 | 5.4 | 5.4 |
| Farm Grape Production (t fresh fruit $yr^{-1}$) | | | | | 300 | | | | | | |
| Grapes GHG emissions (t $CO_2$e $ha^{-1}$ $yr^{-1}$) | - | - | - | - | 1.1 | - | - | - | - | - | - |
| Total site C change (t $CO_2$e $yr^{-1}$) | - | - | - | 1,247 | 29 | - | - | 1,247 | 1,372 | 1,247 | 1,372 |
| **Net GHG emissions** | | | | | | | | | | | |
| Net farm emissions (t $CO_2$e) | 4,612 | 5,190 | 6,144 | 3,680 | 5,160 | 1,480 | 233 | 125 | 0 | -418 | -543 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ LW produced) | 6.0 | 7.1 | 7.2 | 3.6 | 7.1 | 2.0 | 0.3 | 0.0 | 0.0 | -0.5 | -0.7 |

| **Variable** | **Scenario** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Hist** | **Base30** | **LHF** | **TCN** | **ID** | **Asp** | **Asp+PT** | **CN1** | **CN2** | **CN3** | **CN4** |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ CFW produced) | 33.5 | 39.6 | 39.8 | 19.9 | 39.6 | 11.3 | 1.8 | 0.0 | 0.0 | -3.0 | -3.9 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ fruit produced) | | | | | -0.01 | | | | | | |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ LW + CFW produced) | 10.5 | 13.8 | 13.2 | 6.2 | 13.8 | 3.9 | 0.6 | 0.3 | 0.0 | -1.0 | -1.3 |
| Net emission intensity (kg $CO_2$e $kg^{-1}$ protein) | 33.5 | 39.6 | 39.8 | 19.9 | 39.0 | 11.3 | 1.8 | 0.0 | 0.0 | -3.0 | -3.9 |
| **Economics** | | | | | | | | | | | |
| Earnings before interests and taxes (‘000 AU$) | 919 | 1,249 | 1,514 | 2,095 | 1,513 | 1,161 | 1,140 | 1,268 | 1,266 | 1,355 | 1,353 |
| Return on Capital (RoC, %) | 5.11 | 6.95 | 8.27 | 10.88 | 8.42 | 6.46 | 6.34 | 6.92 | 6.92 | 7.18 | 7.17 |

**Table A82.9.** Fitted parameters for capital costs, annual farm variable costs, Towards Carbon Neutral (TCN), Income Diversification (ID) and transformational options costs for both cases of study (beef and sheep farm).

| Variables | Beef farm | Sheep farm |
|---|---|---|
| **Capital costs (Year 1)** | | |
| Land | 13,237,500 | 13,250,000 |
| Livestock | 3,941,860 | 3,600,000 |
| Machinery | 1,113,425 | 1,100,000 |
| Water | 32,350 | 32,000 |
| **Annual Farm Variable costs** (exc. supp feed) | 635,230 | 561,525 |
| Annual Supplementary feed | 100,000 | 48,000 |
| Annual Farm Cash Overhead costs | 516,480 | 600,000 |
| **TCN, ID and transformational options** | | |
| Land for trees purchase cost ($ $ha^{-1}$) | 10,000 | - |
| Land for farm expansion ($ $ha^{-1}$) | 10,000 | - |
| Additional overhead costs with land expansion ($ $annum^{-1}$) | 50,000 | |
| Trees Establishment ($ $ha^{-1}$) | 1,500 | 1,500 |
| Trees maintenance p.a. ($ $ha^{-1}$ $annum^{-1}$) | 30 | 30 |
| Trees depreciation ($ $ha^{-1}$ $annum^{-1}$) | 75 | 75 |
| Vaccine per head ($ $hd^{-1}$ $annum^{-1}$) | Uniform<br>Mean= 10<br>Max= 15<br>Min= 5 | Uniform<br>Mean= 6.5<br>Max= 10<br>Min= 3 |
| Extra cattle variable cost ($ $DSE^{-1}$ $annum^{-1}$) | 11.70 | - |
| Extra sheep variable cost ($ $DSE^{-1}$ $annum^{-1}$) | - | 30 |
| Extra livestock depreciation cost ($ $DSE^{-1}$ $annum^{-1}$) | 11.25 | 11.25 |
| Lucerne establishment cost ($ $ha^{-1}$) | 400 | 400 |
| Lucerne depreciation ($ $ha^{-1}$ $annum^{-1}$) | 40 | 40 |
| Extra annual fert. maintenance ($ $ha^{-1}$ $annum^{-1}$) | 50 | 50 |
| Vineyard Establishment ($ $ha^{-1}$) | - | 300,000 |
| Net profit of vineyard ($ $ha^{-1}$ $annum^{-1}$) | - | 10,000 |
| Vineyard depreciation ($ $ha^{-1}$ $annum^{-1}$) | - | 1,200 |
| Biochar ($ kg $DM^{-1}$) | 1.4 | 2 |
| Feeding *Asparagopsis taxiformis* ($ kg $DM^{-1}$) | 2 | 2 |

**Table A82.10.** The main co-benefits and limitations of adaptation options incorporated in the carbon neutral packages discussed by the Regional Reference Group.CN: carbon neutral, GHG: greenhouse gas emissions.

| Adaptation options | Co-benefits | Trade-offs |
|---|---|---|
| ***Asparagopsis*** | -Large reductions in methane emissions.<br>-Carbon sequestration (ocean).<br>-Better water quality.<br>-Remove nutrients in excess from the ocean and reduce acidification. | -High cost/investment.<br>-Scalability.<br>-Formulation/delivery.<br>-Long-term animal health and safety.<br>-Invasive species introduction. |
| **Planting trees** | -Carbon “offsetting” and “insetting”.<br>-Potential agroforestry systems.<br>-Increase natural capital and farm diversification.<br>-Shelterbelt for animals. | -High cost/investment.<br>-More infrastructure (fencing).<br>-Irreversibility to productive land. |
| **TFCE** | -High animal performance.<br>-Large reductions in GHG emissions.<br>-Reduction of production costs. | -Results in the long-term.<br>-Holistic farm management (epigenetics).<br>-Sustained investment in genetics. |
| **Lucerne** | -Farmer’s acceptance to increase farm area covered by legumes.<br>-Potential association between legume management and delivery of *Asparagopsis*.<br>-Nitrogen biofixation. | -Expensive if it fails.<br>-Adaptation period of ruminants to legumes (Ruminant tympany risks) |

**Table A82.11.** Fitted parameters and market price distributions for beef cattle (c $kg^{-1}$ dressed weight)

| Units | 1 Y.O Heifers (PTIC) | Mixed age cows (PTIC) | Steers | MSA steers | Surplus heifers and feeder heifers | Cull cows |
|---|---|---|---|---|---|---|
| Probability Distribution | Pert | Pert | Pert | Pert | Log-normal | Pert |
| Min | 300 | 300 | 300 | 300 | - | 300 |
| Max | 900 | 700 | 900 | 850 | - | 700 |
| M. Likely | 530 | 500 | 530 | 500 | - | 500 |
| Mean | - | - | - | - | 500 | - |
| Std. Deviation | - | - | - | - | 350 | - |

**Table A82.12.** Fitted parameters and market price distributions for wool production (c $kg^{-1}$ Clean Fleece Weight)

| Units | Lambs (16 um) | Ewes (18 um) | Wethers (18 um) | Merino Ram (18 um) |
|---|---|---|---|---|
| Probability Distribution | Pert | Pert | Pert | Pert |
| Min | 1400 | 1385 | 1385 | 1385 |
| Max | 2500 | 2300 | 2300 | 2300 |
| M. Likely | 1700 | 1636 | 1636 | 1636 |

**Table A82.13.** Fitted parameters and market price distributions for sheep meat ($ $kg^{-1}$ dressed weight)

| Units | Lambs at 6 months | Prime lambs | Wethers | Rams | Cull ewes |
|---|---|---|---|---|---|
| Probability Distribution | Pert[A] | Pert | Pert | Pert | Pert |
| Min | 3.00 | 3.40 | 1.50 | 1.50 | 1.50 |
| Max | 8.00 | 8.00 | 5.93 | 5.93 | 5.93 |
| M. Likely | 5.40 | 5.70 | 3.45 | 3.45 | 3.45 |

[A] Family of continuous probability distributions defined by maximum, minimum and most likely values

**Table A82.14.** Monthly change factors showing fractional change in temperate and rainfall for 2030 and 2050 relative to historical monthly average values. Calculated using raw data from Harris et al.[1] for Representative Concentration Pathways 8.5 (RCP8.5)

| | | Sheep farm | | Beef farm | |
|---|---|---|---|---|---|
| | | Rainfall | Temperature | Rainfall | Temperature |
| 2030 | Jan | 1.06 | 1.04 | 0.99 | 1.05 |
| | Feb | 1.06 | 1.04 | 0.99 | 1.05 |
| | Mar | 0.97 | 1.05 | 0.94 | 1.05 |
| | Apr | 0.97 | 1.05 | 0.94 | 1.05 |
| | May | 0.97 | 1.05 | 0.94 | 1.05 |
| | Jun | 0.95 | 1.08 | 0.93 | 1.06 |
| | Jul | 0.95 | 1.08 | 0.93 | 1.06 |
| | Aug | 0.95 | 1.08 | 0.93 | 1.06 |
| | Sep | 0.92 | 1.07 | 0.89 | 1.06 |
| | Oct | 0.92 | 1.07 | 0.89 | 1.06 |
| | Nov | 0.92 | 1.07 | 0.89 | 1.06 |
| | Dec | 1.06 | 1.04 | 0.99 | 1.05 |
| | **Avg** | 0.97 | 1.06 | 0.94 | 1.06 |
| 2050 | Jan | 1.04 | 1.08 | 0.95 | 1.09 |
| | Feb | 1.04 | 1.08 | 0.95 | 1.09 |
| | Mar | 0.94 | 1.09 | 0.89 | 1.09 |
| | Apr | 0.94 | 1.09 | 0.89 | 1.09 |
| | May | 0.94 | 1.09 | 0.89 | 1.09 |
| | Jun | 0.94 | 1.14 | 0.89 | 1.11 |
| | Jul | 0.94 | 1.14 | 0.89 | 1.11 |
| | Aug | 0.94 | 1.14 | 0.89 | 1.11 |
| | Sep | 0.90 | 1.11 | 0.86 | 1.10 |
| | Oct | 0.90 | 1.11 | 0.86 | 1.10 |
| | Nov | 0.90 | 1.11 | 0.86 | 1.10 |
| | Dec | 1.04 | 1.08 | 0.95 | 1.09 |
| | **Avg** | 0.96 | 1.11 | 0.90 | 1.10 |

**Table A82.15.** Baseline for the beef farm modelled. Summary of parameters and biophysical variables considered such as herd structure and dynamics, livestock, pasture and soil management, including key input factors and assumptions for each thematic adaptation which comprised multiple stacked incremental adaptations suggested by the Regional Reference Group.

| ***Herd*** | **Variable** | **Historical/future climate** |
|---|---|---|
| ***Main herd*** **(Cow-calf and home-bred young stock herd)** | Area grazed | · 402ha |
| | Livestock numbers | · Stocking rate of 1.1 cows/ha |
| | Livestock management | · Breed: Angus<br>· Average liveweight at the start of the analysis:<br>-Cows 580 kg LW/head<br>-Weaners 240 kg LW/head<br>-Yearlings 425 kg LW/head steers and 400 kg LW/head heifers<br>-2-3 years old 650 kg LW/head steers and 625 kg LW/head heifers<br>-Calves 50 kg LW/head<br>· Self-replacing herd, replace 11 Feb<br>· Culled cows sold on 10 Feb (6-7 yrs)<br>· Sell excess heifers 30 Sep (26 months) or at 600 kg target LW<br>· Sell steers 15 Sep (25 months) or at 650 kg target LW<br>· Mate 23 Oct, Calving 2 Aug, wean 7 Feb (27 wks)<br>· Age of first joining 1-2 years<br>· 1 bull per 25 cows (kept for 4 years)<br>· Maint. feed females, when thinnest CS2.5<br>· Maint. feed weaners in paddock when thinnest CS3<br>· Maint. feed 100% hay (DM 85%, ME 11.5 MJ/kg DM, CP 20%) |

| | |
|---|---|
| | · Production feeding rule- feedlot cows every year in feedlot and feed 5.5 kg/head to oldest cows from 1 Jul to 31 Jul<br>· Feed steers in a paddock from 1 Feb to reach 515 kg LW/head on 31 Aug<br>· Feed heifers in a paddock from 1 Feb to reach 505 kg LW/head on 15 Sep |
| Livestock genetics | · Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33<br>· Conception rate 95%<br>· Analysis of historical mortality rate from GrassGro 0.5% |
| Pasture types | · Paddock 1 (8ha), Irrigated Perennial Ryegrass (720mm RD), Cocksfoot (850 mm RD) and White Clover (500mm RD)<br>· Paddock 2 (20ha), Irrigated Lucerne-semi winter active (1200mm RD), Perennial Ryegrass (720mm RD)<br>· Paddock 3 (187ha), Rainfed Perennial Ryegrass (720mm RD), Cocksfoot (850 mm RD) and Sub-Clover – Seaton Park (600mm RD)<br>· Paddock 4 (187ha), Rainfed Perennial Ryegrass (750mm RD) and White Clover (500mm RD) |
| Pasture management (note rooting depth in pasture type) | · Irrigate paddock 1 and 2 between 21 Nov and 31 Mar, applying 20mm and fill to 0.95<br>· Cut paddocks 3 and 4 (whenever DM yield exceeds 5000kg/ha between 2 Sep-14 Dec). Proportion gathered 90%. Cutting height 125mm. Don't cut when DM/ha is below 800 kg/ha |
| Grazing management | · Cows- From 1 Jul to 30 Jun graze paddocks 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>· Heifer Weaners- From 1 Jul to 30 Jun graze paddocks 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day |

| | | |
|---|---|---|
| | | · Heifer Yearlings- From 1 Jul to 30 Jun graze paddocks 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>· Steers Weaners- From 1 Jul to 30 Jun graze paddocks 1, 2, 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>· Steers Yearlings- From 1 Jul to 30 Jun graze paddocks 2, 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>· Steers 2-3 years old - From 1 Jul to 30 Jun graze paddocks 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day |
| | Soils | · All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Uc2.3 classification[2]<br>· Paddocks 1 and 2 FS 0.87<br>· Paddocks 3 and 4 FS 0.85 |
| | Tree plantings | · No environmental plantings beyond currently on farm |
| ***Purchased weaner herd*** | Area grazed | · 127ha |
| | Livestock numbers | · Stocking rate of 1.8 steers/ha |
| | Livestock management | · Breed: Angus<br><br>· Average liveweight at the start of the analysis:<br>-Weaners 225 kg LW/head<br>-Yearlings 425 kg LW/head<br>-2-3 years old 650 kg LW/head<br>-3-4 years old 700 kg LW/head<br>· Purchased 1 Feb at 6 mths of age and sold on 15 Sep (25 mths) or at 633 kg LW/head<br>· Maint. feed mature males and weaners in paddock when thinnest CS2.5.<br>· Maint. feed 100% hay (DM 85%, ME 11.5 MJ/kg DM, CP 20%)<br>· Feed steers in a paddock from 1 Feb to reach 500 kg LW/head on 1 Sep |

| | | |
|---|---|---|
| | Livestock genetics | · Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33 |
| | Pasture types | · Paddock 1 (32ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD)<br>· Paddock 2 (32ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD)<br>· Paddock 3 (31.5ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD)<br>· Paddock 3 (31.5ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD) |
| | Pasture management | · Reset pasture species as necessary 1 Feb<br>· Cut paddocks 1 (Years: 1 and 4), 2 (Years: 1 and 2), 3 (Years: 2 and 3) and 4 (Years: 3 and 5) (whenever DM yield exceeds 5000kg/ha between 2 Sep-14 Dec). Proportion gathered 90%. Cutting height 125mm. Don't cut when DM/ha is below 800 kg/ha |
| | Grazing management | · Weaners, Yearlings and 2-3 years old- From 1 Jan to 31 Dec graze paddocks 1, 2, 3 and 4, withhold 14 days, check every 7 days and move when weight gain margin is > 0.01 kg/day |
| | Soils | · All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Uc2.3 classification[2]<br>· All paddocks FS 0.85 |
| | Tree plantings | · No environmental plantings above what currently on farm |
| ***Purchased yearlings with agisted heifers*** | Area grazed | · 40ha |
| | Livestock numbers | · Stocking rate of 3.9 steers/ha |
| | Livestock management | · Breed: Angus<br>· Purchased 1 Feb at 16 mths of age (375 kg LW/head) and sold on 15 Sep (28 mths) or at 545 kg LW/head<br>· Maint. feed steers in paddock when thinnest CS2.<br>· Maint. feed 100% hay (DM 85%, ME 11.5 MJ/kg DM, CP 20%)<br>· Feed steers in a paddock from 1 Feb to reach 350 kg LW/head on 1 Sep |

| | |
|---|---|
| Livestock genetics | · Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33 |
| Pasture types | · Paddock 1 (20ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD)<br>· Paddock 2 (20ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD) |
| Pasture management | · No hay cutting |
| Grazing management | · Steers (Yearling and 2-3 years old)- From 1 Jan to 31 Dec graze paddocks 1 and 2, withhold 14 days, check every 7 days and move when weight gain margin is > 0.01 kg/day |
| Soils | · All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Uc2.3 classification[2]<br>· Paddock 1 and 2 FS 0.82 |
| Tree plantings | · No environmental plantings above what currently on farm |

**Table A82.3.** Baseline for sheep farm modelled. Summary of parameters and biophysical variables considered such as flock structure and dynamics, livestock, pasture and soil management, including key input factors and assumptions for each thematic adaptation which comprised multiple stacked incremental adaptations suggested by the Regional Reference Group.

| ***Flock/herd*** | **Variable** | **Historical/future climate** |
|---|---|---|
| ***Wool flock*** | Area grazed | · 2,545 ha |
| | Livestock numbers | · Stocking rate of 2.8 ewes and 2.7 wethers/ha |
| | Livestock management | · Self-replacing Merino flock, replace 1 Sep<br>· CFA ewes sold 31 Aug (4-5 yrs) into lamb flock<br>· CFA wethers 14 Oct (5-6 yrs)<br>· Mate 22 Apr, lamb 18 Sep, wean 31 Jan (19 wks) and sell excess 1 Feb (19 wks)<br>· Shearing 20 Jul<br>· Maint. feed ewes, wethers and weaners in paddock when thinnest CS2.5<br>· Maint. feed weaners in paddock when thinnest CS3<br>· Maint. feed 78% wheat, 22% hay (ME 12.3 MJ, CP 12%)<br>· Production feeding rule- feedlot ewes every year in feedlot and feed 0.52 kg/head from 15 Jan to 15 Apr, same quality as maint. Feeding<br>· No other production rule for weaner lambs or wethers |
| | Livestock genetics | · Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33<br><br>· Conception rate 88% singles, 0% twins and 0% triplets<br>· Analysis of historical mortality rate from GrassGro 16.2% |

| | |
|---|---|
| Pasture types | · Paddock 1 (800ha), rainfed Phalaris (750mm RD) and sub clover (500mm RD)<br>· Paddock 2 (1,553ha), rainfed Danthonia and Microlaena<br>· Paddock 3 (64ha), rainfed Phalaris seed crop (750mm RD)<br><br>· Paddock 4 (30ha), rainfed Phalaris (750mm RD) and sub-clover (440mm RD, lower rooting depth of subterranean clover to other paddocks due to soil conditions)<br>· Paddock 5 (67ha), irrigated lucerne (900mm RD)<br>· Paddock 6 (31ha), irrigated ARG as wheat (520mm RD) |
| Pasture management (note rooting depth in pasture type) | · Irrigate paddock 5 and 6 between 1 Sep and 31 Mar, applying 18mm and fill to 0.95<br>· Reset pasture species as necessary on 5 Apr<br>· Cut paddock 5 (irrigated lucerne) 10 Nov |
| Grazing management | · Ewes- 15 Jan to 30 Jun graze paddocks 1 and 3, withhold 14 days, check every 7 days and move when weight gain margin is > 0.02 kg/day<br>· Ewes- 1 Jul to 14 Jan graze paddock 1, without 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>· Wethers- 15 Jan to 14 Mar graze paddocks 1 and 3, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>· Wethers- 15 Mar to 30 Jun graze paddocks 1,2 and 3, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>· Wethers- 1 Jul to 15 Sep graze paddocks 1 and 2, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>· Wethers- 16 Sep to 14 Jan graze paddock 1, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>· Ewe and wether weaners- 1 Jan to 14 Jan graze paddocks 1, 4 and 5, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>· Ewe and wether weaners- 15 Jan to 30 Apr graze paddocks 1,3, 4 and 5, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day |

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| | | · Ewe and wether weaners- 1 May to 31 May graze paddocks 1, 3, 4, 5 and 6, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>· Ewe and wether weaners- 1 Jun to 30 Jun graze paddocks 1, 3, 4 and 6, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>· Ewe and wether weaners- 1 Jul to 31 Aug graze paddocks 1, 4 and 6, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day<br>· Ewe and wether weaners- 1 Sep to 31 Dec graze paddocks 1 and 4, withhold 14 days, check every 4 days and move when weight gain margin is > 0.02 kg/day |
| | Soils | · All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Dy5.61 classification[2]<br>· Paddocks 1, 3-6 FS 0.84<br>· Paddock 2 FS 0.80 (natives can't be fertilised, species altered, area changed etc) |
| | Tree plantings | · No environmental plantings beyond currently on farm |
| ***Prime lamb flock*** | Area grazed | · 360 ha |
| | Livestock numbers | · Stocking rate of 9.6 ewes/ha |
| | Livestock management | · Purchased 1 Sep (from wool flock) at 24 mths of age<br>· Mate 11 Apr, lamb 7 Sep, wean 15 Dec (14 wks), sell lambs 15 Dec at 27kg<br>· Shearing 20 Jul<br>· CFA 16 Dec (3-4 yrs)<br>· Maint. feed ewes in paddock when thinnest CS2.5- rerun historical, 2030 and 2050 with CS 2.5<br>· Maint. feed weaners in paddock when thinnest CS3<br>· Maint. feed 78% wheat, 22% hay (ME 12.3 MJ, CP 12%)<br>· Production feeding rule- feedlot ewes every year in feedlot and feed 0.52 kg/head from 15 Jan to 15 Apr, same quality as maint. Feeding |

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| | · No production feeding rule for lambs |
| Livestock genetics | · Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33<br>· Conception rate 91% singles, 2% twins and 0% triplets<br>· Analysis of historical mortality rate from GrassGro 8.5% |
| Pasture types | · Paddock 1 (120ha), rainfed Phalaris (750mm RD) and subterranean clover (500mm RD)<br>· Paddock 2 and 3 a repeat of paddock 1 |
| Pasture management | · Reset pasture species as necessary 5 Apr (mimic sub-clover germination if required)<br>· Cut one paddock per year 16 Dec, rotating between the three paddocks so always have 2 for grazing |
| Grazing management | · All sheep- 1 Jan to 31 Dec graze paddocks 1, 2 and 3, withhold 14 days, check every 4 days and move when weight gain margin is > 0.025 kg/day |
| Soils | · All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Dy5.61 classification[2]<br>· Paddocks 1,2 &3 FS 0.85 |
| Tree plantings | · No environmental plantings above what currently on farm |

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| ***Cattle herd*** | Area grazed | · 265ha |
| | Livestock numbers | · Stocking rate of 1.5 cows/ha (~ 337 cows, 55 replacement heifers per age group, 145 steers and 90 non-replacement heifers) |
| | Livestock management | · Self-replacing Hereford herd 1 Apr<br>· CFA cows 31 Mar (7-8 yrs)<br>· Mate 20 Nov, wean 31 Mar, sell excess heifers 1 Apr at 31 weeks or 220 kg, sell steers 28 Feb at 18 months or 460 kg<br>· Maint. feed cows in paddock when thinnest CS3<br>· Maint. feed weaners in paddock when thinnest CS2.5<br>· Maint. feed 100% hay (ME 11.0 MJ, CP 14%)<br>· Production feeding rule- feed steers in paddock from 1 Apr to reach 460 kg 28 Feb<br>· Production feeding rule- feed heifers in paddock from 1 Sep to reach 250 kg 31 Mar<br>· Production feed same quality hay as per maint. Feeding |
| | Livestock genetics | · Default within GrassGro<br>· Conception rate of 92% at CS3 |
| | Pasture types | · Paddock 1 (132.5ha), rainfed Phalaris (750mm RD) and subterranean clover (500mm RD)<br>· Paddock 2 same as paddock 1 |
| | Pasture management | · Reset pasture species as necessary 5 Apr (mimic sub-clover germination if required)<br>· No hay cutting |
| | Grazing management | · All cattle- 1 Jan to 31 Dec graze paddocks 1 and 2, withhold 14 days, check every 7 days and move when weight gain margin is > 0.01 kg/day |

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| Soils | · All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Dy5.61 classification[2]<br>· Paddock 1 & 2 FS 0.85 |
| Tree plantings | · No environmental plantings above what currently on farm |

**Table A82.17.** Summarised thematic adaptations co-designed with a Regional Reference Group (RRG) and initially categorized in different themes (low-hanging fruit, towards carbon neutral, income diversification and transformational adaptations). The extent to which each factor was varied from the baseline level was derived from feasible values from the literature.

| | Adaptation | Assumptions | References |
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| Low-hanging fruit adaptations | Increasing soil fertility | Increase soil fertility 3% in all paddocks (3% higher fertility scalar in GrassGro). Fertility scalar is 0-1 value that represents the degree to which a pasture growth will be restricted by soil fertility at times when soil water availability does not limit pasture growth. | [3] |
| | Introduction of Talish clover | Paddocks grazed by wool and prime lamb flocks in the sheep farm including Talish clover with 600 mm rooting depth in GrassGro adapted from white clover. | [4] |
| | Increasing 10% root depth | Increased rooting depth by 10% in all the modelled species within the paddock (upper limit 1200 mm) | - |
| | Increasing 10% SR | Increasing notional stocking rate by 10% from the baseline for the beef and sheefS1p farm to match altered seasonal pasture supply. | - |
| | Altering calving/lambing date | Essentially, we altered lambing/calving dates and selling dates/SR/LW to better match seasonal pasture supply.<br>The updated rules in the beef farm:<br>Mate 8 Oct, Calving 18 Jul, wean 7 Feb (29 wks). The steers were sold 68 kg LW/head heavier and the heifers were sold 18 kg LW/head heavier.<br>Sell excess heifers 8 Oct (27 months) or at 600 kg target LW. Feed steers in a paddock from 1 Feb to reach 535 kg LW/head on 31 Aug. Feed heifers in a paddock from 1 Feb to reach 520 kg LW/head on 15 Sep.<br>The updated rules in the sheep farm:<br>Self-replacing Merino flock, replace 18 Aug<br>CFA ewes sold 17 Aug (4-5 yrs) into lamb flock. Mate 8 Apr, lamb 4 Sep, wean 17 Jan (19 wks) and sell excess 10 Feb as preliminary modelling results suggest feed available until then. Shearing 6 Jul.<br>Purchased 18 Aug (from wool flock) at 24 mths of age. Mate 14 days sooner so 28 Mar, lamb 24 Aug, wean 20 Dec (17 wks) as feed remained until then. Shearing 6 Jul. | - |

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| | Increasing 10-20% FCE | Increasing feed conversion efficiency 10% in 2030 and 20% in 2050 period. Alter FCE in GrassGro increasing factors by 10%, the parameters c-k-1, c-k-2, c-k-13 and c-k-14 were 0.55, 0.022, 0.0385 and 0.363 or 20%, the parameters c-k-1, c-k-2, c-k-13 and c-k-14 were 0.60, 0.024, 0.042 and 0.396.<br>C-k-1 and c-k-2 = parameters controlling efficiency of maintenance<br>C-k-13 and c-k-14 = parameters controlling efficiency of gain | [5] |
| Towards carbon neutral adaptations | Pasture renovation with lucerne | Add Lucerne (semi winter active, 1200mm RD) as deep-rooted species, mix with Perennial Ryegrass in all paddocks for the beef and sheep farm | - |
| | Enteric $CH_4$ inhibitor vaccine | Alter enteric $CH_4$ fermentation in SB-GAF by 30% to reflect an intervention to reduce emissions | [6] |
| | Planting trees | In the beef farm:<br>Extra 50ha for environmental plantings in FullCAM (Tasmanian Blue Gums, *Eucalyptus globolus*).<br>In the sheep farm:<br>Assumed 200ha or 220ha of trees planted to environmental plantings in FullCAM but through thickening of existing non-grazed areas in TCN and CN packages (trees, shrubs and understory species endemic to the region). | |
| Income diversification adaptations | Buying a farm in a different region | Buying an extra farm in a different agroclimatic region (by translocating cow calf systems to Gladstone, NE Tasmania to dedicate the current farm for backgrounding and finishing of weaners). More details about soil and pasture type, pasture and herd management in Table A82.5. | See Table A82.5 |
| | Diversifying land use with grapes | Diversifying land use with grapes (by thickening 20 ha land for sheep farm with a vineyard for Pinot Noir). More details about vineyard management, production and assumptions can be found in subsection *Diversifying land use with grapes on a sheep farm.* | See subsection *Diversifying land use with grapes on a sheep farm.* |
| | Hosting a wind farm | This adaptation implicates a 3- year project leasing a small part of the land to host 12 wind turbines in the beef farm. Given that each turbine generates 7500 AUD $yr^{-1}$ in a period of 35 years and our simulation comprise a 40-year period under futures climates, | Add Epuron reference |

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| | | we assumed an income of 7500 AUD $yr^{-1}$ from 2022 to 2041 and 5625 AUD $yr^{-1}$ from 2042 to 2061 per turbine. $Annual\ income\ per\ wind\ turbine\ (period\ 2022-2041, AUD\ yr^{-1}) = 7500\ AUD\ yr^{-1}$ $Annual\ income\ per\ wind\ turbine\ (period\ 2042-2061, AUD\ yr^{-1}) = \frac{7500\ AUD\ yr^{-1} * 15\ yr}{20\ yr} = 5625\ AUD\ yr^{-1}$ 15 is the remaining number of years of the project in the second simulated period and 20 is the total number of years for such period of time. | |
| Transformational adaptations | Feeding biochar | For this adaptation options, we assumed an increasing liveweight production about 10% for the beef farm and altered enteric $CH_4$ fermentation in SB-GAF by 10% in both case studies to reflect an intervention to reduce emissions. To represent SOC changes by C enrichment in manure, the entire calculation process in described in the section '*Accounting for carbon changes in soil by enrichment of manure with biochar*' | See subsection '*Accounting for carbon changes in soil by enrichment of manure with biochar*' |
| | Feeding red seaweed (*Asparagopsis taxiformis*) | Alter enteric $CH_4$ fermentation in SB-GAF by 80% to reflect an intervention to reduce emissions in weaned animals. Here, we assumed a feeding rate between diet content of *Asparagopsis taxiformis* (kg DM) and pasture intake (kg DM) of 0.5%. $A.taxiformis\ (kg\ DM) = Total\ pasture\ intake\ (kg\ DM) * 0.05$ | [7-9] |
| | Radical increasing in FCE (15-30%) | Increasing feed conversion efficiency 15% in 2030 and 30% in 2050 period. Alter FCE in GrassGro increasing factors by 15%, the parameters c-k-1, c-k-2, c-k-13 and c-k-14 were 0.575, 0.0253, 0.0403 and 0.378 or 30%, the parameters c-k-1, c-k-2, c-k-13 and c-k-14 were 0.65, 0.026, 0.0455 and 0.429. C-k-1 and c-k-2 = parameters controlling efficiency of maintenance C-k-13 and c-k-14 = parameters controlling efficiency of gain | [5] |

**Table A82.18.** Buying an extra farm in a different agroclimatic region (by translocating cow calf systems to Gladstone, NE Tasmania to dedicate the current farm for backgrounding and finishing of weaners). Modelling parameters for Stanley and Gladstone farm.

| *Herd* | Variable | Stanley (Baseline) | Gladstone (main herd) and Stanley (Weaners from Gladstone + Purchased weaners + purchased yearlings and agisted heifers) |
|---|---|---|---|
| ***Main herd* (Cow-calf and home-bred young stock herd)** | Area grazed | · 402ha | · 750ha |
| | Livestock numbers | · Stocking rate of 1.1 cows/ha | · Stocking rate of 0.9 cows/ha |
| | Livestock management | · Breed: Angus<br>· Average liveweight at the start of the analysis:<br>-Cows 580 kg LW/head<br>-Weaners 240 kg LW/head<br>-Yearlings 425 kg LW/head steers and 400 kg LW/head heifers<br>-2-3 years old 650 kg LW/head steers and 625 kg LW/head heifers<br>-Calves 50 kg LW/head<br>· Self-replacing herd, replace 11 Feb<br>· Culled cows sold on 10 Feb (6-7 yrs)<br>· Sell excess heifers 30 Sep (26 months) or at 600 kg target LW<br>· Sell steers 15 Sep (25 months) or at 650 kg target LW<br>· Mate 23 Oct, Calving 2 Aug, wean 7 Feb (27 wks)<br>· Age of first joining 1-2 years<br>· 1 bull per 25 cows (kept for 4 years)<br>· Maint. feed females, when thinnest CS2.5 | · Breed: Angus<br>· Average liveweight at the start of the analysis:<br>-Cows 580 kg LW/head<br>-Weaners 240 kg LW/head<br>-Calves 50 kg LW/head<br>· Self-replacing herd, replace 11 Feb<br>· Culled cows sold on 10 Feb (6-7 yrs)<br>· Sell excess heifers 8 Feb (27 wks) or at 200 kg target LW<br>· Sell steers 8 Feb (27 wks) or at 220 kg target LW<br>· Mate 23 Oct, Calving 2 Aug, wean 7 Feb (27 wks)<br>· Age of first joining 1-2 years<br>· 1 bull per 25 cows (kept for 4 years)<br>· Maint. feed females, when thinnest CS2.5<br>· Maint. feed weaners in paddock when thinnest CS3<br>· Maint. feed 100% hay (DM 85%, ME 11.5 MJ/kg DM, CP 20%) |

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| | · Maint. feed weaners in paddock when thinnest CS3<br>· Maint. feed 100% hay (DM 85%, ME 11.5 MJ/kg DM, CP 20%)<br>· Production feeding rule- feedlot cows every year in feedlot and feed 5.5 kg/head to oldest cows from 1 Jul to 31 Jul<br>· Feed steers in a paddock from 1 Feb to reach 515 kg LW/head on 31 Aug<br>· Feed heifers in a paddock from 1 Feb to reach 505 kg LW/head on 15 Sep | · Production feeding rule- feedlot cows every year in feedlot and feed 5.5 kg/head to oldest cows from 1 Jul to 31 Jul |
| Livestock genetics | · Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33<br>· Conception rate 95%<br>· Analysis of historical mortality rate from GrassGro 0.5% | · Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33<br>· Conception rate 95%<br>· Analysis of historical mortality rate from GrassGro 0.5% |
| Pasture types | · Paddock 1 (8ha), Irrigated Perennial Ryegrass (720mm RD), Cocksfoot (850 mm RD) and White Clover (500mm RD)<br>· Paddock 2 (20ha), Irrigated Lucerne-semi winter active (1200mm RD), Perennial Ryegrass (720mm RD)<br>· Paddock 3 (187ha), Rainfed Perennial Ryegrass (720mm RD), Cocksfoot (850 mm RD) and Sub-Clover – Seaton Park (600mm RD)<br>· Paddock 4 (187ha), Rainfed Perennial Ryegrass (750mm RD) and White Clover (500mm RD) | · Paddock 1 (187ha), Rainfed Perennial Ryegrass (720mm RD), Cocksfoot (850 mm RD) and White Clover (500mm RD)<br>· Paddock 2 (187ha), White Clover (500mm RD), Rainfed Perennial Ryegrass (720mm RD)<br>· Paddock 3 (188ha), Rainfed Perennial Ryegrass (720mm RD), Cocksfoot (850 mm RD) and Sub-Clover – Seaton Park (600mm RD)<br>· Paddock 4 (188ha), Rainfed Perennial Ryegrass (750mm RD) and White Clover (500mm RD) |
| Pasture management (note rooting depth in pasture type) | · Irrigate paddock 1 and 2 between 21 Nov and 31 Mar, applying 20mm and fill to 0.95 | · Rainfed pastures |

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| | · Cut paddocks 3 and 4 (whenever DM yield exceeds 5000kg/ha between 2 Sep-14 Dec). Proportion gathered 90%. Cutting height 125mm. Don't cut when DM/ha is below 800 kg/ha | · Cut paddocks 1 (Years: 1 and 2), 2 (Years: 2 and 3), 3 (Years: 3 and 4) and 4 (Years: 1 and 4) (whenever DM yield exceeds 5000kg/ha between 2 Sep-14 Dec). Proportion gathered 90%. Cutting height 125mm. Don't cut when DM/ha is below 800 kg/ha |
| Grazing management | · Cows- From 1 Jul to 30 Jun graze paddocks 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>· Heifer Weaners- From 1 Jul to 30 Jun graze paddocks 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>· Heifer Yearlings- From 1 Jul to 30 Jun graze paddocks 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>· Heifers 2-3 years old- From 1 Jul to 30 Jun graze paddocks 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>· Steers Weaners- From 1 Jul to 30 Jun graze paddocks 1, 2, 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>· Steers Yearlings- From 1 Jul to 30 Jun graze paddocks 2, 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day<br>· Steers 2-3 years old - From 1 Jul to 30 Jun graze paddocks 3 and 4, withhold 21 days, check every 4 days and move when weight gain margin is > 0.01 kg/day | · As per Stanley (mature breeders and self-replacing herd) |
| Soils | · All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Uc2.3 classification[2]<br>· Paddocks 1 and 2 FS 0.87<br>· Paddocks 3 and 4 FS 0.85 | · All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Uc2.33 classification[2]<br>· Paddocks 1 and 2 FS 0.35<br>· Paddocks 3 and 4 FS 0.35 |

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| | Tree plantings | · No environmental plantings beyond currently on farm | · No environmental plantings above what currently on farm |
| ***Purchased weaner herd*** | Area grazed | · 127ha | |
| | Livestock numbers | · Stocking rate of 1.8 steers/ha | |
| | Livestock management | · Breed: Angus<br><br>· Average liveweight at the start of the analysis:<br>-Weaners 225 kg LW/head<br>-Yearlings 425 kg LW/head<br>-2-3 years old 650 kg LW/head<br>-3-4 years old 700 kg LW/head<br>· Purchased 1 Feb at 6 mths of age and sold on 15 Sep (25 mths) or at 633 kg LW/head<br>· Maint. feed mature males and weaners in paddock when thinnest CS2.5.<br>· Maint. feed 100% hay (DM 85%, ME 11.5 MJ/kg DM, CP 20%)<br>· Feed steers in a paddock from 1 Feb to reach 500 kg LW/head on 1 Sep | • Breed: Angus<br><br>• Average liveweight at the start of the analysis:<br>-Weaners 210 kg LW/head<br>-Yearlings 415 kg LW/head<br>-2-3 years old 640 kg LW/head<br>-3-4 years old 690 kg LW/head<br>• Purchased 1 Feb at 6 mths of age and sold on 15 Sep (25 mths) or at 610 kg LW/head<br>• Maint. feed mature males and weaners in paddock when thinnest CS2.5.<br>• Maint. feed 100% hay (DM 85%, ME 11.5 MJ/kg DM, CP 20%)<br>• Feed steers in a paddock from 1 Feb to reach 490 kg LW/head on 1 Sep |
| | Livestock genetics | · Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33 | |
| | Pasture types | · Paddock 1 (32ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD)<br><br>· Paddock 2 (32ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD)<br>· Paddock 3 (31.5ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD) | |

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| | | · Paddock 4 (31.5ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD) |
| | Pasture management | · Reset pasture species as necessary 1 Feb<br>· Cut paddocks 1 (Years: 1 and 4), 2 (Years: 1 and 2), 3 (Years: 2 and 3) and 4 (Years: 3 and 5) (whenever DM yield exceeds 5000kg/ha between 2 Sep-14 Dec). Proportion gathered 90%. Cutting height 125mm. Don't cut when DM/ha is below 800 kg/ha |
| | Grazing management | · Weaners, Yearlings and 2-3 years old- From 1 Jan to 31 Dec graze paddocks 1, 2, 3 and 4, withhold 14 days, check every 7 days and move when weight gain margin is > 0.01 kg/day |
| | Soils | · All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Uc2.3 classification[2]<br>· All paddocks FS 0.85 |
| | Tree plantings | · No environmental plantings above what currently on farm |
| ***Purchased yearlings with agisted heifers*** | Area grazed | · 40ha |
| | Livestock numbers | · Stocking rate of 3.9 steers/ha |
| | Livestock management | · Breed: Angus<br>· Purchased 1 Feb at 16 mths of age (375 kg LW/head) and sold on 15 Sep (28 mths) or at 545 kg LW/head<br>· Maint. feed steers in paddock when thinnest CS2.<br>· Maint. feed 100% hay (DM 85%, ME 11.5 MJ/kg DM, CP 20%) |

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| | | · Feed steers in a paddock from 1 Feb to reach 350 kg LW/head on 1 Sep | |
| | Livestock genetics | · Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33 | |
| | Pasture types | · Paddock 1 (20ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD)<br>· Paddock 2 (20ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD) | |
| | Pasture management | · No hay cutting | |
| | Grazing management | · Steers (Yearling and 2-3 years old)- From 1 Jan to 31 Dec graze paddocks 1 and 2, withhold 14 days, check every 7 days and move when weight gain margin is > 0.01 kg/day | |
| | Soils | · All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Uc2.3 classification[2]<br>· Paddock 1 and 2 FS 0.82 | |
| | Tree plantings | · No environmental plantings above what currently on farm | |
| ***Weaners from Gladstone to Stanley*** | Area grazed | | • 402ha |
| | Livestock numbers | | • Stocking rate of 1.6 steers/ha |
| | Livestock management | | • Breed: Angus<br>• Average liveweight at the start of the analysis:<br>-Weaners 210 kg LW/head<br>-Yearlings 415 kg LW/head<br>-2-3 years old 640 kg LW/head<br>-3-4 years old 690 kg LW/head |

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| | • Purchased 1 Feb at 6 mths of age and sold on 15 Sep (25 mths) or at 610 kg LW/head<br>• Maint. feed mature males and weaners in paddock when thinnest CS2.5.<br>• Maint. feed 100% hay (DM 85%, ME 11.5 MJ/kg DM, CP 20%)<br>• Feed steers in a paddock from 1 Feb to reach 490 kg LW/head on 1 Sep |
| Livestock genetics | • Default within GrassGro for c-k-1, c-k-2, c-k-13 and c-k-14 are 0.5, 0.02, 0.035 and 0.33 |
| Pasture types | • Paddock 1 (32ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD)<br>• Paddock 2 (32ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD)<br>• Paddock 3 (31.5ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD)<br>• Paddock 4 (31.5ha), Rainfed Perennial Ryegrass (720mm RD) and White Clover (500mm RD) |
| Pasture management | • Reset pasture species as necessary 1 Feb<br>• Cut paddocks 1 (Years: 1 and 4), 2 (Years: 1 and 2), 3 (Years: 2 and 3) and 4 (Years: 3 and 5) (whenever DM yield exceeds 5000kg/ha between 2 Sep-14 Dec). Proportion gathered 90%. Cutting height 125mm. Don't cut when DM/ha is below 800 kg/ha |
| Grazing management | • Weaners, Yearlings and 2-3 years old- From 1 Jan to 31 Dec graze paddocks 1, 2, 3 and 4, withhold 14 days, check every 7 days and move when weight gain margin is > 0.01 kg/day |
| Soils | • All paddocks soil texture defined from Atlas in GrassGro, corresponding to a Northcote Uc2.3 classification[2]<br>• All paddocks FS 0.85 |

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| Tree plantings | | • No environmental plantings above what currently on farm |

**References for Appendices of Appendix 8.2**


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# Appendix 8.3: Effects of increasingly variable climates on the productivity and profitability of red meat farms in Tasmania

A thesis submitted in partial fulfilment of the requirements for the degree of

Bachelor of Agricultural Science with Honours (S4A)

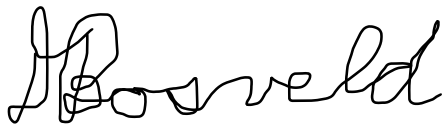
University of Tasmania

October 2021

Daniel Bosveld

## Declaration

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma and, to the best of my knowledge, contains no copy or paraphrase or material published or written by any other person, except where due reference is made in the text of this thesis.



Daniel Grant Bosveld

University of Tasmania, Hobart

29th October 2021

## Abstract

Rainfed pastures comprise the dominant feed supply of most Tasmanian farms, but such feed is highly susceptible to the vagaries of the climate. Previous studies of the impacts of climate change on the Tasmanian agricultural sector have primarily focussed on productivity, very few concurrently consider productivity and profitability.

The purpose of this study was thus (1) to review the impact of a future, more variable climate on pasture and livestock productivity and profitability, and (2) investigate a range of adaptation options to ascertain potential changes in productivity and profitability.

Effects of climate change in 2050 on pasture-based livestock systems were investigated for two representative beef and sheep farms, the former located at Stanley in north-western Tasmania, the latter in the drier region of the Midlands near Campbell Town. Each farm enterprise was modelled using GrassGro; future climate data was generated from an ensemble of global circulation models (GCMs) based on Representative Concentration Pathways (RCP) 8.5. The approach used to generate the future climates included algorithms to perturb historical climates such that future climate data contained greater variability, including droughts, heat waves and extreme rainfall events while still ensuring alignment with projections from the GCMs.

By 2050, the productivity and profitability of both farms modestly increased. This is a significant result in itself, considering these changes occurred in the absence of any adaptations. Mixed effects of adaptations on productivity and profitability were observed. Increasing the size of mature breeding cows (i.e., genetic intervention) resulted in the greatest positive impact on gross margins (+17%) and productivity (+7%) relative to the 2050 non-adapted treatment. Shifting the date of first lambing to later in the year resulted in the greatest increase in productivity (+6%), but profitability did not increase due the greater amount of supplementary feed required. Selling cattle earlier in the year had a positive impact on ground cover, although productivity (-1%) and profitability (-3%) declined. It is concluded that both regions are likely to remain relatively productive and profitable through to 2050 assuming all other aspects of these systems remain unchanged. With adaptation, beef cattle and sheep farmers in Tasmania may have a geographical advantage relative to hotter, lower rainfall regions on the Mainland.

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# Literature review: adapting livestock farming systems to climate change

## Introduction

The purpose of this review is to examine how livestock production systems perform and may adapt to increasingly variable climates expected under climate change. Knowledge gaps are outlined, including coverage of adaptations that have been considered previously. The review examines the effects of adaptations on biophysical, economic and social aspects of adaptation with a view to informing the modelling shown in later chapters.

## Global overview

Livestock production systems are critical in feeding the global population, often not by choice but by need (Harrison et al. 2021b). Livestock production comprises a third of global protein consumption and 17% of calorie intake (Thornton 2010). Without this readily available source of nutrition, large populations of rural poor would be malnourished. Livestock also provide milk, eggs, fibre, manure and hides (Harrison et al. 2021b). Both developed and developing nations use livestock for cash flows, cultural status, draught power and crop nutrient cycling (Harrison et al. 2021b).

Globally, nearly a billion people depend on 1.43 billion cattle and 1.87 billion sheep for their livelihood and food security (Robinson et al. 2014). Cattle, sheep and goats are utilised for their meat and dairy. In 2050, the global population is expected to reach around 10 billion (UN 2015), increasing demand for animal protein as a food source. In the next 20 years, 80% of growth in livestock production is expected in occur in developing countries (Harrison et al. 2021b). Income diversification and nutritional diversification are often dependent on small livestock holdings (Harrison et al. 2021b), while more arid regions are often unable to sustain cropping. In contrast, livestock are better adapted to these conditions, where ruminants are able to convert fibrous forages into protein-rich food for human consumption.

Sheep comprise a source of meat, wool and occasionally milk. In terms of global production, most wool transits through China for processing before being sold around the world (Mornement 2021). In recent times, wool tends to be a luxury product, with prices that are highly sensitive to changes in global market conditions. In 2019, the Chinese apparel market was worth US$371 billion, but as much as US$60 billion was wiped off in one year by the financial uncertainty caused by coronavirus (Oliver Wyman 2020). A serious challenge for wool producers is thus maintaining gross margins under variable market and climatic conditions.

## Overview of livestock in Australia

The livestock industry provided AU$17.6 billion towards the Australian Gross Domestic Product (GDP) in 2018-19 (MLA 2020b). Australia's large land surface and relatively small population allows the export of much of the meat, wool and dairy produced. While Australia produces only around four percent of global beef supply, Australia is the world's third largest beef exporter after India and Brazil (MLA 2017). In 2020, the national cattle herd was around 26 million head (MLA 2020a), as shown in Fig. 1.

Australia is the largest sheep meat exporter in the world, but places behind China as the second largest producer (MLA 2016). Australia contributes around 25% of the wool sold globally, with national domestic export in 2017 worth AU$3.6 billion (ABARES 2020b). The wool produced in that year came from around 74 million sheep but declined to 67 million in 2020 (MLA 2020c).

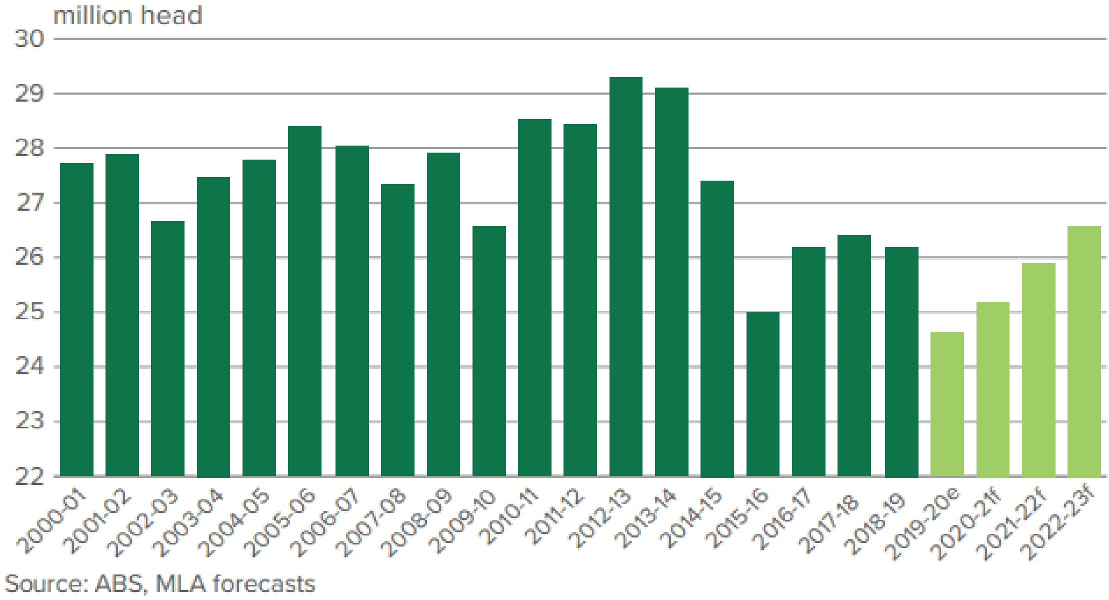


**Figure 2**. Australian beef cattle numbers and forecasts from 2000 to 2023. (MLA 2021a)

As shown in Fig. 1, cattle numbers are highly variable from year to year. This variability is driven primarily by drought and markets. Droughts cause an oversupply in the meat market and a drop in prices as farmers destock their farms due to the absence of pasture-based or rangeland feed. In contrast, when rains eventually return, the demand for cattle increases, raising market prices. At the time of writing, the enduring drought in central New South Wales and Queensland has caused dramatic increases in demand, driving up national wholesale and retail prices for red meat. Farmers that are able to continuing farming through droughts are more able to sell livestock and benefit from the situation (MLA 2021d).

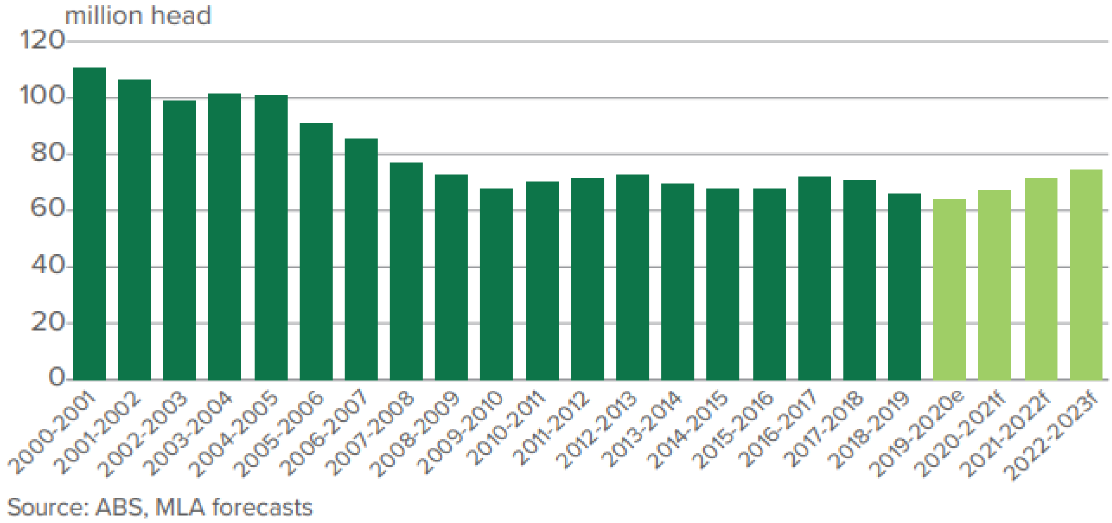


**Figure 3**. Australian sheep numbers and forecasts from 2000 to 2023. (MLA 2021b)

A long-term decline in the national sheep flock (Fig. 2) can be traced back to the end of the wool price index. Despite this, rising prices for lamb and mutton over the last 11 years have allowed national sheep production to remain buoyant.

The Australian feedlot industry is smaller than the national herd grazing pastures and rangelands. Of the 26 million cows in Australia, only a million are in feedlots, with the majority in Queensland (Murray 2020). While cattle often spend the majority of their life on pasture, as much as 50% can be finished (fattened rapidly prior to market) using grain before slaughter (MLA 2020d). Pasture-based systems predominate in Australia because for most of the year, temperatures are mild relative to those of livestock systems in Europe and North America (Harrison 2021).

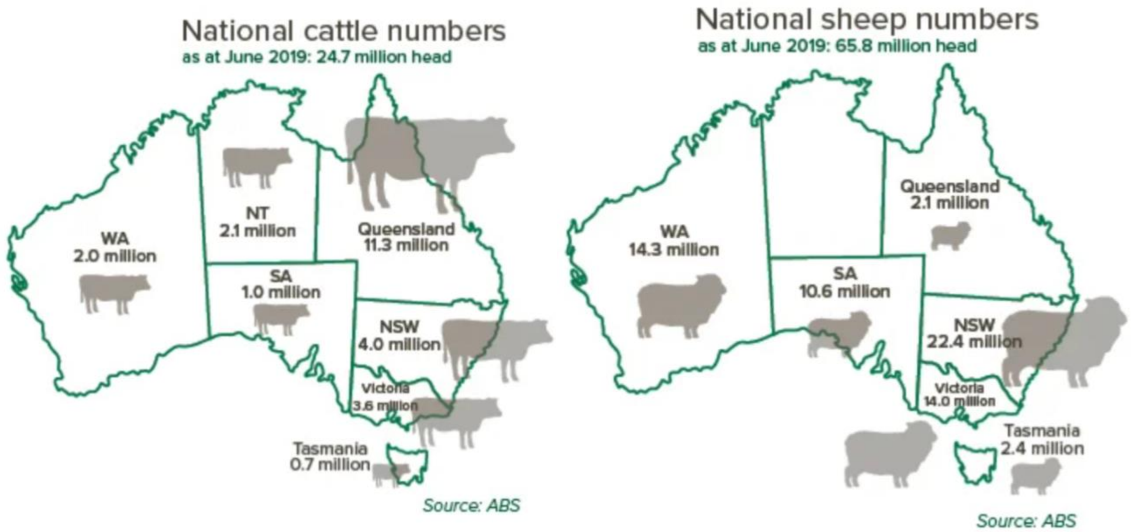


**Figure 4**. Distributions of cattle (left) and sheep (right) in Australia as of June 2019 (MLA 2020b)

Cattle production systems are more common in the central inland environments of Queensland and the Northern Territory (Fig. 3), as bovines are both more resilient to high temperatures and predators, such as wild dogs and dingoes. In fact, sheep are banned in the Northern Territory due to the presence of bluetongue virus that can cause severe illnesses to sheep (Northern Territory Government 2021). Dairy production systems tend to be concentrated in the southern regions of Australia due to cooler climes, longer pasture growing seasons, greater access to irrigation systems and external supplementary feed. Victoria is the biggest dairy producer by volume, followed by New South Wales and then Tasmania (Dairy Australia 2021). These states respectively produce 64%, 12%, and 11% of national milk production in Australia.

## Livestock production in Tasmania

In Tasmania, meat from beef and superfluous dairy cattle account for $314 million per year (DPIPWE 2017). Tasmanian dairy is worth a billion dollars annually (DairyTas 2020) and is concentrated in (but not limited to) the northern parts of the state. The inexpensive, reliable and highly digestible source of pasture feed is a major driver of profitability for Tasmania, along with the marketable avoidance of grains and Hormone Growth Promotants (DPIPWE 2017). Pasture-based feed produced by rainfall is often much less expensive than other forms of feed, such as pellets or hay (Ho et al. 2014).

Beef cattle and sheep in Tasmania are fewer in number than dairy cattle, but still very much a vital part of the Tasmanian agricultural economy. In 2017, there were around 600,000 beef cattle and 2.2 million sheep in Tasmania (MLA 2017), collectively worth $50M (ABARES 2020). The majority of Tasmanian sheep are located in the centre of the state (the Midlands) due to large expanses of pastures and more suitable climate, with lower rainfall regions less likely to cause footrot or wool mould. Similar to beef and dairy production, sheep mostly rely on rainfed pastures as their primary source of feed, although supplementary feeding of hay or grain during drier seasons (late summer and early autumn) is common.

## Climate change in Australia

Anthropogenic climate change is intensifying in Australia, with more than half of the increase in global surface temperatures from 1951-2010 linked to greenhouse gas (GHG) emissions produced by humans (CSIRO & Bureau of Meteorology 2020). Greenhouse gases (GHGs) absorb radiation from the sun and re-radiate it back to earth, analogous to a glasshouse where closed environments facilitate warming. Continuing global industrialisation in many countries means that temperatures will continue rising over the next few decades, even if governments imposed urgent mitigation actions today (Harrison et al., 2021b).

The International Panel on Climate Change (IPCC) developed four emissions scenarios to represent possible climate futures, accounting for projected socio-economic pathways. In the IPCC Assessment Report 5 (AR5), emissions scenarios are termed *Representative Concentration Pathways* (RCP; Fig. 5). The extreme emissions scenario (RCP8.5) most closely represents realised temperature change in Australia and for much of the world (Riahi et al. 2011; Schwalm, Glendon & Duffy 2020). The emissions scenario assumes an absence of mitigation introduced by global governments and a continuing increase in fossil fuel consumption (Schwalm, Glendon & Duffy 2020).

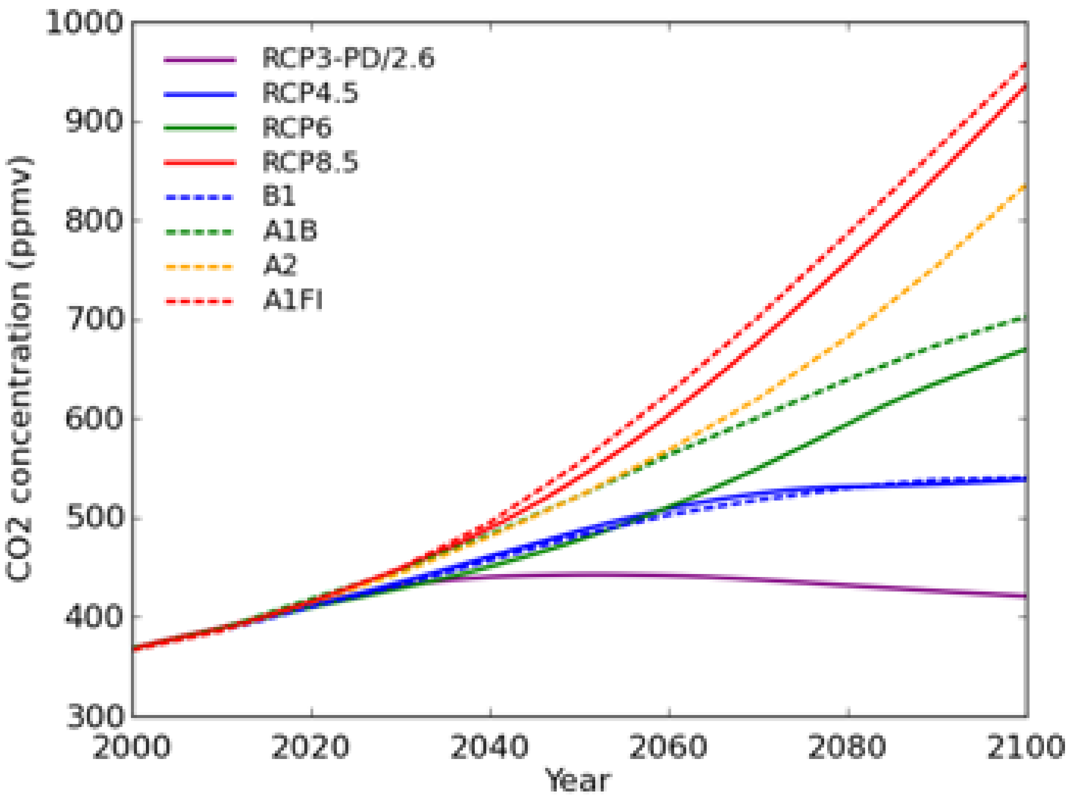


**Figure 4.** Carbon dioxide concentrations for (more recent) RCPs (solid lines) and (older) SRES scenarios (dashed lines). The graph shows the changing projected carbon dioxide ($CO_2$) emissions over the 21st century for a series of models. Each model relies on a different set of socio-economic assumptions as to how the world will respond to climate change and emissions mitigation. Actual ambient $CO_2$ concentrations are tracking most closely to RCP8.5. (Adapted from Climate Change in Australia website 2021).

In southern Australia, average temperatures are expected to increase by 0.8-2.8°C by 2050 (Moore & Ghahramani 2013a), leading to fewer frosts and more warm spells. Annual rainfall is expected to decrease by over the same period by 0-20%, with the greatest effect in spring (Moore & Ghahramani 2013a).

But very likely the most important impact of climate change will be that associated with extreme climatic events (Harrison 2021). Rainfall events are expected to be more extreme, with altered seasonal distribution, and greater durations of dry days (drought) (CSIRO 2020). More dry days with more extreme temperatures leads to heat waves and higher temperatures. Increasing severity and frequency may also result in cascading extreme events, where several climatic episodes occur concurrently or contiguously. A severe event could be defined as three or more mild events that would not otherwise be noticed if it occurred as a sole event. However, when they occur contiguously and/or in sequence, their implications for agricultural production can be dire (Field et al. 2012).

## Implications of changing climates for livestock production systems

Climate change will impact livestock production systems in many ways. Increasing daily temperatures and lower, more sporadic rainfall patterns will challenge the production of pasture-based feed production. Pasture growth rates and quality (digestibility and energetic content) will most likely decline (Chang-Fung-Martel et al. 2017), while the feeding of supplementary grain will become more difficult and expensive to grow and therefore, harder to source (Henry et al. 2012). Human demand for grain will increase and will compete with the demand from animals as both populations increase. Currently, over 200,000 tonnes of grain are consumed by Tasmanian livestock each year, with the demand being mostly driven by the growing dairy industry (Stevens 2016). This demand rises and fall depending on annual pasture production. Climate change thus is a real threat to livestock production due to the tight linkages between pasture production and feed supply. Warmer weather, higher atmospheric $CO_2$ and reduced frost occurrence in winter tend to drive more growth over winter (Cullen et al. 2009; Harrison, Cullen & Armstrong 2017), though cumulated annually, growth under future climates are often lower (Harrison et al. 2017).

Perennial ryegrass (*Lolium* perenne L.) is one of the most common pasture species in Tasmanian pasture systems (Langworthy et al. 2018; Rawnsley et al. 2019). Growth of irrigated perennial ryegrass pastures in Tasmania are expected to increase until 2040 and decline in the following years (Holz et al. 2010). While pasture production may be higher in some years, increased incidence of hot and dry spells will be conducive to inconsistent pasture production and utilisation, requiring more grain/supplementary feed purchases, greater versatility in livestock management (e.g. animal trading) and in dairy systems will likely lead to lower profitability (Harrison, Cullen & Rawnsley 2016). Rising atmospheric $CO_2$ concentrations and higher temperatures act as stimulate ryegrass growth when soil water is not limiting. Declining rainfall in the traditionally wetter seasons of autumn and spring cause later beginnings or earlier contractions to the growing season, reducing feed availability in late spring and summer (Fig. 5) (Cullen et al. 2009; Harrison, Cullen & Armstrong 2017). Drier spring periods then limit the ability to produce surplus feed (hay and silage) that under normal conditions would be fed to livestock in subsequent autumn and winter periods.

Effects of pasture species (photosynthetic pathways) has often been proposed as an adaptation to climate change (Bell et al. 2013) In southern regions of Australia such as Tasmania, pasture species with the more primitive C3 photosynthetic pathway are more common (e.g. perennial ryegrass). In contrast, pastures in northern Australia are often characterised by the C4 pathway; these produce more dry matter and are more suited to hotter environments. As the global climate warms, northern pasture species may become more suitable to regions traditionally dominated by C3 grasses and legumes (Cullen et al. 2009; Langworthy et al. 2019). C4 plants will benefit from higher temperatures and tend not to be as affected by lower rainfall as they have greater water-use efficiency, potentially offsetting shorter growth periods of C3 plants. Both C3 and C4 species benefit from higher $CO_2$ levels, but more so the former (Cullen et al. 2009) due to the bundle sheath cell in C4 plants used to concentrate $CO_2$. Conversely, C4 plants tend to have lower digestibility than C3 plants (Barbehenn et al. 2004), potentially reducing livestock intake and liveweight gain of animals grazing these pasture types (Lilley et al. 2001).

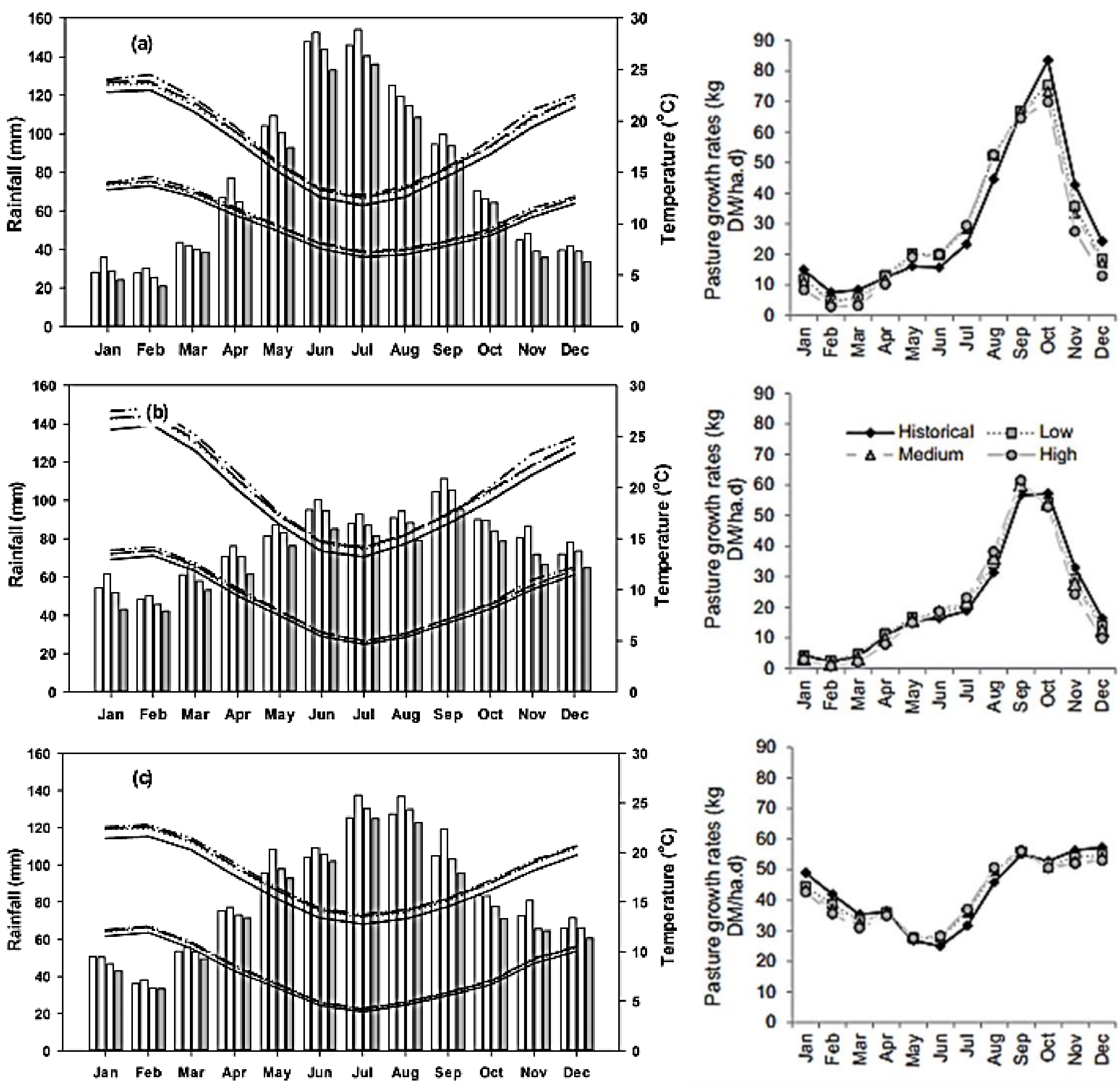

**Figure 5.** Monthly average rainfall (bars), temperature (lines) and pasture growth rates (lines) for the historical ( and ____) and 2040 climate scenarios with either Low ( and **…..…**), Medium ( and __ __) or High ( and **_ .. _ ..**) climate change trajectories at (a) Fleurieu Peninsula (SA), (b) Gippsland (Vic) and (c) NW Tas (Harrison, Cullen & Armstrong 2017).

In addition to effects of climate on pastures, changing climates also influence animal performance. For instance, heat waves induce livestock heat stress, increase reproductive mortality and incidence of diseases for both cattle and sheep (MLA 2008; Stokes & Howden 2010). In Victoria, livestock heat stress is expected to increase by between 5 and 37 days a year by 2050 and the number of consecutive heat stress days is also likely to increase (Chang-Fung-Martel et al. 2017). Heat stress in the USA decreases cattle conception rates by as much as 36% (Mader 2014) and milk production (Harrison 2021). Climate warming also influences the likelihood of experiencing pests or diseases. Modelling of warmer years has shown that flies and ticks normally associated with tropical regions of Australia may migrate south to cooler regions (Henry et al. 2012). Livestock production areas most affected will be those in drier regions (Stokes & Howden 2010). While livestock conception rates are likely to be reduced with warming climates, both calf and lamb survival may increase, although scientific debate on this continues. Kleemann and Walker (2005) found no ostensible linkages between chill and lamb mortality in South Australia, while Horton et al. (2018) found that the mortality rates of lambs 1-3 days after birth was significantly increased by chill index, particularly for ewes giving birth to twins and triplets. These differences may be explained by study location: Kleemann and Walker (2005) mainly examined sheep in warmer environments, while Horton et al. (2018) primarily focussed on sheep reproductive performance in the cooler region of Tasmania.

Other impacts of higher temperatures on livestock performance are also important. As more energy will be diverted to thermoregulation, sheep and cattle welfare declines, resulting in reduced liveweight gain and lower milk production. Feed intake is reduced due to animals have less energy to search for food (Chang-Fung-Martel et al. 2017). For beef and sheep grazing enterprises in Tasmania, changing future climates affect total pasture production and growth rates, creating uncertainty and greater risk for farmers seeking to maintain consistency of production and/or increase profitability under future climates in a sustainable way.

## How can livestock farms be adapted to climate change?

There are several adaptations that warrant further attention using a systems framework. As shown in Table 1, these include (1) increasing soil fertility using fertilisers, (2) changing pasture species and pasture management, (3) joining sheep at younger ages (Harrison et al. 2014a; Harrison et al. 2014b) and (4) altering stocking rates. Stocking rate (ie the number of animals carried on farm over the year) is a key factor relating to profitability due to its impact on pasture and liveweight production. Higher stocking rates result in faster depletion of pasture supply and reduce the amount of feed available per animal (Badgery et al. 2017). In Queensland, (Pahl et al. 2011) simulated seasonally variable stocking rates in response to climate change. High inter-annual variability in rainfall resulted in higher rates of ground cover erosion under higher stocking rates (O'Reagain, Bushell & Holmes 2011; Pahl et al. 2011). Tactical adjustment of stocking rate was more profitable than set stocking rates that did not change year-on-year (O'Reagain, Bushell & Holmes 2011). These adaptations give insight into adaptations to historical climates, but more research needs to be done to examine how they can be applied to future climates, particularly in Tasmania.

Previous work examining effects of climate change on pasture productivity showed that Tasmania would be the only area in southern Australia that may have greater productivity (Moore & Ghahramani 2013a). However, Moore and Ghahramani (2013a) did not account for increased frequencies of extreme climatic events and did not use the most recent climate change projections from global climate models. Another study showed that growth of pasture and crops in Tasmania may increase to 2085, largely due to an increase in spring growth (Phelan et al. 2015) in response to warmer temperatures in winter, and elevated atmospheric $CO_2$ concentrations. Similar to Moore and Ghahramani (2013b), (Phelan et al. 2015) did not account for increased frequencies of extreme climatic events (such as droughts and heat waves), even though these factors will have much greater impact on pasture production than gradual (mean) changes in climate (Badgery et al. 2017; Harrison, Cullen & Armstrong 2017; Harrison, Cullen & Rawnsley 2016).

Based on the literature, a number of potential animal husbandry, pasture or soil management and pasture genotype adaptation have potential to enable improved productivity and profitability under increasingly variable climates:

1. Changes to animal management are a simple and cost-efficient adaptation. For example, shifting forward the lambing or calving date may enable utilisation of earlier pasture growth in winter. The majority of farms tend to have lambing at the same time of year, though this depends on enterprise mix. Alcock et al. (2015) found higher profits when weaner flocks lambed in September and yearling flocks lambed in August. Farms traditionally lamb or calve in spring to utilise the bulge in spring feed: we can therefore hypothesise that shifting lambing or calving to an earlier date may be beneficial under a future climate, as spring growth tends to begin earlier (Harrison et al. 2014b).
2. Increasing or decreasing the time that lambs and calves are fattened before sale may be a relatively straightforward management adaptation to increase profitability by productivity, but such management changes should be examined using a systems lens. Previous research has shown that retaining crossbred sheep longer on farm to increase their carcass weight and sale price decreased profits, because breeding ewe stocks had to be reduced so there was enough feed to maintain lambs for longer (Harrison et al. 2014a). Retaining lambs on farm for longer created an energy deficit in summer and autumn. The reduced food intake meant that the growth rates for the sheep were not as high as during the spring, and thus not as profitable. On top of this, the environmental impact increased as the grazing pressures no longer matched the seasonal growth pattern of the pastures. As pasture feed declined, fewer breeding ewes were used and less lambs were produced, so profitability declined (Harrison et al. 2014a). In some contexts, selling young progeny before they reach the mature liveweight may conserve pasture feed and allow other animals to benefit. However, these insights were derived from a relatively temperate site in Victoria and thus may not hold when applied to Tasmania due to the differences in prevailing climates, management and enterprise structure. Production feeding of lambs with grain can considerably increase profits over simply pasture feeding. Alcock and Hegarty (2011) found that lambs could be sold at 30 weeks instead of 52 weeks and at the same weight by production feeding of grain at a large profit, provided that the grain was less than $300/tonne. This finding shows that lambs can be sold earlier and continue to make a profit (Alcock & Hegarty 2011).
3. Matching feed demand (ie seasonal animal numbers) to long-term ground cover (growth curve) may also have potential. Previous work has shown that soil erosion increases substantially as ground cover declines around 70% (Moore & Ghahramani 2013a). While holding more animals may increase the total amount of liveweight production, the liveweight gain per animal is likely

to decline (Badgery et al. 2017), and the need for supplementary and purchased feed is likely to increase.

4. Reducing the age maiden ewes are mated may be another possibility for adaptation, because a greater proportion of the whole sheep flock is used for reproduction and generation of income. While this adaptation has been shown to reduce greenhouse gas emissions intensities (Harrison et al. 2014a; Harrison et al. 2014b), its effect on profitability is not yet known.
5. Renovating pastures with new species may hold promise in the quest for climate change adaptation. Native pasture species have lower growth potential than introduced pasture species such as perennial ryegrass. Sowing improved pasture species may be conducive to adaptation and raise profitability. Alcock and Hegarty (2006) showed that the number of sheep per unit area can increase by renovating pastures with improved species. Alcock and Hegarty (2006) showed that wool and liveweight production of crossbred ewes increased, as did gross margins, yet their study did not examine climate change.
6. Genetic adaptation of pastures enables expression of different traits which can facilitate adaptation to climate change. The genetically predisposed rooting depth is one such pasture trait. Pasture root depth is affected by numerous factors, including defoliation intensity, soil type and climate (Lodge & Murphy 2006). Root depth and density influence the ability of pastures to survive in drier climates or heat waves (Langworthy et al. 2020). Native perennial pastures have been replaced in much of southern Australia by more shallow rooted varieties such as ryegrass and clovers. Perennial pastures with deeper roots may lose less water to deep drainage compared with annual ryegrasses lost in the same rainfall (Heng et al. 2001), allowing greater dry matter production from the additional water captured. Compared with annual species, perennials are generally more durable and better at maintaining seasonal ground cover (Harrison et al. 2014a). Despite this, the influence of pasture type and root depth has received little attention as an adaptation to future climates.
7. Using more water to irrigate pastures may facilitate climate change, assuming irrigation water is available (Harrison, Cullen & Armstrong 2017; Langworthy et al. 2020). The use of irrigation also depends on inexpensive, clean and available irrigation systems to be located nearby (Mendelsohn & Seo 2007).
8. Increasing the soil fertility may increase pasture productivity, but at some point, the added fertiliser will cost more than the benefit derived. Using fertilisers (particularly synthetic NPK) produced 27% more yearling cattle per hectare than organic pasture management using only manure (Román-Trufero et al. 2020). The study of Román-Trufero et al. (2020) focussed on calves: it remains to be seen whether increased fertility similarly benefits livestock productivity in more complex but realistic production systems, such as cow-calf self-replacing systems. An Australian study of 920 field trials found that dry matter production could be increased between 90% and 300% by using nitrogen applications up to 160 kg/ha. These trials were able to demonstrate the diminishing return of increasing nitrogen fertiliser applications (Gourley, Hannah & Chia 2017). The cost of fertilisers is specific to the country of origin and purchase, especially when a country is geographically isolated like Australia. None of the studies above identified the economic optimum value of fertilisers or the fertilisation level at which returns began to diminish.

**Table 1.** Effects of climate change adaptations on profitability, productivity and the environment: examples from Australian studies.

| Adaptation | Profit change (%) | Productivity change (%) | Environmental impacts |
|---|---|---|---|
| Lambing time | 10 | NA (Alcock et al. 2015) | Higher GHG release due to greater feed demands |
| Sale date and liveweight of juvenile animals | NA | -17 (Harrison et al. 2014a) Holding sheep on farm until 39 weeks old | Greater liveweight or holding durations means that higher GHGs are released, and greater stress is placed on pastures |
| Seasonal stocking rate | NA | 25 (Harrison et al. 2014a) Higher sheep DSE | Greater stocking rates may lead to greater emissions |
| Lambing at a younger age | NA | 2 (Harrison et al. 2014a; Harrison et al. 2014b) | Joining lambs earlier means they do not emit as much before first lambing |
| Alternative grass species | 378 | 300 (Alcock & Hegarty 2006) Using improved pasture for sheep | Different pasture species produce/absorb greater emissions |
| Increasing rooting depth | NA | NA | More productive species with better qualities/greater groundcover |
| Use of irrigation to alleviate water deficit | NA | NA | Can instigate greater production, allow higher stocking rate and greater emissions |
| Soil fertility | NA | 15 (Harrison et al. 2014a) by increasing soil fertility | Fertilisers can cause greater groundcover but may result in more nitrous oxide emissions |

The model GrassGro has been used to simulate the production of farms in pasture based systems throughout Australia (Robertson 2006). The model is mainly used to aid decision making on pasture use, plant species, grazing and flock dynamics. Environmental factors such as temperature, soil moisture, and rainfall are used to formulate results. Both cattle and sheep operations have been modelled and general agreement has been found between simulated and observed results in many locations (Clark, Donnelly & Moore 2000).

A unique opportunity exists to compare two Tasmanian farms operating beef and sheep livestock in pasture-based systems in the context of climate change. The Tasmanian climate is distinctly cooler than the mainland climate. A focus on an extreme weather events will facilitate insight into the efficacy of farm adaptations. A similar gap in the research exists on the profitability ($/ha) of beef and sheep farms in a future climate. While some research has examined Tasmanian pasture based dairy farms using future climates with greater variability (Harrison, Cullen & Rawnsley 2016), no studies have focused on beef or sheep enterprises. The drivers of profitability in beef and sheep systems are different from those of dairy system, as the former are more reliant on pastures for their main feed supply.

The research questions of this study include:

1. How will the two farms be affected by shifting to a 2050 climate?
2. What adaptations can be used to increase the profitability of the two farms?
3. What adaptations can be used to increase the productivity of the two farms?

## Methods

Two real Tasmanian livestock farms were modelled using GrassGro version 3.3.10 (Donnelly, Moore & Freer 1997). Each farm was part of a broader research project funded by the Tasmanian Institute of Agriculture (TIA) and Meat and Livestock Australia (MLA). One farm (a beef cattle enterprise) was located in the wetter, more temperate region of Tasmania's north-west coast, the other (a sheep and beef enterprise) was located in the relatively drier, more arid zone of the Midlands. Positioning these case studies in this way facilitates comparison of climatic impacts across regions.

### Midlands sheep and beef farm at Campbell Town

The superfine wool, prime lamb and beef enterprise located west of Campbell Town, in the Midlands of Tasmania. Long-term (2000-2019) mean and standard deviation of annual rainfall at Campbell Town is 489 ± 122 mm, with equiseasonal monthly rainfall (36-49 mm/month). Average daily temperatures peak and trough at 17.9°C in January and 6.6°C in July, respectively. The farm area is 7,777 ha, including 21% of developed country, 3% centre pivot irrigation (grasses and legumes, including cropping), 20% native grasslands (including 3% native woodlands), 4% riparian zone/wetlands and 54% native woodlands/forest. The soil type was described by the case study farmer as "variable, from black-cracking clays through to raw sand and everything in between". The farmer described pasture species on the farm as 'highly variable'. This variability is however reflective of typical soil and pastures across livestock farms in the Midlands of Tasmania. Native pastures consisted of *Themeda, Microlaena, Austrodanthonia* and *Poa* tussock grasses. Developed pastures include a mixture of Phalaris, perennial ryegrass, cocksfoot, and clovers (subterranean and strawberry), although the pastures are predominantly Phalaris and sub-clover. The land under the centre pivot irrigation is used to grow poppies, dual-purpose grazing wheat (grazed for four months prior to harvesting), lucerne (grazed and for hay-making), a Phalaris seed production crop (grazed outside window for seed production) and a Phalaris-sub clover pasture.

The wool flock consisted of 4,500 mature superfine Merino ewes, 6,500 wethers and 7,300 replacements. All ewes lamb from mid-September, with maiden ewes lambing at 2 years of age. The majority of ewes are retained in the commercial flock for several years, before being cast for age (CFA) at 7 years of age.

The GrassGro model was parameterised for the baseline climate period (1986-2005) to replicate pasture and livestock production of the farm, accounting for pasture species, dryland and irrigation management, supplementary feeding (i.e. feed lotting ewes over summer/early autumn) flock and herd husbandry (i.e. lambing/calving dates), reproduction efficiency (i.e. lamb weaning rates) and meat/wool production. The native pasture species simulated using GrassGro were *Microlaena* and *Austrodanthonia,* while developed pastures included lucerne, Phalaris and subterranean clover. Wheat is not included in GrassGro, so this was substituted with annual ryegrass to replicate a similar seasonal growth pattern. The lucerne and wheat paddocks were irrigated from 1 September to 31 March each year, with each irrigation filling the soil profile to 95% of field capacity. This approach most effectively replicated the long-term average irrigation water applied on the case study farm.

Soil parameters adopted in GrassGro were determined by selecting the most common soil type for the region (Dy5.61), representing sandy loam over heavy clay loam (Northcote 1979). The soil fertility factor in GrassGro was incrementally altered so that historical climate animal productivity and supplementary feed inputs matched those of the case study farm similar to the process applied by Harrison et al. (2014b). These varied between 0.84 and 0.85 for the developed species paddocks (rainfed and irrigated) down to 0.8 for the native pastures paddock (0 and 1 represent in GrassGro nil and maximum soil fertility, respectively). For simplicity, the present study focussed on the self-replacing fine wool flock that annually grazes 4,454 ha of rainfed native and introduced pastures, along with irrigated pastures.

## North-west beef farm at Stanley

The beef operation was located at Stanley on the northwest coast of Tasmania. Long-term (2000-2019) mean and standard deviation annual rainfall at Stanley is 914 ± 179 mm, with the majority of rainfall falling between late autumn and mid spring. Average daily temperature is ~16.9°C in January and ~9.3°C in July.

The self-replacing cow and calf operation produces 350 predominantly Angus cattle (small number South Devon and Charolais) in late winter each year (from 1st August). Pasture species comprise perennial ryegrass, cocksfoot, prairie grass, lucerne and clovers (white, red and subterranean) grown on 402 ha with sandy loam, clay loam and ferrosol soils. The farm also raises purchased animals on additional land, although for the purposes of this study, the focus was on the cow-calf operation. GrassGro was parameterised for a baseline climate period of 1986-2005. Actual details of pasture species, irrigation management, herd husbandry (i.e. calving date), reproduction efficiency (i.e. weaning rate) and meat production (i.e. kg liveweight/head turnoff) were accounted for in the model. Pasture species included perennial ryegrass, cocksfoot, white clover, subterranean clover and lucerne. Irrigation was applied to one lucerne/ryegrass paddock and one ryegrass/cocksfoot/white clover paddock, based on a schedule of between 21 Nov and 31 Mar each year, and applying 20mm/event on a 14-day interval. Predominant soil types of the farm included sandy loams, clay loams and ferrosols on the higher parts. Soil parameters were determined by selecting the most common soil type for the region: a Uc2.3 soil type (sandy loam) based on the Northcote classification (Northcote 1979). The soil fertility factor in the model was incrementally altered so that historical animal productivity and supplementary feed inputs matched those of the case study farm (final fertility factors were 0.82-0.85 for rainfed paddocks and 0.87 for the two irrigated paddocks). Soil fertility scalars were not altered for the future climate scenarios, except where fertility was examined as a climate adaptation *per se*. The number of calving cows in GrassGro was set at 365 with 20% replaced each year to replicate the case study farm's total meat production turnover.

## Historical and future climate data

Daily historical climate data (1980-2005) for the study sites were sourced from the SILO (Scientific Information for Land Owners) meteorological archives (Queensland Government 2021). Atmospheric $CO_2$ concentrations in GrassGro were set at 350 ppm and 530 ppm for the historical and 2050 climate scenarios respectively, following Representative Concentration Pathways 8.5 (RCP8.5) adapted from CSIRO and Bureau of Meteorology (2020). The most extreme climate prediction for 2050 within RCP8.5 was extracted following actual climatic trends (Schwalm, Glendon & Duffy 2020).

A novel approach to simulating climatic extremes under future climate horizons (2036-2061) was developed in which monthly change projections from global circulation models (GCMs) were combined with statistical approaches for generating more heatwaves, longer droughts and more extreme rainfall events (Harrison, Cullen & Rawnsley 2016). Monthly temperature and rainfall change factors associated with a given climate scenario for each site and month were applied to the detrended historic climate (Table 2). Monthly change factors for the 2050 period were extracted from the latest projections (CMIP5) using the Climate Futures Tool (CSIRO & Bureau of Meteorology 2020), an algorithm that synthesises projections from 40 GCMs. Changes in potential evapotranspiration and vapour pressure deficit in the future climates were calculated using the Penman–Monteith equation (Monteith 1965; Penman 1948) and Teten's formula, respectively (Campbell & Norman 2012). Daily incident solar radiation (MJ/$m^2$) used for the future climates were as for the baseline. Following Harrison et al. (2016), rainfall events for the future climates were computed based on historical rainfall percentiles, with 80% being scaled by monthly rainfall change factors and the remaining 20% unmodified. For maximum daily temperatures, 50% of the historical maximum daily temperature data was randomly selected and scaled by the monthly change factor. The remaining 50% were not modified. Minimum daily temperatures under future climates were multiplied by the ratio of future to historical maximum daily temperature (Harrison, Cullen & Rawnsley 2016).

**Table 2.** Rainfall and temperature monthly average change factors (%) applied to historical rainfall and temperature data for RCP 8.5 at Campbell Town and Stanley, for a 2050 climate horizon, (Harrison, Cullen & Rawnsley 2016).

| | Campbell Town | | Stanley | |
|---|---|---|---|---|
| | **Rainfall** | **Temperature** | **Rainfall** | **Temperature** |
| Jan | -1.5 | 5.0 | -1.5 | 5.6 |
| Feb | 10.1 | 8.8 | 10.1 | 9.8 |
| Mar | -24.4 | 9.6 | -24.4 | 10.4 |
| Apr | -8.2 | 11.1 | -8.2 | 11.3 |
| May | 10.0 | 7.5 | 10.0 | 7.2 |
| Jun | -9.0 | 10.1 | -9.0 | 8.9 |
| Jul | 8.7 | 10.4 | 8.7 | 9.3 |
| Aug | -8.5 | 10.2 | -8.5 | 9.7 |
| Sep | -10.6 | 9.5 | -10.6 | 9.6 |
| Oct | -24.0 | 9.3 | -24.0 | 9.9 |
| Nov | -24.0 | 12.5 | -24.0 | 13.9 |
| Dec | -10.7 | 6.3 | -10.7 | 7.1 |
| **Average** | **-7.7** | **9.2** | **-7.7** | **9.4** |

## Economic analyses

Commodity prices (wool, meat) and production costs were informed by the case study farmers and relevant online literature. Meat prices were adopted from Meat and Livestock Australia (MLA 2021c) and wool prices were drawn from Nutrien Ag Solutions (2021). Future prices were not changed from historical prices; inflation was deliberately omitted from this analysis to avoid confounding the effects of climate change with those of future prices on profitability. Animal husbandry and shearing costs were informed by the Fair Work Ombudsman (2020). Irrigation costs were not considered here as they were minimal relative to other costs. See Figs. A83.1 and A83.2 for the full breakdown of incomes and costs used within GrassGro for the economics assessments.

## Climate change adaptations simulated using GrassGro

The first six years of each simulation were discarded to allow for model stabilisation, model outputs for the following 20 years were used. The period from 1 January 1996 – 31 December 2005 was used for the historical (**Historical**) treatment and the period from 1 January 2042 to 31 December 2061 produced the 2050 baseline (**Baseline**) treatment. The climate (including atmospheric $CO_2$ concentrations) was the only difference between these two treatments. A range of adaptations were implemented for the Midlands farm (Table 3). These included altering lambing date, sale date of lambs, soil fertility scalar and rooting depth of the pastures and were informed by the NEXUS project (Harrison et al. 2021a). To determine the sensitivity of each adaptation, each treatment involved modifying the baseline by ±10%. Relatively small changes from the baseline levels of production or profitability as a result of ±10% perturbation indicate that the treatment (e.g. soil fertility etc.) was relatively insensitive, and vice versa for large changes. The rationale underlying changes to each treatment in Table 3 is described below.

## Climate change adaptations for the Campbell Town sheep farm

A range of adaptations were implemented for the wool enterprise (Table 3). These included altering lambing date, sale date of lambs, soil fertility scalar and rooting depth of the pastures and were informed by the Nexus project (Harrison et al. 2021a) as well as input from case study farmers.

**Table 3.** Climate change adaptations simulated for the Campbell Town sheep farm.

| **Adaptation** | **Baseline** | **Baseline +10%** | **Baseline -10%** |
|---|---|---|---|
| Lambing date | 18th September | 28th August | 9th October |
| Lamb sale date | 1 February | 14 February | 18 January |
| Soil fertility scalar | Rainfed and irrigated pastures/crops (grasses, lucerne, wheat) 0.84<br>Natives 0.8 | Rainfed and irrigated pastures/crops (grasses, lucerne, wheat) 0.89<br>Natives 0.8 | Rainfed and irrigated pastures/crops (grasses, lucerne, wheat) 0.79<br>Natives 0. |
| Maximum root depth of grasses/legumes | Phalaris 750mm<br>Subterranean clover 500mm<br>Lucerne 900mm<br>Annual ryegrass 520mm | Phalaris 825mm<br>Subterranean clover 550mm<br>Lucerne 990mm<br>Annual ryegrass 570mm | Phalaris 675mm<br>Subterranean clover 450mm<br>Lucerne 810mm<br>Annual ryegrass 470mm |

### *Lambing dates*

The historical mating and lambing dates for the wool flock were 22nd April and 18th September, respectively (Table 3). These dates were altered by joining either earlier **(+ve Lamb D**) or joining later (**-ve Lamb D)**. All other aspects, such as weaning date, sale date etc, were adjusted accordingly.

### *Lamb sale dates*

The historical sale date of non-replacement lambs (i.e. ewe and wether lambs not required to maintain flock size) was 1st February (Table 3). This sale date was altered by selling the lambs either two weeks earlier (**-ve Sale DW**) or two weeks later (**+ve Sale DW)**. These sale dates were informed by farmers in the NEXUS project. Weaning dates remained a day earlier than sale date for both treatments.

### *Altering soil fertility*

The historical soil fertility scalar (0-1 scale) for paddocks containing introduced pasture/crop species was 0.84 (Table 3). This scalar was altered by decreasing by 0.05 (**-ve Fert**) or increasing by 0.05 (**+ve Fert**). The change in soil fertility scalar was assumed to be achieved by either decreasing or increasing inorganic fertiliser applications. The soil fertility for paddocks containing native pastures was not altered following actual farm practices.

### *Altering rooting depth*

The historical rooting depth for Phalaris, subterranean clover, lucerne and wheat was 750 mm, 500 mm, 900 mm and 520 mm, respectively (Table 3). These were either decreased by 10% (**-ve Root D**) or increased by 10% (**+ve Root D**). Similar to soil fertility, the rooting depth of the native pastures were not altered in this analysis.

## Climate change adaptations for the Stanley farm

A range of adaptation options were implemented for the beef farm at Stanley (Table 4), including altering the mature liveweight of breeding cows, sale dates and liveweight of the steers and non-replacement heifers, soil fertility and maximum pasture root depth. Changes the each baseline treatment were similarly informed by the NEXUS project (Harrison et al. 2021a).

**Table 4.** Adaptations for the beef herd modelled at Stanley.

| Adaptation | Baseline | Baseline +10% | Baseline -10% |
|---|---|---|---|
| Adult mature liveweight – breeder cows | 580 kg | 638 kg | 522 kg |
| Sale date and weight of steers combined with sale date and weight of heifers | Steers: 15 Sept & 650 kg<br>Heifers:30 Sept & 600 kg | N/A (see below) | Steers: 15 Aug & 620 kg<br>Heifers: 30 Aug & 570 kg |
| Soil fertility | Irrigated 0.87, rainfed 0.85 | Irrigated 0.92, rainfed 0.90 | Irrigated 0.82, rainfed 0.80 |
| Root depth | White Clover (WC) 500 mm<br>Lucerne (L) 1200 mm<br>Subterranean clover (SC) 600 mm<br>Perennial Ryegrass (PR) 720 mm<br>Cocksfoot (C) 850 mm | WC 550 mm<br>L 1200 mm<br>SC 660 mm<br>PR 792 mm<br>C 935 mm | WC 450 mm<br>L 1080 mm<br>SC 540 mm<br>PR 648 mm<br>C 765 mm |

### *Mature cow weight*

The historical liveweight of mature breeder cows was 580 kg (Table 4). The liveweight of all other stock was proportional to the breeder cow, with bulls at 812 kg and steers and non-replacement heifers sold at 650 kg and 625 kg, respectively. The liveweight of the mature breeder cow was either adjusted down by 10% (**-ve Cow W**) or up by 10% (**+ve Cow W)**. Bull liveweight was adjusted similarly by ±10%. Liveweights of steers and heifers were reduced to 522 kg with the **–ve Cow W** treatment, while remaining at 650 kg and 625 kg liveweight for the **+ve Cow W** treatment. The change for **-ve Cow W** was modelled to represent the smaller cows produced by the self-replacing herd, while the larger cows grew longer.

### *Sale times of steers and heifers*

The historical sale date and liveweight for steers was 15 September at 650 kg, while for non-replacement heifers it was 30 September at 600 kg (Table 4). The sale date of steers and heifers was shifted one month earlier (**-ve Sale DW**). Production feeding in GrassGro was adjusted such that the same target weight of both heifers and steers was attained one month earlier. All other variables remained as for the Baseline 2050 treatment. Preliminary modelling of selling cattle a month later showed that heifers and steers did not grow heavier than the historical liveweight, even with additional supplementary feeding (data not shown). Thus, we did not model a later sale date of steers or heifers.

### *Soil fertility*

The historical soil fertility scalar (0-1 scale) for irrigated and rainfed paddocks was 0.87 and 0.85, respectively. This scalar was either reduced by 0.05 (**-ve Fert**) or increased by 0.05 (**+ve Fert**). Other details are shown in Table 4.

### *Maximum pasture root depth*

Historical maximum root depths for perennial ryegrass, white clover, subterranean clover, lucerne and cocksfoot were set at 720 mm, 500 mm, 600 mm, 1200 mm and 850 mm, respectively (Table 3), while root depths for subterranean clover, lucerne and wheat were set at 750 mm, 500 mm, 900 mm and 520 mm, respectively (Table 4). These were either decreased by 10% (**-ve Root D**) or increased by 10% (**+ Root D**), with the exception of increased root depth of lucerne (soil layers below 1200 mm were impermeable, so it was assumed roots could not pass beyond this depth).

## Statistical analyses

Box and whisker plots were used to illustrate the majority of results (Fig. 6), where the box represents the 25th (Q1) and 75th (Q3) percentiles, the horizontal line within the box represents the median and the 'x' within the box represents the mean. Whiskers extend to 1.5 times the interquartile range (IQR; i.e. difference between Q3 and Q1). No other formal statistics were undertaken here as it is not appropriate to apply statistical inferences (e.g. ANOVA) to data outputs from biophysical models.

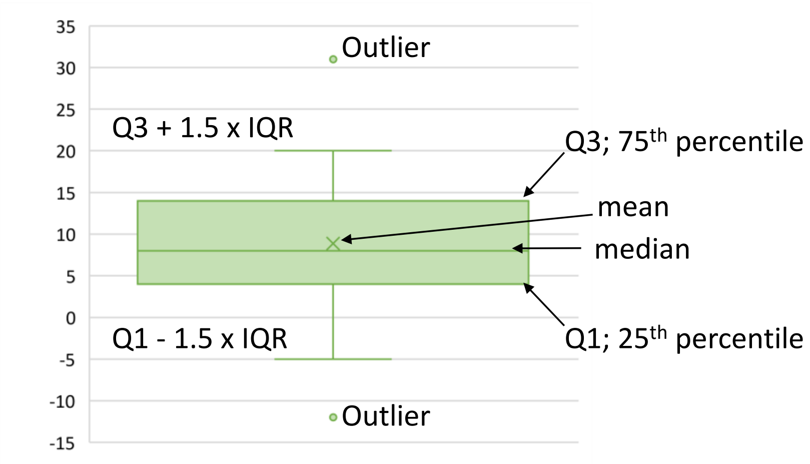


**Figure 6.** Illustration of the components of a box and whiskers plots, where IQR is the difference between Q3 and Q1. The upper whisker represents the next largest datapoint ≤ Q3 + 1.5 x IQR. The lower whisker represents the next smallest datapoint ≥ Q1 – 1.5 x IQR.

## Results

### Sheep/wool farm at Campbell Town

Evapotranspiration was lowest in May and June and highest in October (Fig. 7). Monthly rainfall was lowest in March and highest in October but was similar across from July through to January. Evapotranspiration was similar for all months except for spring; in spring, evapotranspiration was slightly lower in the 2050 climate. Rainfall trends were similar across historical and future climates except in spring when it was generally lower for the 2050 rainfall.

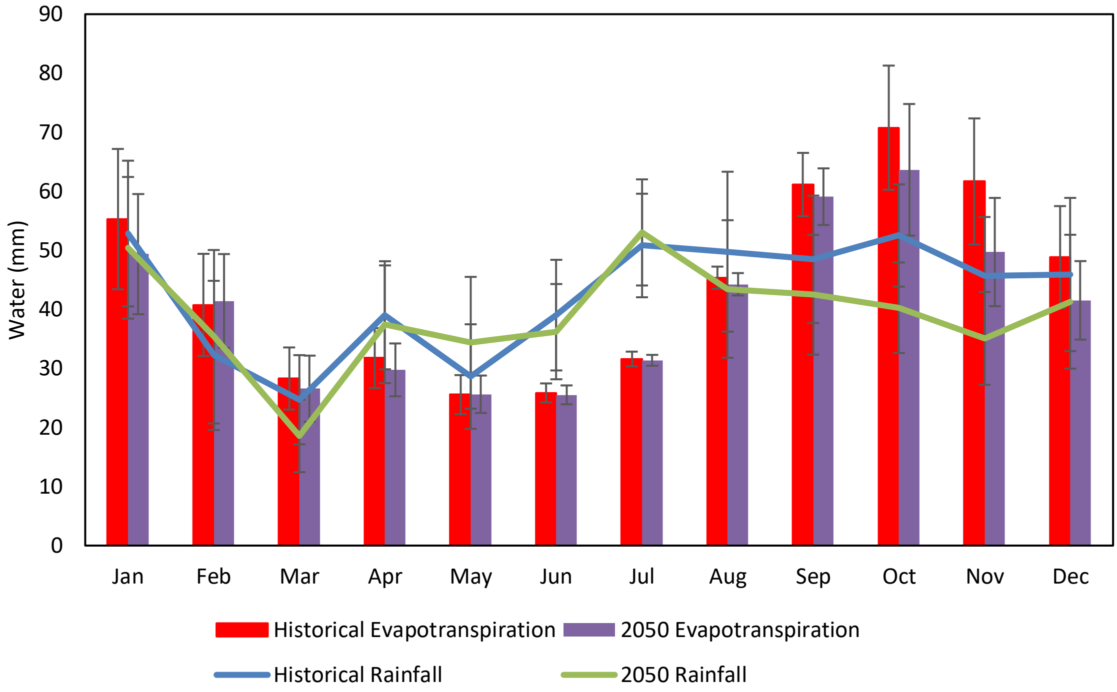


**Figure 7.** Average (±1.96 SEM) monthly rainfall (mm) and average (±1.96 SEM) monthly evapotranspiration (mm) for a historical and 2050 climate (n=20) for Campbell Town.

The average maximum temperature for the 2050 climate was significantly warmer across the entire year (Fig. 8). The maximum temperature was 1.5°C warmer in winter and 2.7°C warmer in summer compared to historically. Average minimum temperature did not differ between climate periods for the months between May and September. In summer, average minimum temperature for the 2050 climate was slightly greater.

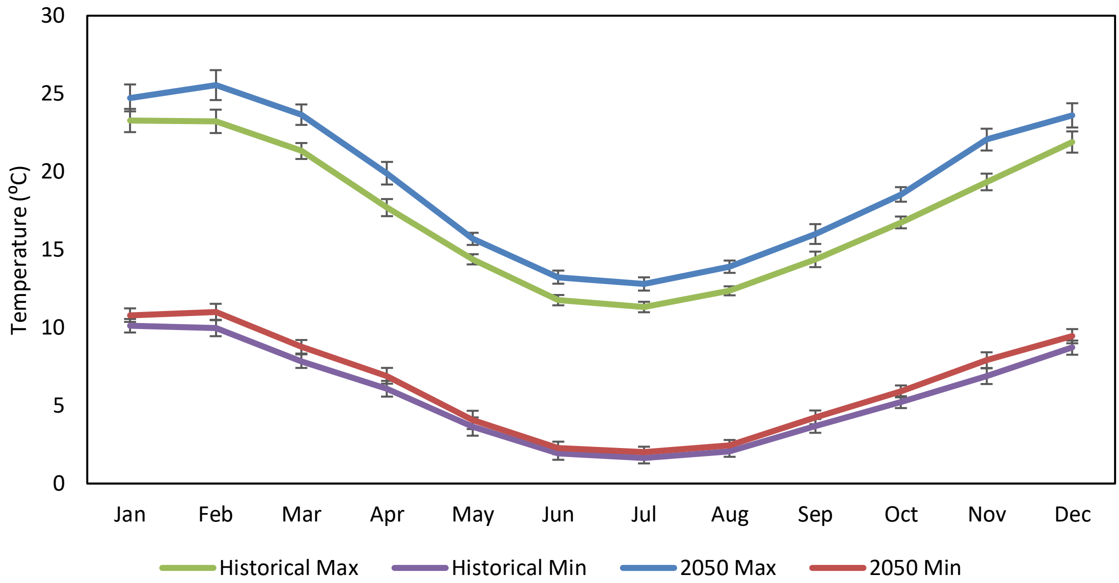


**Figure 8.** Average monthly minimum and maximum temperature (±1.96 SEM) for a historical and 2050 climate (n=20) at the Campbell Town sheep farm.

Irrigated pasture growth rates in 2050 were higher all year with the exception of January (Fig. 9). Rainfed pasture growth rates in 2050 were higher from July through September. In November and December, historical rainfed pasture growth rates were higher than those in 2050, suggesting future climates will be most detrimental to spring growth rates of rainfed pastures.

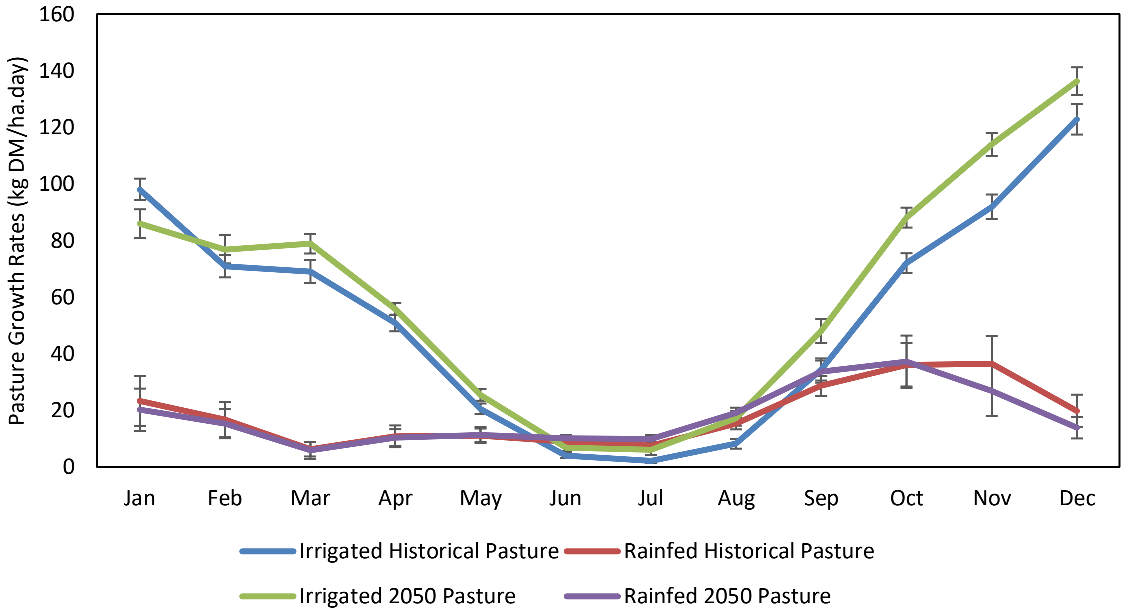


**Figure 9.** Average (±1.96 SEM) monthly pasture growth rate (kg DM/ha.day) for the historical and 2050 climates (n=20) under irrigated and rainfed conditions at the Campbell Town sheep farm.

Gross margins were similar for most adaptations (Fig. 10) but were slightly higher for 2050 regardless of adaptation. Increasing root depth had the greatest impact ($13/ha) albeit even this was marginal.

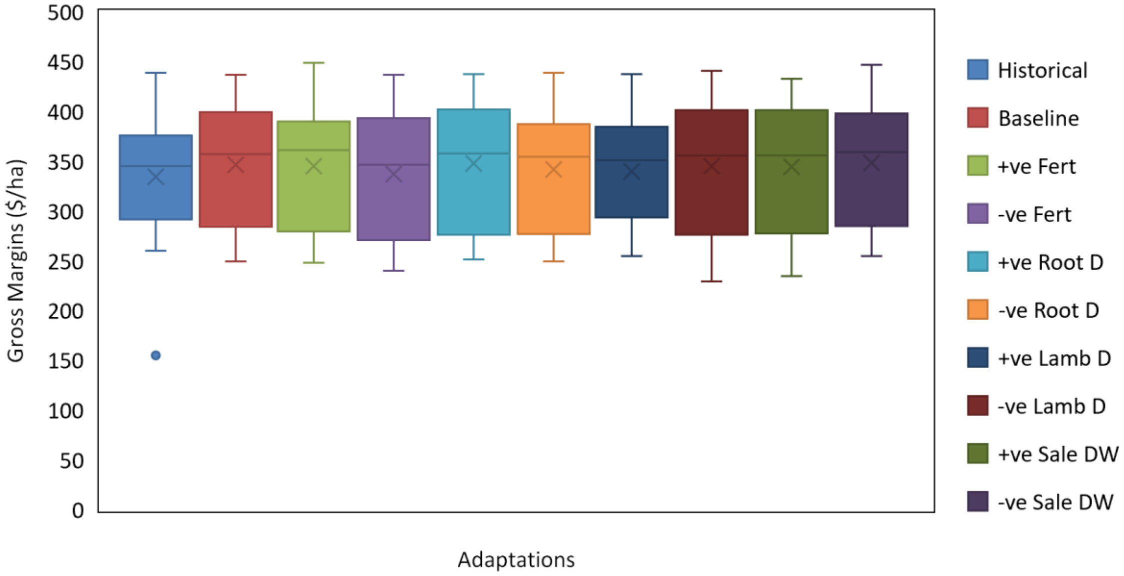


**Figure 10.** Interannual variation (n=20) in gross margins ($/ha) of the fine wool ewe and wether Campbell Town sheep farm. See methods for legend abbreviations.

Supplementary feed inputs varied little across adaptations and climates (Fig. 11). The 2050 climate resulted in greater supplementary feed requirement (+12 tonnes dry matter/annum). Reducing soil fertility resulted in the greatest increase in supplementary feed in 2050 (+70 tonnes dry matter/annum). An outlier in the historical climate was caused by two successive years of dry weather requiring huge amounts of supplementary feed in the second year. This did not occur in the 2050 climate.

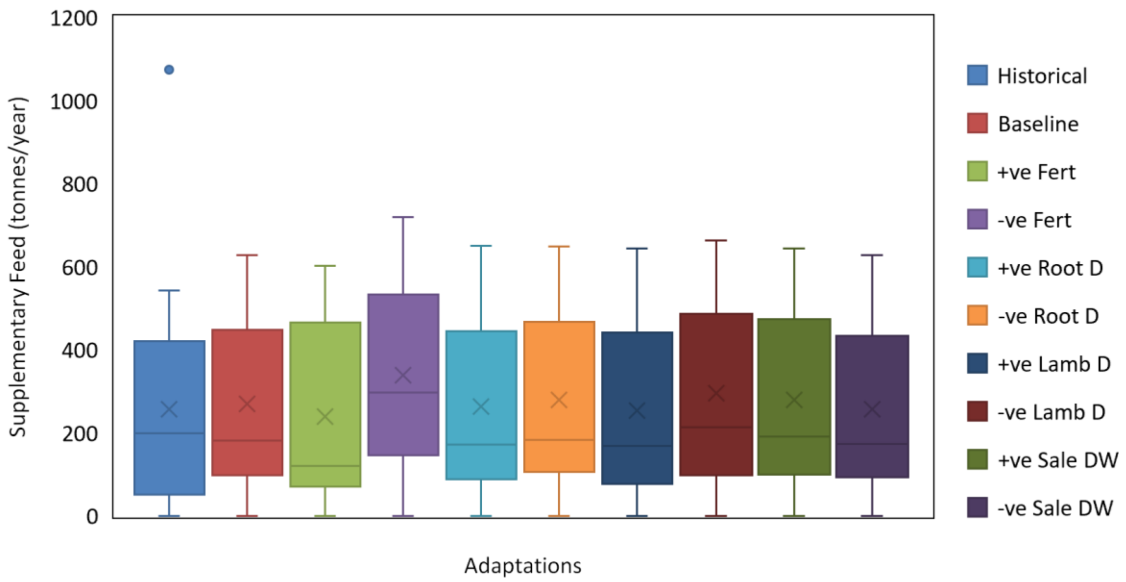


**Figure 11.** Interannual variability in supplementary feed requirements (tonnes DM/year) across the historical (first boxplot) and 2050 climates and adaptations (n=20) at the Campbell Town sheep farm. See methods for legend abbreviations.

The baseline 2050 climate had higher average liveweight production (+5 tonnes/annum) than the historical liveweight production at Campbell Town sheep farm (Fig. 12). The average liveweight production increased in almost adaptations. Later lambing dates had the greatest positive influence (+6 tonnes liveweight/annum) on production over the baseline 2050 climate and was the only adaptation to increase production. In contrast, the earlier lambing date resulted in a decline in livestock production (-6.5 tonnes liveweight/annum).

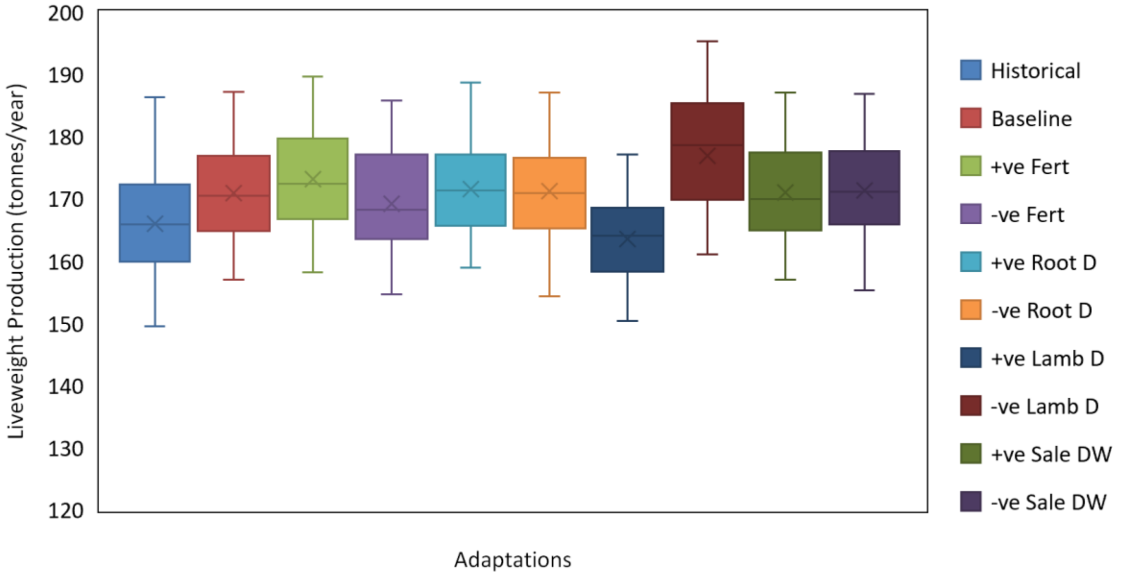


**Figure 12.** Interannual variation in sheep liveweight (tonnes/year) production across the historical and 2050 climates (n=20) at the Campbell Town sheep farm. See methods for legend abbreviations.

Neither the historical climate nor the baseline 2050 climate resulted in large changes in wool production from any of the adaptations (Fig. 13). Lambing earlier had the biggest average increase of wool production with an increase of 1.2 tonnes of clean fleece weight per annum.

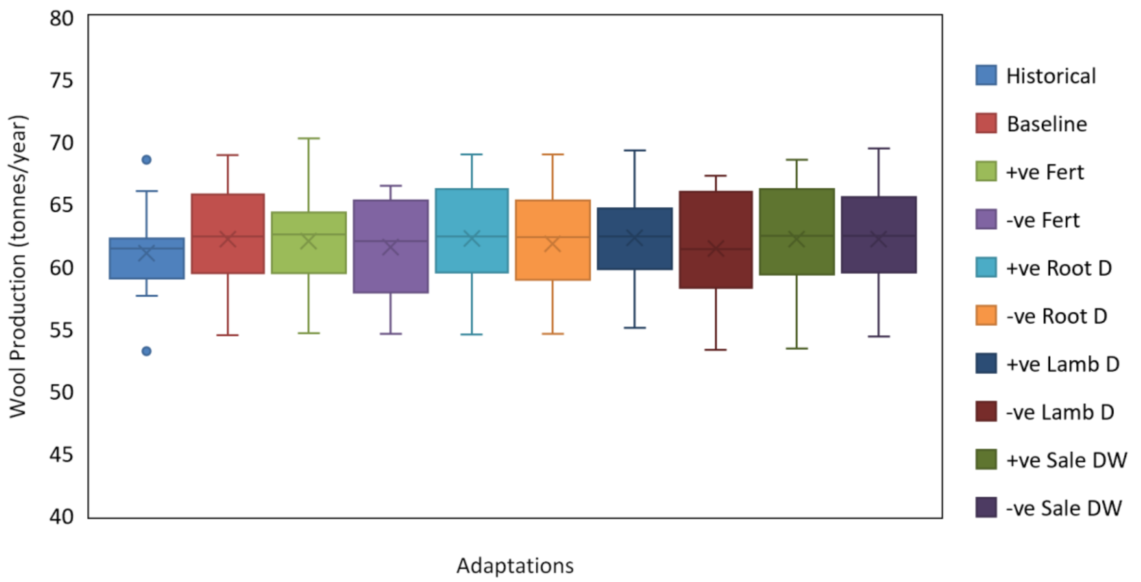


**Figure 13.** Interannual variation in the Campbell Town sheep farm wool production (tonnes/year) over the historical and 2050 climates (n=20) for the Campbell Town sheep farm. See methods for legend abbreviations.

Pasture production did not differ between the historical climate or the 2050 climate for any adaptations at the Campbell Town sheep farm (Fig. 14).

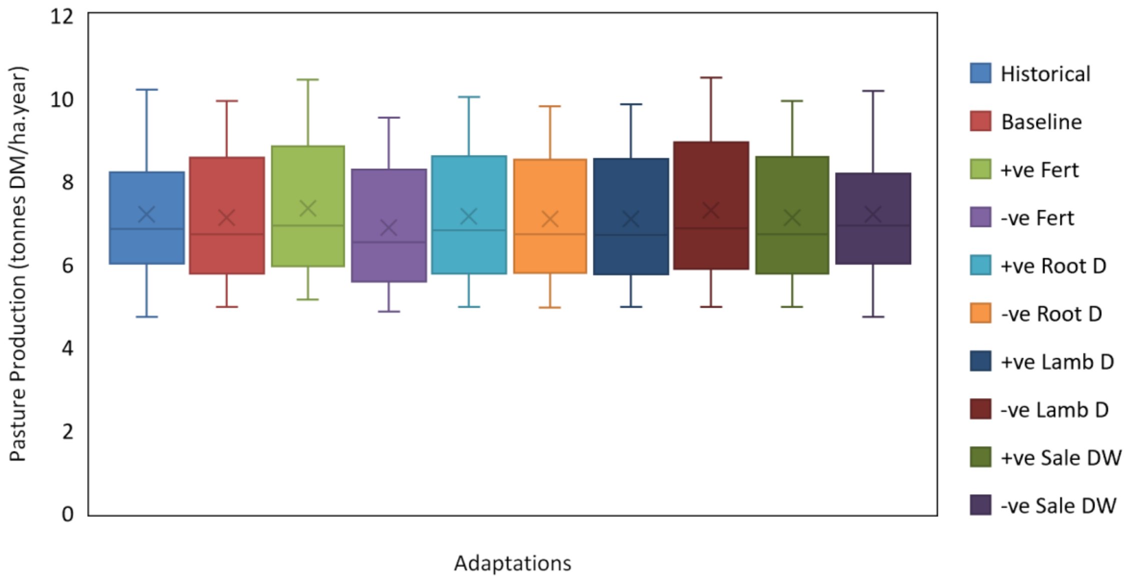


**Figure 14.** Interannual variation in cumulative annual pasture production (tonnes DM/ha.year) for the historical and 2050 climates (n=20) for the Campbell Town sheep farm. See methods for legend abbreviations.

All adaptations allowed higher stocking rates than the historical climate except for lambing earlier (Fig. 15). Lambing later had the greatest increase (0.06 sheep/ha) in stocking rates over the 2,545 hectares of the farm.

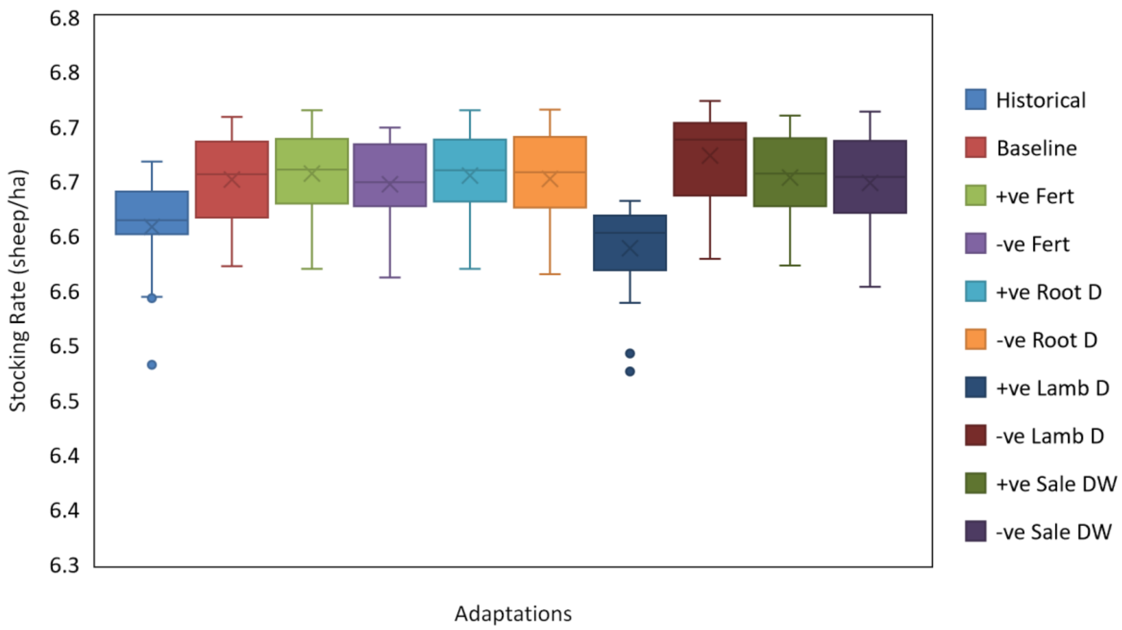


**Figure 15.** Interannual variation in average annual stocking rates (sheep/ha) for the historical and 2050 climates and all adaptations (n=20) for the Campbell Town sheep farm. See methods for legend abbreviations.

All adaptations to the 2050 climate resulted in lower ground cover than the historical climate (Fig. 16). Reducing the fertility of pastures had the greatest impact on ground cover with 4.3% lower ground cover than the historical climate.

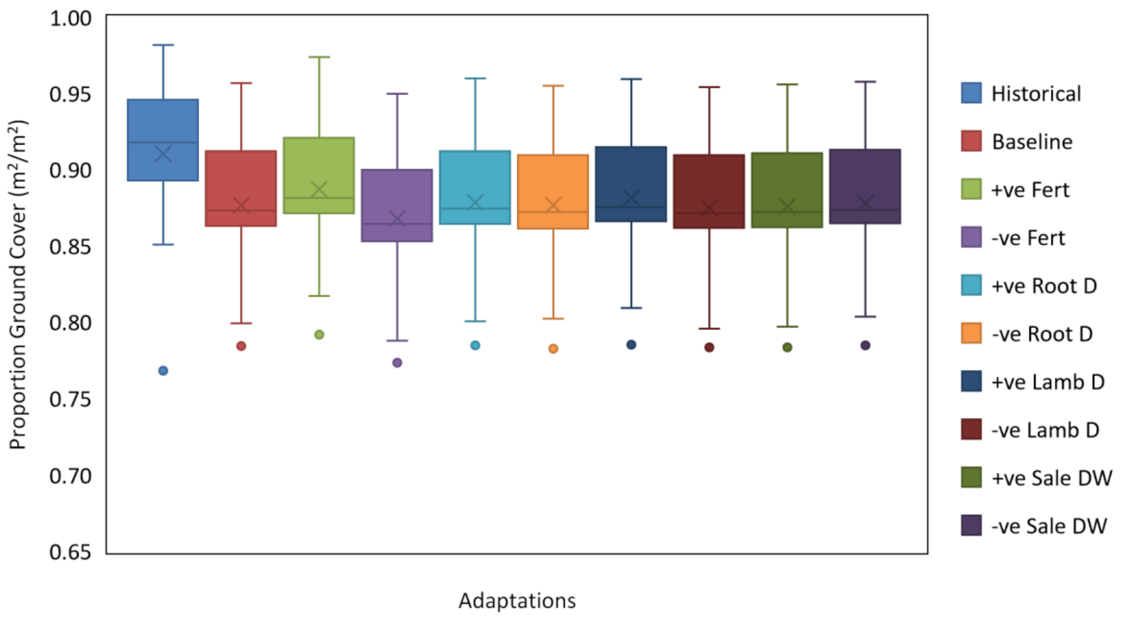


**Figure 16.** Interannual variation in annual ground cover ($m^2/m^2$) under the historical and 2050 climate for each adaptation (n=20) at the Campbell Town sheep farm. See methods for legend abbreviations.

## Beef cattle farm at Stanley

Monthly rainfall declined in October and November in the 2050 climate compared with the historical climate (Fig. 17). Monthly evapotranspiration did not differ over the year except in November and December when evapotranspiration was higher historically.

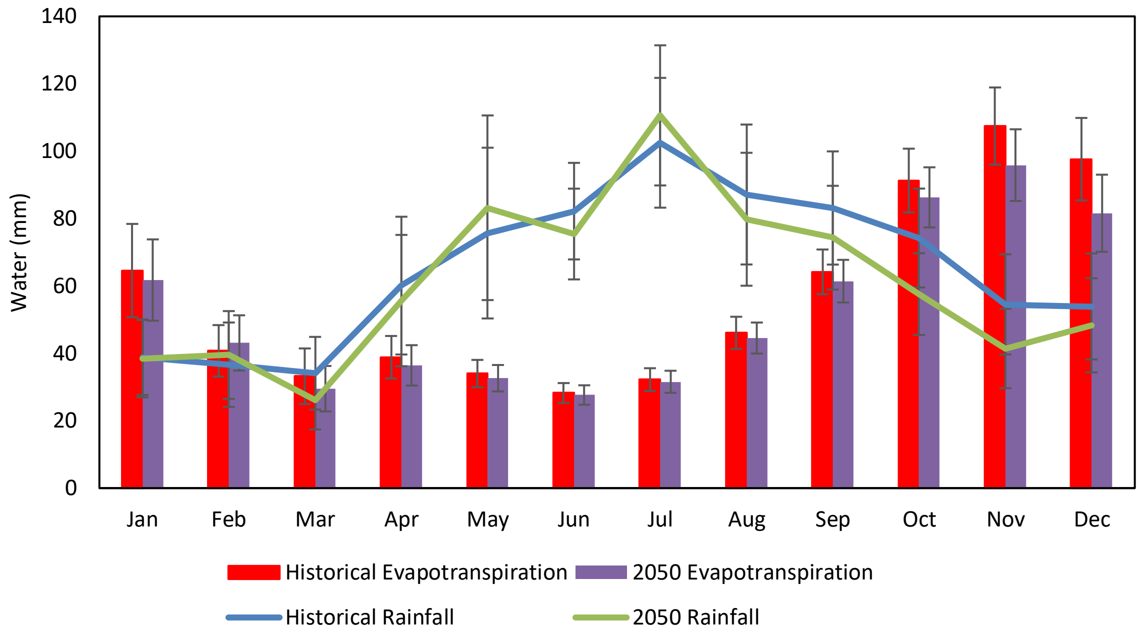


**Figure 17.** Average (±1.96 SEM) monthly rainfall (mm) and average (±1.96 SEM) monthly evapotranspiration (mm) over a historical and 2050 climate (n=20) for the Stanley beef farm.

The average maximum temperature for 2050 did not differ significantly ($p<0.05$) from the average maximum temperature of the historical climate across the year with the exception of November (Fig. 18). The 2050 maximum temperature was 1.1°C warmer in winter and 2.2°C warmer in summer compared to historical temperatures. The average minimum temperature did not differ across the course of the year between the historical climate and the 2050 climate. The largest average difference was only approximately 1°C in late summer and early autumn.

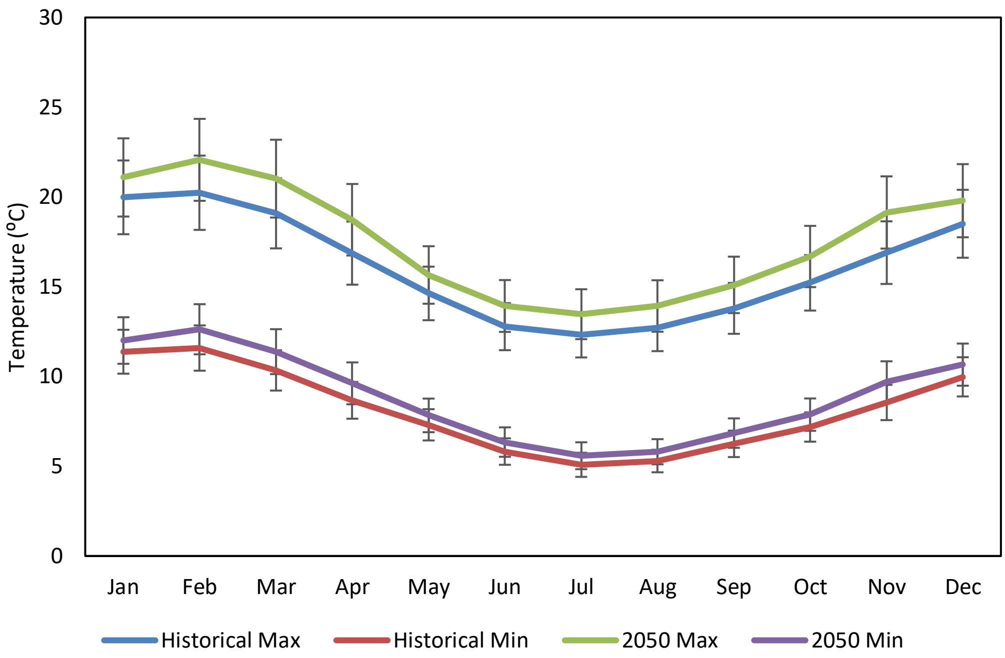


**Figure 18.** Average (±1.96 SEM) monthly minimum and minimum temperature (°C) over a historical and 2050 climate (n=20) at the Stanley beef farm.

Irrigated pasture production in 2050 was higher in August and September but lower November and December when compared with the historical climate (Fig. 19). The rainfed 2050 pasture production was higher from July through October. In November and December, the historical rainfed pasture had higher than the 2050 pasture.

Increasing fertility resulted in an increase in pasture production when higher rates of fertiliser were applied for both rainfed and irrigated pasture in the period from September through to December. Rainfed pastures did not benefit from higher soil fertility across the rest of the year while irrigated pasture benefitted from increased fertility in autumn (data not shown).

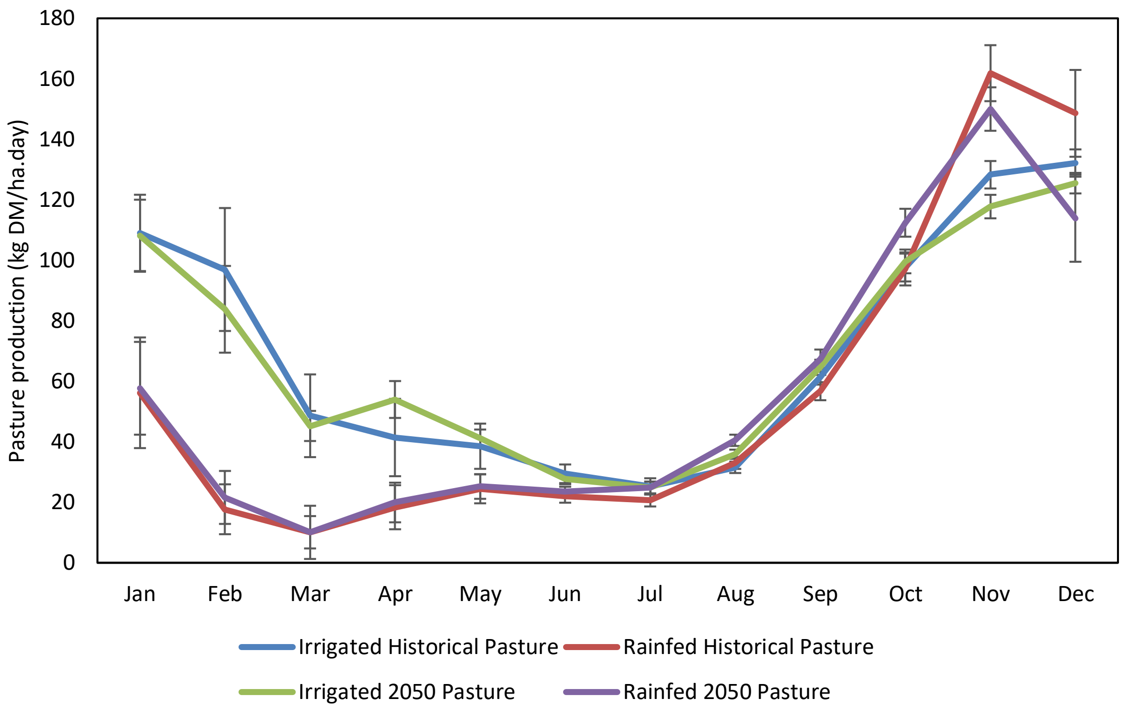


**Figure 19.** Average (±1.96 SEM) daily pasture growth rate (kg DM/ha.day) over a historical and 2050 climate (n=20) both under irrigation and rainfed conditions at the Stanley beef farm. See methods for legend abbreviations.

There was no difference in gross margin between the historical and 2050 baseline climates (Fig. 20). However, reducing pasture fertility resulted in a higher average gross margins ($36/ha) compared to the historical gross margins. Increasing the mature cow weight had the greatest positive impact on gross margins ($149/ha). Decreasing the mature cow weight resulted in the greatest negative impact on gross margins (-$119/ha).

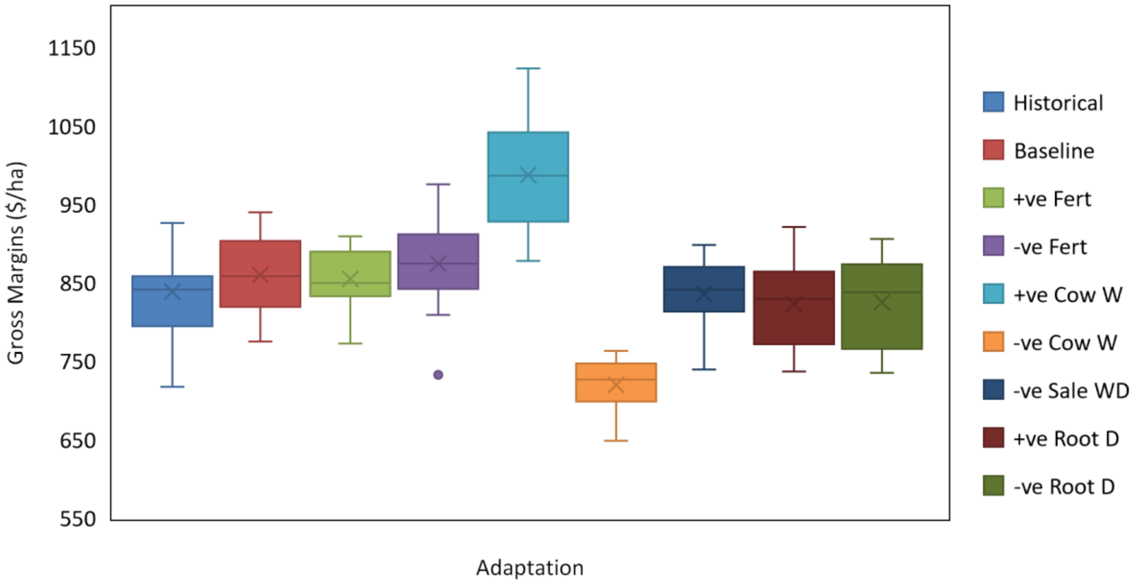


**Figure 20.** Interannual variation in gross margins ($/ha) of the Stanley beef farm for historical and 2050 climates and all adaptations (n=20). See methods for legend abbreviations.

Average liveweight production under the historical climate did not differ from the liveweight production of the baseline 2050 climate (Fig. 21). Increasing the mature cow weight had the greatest positive impact on liveweight production (+13 tonnes liveweight/year) with the 2050 baseline climate. Decreasing the mature cow weight resulted in the greatest negative impact on liveweight production (-13 tonnes liveweight/year).

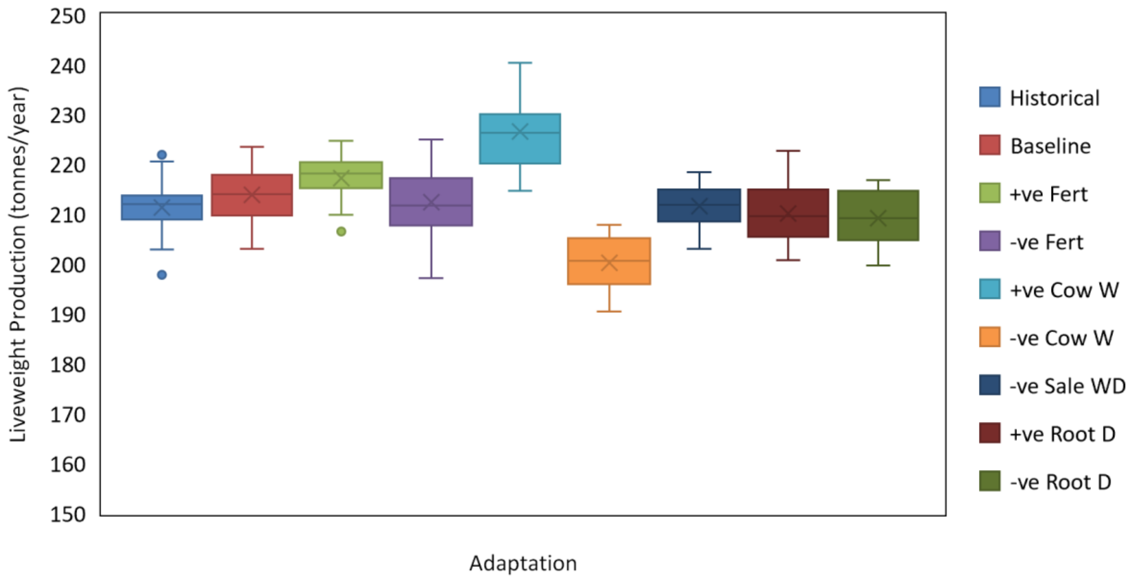


**Figure 21.** Interannual variation in liveweight production (tonnes/year) of the Stanley beef farm for historical and 2050 climate and all adaptations (n=20). See methods for legend abbreviations.

The average supplementary feed requirements of historical climate did not differ from the baseline 2050 climate (Fig. 22). Increasing the mature cow weight resulted in a reduction in supplementary feed requirements (-90 tonnes DM/year) when compared to the 2050 baseline climate. In contrast, reducing the mature cow weight resulted in an increase in supplementary feed requirements (+94 tonnes DM/year) when compared to the 2050 baseline climate.

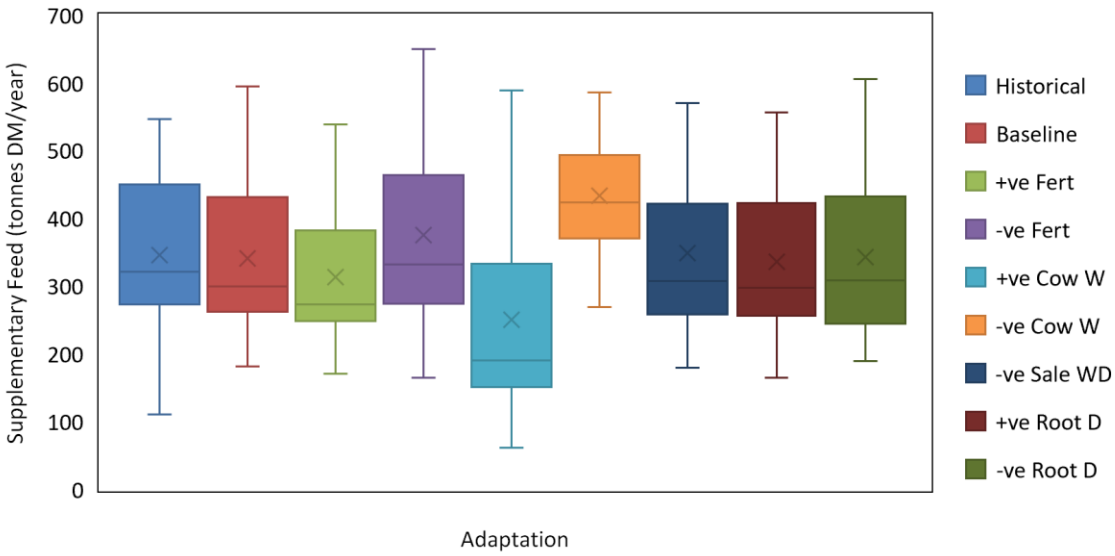


**Figure 22.** Interannual variation in supplementary feed (tonnes DM/year) requirements of the Stanley beef farm for historical and 2050 climate and all adaptations (n=20). See methods for legend abbreviations.

Average pasture production did not differ between the historical climate or the 2050 climate on the Stanley beef farm (Fig. 23). Increasing fertility had the largest positive impact (+860 kg DM/ha.year) on pasture production but was not different to the baseline 2050 climate. Decreasing fertility had a negative impact (-1,460 kg DM/ha.year) on pasture production when compared to the baseline 2050 climate.

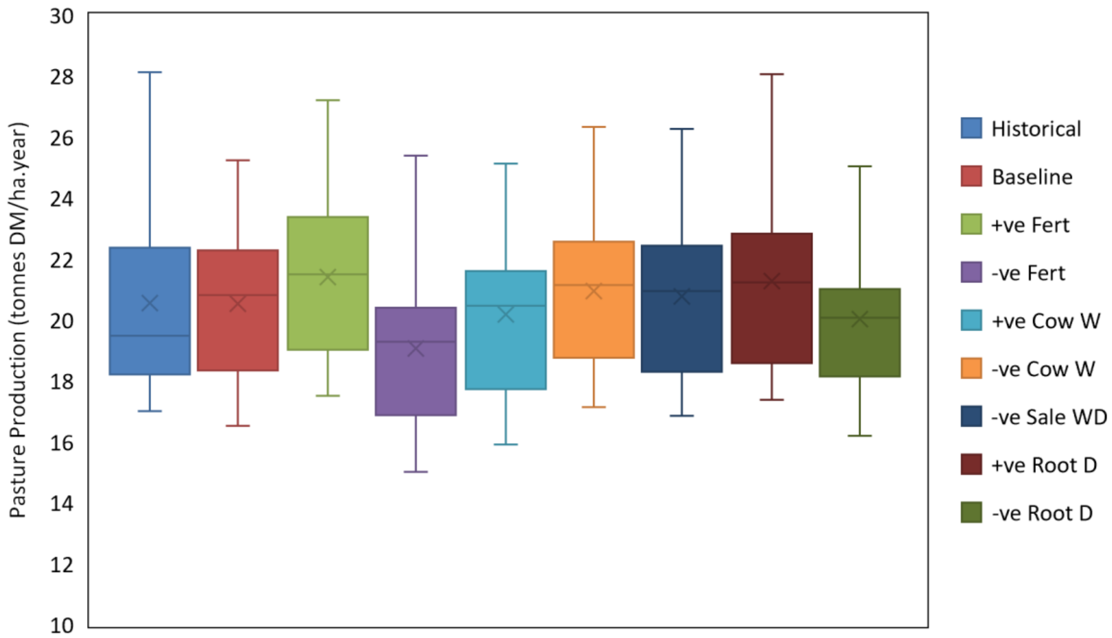


**Figure 23.** Interannual variation in annual pasture production (tonnes DM/ha.year) of the Stanley beef farm for historical and 2050 climate and all adaptations (n=20). See methods for legend abbreviations.

Stocking rate varied across the range of adaptations. The 2050 climate allowed higher (+0.02 cows/ha) stocking rates than the historical climate stocking rates (Fig. 24). The reduced mature weight of cattle caused the greatest increase in stocking rate with a 0.03 cows/ha increase in stocking rates. Reducing pasture maximum root depth caused the biggest declines in average stocking rates (-0.05 cows/ha).

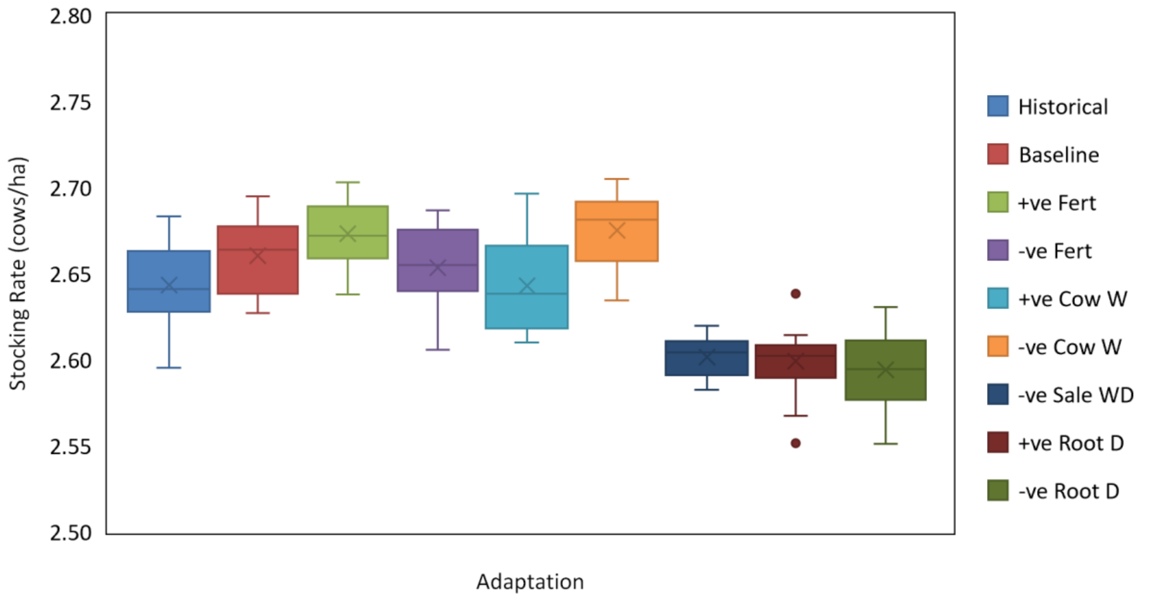


**Figure 24.** Interannual variation in stocking rates (cows/ha) of the Stanley beef farm for historical and 2050 climate and all adaptations (n=20). See methods for legend abbreviations.

The annual mean groundcover declined by 3.6% from the historical climate to the 2050 climate (Fig. 25). Reducing pasture fertility had the least effect on groundcover of all the adaptations, while increasing the average weight of mature cows had the greatest effect (-4.6%).

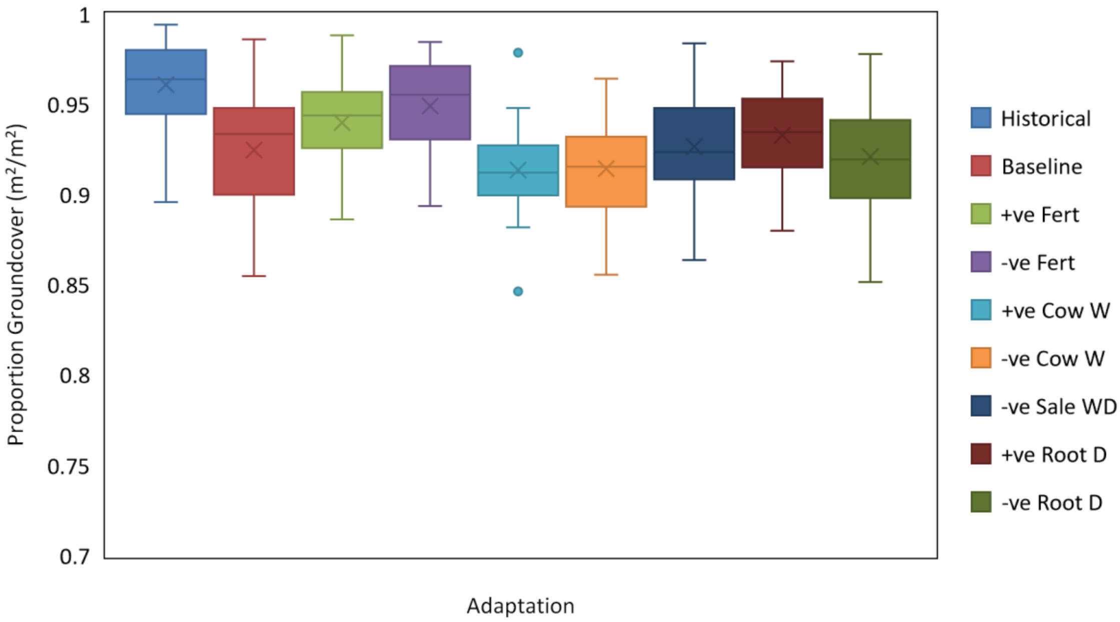


**Figure 25.** Interannual variation in average annual ground cover ($m^2/m^2$) of the Stanley beef farm for historical and 2050 climate and all adaptations (n=20). See methods for legend abbreviations.

## Farm comparisons

Adaptations to the 2050 climates did not always cause significant differences relative to the historical climate in terms of gross margin or livestock production (Fig. 26). Increasing mature cow liveweight (+ve Cow W) had the greatest positive impact on both gross margins (18%) and liveweight production (7%) for the Stanley beef farm for the historical climate. Selling lambs earlier (-ve Sale DW) had the greatest positive impact on the Campbell Town sheep farm gross margins (4%) while shifting lambing later (-ve Lamb D) resulted in the largest increase in liveweight production (7%) over the historical climate.

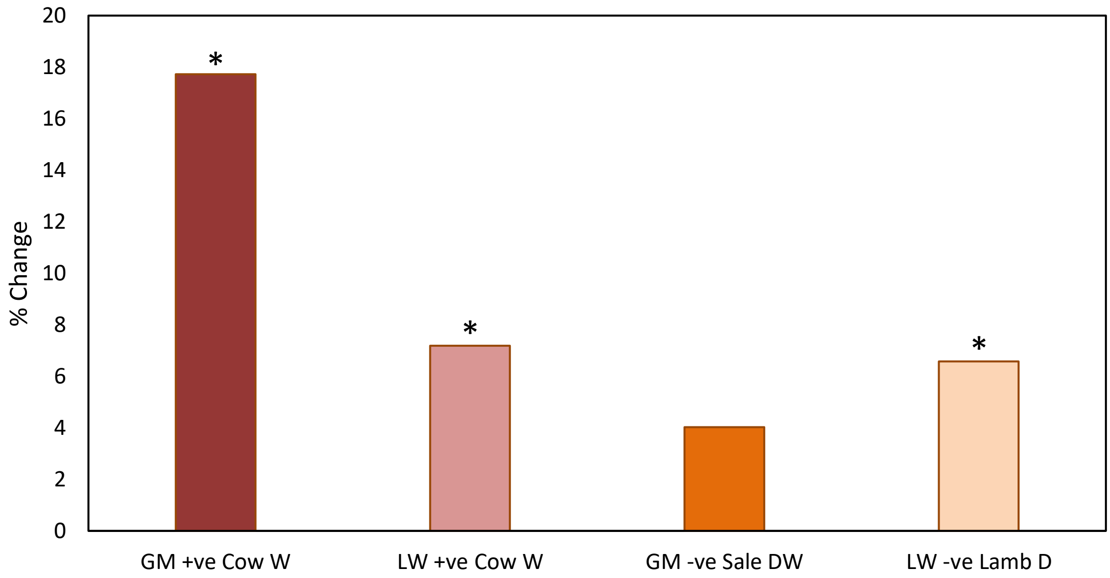


**Figure 26.** The largest percentage increases in adaptation for gross margins (GM) and liveweight production (LW). Significant differences over the historical climate treatment were represented by asterisks (*). See methods for column abbreviations.

Pasture production did not vary between the historical and 2050 climates for either farm, but supplementary feed increased at the Campbell Town sheep farm in 2050 compared with the historical climate treatment (Fig. 27). For both farms, pasture production declined by 0.1% and 1.2% respectively. Supplementary feed requirements declined for the Stanley beef farm by 1.4% and increased at the Campbell Town sheep farm by 4.8%, indicating beneficial and negative effects of climate change in the Stanley and Campbell Town regions, respectively.

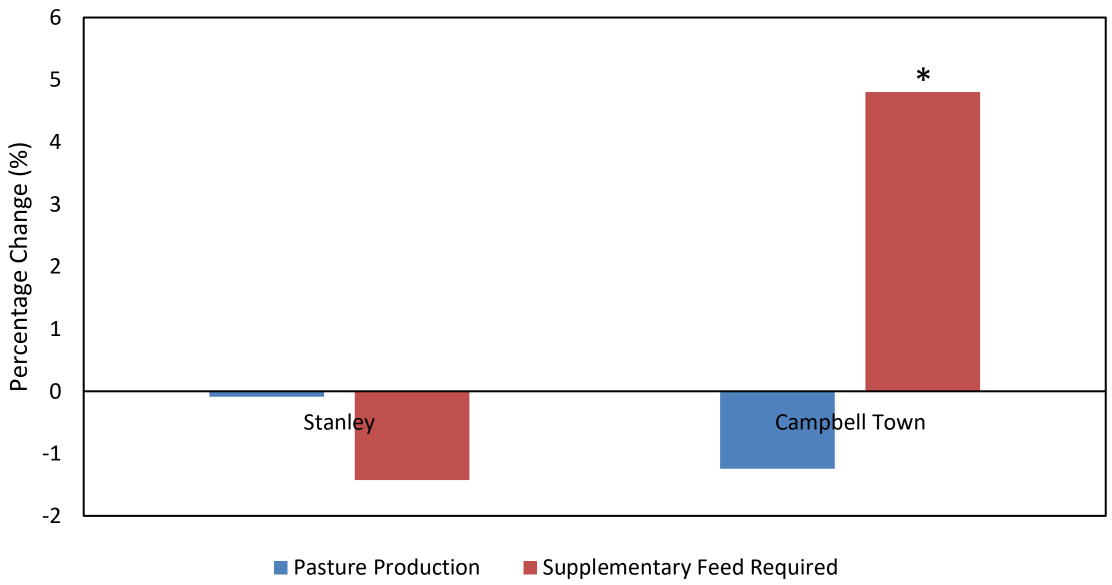


**Figure 27.** Changes in pasture production and supplementary feed requirements between the historical climate and 2050. Significant differences over the historical climate treatment are represented by an asterisk (*).

# Discussion

This thesis used real case study farms to model the impact of climate change on long-term productivity and profitability. The study aimed to elucidate systems adaptations that farmers may consider to help remain economically sustainable under an increasingly variable climate. Using the latest IPCC global climate projections, it was shown that the farms at both Stanley and Campbell Town were little effected by climate change out to 2050. In itself – even without adaptation – this is a very promising result for Tasmanian farmers. To adapt to the warmer, more variable conditions, we modelled a range of systemic interventions to the whole farm system, including changes to animal husbandry, the feedbase, pasture management and animal genetics. At the Stanley beef farm, genetic size of mature cattle had the greatest impact, with larger cows resulting in greater production and gross margins under future climates. At the Campbell Town sheep farm, shifting lambing time to later in the season increased production of lambs, but the additional supplementary feed required will have a negative effect on gross margins.

## Climate change impacts on pasture growth

To account for regional variation in projected climate impacts, we examined two farms: one in the northwest (relatively high rainfall), the other in the lower rainfall area of the Midlands. Both Stanley and Campbell Town experienced declining rainfall and rising temperatures under future climates. The Campbell Town rainfall declined significantly by 8% over the course of the year, particularly in the months of spring. The Stanley farm declined by 7% but given that the northwest of Tasmania has higher annual rainfall, this actually represented a greater total decline in rainfall. Similarly, rainfall in Campbell Town, declined the most in spring. At both locations, annual evapotranspiration declined at a similar rate to rainfall. This suggests that rainfall was a key factor in determining evapotranspiration. The combination of less rainfall with lower evapotranspiration in late spring was a key factor limiting seasonal and annual pasture growth. The lower evapotranspiration found in this study is in direct contrast to previous findings (CSIRO 2021). It has previously been assumed that potential evapotranspiration rates will increase as the atmospheric moisture levels decline. This study hypothesises that lower rainfall rates with rain falling in more singular extreme events, will lower the ultimate evapotranspiration over the length of the year. Rainfall in more extreme singular events is more likely to escape through the soil profile into deep drainage instead of being drawn out through the surface again. Lower rainfall overall also limits the moisture in the soil and so evapotranspiration is limited by the availability of water.

In 2050, higher temperatures in winter coupled with elevated atmospheric $CO_2$ resulted in higher rates of pasture growth in winter on rainfed pastures, although pasture growth declined in late spring and over summer for both locations.

Cullen et al. (2009) showed that Northwest Tasmania would likely realise greater pasture production under future climates. In contrast the present study showed that pasture production in north-western Tasmania would not change significantly. Hovenden et al. (2020) found that increasing $CO_2$ concentration would suppress production of above-ground biomass of ryegrass but increase below ground biomass. The majority of global studies (Clark et al. 1995; Greer, Laing & Campbell 1995; Newton et al. 1994) indicate an overall increase in pasture production, but ryegrass competitiveness against clover may decline. The advancement of the present study compared with previous studies is that we explicitly accounted for more frequent and detrimental extreme events (such as droughts and heat waves) in the modelling. Previous modelling (e.g. Cullen et al. 2009) did not account for these extremes and thus has predicted a more mild effect of climate change in Tasmania. Our work demonstrated that consideration of extremes in modelling of future climates is critically important to accurate estimation of pasture production, similar to results documented by Harrison, Cullen and Rawnsley (2016).

Future climates with reduced spring growth will inhibit the amount of hay or silage able to be cut, and thus supplementary feed available for farmers. The forward shift of pasture growth from late spring to winter may lead to greater livestock reproductive success by reducing mortality rates of juvenile livestock (e.g. (Alcock et al. 2015; Harrison et al. 2014a)). If lambing period does not change, lamb mortality rates may fall due to warmer spring temperatures. While Kleemann and Walker (2005) found no link between chill and lamb mortality in South Australia, Horton et al. (2018) found that the mortality rates of lambs 1-3 days after birth was significantly increased by the chill index, particularly for ewes giving birth to twins and triplets. Cattle with additional feed in winter can reach calving with a higher condition score, allowing them to go into oestrus sooner and give birth to more calves (Richards, Spitzer & Warner 1986).

Irrigated pastures at the Campbell Town sheep farm were better suited to climate change adaptation compared with the Stanley beef farm, with irrigation at the Campbell Town sheep farm resulting in higher growth rates year-round (except for January). Pasture growth at the Stanley beef farm was very different; irrigated growth was lower in late spring and summer in 2050 compared with the historical climate. These results contrasted with the results found in other recent studies (Langworthy et al. 2018; Phelan et al. 2018), who showed that irrigated ryegrass growth would increase in a future 2050 climate. The primary irrigated pasture species at both locations was lucerne. The two ecotypes modelled here differed both in growth rates and rooting depth. Both farms used semi-winter active lucerne, however growth was more vigorous at the Campbell Town sheep farm. The warmer temperatures associated with Northwest Tasmania may require farmers to select lucerne genotypes that are fully active in winter rather than semi-active. Changing pasture species at the Stanley beef farm site is an opportunity for further research and adaptation to future climates.

While both livestock farms examined here had irrigation, it is important to note that many farms in the Midlands and indeed in Tasmanian more generally have limited access to irrigation water. For example, only about 4% of the Campbell Town sheep farm was irrigated. While irrigation is an effective strategy to adapt to climate change, it will not be readily available to many Tasmanian farms (Harrison, Cullen & Armstrong 2017; Harrison, Cullen & Rawnsley 2016). Where irrigation does become available, it will come at a high cost that will only justify crops with high gross margins rather than pasture livestock production systems.

## Pasture genetics adaptations: altering the depth of legume and grass roots

Another adaptation we modelled was that of pastures with greater root depths. Increased root depths occur naturally in some pasture species, such as lucerne. As well, future pasture breeding may examine improvements to pasture root depth, thus providing an ideal trait for modelling potential adaptation under future climates. We found that adjusting the maximum root depth of pastures had little effect on either gross margins or annual liveweight production. Neither gross margins nor annual liveweight production differed significantly from the 2050 climate or the historical climate treatment. As well, the cost of altering the depth of pasture roots may be high if conducted through traditional breeding routes, and sowing such varieties requires pasture renovation. This can be implemented by direct drilling or traditional cultivation, resulting in both financial costs and potentially environmental implications. Cultivation and resowing in unreliable rainfall zones could lead to pasture failure and soil degradation if pastures do not germinate effectively (Bell et al. 2013).

Pasture production by 2050 for genotypes with the deep root trait was not significantly different from the baseline 2050 climate or the historical climate. While deeper roots may have the ability to reach deeper water, higher below-ground growth simulated here did not significantly benefit above-ground production. This contrasts with the work of Cullen et al. (2009), who found that deeper roots increased the length of the spring growing season and significantly increased the daily above ground dry matter production. Increased production in the Cullen et al (2009) study may have occurred because less water escaped as deep drainage. Cullen et al (2009) most likely had greater effects of root depth because their site was for a much hotter, drier region in Victoria, compared with the cooler, milder regions in Tasmania examined in the present study.

## Pasture management adaptations: increasing the fertility of pasture at both locations

Adjusting the fertility of pasture had trade-offs for both gross margins and liveweight productivity. Rainfed pastures were only significantly impacted in spring by applying additional fertiliser. Because we applied a generic fertility scalar in our modelling approach actual changes in fertiliser application were not quantified, but effects of changes in soil fertility were reflected in pasture production.

Gross margins at Stanley for both reducing or increasing the fertility scalar under the 2050 climate were significantly higher than the historical climate, but not significantly greater than having no change in fertiliser. Decreasing the fertility scalar (a proxy for fertiliser production) increased profitability by 4%, while increasing the fertility scalar increased profitability by 2% relative to the historical climate treatment. Liveweight production was not significantly impacted by lower soil fertility but increasing the fertility scalar increased liveweight production by 2% relative to that under the historical climate treatment (although this was similar to no change in fertility under the 2050 climate; 1.6%).

Gross margins at Campbell Town for both reducing and increasing the fertility scalar under the 2050 climate were significantly higher than the historical climate. Decreasing the fertility scalar increased profitability by 0.5%, while increasing the fertility scalar increased profitability by 3% relative to the historical climate treatment. Liveweight production was 2% lower with reduced soil fertility but increasing the fertility scalar increased liveweight production by 4% relative to that under the historical climate treatment (although this was similar to no change in fertility under the 2050 climate; 1.2%).

Increasing soil fertility of irrigated pastures may result in greater pasture production and thus livestock carrying capacity. This in turn may increase enteric methane production, such that higher production results in higher greenhouse gas emissions. Such trade-offs were observed by Cottle, Harrison and Ghahramani (2016) in terms of both greenhouse gas emissions per hectare and per head. Together these findings underscore the need to examine multiple metrics to determine whether positive changes in one dimension are offset be detrimental changes in another.

Irrigated pastures were generally more able to take advantage of the higher soil fertility, particularly in autumn and spring. In contrast, rainfed pasture were only able to utilise the additional fertiliser in spring when rainfall was higher. One limitation of the GrassGro model used here is that it does not allow targeted seasonal applications of fertiliser in the seasons where it is most useful. This would be particularly beneficial to evaluate seasonal responsiveness of pasture growth to nitrogen application, as well as associated nitrogen losses in a whole farm system (Christie et al. 2018; Eckard et al. 2020; Smith et al. 2018). Further research is required to understand the efficiency of seasonal applications of additional fertiliser and the declining return on investment by applying fertiliser at different times of the year in sheep and beef production systems.

## Adapting livestock genetics: increasing mature adult frame size

The larger mature cow size had the greatest positive impact on both the gross margins and the liveweight production at the Stanley beef farm. Liveweight production and was aided by the greater weight of cows cast for age (CFA). Achieving this goal would require breeding for larger animals. All farmers select bulls and sperm (when using artificial insemination) based on physical and genetic traits such as fat percentage or fertility. Selecting based on growth rate and mature animal size is not new but this study is one of the first to show that increasing mature animal size aids both production and profitability. The cost of breeding for larger animals is not likely to be any greater than the normal breeding program that farmers would carry out normally, so these findings suggest that larger animal size may be a genuine adaptation to climate change.

Increasing mature animal size meant that their energetic requirements also increased. Larger mature animals consumed more pasture, necessitating a reduction in stocking rate. This finding highlights an important trade-off between stocking rate and animal size and underscores the importance of examining such trade-offs in a systems framework (Harrison et al. 2014a; Harrison et al. 2021b). The increase in livestock production came despite a decline in the farm stocking rate. Inversely, reducing the size of mature cows led to higher stocking rates on average. Larger cows produced more liveweight production despite the lower stocking rate. The supplementary feed requirements were lower for the larger animals than for the smaller animals, similar to that shown by Harrison et al (2014). Larger cows increased liveweight output by 7% and increased gross margins by 17%. These are substantive changes for any livestock operation. The animals bred to be larger may have a higher efficiency of feed digestion and thus feed conversion efficiency. It is also possible that larger adult frame sizes allowed more fat and glycogen reserves to manage stress periods such as hot spells and reproduction. This could indicate that larger cows are more resilient to more variable climates, although experimental evidence to support this claim is lacking. Rather, smaller cows with greater relative surface area are typically assumed to have greater heat tolerance (Bradford et al. 2016).

Larger cow size has previously been shown in climate modelling to increase profits and liveweight production (Moore & Ghahramani 2013b). This modelling was done with a focus on Victorian and New South Wales pasture production system and showed that the trend is durable even under slightly drier and more extreme conditions. The model was extrapolated into Tasmania and suggested the success of breeding larger animals highlighted by this project (Moore & Ghahramani 2013b). In contrast the more arid climate in Texas represented a different perspective. The lack of available feed to help cattle attain higher weights and the lower stocking rate required meant that profits declined and liveweight production declined. This was despite supply chains providing a premium for larger framed cattle (Doye & Lalman 2011). Between these two comparisons, the

Australian study is obviously more closely related to the study presented here. The modelling tool used matched the one used in this research. The Texas study modelled conditions massively different from Tasmania and failed to detail the type of cattle used.

Genetic breeding for larger cattle in Australia has been going on for several decades. Large increases have been made annually in terms of the 400-day weight of beef cattle (Johnston 2007). The year of 2050 is realistically very distant in terms of breeding. With the advancement of EBVs, particularly in angus herds, the potential to reach the modelled 10% increase in mature cow size is highly achievable.

## Adapting animal management: shifting sale times of young animals

Selling juvenile animals earlier has the potential benefit of allowing the remaining herd (mostly breeding animals) to utilise more pasture biomass (Harrison et al. 2014a) and this can potentially improve profitability (Alcock et al. 2015). With regards to supplementary feeding, superfluous feeding beyond a certain point (ie *ad libitum* feeding) may not result in additional liveweight gains and may cause dry matter ingested to be excreted as waste. Selling juvenile animals at a later date may not result in greater liveweight production if the full adult size has already been reached (Harrison et al. 2014a). In our simulations, mature animals at the Stanley beef farm did not become significantly larger when held for longer indicating that peak liveweight had been reached.

The early sale of cattle reduced whole farm stocking rate as more cattle were sold earlier; this was beneficial in terms of sustainability (lower ground erosion etc) but also in terms of production (liveweight production was similar). Selling younger animals earlier under the future climate meant that breeder animals utilised more of the remaining pastures and were cast for age at greater weights. Holding young animals later could create slightly heavier animals at sale but detracted from pasture available for the next year's herd. Selling animals later means lighter animals, but the next year's herd will be able to utilise the greater feed supply. Lower available biomass increases the need for supplementary feeding of grain and hay, which increases costs. Selling cows earlier did not impact on supplementary feed required and thus neither saved money or cost money to implement.

Overcoming the genetic limitation to growth can be done by breeding for larger cows. Previously discussed in this project is the highly profitable adaptation of using larger mature cows. Genetically larger animals may have a propensity to grow for longer. In this respect, combining multiple beneficial adaptations may result in the greatest changes to farm production and profitability. Indeed, these findings have been observed for extensive beef systems in QLD (Harrison et al. 2016), prime lamb enterprises in Victoria (Harrison et al. 2014a), as well as dairy production systems in south-eastern Australia (Harrison, Cullen & Armstrong 2017; Phelan et al. 2015). Enterprise stacking, combining beneficial adaptations and assessment using multiple sustainability metrics is an area that deserves further attention in future studies that examine climate change adaptation of livestock systems (Harrison et al. 2021b).

## Adaptations to animal management: altering the lambing date or the lamb sale date

Changing lambing time had significant impacts on the liveweight production, but little effect on gross margins, demonstrating that changes in productivity do not necessarily impact on profitability. Moving lambing time forwards led to heavier young lambs, but fewer of them. Later lambing means that ewes are in much better condition and conceive higher rates of twins. However, the lambs are fattening in late summer at a time when less feed is available, and twin lambs are generally born at lower liveweights than singles (Harrison et al. 2014b; Ho et al. 2014). Earlier lambing had lower conception rates, but the lambs fattened during peak pasture production and many animals were thus heavier at sale. The current lambing date (September 18) appears to be profitable despite lambing later having significantly higher liveweight production with a later lambing period.

Supplementary feed requirements did not alter significantly by shifting the lambing date. Lambing earlier caused a 6% decline in supplementary feed required; lambing later had a 9.5% increase in supplementary feed required. Stocking rate increased when lambing later due to the higher number of lambs produced. This however did not create significant impacts on wool production, pasture production, or ground cover. Low rainfall and volatile seasonal conditions at the Campbell Town sheep farm meant that supplementary feed requirements year on year were extremely variable. This can increase economic risk associated with later lambing, particularly under future climates with greater variability (Ho et al. 2014).

Adjusting the sale date of Merino lambs had little impact on either the annual liveweight production or the gross margins when compared to the baseline 2050 climate. Both selling lambs earlier and selling lambs later had a less than 2 $/ha impact on gross margins. Both adaptations increased liveweight production but by less than half a tonne over the baseline 2050 climate but was still significantly greater than the historical climate treatment.

Stocking rate, pasture production and groundcover were unaffected by lambing date. Adjusting the selling date by just two weeks may have been too small of an adjustment to properly assess the impact of selling date on profitability and productivity of the farm. Further research on more extreme adjustments will be required to get any indication on the efficacy of adjusting sale date. Earlier sale dates may be less valuable as immature sheep may be too young to wean off their mothers. Holding the lambs for another 1-2 months may allow the sheep to grow longer but would require holding the lambs over the driest period of the year with the least pasture production and could impact on the condition of ewes for the following year’s lambing period.

## Concluding remarks

This thesis found that 2050 climates in Tasmania will be mild but also regionally specific. Rainfall is expected to fall by 7-8%, much of which will be in autumn and late spring. Maximum daily temperatures are expected to rise by 1-1.5°C, while minimum temperatures are unlikely to change. Collectively, these effects will reduce annual pasture production, with less growth in late spring and more in winter. However, climate change was not significantly detrimental to either liveweight productivity or gross margins in 2050. The stark contrast between climate change impacts on Tasmania and that on most mainland systems will likely drive interest in livestock production and indeed agriculture more generally in Tasmania.

In terms of adaptations to the changing climate, larger mature cow size had the greatest positive impact on both the gross margins and the liveweight production at the Stanley beef farm. Pursuit of this adaptation could be realised through using genetic selection with a focus on mature size. While this model did not highlight issues with heat tolerance, larger cows are traditionally less likely to cope with higher temperatures. Tasmania traditionally is cooler and heat stress will unlikely be an issue under a 2050 climate, even for the warmer regions of the Midlands. The thirty years between the present and 2050 allows time for genetic progress towards increased mature cow size.

Earlier sale of juvenile cattle reduced whole farm stocking rate and was beneficial in terms of sustainability (lower ground erosion etc) but also in terms of production (liveweight production was similar). Ground cover has not been an issue for either of the case study farms but reducing opportunities of soil erosion are still valuable. The fact that liveweight production did not decline may present opportunities to sell cows earlier to capitalise on other opportunities.

Changing lambing time had significant impacts on the liveweight production, but little effect on gross margins, demonstrating that changes in productivity do not necessarily impact on profitability. The most profitable adaptation came from selling lambs earlier, but only slight increases could be found; this may be partly explained by the fact that the case study farms were already operating at high efficiency. Further research into combining (or stacking) these adaptations may have the potential to improve gross margins.

Changing fertiliser applications (via soil fertility scalars) highlighted the limitations of applying fertiliser in lower rainfall regions. Future research conducted drier parts of Tasmania could investigate the benefits of low fertiliser systems, while research in wetter regions may focus on fertiliser application during wetter months when pasture growth is more prolific. The present study also showed that deeper roots had little impact on performance and would have the greatest cost of implementation of any adaptation assessed here.

This thesis has shown that future Tasmanian pasture-based beef and wool production systems will be in a better position under future climates relative to mainland Australia. Despite implementing more severe emissions scenarios and more variable climates than those applied in previous work, this thesis showed that the seasonal reliability and quantum of pasture supply under future climates will be viable, even without adaptation. These results shine a generally positive light on the future of livestock farming and business prosperity in Tasmania.

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## Appendix 8.3 Supplement 1: Costs and prices used in GrassGro

The costs of the Campbell Town sheep farm were calculated within GrassGro. Not all prices shown in Fig. A83.1 are relevant, as only hay and wheat were used as supplementary feed in this study. Income was calculated within excel as some prices fell outside the range of programmable values (wether lamb sales).

| Costs: Sheep costs -Merino | | |
|---|---|---|
| Wether Shearing | | $3.50 /head |
| Wether Husbandry | | $2.25 /head |
| Wether Replacement | | $100.00 /head |
| Ewe Shearing | | $3.50 /head |
| Shearing Lambs | | $3.50 /head |
| Ewe Husbandry | | $2.25 /head |
| Lamb Husbandry | | $1.50 /head |
| Ewe Replacement | | $220.00 /head |
| Rams | | $1780.00 /head |
| Sheep sales commission | | 5.00 % |
| Sheep sales cost | | $2.00 /head |
| Hay Fixed cost | | $0.00 /ha cut |
| Hay Variable cost | | $40.00 /tonne FW stored |
| Pasture costs | Fertilty scalar = 0.60 | $210.00 /ha |
| | Fertilty scalar = 0.70 | $240.00 /ha |
| | Fertilty scalar = 0.80 | $270.00 /ha |
| | Fertilty scalar = 0.90 | $300.00 /ha |
| Irrigation water | | $0.00 /ML |
| Supplement costs | Barley, whole | $185.00 /t |
| | Canola meal | $270.00 /t |
| | Cottonseed meal | $250.00 /t |
| | Cottonseed, whole | $170.00 /t |
| | Peas | $190.00 /t |
| | Hay | $95.00 /t |
| | Lupins | $230.00 /t |
| | Molasses | $47.00 /t |
| | Oats, whole | $170.00 /t |
| | Sorghum, whole | $180.00 /t |
| | Triticale, whole | $190.00 /t |
| | Wheat, whole | $285.00 /t |
| | Pea straw | $95.00 /t |

| Prices: Merino prices -fine wool | | |
|---|---|---|
| Description | Fine wool prices 2002-07 (50%ile) 75-84mm, 35-39 N/ktex (Independent Commodity Services P/L) | |
| Wool prices for wethers | 16 micron | 2383 c/kg |
| | 17 micron | 2263 c/kg |
| | 19 micron | 1557 c/kg |
| | 20 micron | 1315 c/kg |
| | Av. Fleece Price | 85.0 % |
| | Wool commission | 5.0 % |
| Wool prices for ewes | 16 micron | 2383 c/kg |
| | 17 micron | 2263 c/kg |
| | 19 micron | 1557 c/kg |
| | 20 micron | 1315 c/kg |
| | Av. Fleece Price | 85.0 % |
| | Wool commission | 5.0 % |
| Wether sales | Base price | 680.0 c/kg |
| | Dressing percentage | 46.0 % |
| | Skin price | $10.00 /head |
| Ewe sales | Base price | 680.0 c/kg |
| | Dressing percentage | 45.0 % |
| | Skin price | $15.00 /head |
| Ewe lamb sales | Sale price | $105.00 /head |
| | Unshorn fleece | $22.00 /head |
| Wether lamb sales | Sale price | $30.00 /head |
| | Unshorn fleece | $5.00 /head |
| Hay sales | Price | $170.00 /tonne |

**Figure A83.1.** Prices used in the economic calculations of gross margins at the Campbell Town sheep farm.

The costs, income and gross margins of the Stanley beef farm were calculated within GrassGro (Fig. A83.2). Not all values are relevant as the only supplementary feed costs used were wheat and hay. Hay prices were adjusted to overcome a limitation of the model that resulted in too much pasture growth over late spring.

| Costs: Cattle costs | | |
|---|---|---|
| Cow Husbandry | | $20.00 /head |
| Calf Husbandry | | $16.00 /head |
| Cow Replacement | | $2400.00 /head |
| Bulls | | $5000.00 /head |
| Cattle sales commission | | 5.00 % |
| Cattle sales cost | | $18.60 /head |
| Hay Fixed cost | | $0.00 /ha cut |
| Hay Variable cost | | $45.00 /tonne FW stored |
| Pasture costs | Fertilty scalar = 0.60 | $185.00 /ha |
| | Fertilty scalar = 0.70 | $215.00 /ha |
| | Fertilty scalar = 0.80 | $245.00 /ha |
| | Fertilty scalar = 0.90 | $275.00 /ha |
| Irrigation water | | $0.00 /ML |
| Supplement costs | Barley, whole | $185.00 /t |
| | Canola meal | $270.00 /t |
| | Cottonseed meal | $250.00 /t |
| | Cottonseed, whole | $170.00 /t |
| | Peas | $190.00 /t |
| | Hay | $95.00 /t |
| | Lupins | $230.00 /t |
| | Molasses | $47.00 /t |
| | Oats, whole | $170.00 /t |
| | Sorghum, whole | $180.00 /t |
| | Triticale, whole | $190.00 /t |
| | Wheat, whole | $285.00 /t |
| | Pea straw | $95.00 /t |
| | Barley, crushed | $200.00 /t |
| | Silage | $0.00 /t |

| Prices: Cattle prices | | |
|---|---|---|
| Description | Eastern States Indicator -approx values Feb 2007 | |
| Cow sales | Base price | 350.0 c/kg |
| | Dressing percentage | 55.0 % |
| | Hide value | $1.00 /head |
| Steer sales | Base price | 590.0 c/kg |
| | Dressing percentage | 55.0 % |
| | Hide value | $1.00 /head |
| Heifer sales | Base price | 550.0 c/kg |
| | Dressing percentage | 55.0 % |
| | Hide value | $1.00 /head |
| Hay sales | Price | $15.00 /tonne |

**Figure A83.2.** Prices used in the economic calculations of gross margins at the Stanley beef farm.

# Appendix 8.4: Soil carbon assessment for the beef case study farm

Some members of the Regional Reference Group (RRG) have voiced at different times that the current ERF/CSF methodologies and alternative voluntary carbon credit schemes do not give due recognition to farm management practices that have sequestered carbon either in tree vegetation or soils in the years and decades prior to the establishment of such initiatives (i.e. the Carbon Farming Initiative and subsequent schemes). Leading farmers feel that they may be seen as 'not pulling their weight' to reduce GHG emissions in the current marketplace, primarily because they can't participate in these schemes. This was particularly true of the beef farm.

Case study 1 farm already has high soil carbon levels, undertakes many of the practices which are considered new activities (e.g. soil liming, irrigation, pasture renovations), and thus would not qualify for any current soil carbon initiatives due to aspects such as the Additionality requirements. There's currently no Carbon Farming Initiative/ Emissions Reduction Fund/ Climate Solutions Fund (CFI/ERF/CSF) methodology to retrospectively financially rewards farmers for good land stewardship. The farmer requested TIA to hindcast the likely farm management practices required over time to achieve current soil carbon stocks.

Following is segments of the email documentation between TIA and the farmer exploring the results from this modelling activity. This work was undertaken by Franco Bilotto with input and guidance from Matthew Harrison.

A single rainfed perennial ryegrass/clover paddock was analysed in GrassGro from 1907 to 2005 using climate data from the closest SILO weather site. The paddock was grazed by a cow-calf operation as per the modelling undertaken for the NEXUS project. Outputs from GrassGro were incorporated into the Roth C model to ascertain annual soil carbon stocks (Mg C/ha.annum, 0-30cm (Figure 1) and 0-100cm (Figure 2)).

The current soil organic carbon (SOC) stocks were estimated using data from a comprehensive literature review developed by Bill Cotching (renowned soil scientist at UTAS for many years) which considers many published manuscripts and university theses on available SOC in Tasmanian soils in the north-west (Cotching, 2018) and the Cradle Coast Organic Carbon Monitoring Trial (McDonald et al., 2007). Data on land use change is recent and the publication archives publications before 1980, specifically relating to data in northern Tasmania, are limited. However, we have some information about beef cattle numbers by state since 1900 onwards: these were more than doubled between 1910 and 1980 in Tasmania (Commonwealth Yearbooks). Historical events such as the sowing and topdressing of pastures have been facilitated by increasing use of aircraft (aerial dressing) since 1950. During the long course of BPC (British Phosphate Commission) phosphate production from 1920 to 1981, Australia consumed 66% of total phosphate rock traded (Dixon, 2018) and exhibited phosphorus accumulation applied on pastures (Lewis et al., 1987).

Three stocking rates were examined, reflecting changes in management practices and carrying capacity of the farm over time. Within GrassGro stocking rate refers to the number of mature animals plus replacement females. For example, a SR of 0.6 for a 100ha paddock would mean 40 mature cows, 10 rising one year old heifers and 10 rising two year old heifers. Each stocking rate was matched to a soil fertility scalar (0-1) within GrassGro. The three scenarios modelled were:

1. 1907-1936 with 0.6 SR (13.3 DSE/ha) resulting in long-term pasture consumption of 3.8 t DM/ha.annum, combined with a soil fertility scalar of 0.5
2. 1937-1986 with 0.9 SR (20.6 DSE/ha) resulting in long-term pasture consumption of 5.9 t DM/ha.annum, combined with a soil fertility scalar of 0.7
3. 1986-2005 with 1.1 SR (25.5 DSE/ha) resulting in long-term pasture consumption of 7.3 t DM/ha.annum, combined with a soil fertility scalar of 0.9

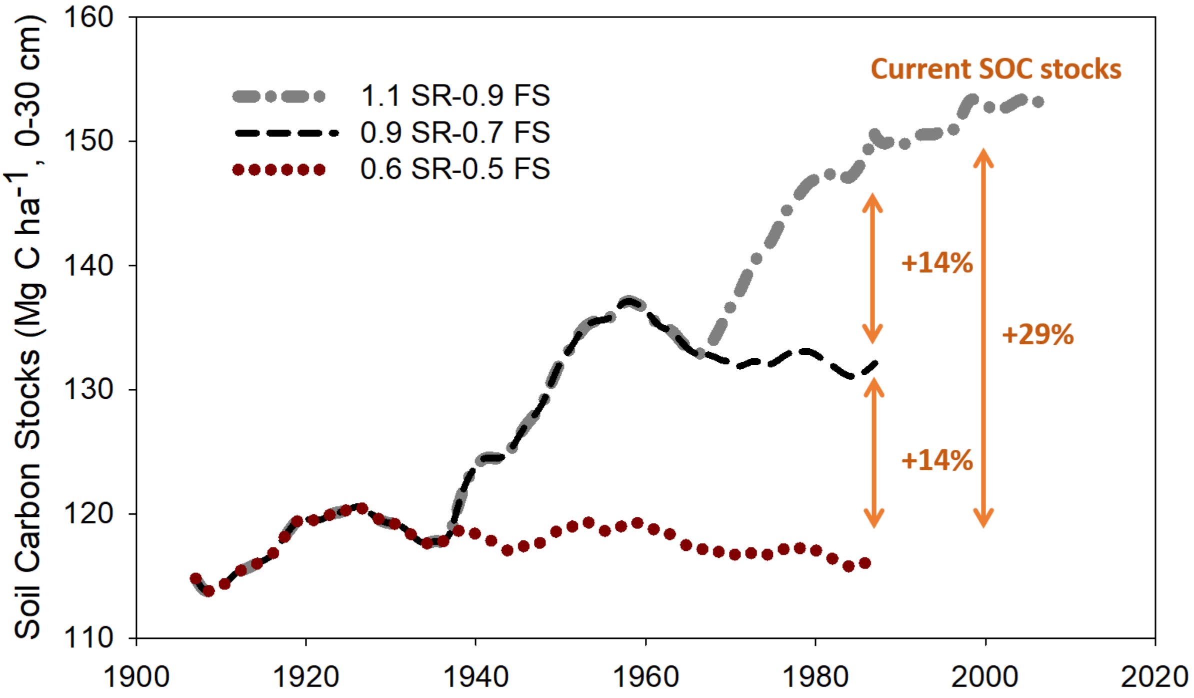



**Figure 1.** Soil carbon stocks (0-30cm) from 1910 to 2010 under three varying stocking rates/fertility statuses. Note different y-axis scaling between Figures 1 and 2.

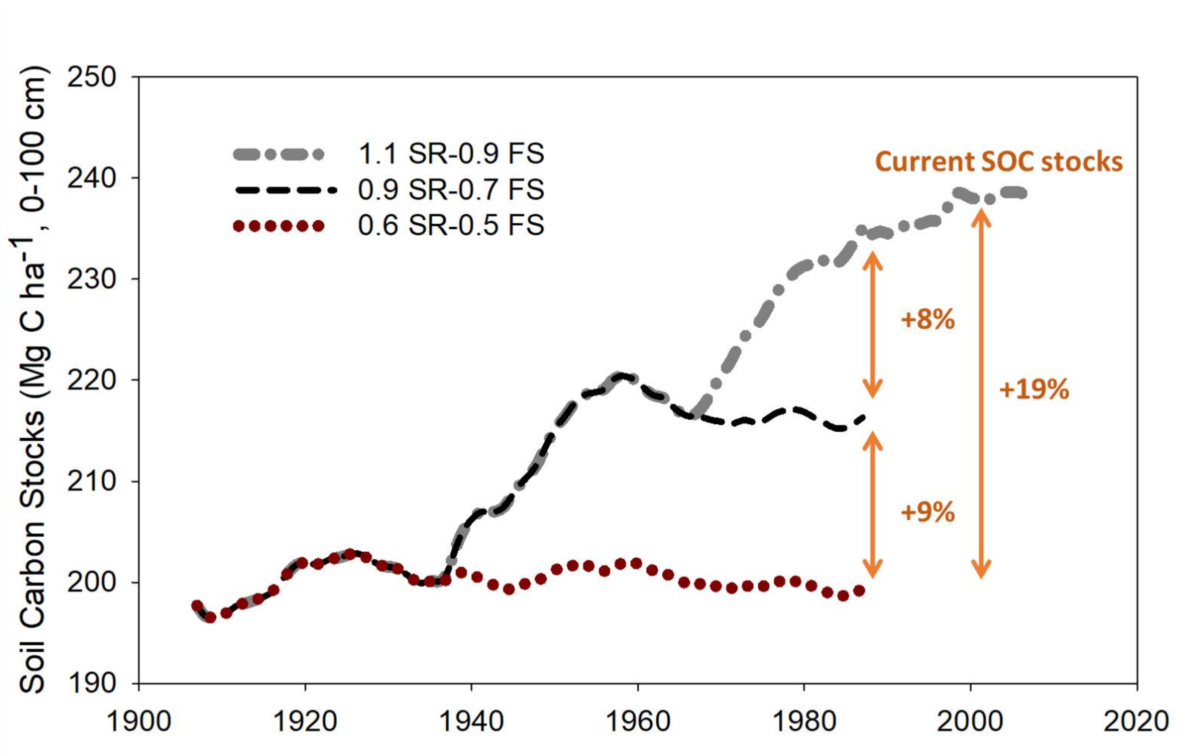


**Figure 2.** Soil carbon stocks (0-100cm) from 1910 to 2010 under three varying stocking rates/fertility statuses. Note different y-axis scaling between Figure 1 and Figure 2.

Assuming continuing gradual increases, eventually your SOC will plateau (Figure 3), after which it becomes very difficult to improve further. On the other hand, it becomes very easy to lose SOC – e.g. drought, over grazing, reduced ground cover, cultivation etc. For Dermosols and Ferrosols in NW Tasmania, “high” soil carbon levels would be 6-8%. This would be harder to maintain if rainfall decreased in future or if your soils warmed up (due to warmer days) although we have shown the climate change effect in NW Tas out to 2050 will be low. The are some changes you could make to improve soil carbon, but you would need to maintain them – e.g. introducing more irrigated areas.

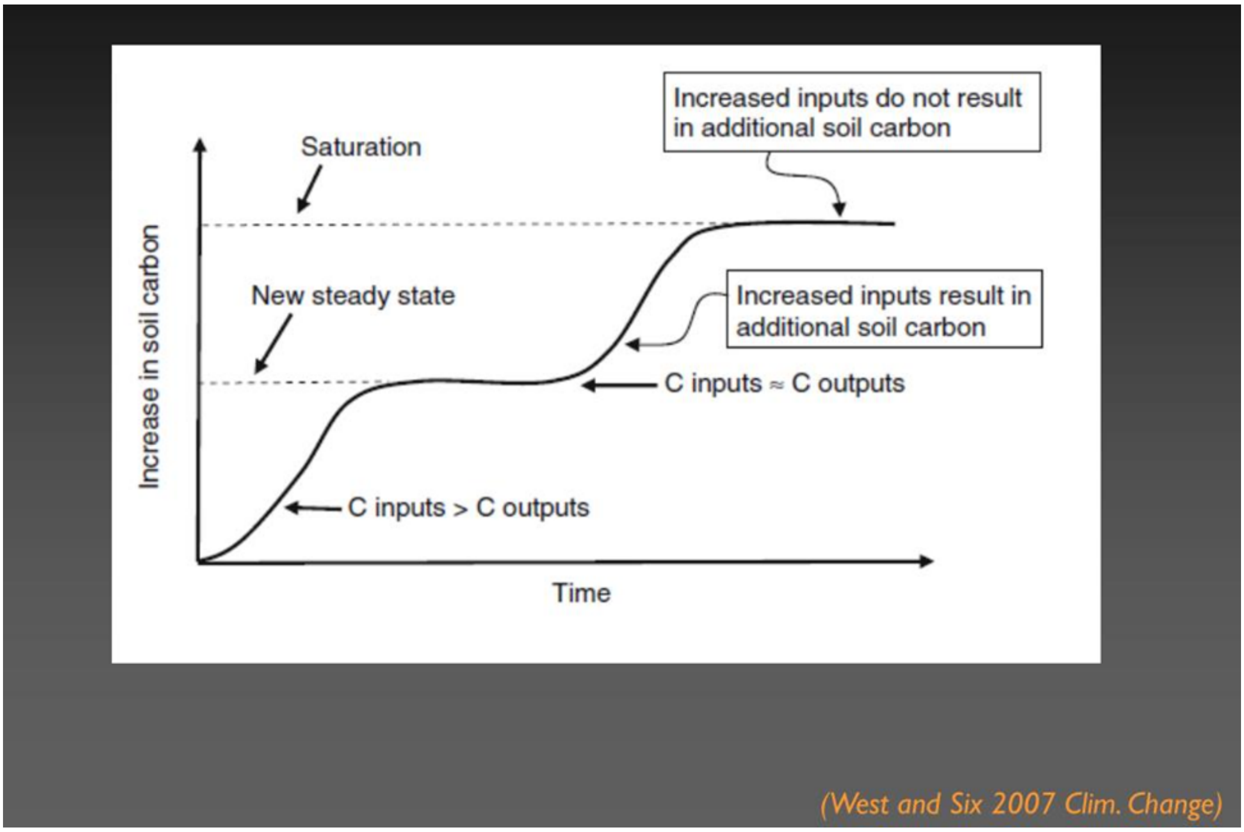



**Figure 3.** Typical pattern of soil carbon stocks over time, requiring additional inputs or changes to management to increase stocks over time.

For example, a future environment where rainfalls are predicted to decline, combined with higher temperatures, with no change in farm management practices, annual soil carbon fluxes are likely to decline, thus soil releasing more carbon dioxide into the atmosphere (Figure 4).

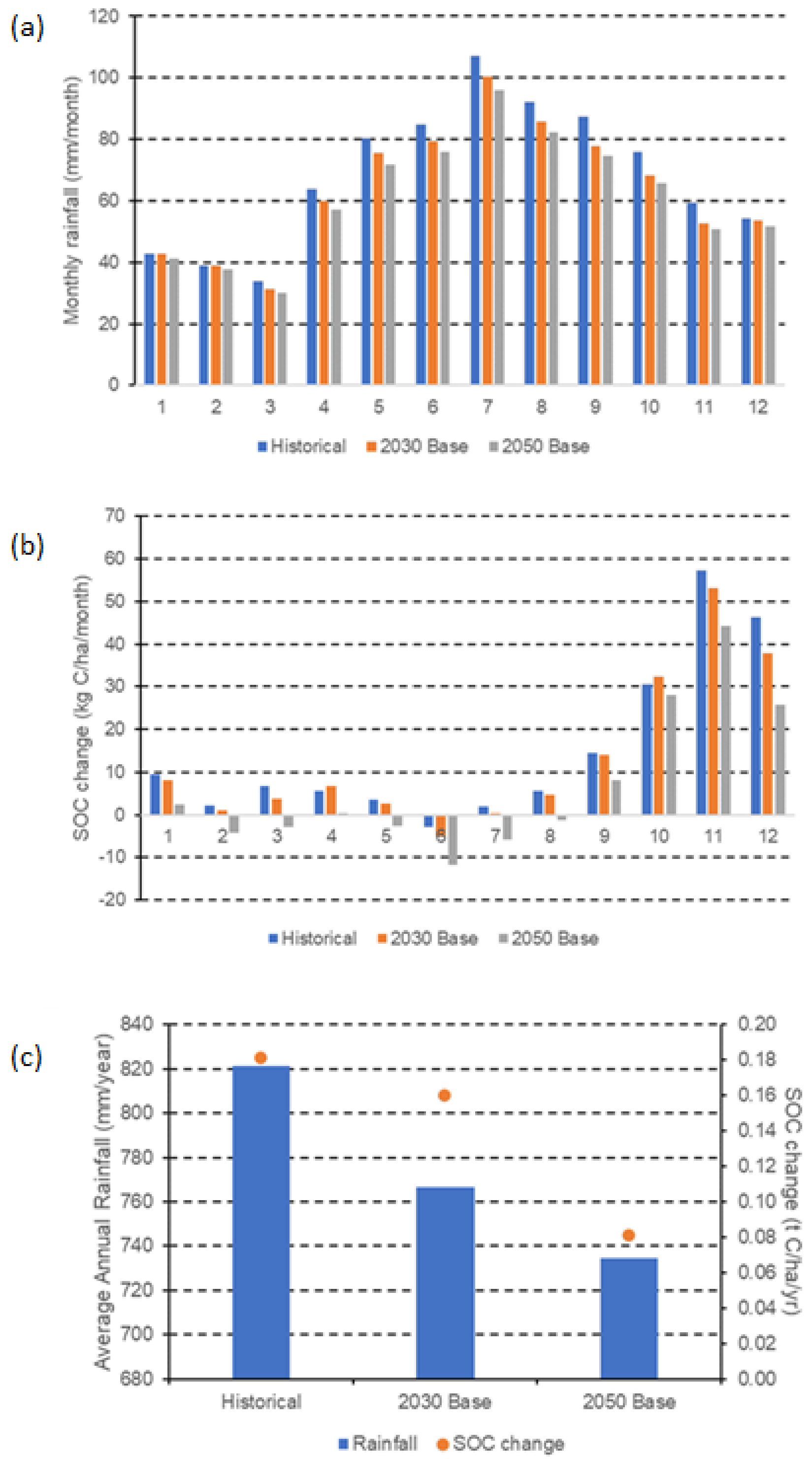



**Figure 4.** Review of the effects of (a) a future changing rainfall pattern on (b) monthly and (c) annual long-term mean soil carbon fluxes. Historical reflects years 1986-2005, 2030 baseline reflects years 2022-2041 and 2050 baseline reflects years 2042-2061. Note that the same management practices implemented in the historical timeframe are maintained in the two future timeframes.

The detailed net GHG emissions we computed in previous NEXUS milestone reports were done using the management details we collected from you, so these emissions profiles would most closely represent your current farming system. To compute changes in GHG emissions over the last 100 years, we go into much more uncertainty because we made assumptions about changes in management over time, animals on farm and sold per year, changes in N fertiliser use etc. However, we can make an initial and simplified assessment of how net GHG emissions would change over time assuming the management/fertility used to generate the graphs above.

Below we compute net GHG emissions for the baseline and for the Adapt option (your current farm system with small beneficial changes to pasture type, soil fertility etc as suggested by the regional reference group in our initial meetings; see Section 3.1.1 of this milestone report). SR in the table headers represents stocking rate and FS = fertility scalar (the higher, the more fertile the soil). Positive SOC sequestration numbers mean net removal of $CO_2$ from the atmosphere. So, each column represents different stocking rates and soil fertility over time.

For the baseline (Table 1), SOC is improved by increasing soil fertility. While SOC does influence net farm GHG emissions, stocking rates have a much greater influence (enteric $CH_4$) on net GHG emissions. SOC over time (under future climates) will decrease as soil surfaces warm and respire more $CO_2$. SOC can be improved by making some management changes, but not by much – this is represented by the two rows at the bottom. The 'Adapt option' was developed using recommendations we gathered from the regional reference group over the last two or three meetings. The individual changes made in the Adapt option were:

- increasing rooting depth of grasses/legumes by 10% (except lucerne paddocks),
- increased soil fertility scalar by 3% for paddocks,
- all stock assumed to have a 10% increase feed conversion efficiency,
- increase in stocking rate of the main herd by 10% to utilise additional pasture production
- cows calving 15 days sooner in the year,
- selling steers and heifers at a heavier liveweight, targeting an addition 20 and 15 kg/head for steers and heifers, respectively.

**Table 1.** Change in greenhouse gas emissions and soil carbon sequestration associated with varying stocking rates and soil fertility scalars over time from 1907-2005 and derived from other modelling as part of the NEXUS project for 2022-2041 and 2042-2061.

| Stocking Rate and Soil Fertility | Period | GHG emissions (t $CO_2$e/ha/yr) | SOC sequestration (t $CO_2$e/ha/yr) | Net Emissions (t $CO_2$e/ha/yr) |
|---|---|---|---|---|
| SR 0.6-FS 0.5 | 1907-1936 | 3.3 | 0.3 | 3.0 |
| SR 0.9-FS 0.7 | 1937-1966 | 5.1 | 1.7 | 3.4 |
| SR 1.1-FS 0.9 (Baseline) | 1967-1986 | 6.2 | 3.4 | 2.8 |
| | 1986-2005 | 6.2 | 0.5 | 5.7 |
| | 2022-2041 | 6.2 | 0.2 | 6.0 |
| | 2042-2061 | 6.3 | -0.2 | 6.5 |
| SR 1.1-FS 0.9 (Adapt) | 2022-2041 | 7.3 | 0.4 | 6.9 |
| | 2042-2061 | 7.3 | 0.2 | 7.1 |

In addition, higher GHG emissions per ha in 'Adapt' scenarios obtained lower GHG emission intensities per unit of product. To decrease GHG per ha and emission intensities (win-win scenarios), several options are being explored within the *Towards Carbon Neutra*l package, which can increase soil carbon and sharply decrease net farm emissions.

**References**

Cotching WE (2018) Organic matter in the agricultural soils of Tasmania, Australia – A review. *Geoderma* **312**, 170-182.

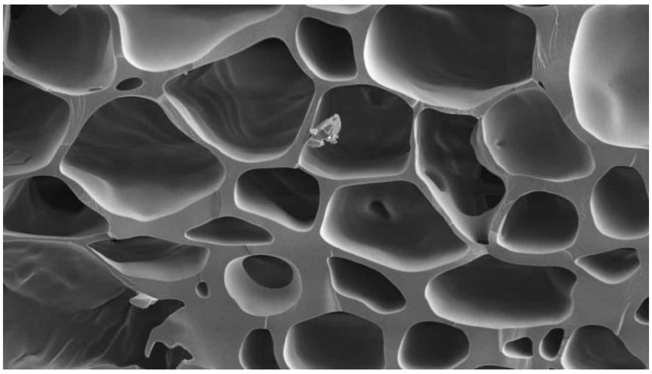
Dixon MW (2017) Chemical fertilizer in transformations in world agriculture and the state system, 1870 to interwar period. *Journal of Agrarain Change* **18**, 768-786.

Lewis DC, Clarke AL, Hall WB (1987) Accumulation of plant nutrients and changes in soil properties of sandy soils under fertilized pasture in south-eastern South Australia. 1. Phosphorus. *Australian Journal of Soil Research* **25**, 193-202.

McDonald D, Baldock J, Kidd D (2007). Cradle Coast Organic Carbon Monitoring Trial: National Monitoring and Evaluation Framework (National Land & Water Resources: Canberra, ACT, Australia).

# Appendix 8.5: Involve and Partner workshop package

Biochar Resource Package



Biochar Workshop 3

Wednesday 15th February 2023

### *Program*

| Time | Activity | Presenter |
|---|---|---|
| 10:00-10:30 | Morning Tea | |
| 10:30-10:45 | Welcome<br>Package Tour<br>Pre workshop data capture | Nici Barnes – TIA |
| 10:45-11:00 | Biochar Involve and Partner Project | Matt Harrison - TIA |
| 11:10-11:25 | Biochar | Steve Sullings and Karen Enkelaar – Agspand FEEDCHAR® |
| 11:25-11:50 | Biochar in practice | Aiden Coombe – Westmore Farm Manager |
| 11:50-12:20 | Farm Tour | Aiden Coombe |
| 12:20-12:30 | Post workshop data capture | Nici Barnes – TIA |
| 12:30 | Lunch | |

### *Thank you to our sponsors*

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TIA Tasmanian Institute of Agriculture

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***Matt Harrison Presentation –***

## NEXUS Project: feed supplementation with biochar as a win-win-win?

Matthew.Harrison@utas.edu.au | 0437 655 139

As part of the NEXUS project, we are examining biochar supplementation as a potential greenhouse gas emissions mitigation option: https://www.utas.edu.au/tia/research/research-projects/projects/nexus-project-exploring-profitable,-sustainable-livestock-businesses-in-an-increasingly-variable-climate

- **Biochar as a livestock feed supplement is said to:**
    - Reduce livestock enteric methane
    - Improve animal growth rates (improve animal health and rumen surface area)
    - Improve soil organic carbon through biochar-enriched manure (we are measuring this)
- We are feeding calves on TasAgCo a commercial grade biochar '*FeedChar*'
- We are measuring biochar consumption, liveweight gain, manure organic carbon, pasture dry matter, botanical composition
- We will model effects of biochar on whole farm greenhouse gas emissions (enteric methane, soil carbon, LW gain)
- We will model the effects of biochar on greenhouse gas emissions intensity, cost and profitability (need more than 10% improvement in liveweight gain to be profitable)
- We are examining impetus to change through on-farm discussions – hence the discussion today
- Future workshops will be held at other locations (farmers that have used biochar for a long time)

***Results to date***

- Comparison of two methods of measuring pasture biomass showed little difference, which was good (hand cuts and plate meter) – indicates that plate meter is an acceptable method of measuring pasture biomass (Fig. 1). The one exception was the biochar hand cut measurement which was significantly higher than the control hand cut in late summer 2022 (Fig. 1).

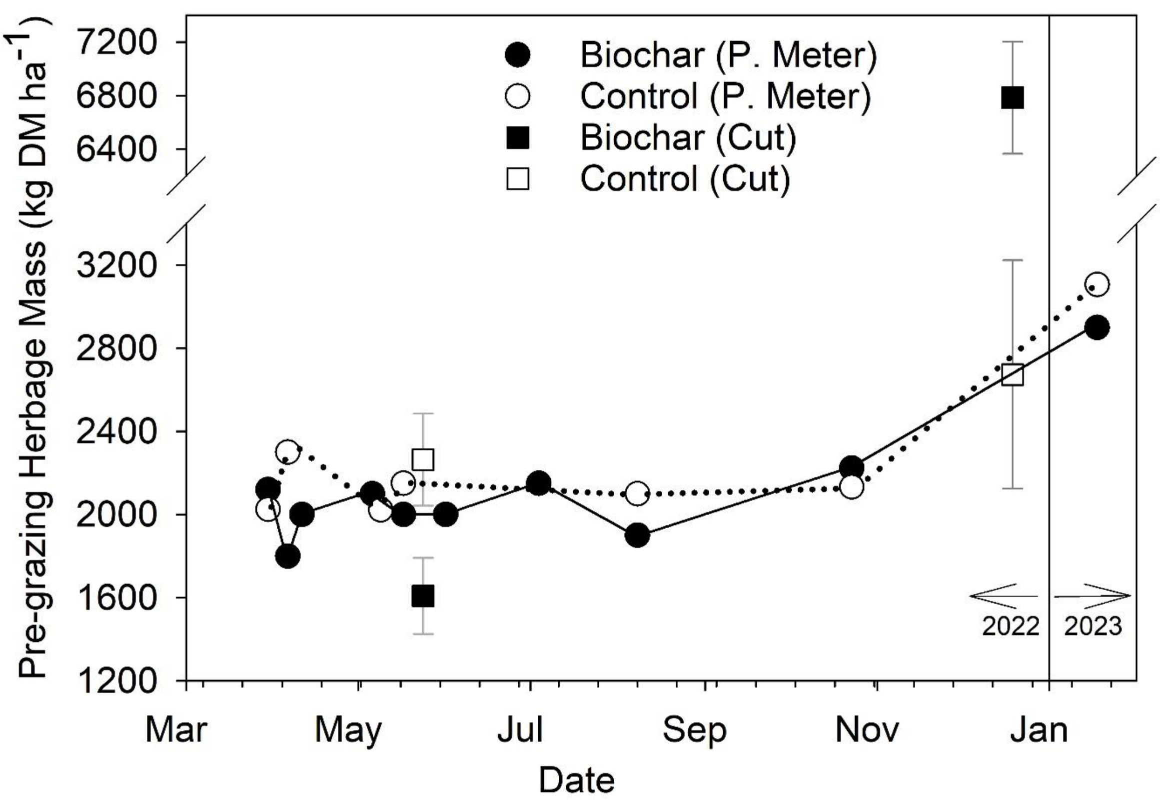



**Fig. 1:** Pre-grazing herbage mass of the control and biochar treatments has been similar over the duration of the experiment. Comparison of plate meter samples and hand cuts indicated little difference in methods for measuring pasture biomass.

- Pasture dry matter and botanical composition of paddocks with **controls** (no supplement) and **treatment** (biochar supplemented) groups very similar in May 2022. By December 2022, there was a three-fold level of legumes in the **treatment** group, compared to the **control** group, reducing the proportion of grasses in the Dec 2022 treatment group (Fig. 2).

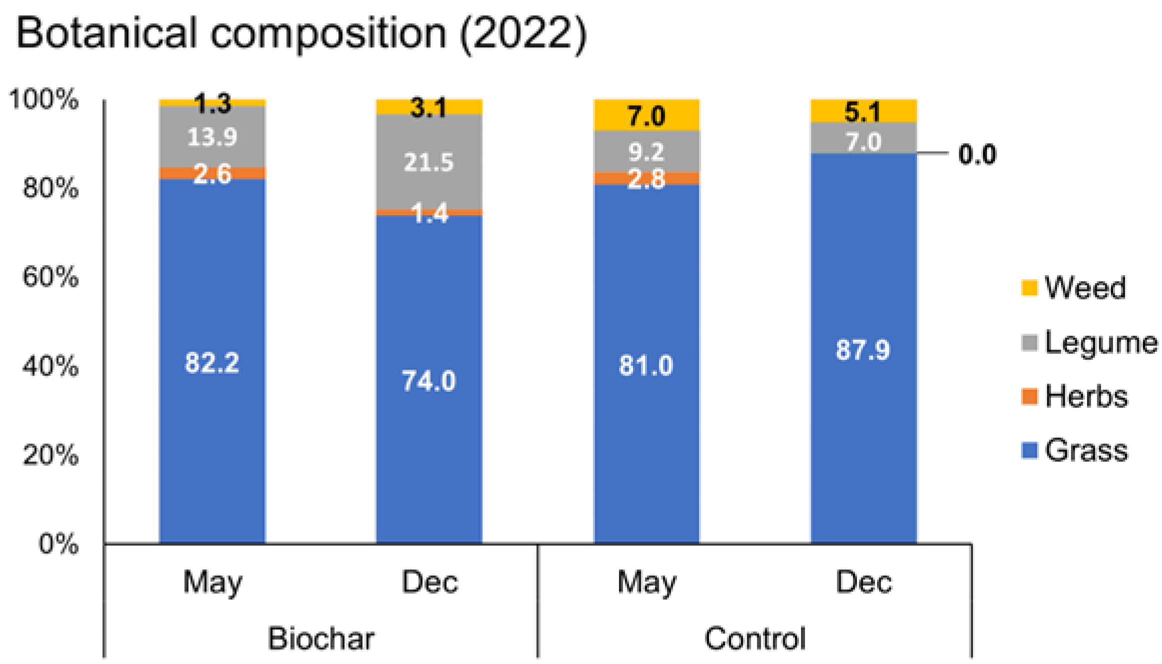



**Fig. 2:** Botanical composition in May and December 2022 of the control and biochar treatment groups.

- Liveweight of the control and biochar cohorts has remained relatively similar over the duration of the experiment (Fig. 3)

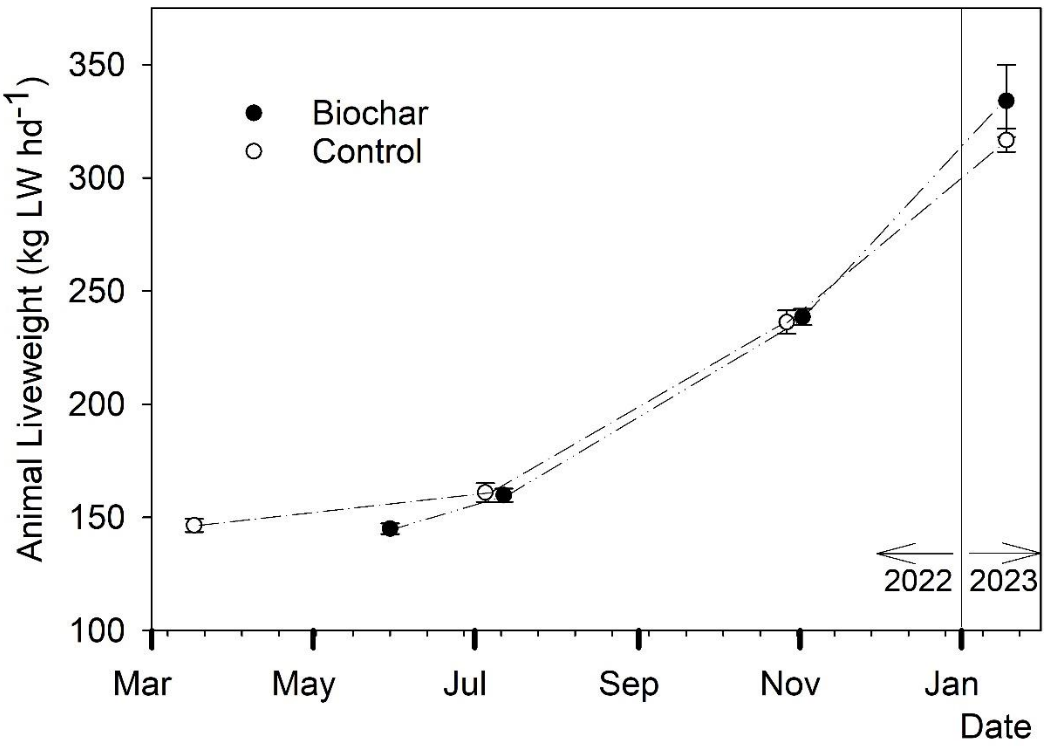



**Fig. 3:** Liveweight of the control and biochar cohorts over the duration of the experiment.

- Carbon in manure (%) has been measured twice since the commencement of the study, with similar results between treatments in both in autumn and spring 2022 (Fig. 4).

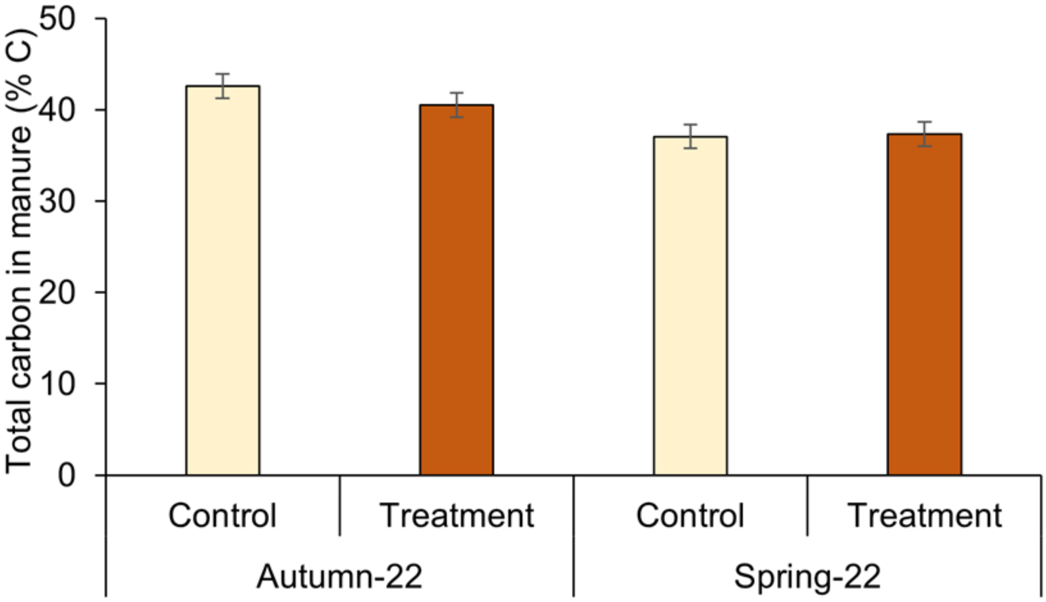
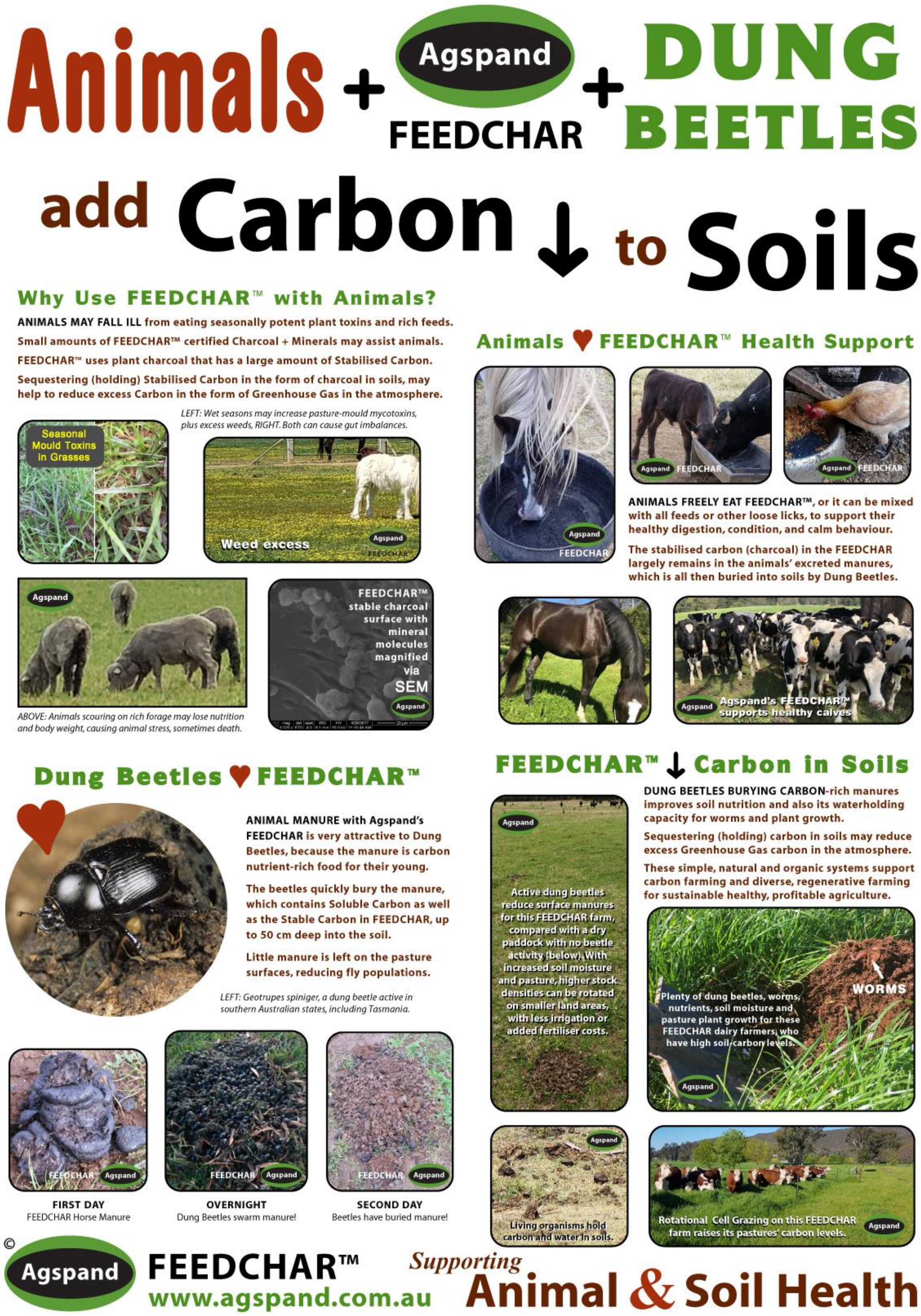



**Fig. 4:** Manure organic carbon of the control and biochar cohorts.

***Steve Sullings & Karen Enkelaar*** **(**Agspand's FEEDCHAR®) ***Presentation Material***



Animals + Agspand FEEDCHAR + DUNG BEETLES
add Carbon ↓ to Soils
Why Use FEEDCHAR™ with Animals?
ANIMALS MAY FALL ILL from eating seasonally potent plant toxins and rich feeds.
Small amounts of FEEDCHAR™ certified Charcoal + Minerals may assist animals.
FEEDCHAR™ uses plant charcoal that has a large amount of Stabilised Carbon.
Sequestering (holding) Stabilised Carbon in the form of charcoal in soils, may help to reduce excess Carbon in the form of Greenhouse Gas in the atmosphere.
LEFT: Wet seasons may increase pasture-mould mycotoxins, plus excess weeds, RIGHT. Both can cause gut imbalances.
Seasonal Mould Toxins in Grasses
Weed excess
ABOVE: Animals scouring on rich forage may lose nutrition and body weight, causing animal stress, sometimes death.
FEEDCHAR™ stable charcoal surface with mineral molecules magnified via SEM
Animals ♥ FEEDCHAR™ Health Support
ANIMALS FREELY EAT FEEDCHAR™, or it can be mixed with all feeds or other loose licks, to support their healthy digestion, condition, and calm behaviour.
The stabilised carbon (charcoal) in the FEEDCHAR largely remains in the animals' excreted manures, which is all then buried into soils by Dung Beetles.
Agspand's FEEDCHAR™ supports healthy calves
Dung Beetles ♥ FEEDCHAR™
ANIMAL MANURE with Agspand's FEEDCHAR is very attractive to Dung Beetles, because the manure is carbon nutrient-rich food for their young.
The beetles quickly bury the manure, which contains Soluble Carbon as well as the Stable Carbon in FEEDCHAR, up to 50 cm deep into the soil.
Little manure is left on the pasture surfaces, reducing fly populations.
LEFT: Geotrupes spiniger, a dung beetle active in southern Australian states, including Tasmania.
FIRST DAY
FEEDCHAR Horse Manure
OVERNIGHT
Dung Beetles swarm manure!
SECOND DAY
Beetles have buried manure!
FEEDCHAR™ ↓ Carbon in Soils
DUNG BEETLES BURYING CARBON-rich manures improves soil nutrition and also its waterholding capacity for worms and plant growth.
Sequestering (holding) carbon in soils may reduce excess Greenhouse Gas carbon in the atmosphere.
These simple, natural and organic systems support carbon farming and diverse, regenerative farming for sustainable healthy, profitable agriculture.
Active dung beetles reduce surface manures for this FEEDCHAR farm, compared with a dry paddock with no beetle activity (below). With increased soil moisture and pasture, higher stock densities can be rotated on smaller land areas, with less irrigation or added fertiliser costs.
Plenty of dung beetles, worms, nutrients, soil moisture and pasture plant growth for these FEEDCHAR dairy farmers, who have high soil carbon levels.
WORMS
Living organisms hold carbon and water in soils.
Rotational Cell Grazing on this FEEDCHAR farm raises its pastures' carbon levels.
© Agspand FEEDCHAR™
www.agspand.com.au
Supporting Animal & Soil Health

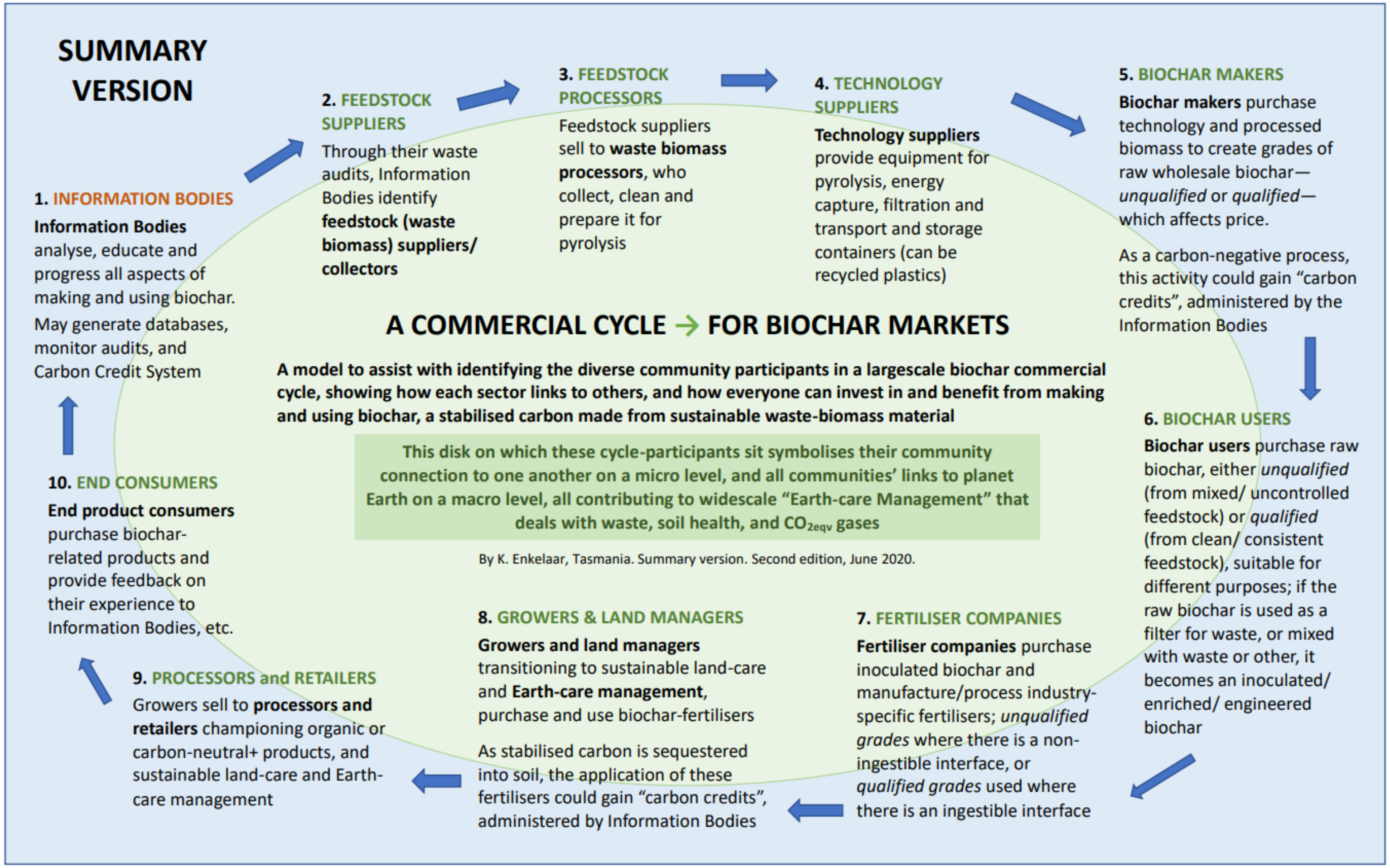
# A COMMERCIAL CYCLE → FOR BIOCHAR MARKETS

**A model to assist the BIOCHAR INDUSTRY by identifying the diverse community participants in a largescale biochar–CARBON commercial cycle, showing how each sector links to others, and how everyone can invest in and benefit from making and using BIOCHAR, a stabilised carbon made from sustainable waste-biomass material.**

**Making and using biochar contributes to "EARTH-CARE" management goals — (1) utilise waste, (2) support healthy soils, (3) sequester $CO_{2eqv}$ gases**

By K. Enkelaar, Tasmania, Australia. Third Edition, October 2021

# Summary Version



***Nicoli Barnes – Biochar Resources and Survey***

***Biochar general interest resources to read/view.***

- Parliamentary Report - Anna Talbery

The basics of biochar – Parliament of Australia

https://www.aph.gov.au › Parliamentary_Library › pub

- Biochar Capacity Building Program: a current list of DAFF Funded Biochar Programs and Projects

https://www.agriculture.gov.au/agriculture-land/farm-food-drought/climatechange/mitigation/cfi/biochar

- Landline - Biochar

https://www.abc.net.au/news/rural/programs/landline/2022-10-02/business-of-biochar:-turning-agricultural-waste/14072672

- Refilling the carbon sink: biochar's potentials and pitfalls

https://e360.yale.edu/features/refilling_the_carbon_sink_biochars_potential_and_pitfalls

- Beware the Biochar Initiative – Dr Mae-Wan Ho

https://www.permaculturenews.org/2010/11/18/beware-the-biochar-initiative/

***If you are interested in a small sample of the research, here's a summary and more links:***

Research about biochar generally focuses on four areas:

1. About the biochar itself
2. The production of biochar
3. The economics of biochar use
4. The use of biochar
5. Issues in biochar use

***About the biochar itself***

*1. What is biochar?*

- Biochar is a fancy name for charcoal that has been produced from biowaste/biomass in a very low or no oxygen environment.

- This process is called pyrolysis and it produces carbon with a highly pitted surface that dramatically increases its surface area and porosity and water holding capacity.
- The various types of biowaste/biomass used to make biochar will produce even greater surface areas and different nutrient values.

  2. *The nutrient value of biochar*

- Biochar's nutrient values appear to be determined by the source of the biomass.
- Examples that have been studied are corncobs, livestock manure, poultry litter, dairy wastewater, algae, straw, coconut husks, almond shells, banana skins, forestry, rice husks. Rice husks for example, give greater nutrient retention due to their high silica levels. Almond shells and banana skins are high in potassium (K).
- Many sources of biochar have come about from the need to deal with waste products from other industries. This then contributes to a circular economy (see below in economics).
- Various techniques for analysing biochar have been researched.

  3. *The international scope of biochar's reach*

- Biochar research is very focused in Asia (especially China) and other developing countries (Pakistan, Zambia, West Africa, Eastern Himalayas), but the impact of its use and therefore reach is spreading (Canada, Poland, Australia, US).

https://www.taylorfrancis.com/chapters/edit/10.4324/9781849770552-12/biochar-nutrient-properties-enhancement-yin-chan-zhihong-xu

https://www.sciencedirect.com/science/article/pii/S1658077X21001041

https://link.springer.com/article/10.1007/s40093-019-00313-8

https://www.sciencedirect.com/science/article/pii/S1364032117306937

https://www.taylorfrancis.com/chapters/edit/10.4324/9781315884462-12/biochar-properties-elisa-lopez-capel-kor-zwart-simon-shackley-romke-postma-john-stenstrom-daniel-rasse-alice-budai-bruno-glaser

https://link.springer.com/chapter/10.1007/978-981-13-3768-0_5

***The Production of biochar***

- The processes of gasification, torrefaction, encapsulating, ball milling, microwaving, steam, hydrothermal carbonization and others, to produce biochar, have been explored
- Temperatures for producing biochar have been explored.
- Slow and fast pyrolysis methods are available. Fast pyrolysis has raised issues of carcinogenic substances being produced in the production process.
- The biomass sources used to produce biochar will determine the best/most useful nutrient values. They also determine the Carbon origins that are sequestered.
- There are multiple processes in which biochar can be engineered for different purposes. These include micro biochar, nano biochar and nanocomposites, magnetic biochar. These processes are mostly about increasing the surface area of biochar for particular purposes such as decontamination.
- There is a caution re mass production as it could reduce food security (ie food farming is taken over for biochar crop production) and the impact on oxygen levels.

https://link.springer.com/article/10.1007/s11368-019-02350-2

https://www.mdpi.com/2077-0472/5/4/1076

https://www.sciencedirect.com/science/article/pii/S0959652620325099

https://www.sciencedirect.com/science/article/pii/S1387181117304341

https://www.sciencedirect.com/science/article/pii/S0045653522018847

https://www.sciencedirect.com/science/article/pii/S2666154321000934

***The Economics of Biochar***

- Current pricing of biochar prevents or inhibits use.
- Biochar is often a scarce product
- Circular economies are promoted for small scale farming and for industry such as forestry. This refers to the dealing of waste from particular production activities which then feeds back into the same system as fertilizer or another value added product.
- Research suggests that biochar could be used for economic stimulus in Australian regions. However, again, there is caution about mass production.
- There could well be issues of food security if biomass crops replace food crops as a profit making venture. The 'biochar industry' would therefore need to be regulated in this and numerous other ways eg type of pyrolysis used, biomass used, quality of char etc.

https://www.tandfonline.com/doi/full/10.1080/17583004.2016.1213608

https://onlinelibrary.wiley.com/doi/full/10.1002/fes3.188

https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12180

https://www.publish.csiro.au/SR/SR14112

https://www.sciencedirect.com/science/article/pii/S0048969720373514

https://link.springer.com/article/10.1007/s10098-016-1113-3

***The uses of Biochar***

- Biochar is mostly in agriculture. This has become important to producers with the current push for sustainable practices. Uses outside of agriculture are in waste management.
- Five traditional uses of biochar.
    1. Filtration (agricultural and non-agricultural applications)
        a. Removal of organic and inorganic contaminants from both soil and other contaminated substances. This is especially important for heavy metal removal.
        b. Waste management – water filtration, effluent/sewage management, hydrogen sulfide ($H_2S$) from biogas, animal waste composting, humic and tannic acid removal.
        c. Purification eg spirits/wine, water

   d. Phytoremediation – the use of biochar to remove, degrade or stabilize toxic substances in soil or water
2. Fertiliser
   a. Plays a role in N/P/K cycles
   b. Comparisons have been made between processed (as biochar) and non-processed waste as fertilizers. Benefits of biochar varies eg straight chook poo is better than its biochar form but for other biomass sources this is not the case.
   c. Acts as a slow release fertilizer using encapsulated technology. This can be beneficial especially when combined with other minerals As, Ad, Cu, Ni, P, Pb, Cr
   d. Used in compost and worm farms to support the breakdown of organic waste
   e. Important in rainfed agriculture as it holds water and nutrients as it slowly breaks down.
   f. Types – eg as a slurry or powder.
   g. Nutrition is dependent on source eg algae base is high in nutrients
3. Soil
   a. Improves the hydrology of soil
   b. Composting
   c. Remediation of soil and removal of contaminants
   d. Acts in organic nutrient capture and recycling eg it acts to trap Carbon in soil and reduces the Nitrogen available in soil and therefore decreases the acidification
   e. There are pluses and minuses depending on the 'type' (original biomass source) and processing of biochar used
   f. Useful as an amendment by increasing microbial mass and macro nutrients and their efficiency
   g. Improves sandy soils
4. Cropping
   a. Increases yields of barley, maize, wheat
   b. Increases drought tolerance by decreasing water loss and nutrient leaching from the soil
   c. Increases shoot and root growth and nodulation
   d. General increases in plant growth and production
   e. Decreases $CO_2$ respiration
5. Livestock feed
   a. Tested with cattle, goats, pigs, poultry
   b. Adds to fertilization of soil via manure
   c. Increases found in nutrient intake
   d. Decreases found in in vitro methane and ammonia production (GHG emissions)
   e. Some suggestion of weight gain
   f. Some suggestion of improvements to animal health

- Novel use of biochar - examples
  - Biodiesel
  - Inoculant carrier
  - Microplastics degradation

https://link.springer.com/article/10.1007/s42398-018-0010-6

https://www.mdpi.com/2071-1050/9/4/655

https://www.sciencedirect.com/science/article/pii/S0929139316304954

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https://acsess.onlinelibrary.wiley.com/doi/abs/10.2136/sssaspecpub63.2014.0052

https://www.taylorfrancis.com/chapters/edit/10.4324/9780203762264-2/traditional-use-biochar-katja-wiedner-bruno-glaser

https://www.taylorfrancis.com/chapters/edit/10.4324/9781315884462-20/current-future-applications-biochar-adam-toole-david-andersson-achim-gerlach-bruno-glaser-claudia-kammann-j%C3%BCrgen-kern-kirsi-kuoppam%C3%A4ki-jan-mumme-hans-peter-schmidt-michael-schulze-franziska-srocke-marianne-stenr%C3%B8d-john-stenstr%C3%B6m

### *Biochar Issues*

- Biochar acts as an extremely effective carbon sink, (carbon sequestration) BUT it is also very good as an oxygen sink. This is problematic as we humans and most animals still need to breathe oxygen …… so depleting oxygen supplies is probably not the way to go!! Therefore, large scale production is NOT being encouraged unless the oxygen sink effect can be addressed.
- Biochar is extremely effective at trapping things like heavy metals. If biochar remains in the soil it can affect soil microbes (soil biome) and if highly 'contaminated' biochar is produced from contaminated sources it can have an impact.
- Fast pyrolysis produces PAH's (polycyclic aromatic hydrocarbons) which are a class of environmental carcinogen. Slow pyrolysis should be used to produce char.
- The economics of biochar production may produce further food insecurity.
- Much of the research is based on the understanding that biochar is the same as ancient 'terra preta' as found in the Amazon Basin and some African countries. The research is saying this is not the case, particularly in claims of decreasing the time carbon remains in the soil. Biochar has a much reduced C capture time before it starts releasing $CO_2$ back into the atmosphere.
- Standards and guidelines are needed such as identification of slow or fast pyrolysis, biomass source, pH, chemical/nutrient properties; the soils types for each biochar.

https://link.springer.com/article/10.1007/s11356-019-05153-7

https://www.sciencedirect.com/science/article/pii/S096085241930570X

https://link.springer.com/article/10.1007/s10098-016-1284-y

https://link.springer.com/article/10.1007/s13399-020-01013-4

https://www.taylorfrancis.com/chapters/edit/10.4324/9781315884462-21/biochar-horizon-2025-hans-peter-schmidt-simon-shackley

https://link.springer.com/article/10.1007/s42773-020-00055-1

# Biochar Workshop Participant Feedback

1. Which group best describes your role? *(please circle)*

| | |
|---|---|
| Producer | Researcher |
| Advisor | Government |
| Agribusiness Service Provider | Supply Chain Participant |
| Industry Association | Other: ________________ |

2. Your main production region? *(please circle)*

| | |
|---|---|
| Northern Tasmania | Midlands |
| North West Tasmania | Southern Tasmania |
| North East Tasmania | Other: ________________ |

3. If you are a producer, approximate size of property (in hectares) and flock/herd size:

   ______________ha

   Number of head of cattle: ________ Number of head of sheep: _______

   Other:_______________

4. If you are a service provider, approximate client base of red meat producers: _________

5. Please rate your awareness, knowledge and/or skills related to biochar use, before and after this workshop.
   *(Rating 1-5: 1= new knowledge, 2 = some knowledge, 3= some knowledge and limited experience, 4 = adequate knowledge and confidence, 5= excellent knowledge and confidence)*

| | Before the workshop | | | | | After the workshop | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Biochar awareness, knowledge and/or skills | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |

6. Do you intend to use biochar as a feed supplement or other use after today? *(circle response and make comment)*

| Yes | No | Unsure |
|---|---|---|
| Comment | | |

What are the main reasons for your decision in Q6? *(circle and comment)*

| Topics | | | |
|---|---|---|---|
| Improve soil carbon | Yes | No | Unsure |
| Improve animal health | Yes | No | Unsure |
| Reduce farm GHG emissions | Yes | No | Unsure |
| Reduce enteric methane | Yes | No | Unsure |
| Biochar costs too much | Yes | No | Unsure |
| Feeding a supplement is too impractical | Yes | No | Unsure |
| I already feed other supplements | Yes | No | Unsure |
| Other? *Please comment* | | | |

7. After today's workshop, are you able to make more informed decisions about the following: *(circle response for each topic listed)*

| Topics | | | |
|---|---|---|---|
| Biochar in general | Yes | No | Unsure |

| | | | |
|---|---|---|---|
| Forms of Biochar available in agriculture | Yes | No | Unsure |
| The purposes of biochar in agriculture | Yes | No | Unsure |
| How to use biochar on your farm | Yes | No | Unsure |
| Practical issues in using biochar | Yes | No | Unsure |
| Where you might find biochar information | Yes | No | Unsure |
| Benefits and issues in using biochar | Yes | No | Unsure |

8. Outline what other information or assistance you might need in order to use biochar or recommend biochar use to others.

| |
|---|
| Comment |

9. How satisfied were you with this event? *(please circle your rating out of 10, 1= not at all satisfied, 10=extremely satisfied)*

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Event Satisfaction | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| What should be continue/change? | | | | | | | | | | |

10. Please provide your contact details if you would be willing to be contacted in 12 months about your use (or not) of biochar: *(optional)*

| |
|---|
| Name: |
| Business: |
| Email: |
| Phone: |

Thank you for taking the time to complete the feedback

# Appendix 8.6: Five capitals from interviews with red meat producers

Dimensions of the five capitals from interviews with seven red meat producers in the Midlands of Tasmania that incorporate a prime lamb enterprise (M1-7), with associated **positive (+)** or **negative (-)** contribution of these dimensions to adaptive capacity.

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| **M1** | **Succession planning (+)**<br>**Long-Term view (+)**<br>**Self-efficacy (+)**<br>**Education (+)**<br>**Age (+)**<br>*Young couple from farming backgrounds, educated in Ag Science and actively setting up family farm for children. Noted their agility in adaptive management compared with older producers.* | **Family unit (+)**<br>**Social networks (+)**<br>**Extension services (-)**<br>**Access to information (-)**<br>*Well established in R&D, governance and social learning networks themselves yet noted an 'enormous change in extension services offered…MLA should have beef officer in Tasmania to help push their programs…research is good but extension is poor'.*<br>*Limited access to regionally relevant advice about selecting perennial pasture species.* | **Irrigated pasture productivity (+)**<br>**Unproductive dryland pastures (-)**<br>**Temperate feed curve (-)**<br>**Access to water (-)**<br>**Soil fertility (+)**<br>*Intensifying pasture production under irrigation.*<br>*Condensed temperate feed curve in Tasmania leads to condensed lambing period that does not provide a consistent enough supply for greater processing capacity in Tasmania (interaction with physical capital).*<br>*Sudden and severe summer feed gap negatively impacts lamb condition – especially evident with legume stands 'shattering'.*<br>*Limited access to water currently constrains pasture quantity and quality.*<br>*Have increased soil fertility to increase future land capability.* | **Farm size (+)**<br>**Processing capacity (-)**<br>**Water infrastructure (-)**<br>*Expanded farm size already, with plans to invest in more land over time.*<br>*Limited processing capacity in Tasmania noted as the greatest industry challenge due to issues associated with transport and shipping and negative implications for animal management and welfare.*<br>*Currently do not have the water infrastructure to further increase pasture production.* | **Access to income/savings (+)**<br>*Expansion focus includes buying more land and driving the progress of a new water scheme, with a view to investing in water and associated infrastructure. Strategically building financial capacity for this investment, indicating confidence in access to income/credit.* |

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| **M2** | **Succession planning (+)**<br>**Long-term view (+)**<br>**Self-efficacy (+)**<br>**Education (+)**<br>**Age (+)**<br>*Adult siblings now managing various aspects of family mixed farming system. Trials and monitors suitability and productivity of pasture/forage species.* | **Family unit (+)**<br>**Social networks (+)**<br>*Well established in social learning networks with long term involvement in Longford red meat producer group, and regular interactions with other producers, transport contractors and service providers.* | **Pasture productivity (+)**<br>**Biodiversity – mixed pastures (+)**<br>**Access to water (+)**<br>**Temperate feed curve (-)**<br>*Has been intensifying pasture production under irrigation. Better weight gain and animal health noted from grazing mixed pastures, with relatively low lamb mortality/metabolic issues. Autumn/winter feed gap negatively impacts lamb condition.* | **Processing capacity (-)**<br>*Monitored lamb weights before shipping to Victoria and reported greater lamb weight loss during transport than lambs processed locally, with associated decrease in income.* | **Access to income/savings (+)**<br>*Long-term family ownership indicates stable access to income/savings.* |
| **M3** | **Long-term view (+)**<br>**Self-efficacy (+)**<br>**Education (+)**<br>**Age (+)**<br>*Highly educated couple strategically intensifying their mixed cropping-livestock business. High level of attention to detail around monitoring cost of production.* | **Family Unit (+)**<br>**Social networks (+)**<br>**Labour workforce (-)**<br>**Social license (-)**<br>**Access to information (-)**<br>*Well established in R&D and governance networks. Increased workforce skill development required to support intensive red meat farming systems. Limited access to advice about how to manage the* | **Irrigated pasture productivity (+)**<br>**Animal health (-)**<br>**Unproductive dryland pastures (-)**<br>**Access to water (+)**<br>*Has been intensifying some pasture production under irrigation. Identified significant animal health problems relating to intensification, including increased lamb mortality rates,* | **Unreliable demand and supply system (-)**<br>**Processing capacity (-)**<br>**Fencing and water points (-)**<br>**Drainage (+)**<br>*Unreliability of the supply system and 'inability to sell lambs on the day you're supposed to' constrains the prime lamb industry in Tasmania. If there was a more reliable supply system, they would move entirely to* | **Access to income/savings (+)**<br>*Current investments in significant draining indicating current access to income/credit.* |

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| | | *animal health implications (e.g. nutrient imbalances, metabolic issues and increased lamb mortality) associated with increased stocking rate and intensively grazing monocultures under pivots. These factors are associated with increasing risk in relation to maintaining social license.*<br>*Limited access to advice about dryland pasture species selection and establishment.* | *and metabolic issues and unwanted weight gain in ewes.*<br>*High proportion (70%) of more extensively grazed, dryland, marginal pasture. 'Doubling the productivity of dryland pastures' highlighted as significant potential across the farm.* | *trading prime lambs (i.e. no ewes). Delays in transport to Victoria due to poor weather conditions results in lamb weight loss and difficult feed management.*<br>*Further intensification across the industry is limited by basic infrastructure to support rotational grazing management (fencing and water points).*<br>*Under pivots, large paddocks hinder grazing management, with negative effects on animal health.*<br>*Currently investing in significant drainage to improve pasture productivity.* | |
| **M4** | **Self-efficacy (+)**<br>**Education (+)**<br>**Age (+)**<br>**Perception of climate change (+)**<br>*Discussed climate change as a 'huge issue' in terms of disappearing shoulder seasons and increasing* | **Access to information (-)**<br>**Social license (-)**<br>*Limited access to advice about how to manage the animal health implications (e.g. nutrient imbalances, metabolic issues and increased lamb mortality) associated with intensively* | **Access to water (-)**<br>*Although nearly 80% of the farm is currently irrigated, limited access to more water is likely to limit expansion.* | **Irrigation infrastructure (+)**<br>*Investing in irrigation infrastructure has been a sure way to increase productivity, 'low hanging fruit'.* | **Cost of production (-)**<br>*Increasing cost of store lambs 'squeezes our margin'. Potential government pricing of future water access may limit further investment in water and irrigation infrastructure.* |

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| | *variability of traditionally productive spring and autumn seasons.*<br>*High level of self-efficacy and business skills, with independent benchmarking driving decision making around management and expansion. 'Driven by price and opportunity'* | *grazing legume monocultures under pivots.*<br>*Limited access to advice about pasture and forage species with increased water use efficiency.*<br>*Concern about maintaining social license in relation to lambs being transported to Victoria for processing and the associated animal welfare risks combined with increased visibility to the public as trucks drive through Melbourne.* | | | |
| **M5** | **Long-term view (+)**<br>**Self-efficacy (+)**<br>**Education (+)**<br>**Perception of climate change (+)**<br>**Succession planning (-)**<br>*Discussed climate change as greater seasonality, especially in terms of variable rainfall, as well as longer periods of being* | **Social license (+)**<br>**Labour workforce (-)**<br>**Access to information (+)**<br>**Social networks (+)**<br>*Considers what current and next generations of consumers think is acceptable around climate change, sustainability and animal welfare, and is aware this changes over* | **Conservation and biodiversity (+)**<br>**Access to water (+)**<br>*Reduced amount of grazing land and set it aside for conservation as a means to increase resilience to climate change (especially drought).*<br>*Current irrigation infrastructure and plans to further invest in water indicate ready access.* | **Farm size (+)**<br>**Irrigation infrastructure (+)**<br>*Extra large farm size contributes 'huge amount of capital value and capital gain' (interaction with financial capital).*<br>*Invested in irrigation infrastructure to reduce risk posed to 'productive ag' by increased rainfall variability.* | **Access to income/savings (+)**<br>*Viability and scale of the business enables him to 'make the hard decisions early, buy and sell stock, look after the land…Looking after land and animals is ten times more important than the balance sheet.'*<br>*Uses Tasmanian clean, green image and conservation* |

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| | *exposed to weather extremes that cause fires and drought. In response farmers need to 'take ownership of condition score, ground cover and stocking rate' and reduce risk.*<br>*At 10 years from retirement, succession planning is uncertain, with further expansion hinging on children coming back to the farm.* | *time. Uses this to his advantage to maintain market edge with wool, 'chasing best practice for best price'.*<br>*Would like to reduce reliance on unreliable labour by adopting more technology.*<br>*'MLA have some good tools and deliver them well. Often surprised by lack of uptake from farmers, with many not getting the basics right…Loads of information out there, never hard to find.'*<br>*Member of a community of farms with conservation focus and discusses issues with other farmers.* | | | *practices to secure premium wool branding and prices.* |
| **M6** | **Succession planning (+)**<br>**Long-term view (+)**<br>**Self-efficacy (+)**<br>**Education (+)**<br>**Perception of climate change (+)** | **Social networks (+)**<br>**Social license (-)**<br>**Labour workforce (-)**<br>**Access to information (-)**<br>**Extension services (-)** | **Access to water (+)**<br>**Pasture productivity (+)**<br>**Deer vermin (-)**<br>*'Plenty of water to expand and manage risk posed by seasonal variation.'* | **Irrigation infrastructure (+)**<br>**Fencing infrastructure (+)**<br>**Value chain (-)**<br>*Irrigation and subdivision of land by renovating pastures and splitting them into 6ha* | **Access to income/savings (+)**<br>*Current investments in significant pasture renovations and irrigation infrastructure indicating* |

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| | *Educated young people (i.e. farmers' children) returning to farms will see the world differently and bring energy and innovation to the industry.*<br>*'We know climate variability is happening, what are the levers we can pull?'* | *Well established in R&D and governance networks. Proactivity needed to maintain social license in the areas of animal welfare (i.e. live sheep trade) and environmental regulations (i.e. managing slopes and forested areas).*<br>*Increased workforce skill development required to support intensive red meat farming systems.*<br>*Compared with New Zealand, Tasmania has little publicly available information and resources – they are linked to private consultant or merchant. This translates to a lower baseline in knowledge and practice change, particularly around pasture management.* | *Have focused on converting pasture on good soil that has been 'left in its natural state' into highly productive pasture. 'What drives me is seeing we can make a difference. We are changing our place from natural pastures with an animal/ha to 35DSE/ha.'*<br>*Deer vermin significantly constrain pasture production and stocking rate, 'could have twice as many stock without deer'.* | *paddocks, 'no point in renovating if we don't have the ability to manage and graze it properly.'*<br>*Dissatisfied with the value chain once animals leave the farm.* | *current access to income/credit.* |
| **M7** | **Succession planning (+)**<br>**Long-Term view (+)**<br>**Self-efficacy (+)**<br>**Education (+)** | **Family unit (+)**<br>**Social networks (+)**<br>**Access to information (-)**<br>**Extension services (-)** | **Access to water (+)**<br>**Pasture productivity (+)**<br>**Conservation and biodiversity (+)** | **Farm size (+)**<br>**Irrigation infrastructure (+)**<br>**Feedlot infrastructure (+)**<br>**Fencing infrastructure (+)** | **Access to income/savings (+)**<br>*In the process of using Tasmanian clean, green image and animal welfare* |

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| | **Perception of climate change (+)**<br>*Children studying agricultural science and interested in continued adaption of the family farm to align with consumer values.*<br>*Science background with farming systems and business knowledge and skills to experiment, access and interpret information.*<br>*Has participated in and developed benchmarking skills.*<br>*Observed and adapted to increasing climate variability, 'we can and will adapt'.* | **Social license (+) (-)**<br>**Labour workforce (-)**<br>*Family unit work together, seek out information and discuss farm management and adaptation.*<br>*Established in social learning, R&D and governance networks, and readily hosts trials.*<br>*Noted that many farmers do now know how to source independent information and interpret it, increasingly so with the decrease in public extension in Tasmanian red meat industry.*<br>*Aware of consumer perceptions and working to be proactive in maintaining social license through ceasing mulesing and joining Land Stewardship program (Midlands Conservation Fund) and Responsible Wool Standard (TBC), 'at* | *Current irrigation infrastructure and plans to further invest in water indicate ready access.*<br>*More vigorous pasture budgeting and making evidence-based decisions in the last decade as a response to managing climate variability.*<br>*Actively setting land aside for the purposes of conservation and increasing biodiversity, 'working with Greening Australia to revegetate areas'.*<br>*Going 'over and above what we should be doing…we should get paid annually for agreed outcomes' to further decrease vulnerability to climate variability.* | **Laneways (+)**<br>**Unreliable demand and supply system (-)**<br>*Extra large farm size provides diversification options and allows significant proportion of land to be retained for conservation and biodiversity.*<br>*Matching livestock sales to demand is challenging and constrains increasing proportion of prime lamb in mixed farming system.*<br>*Opportunistic investment in irrigation to grow profitable crops, including grass seed and poppies, with rotations of lucerne, white clover and ryegrass. Plans to further increase irrigation infrastructure.*<br>*Feedlot infrastructure installed to feed ewe's supplements while giving pastures a rest until the autumn break – highly successful adaptation that has had a positive effect on staff* | *practices (i.e. ceased mulesing) to secure premium wool branding and prices.*<br>*When the market value of lamb and wool increased, he increased the livestock proportion of the business.* |

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| | | *the end of the day we need to listen to customers.'* *Gap between public and farming, and lack of education about agriculture increases the risk of losing social license, 'at some point it will become unprofitable to run livestock if restrictions become too great.'* *Run a lean labour operation for efficiency and due to the shortage of skilled workforce.* | | *morale (interaction with social capital).* *More fencing and laneways have been developed to 'make life easier and more fun' for staff (interaction with social capital).* | |

Dimensions of the five capitals from interviews with six red meat producers in the North West of Tasmania that incorporate a beef enterprise (NW1-6), with associated **positive (+)** or **negative (-)** contribution of these dimensions to adaptive capacity.

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| **NW1** | **Succession planning (+)**<br>**Long-Term view (+)**<br>**Self-efficacy (+)**<br>**Education (+)**<br>**Age (+)**<br>**Perception of climate change (+)**<br>*Father and son managing family farm, with long-term view to expand for the purpose of supporting further succession planning.*<br>*Acknowledge climate change is making it more difficult to work with the variable seasons, longer dry periods and more extreme rainfall events and wind.* | **Family unit (+)**<br>**Social networks (+)**<br>*Established in the NW social learning networks, and R&D networks. Attend Red Meat Updates and recently changed to a 6-week mating period based on a presentation given there.*<br>*Minimal use of agronomists.* | **Irrigated pasture productivity (+)**<br>**Access to water (+)**<br>**Winter water logging (-)**<br>**Access to finishing cattle (-)**<br>*'Having the ability to irrigate has given us the confidence to buy cattle when the season is looking risky.'*<br>*Recent installation of irrigation infrastructure indicates ready access to water.*<br>*Winter is the hardest season to manage cattle due to waterlogging and pasture damage on the flat land - considering agisting breeding cows elsewhere during winter.*<br>*Difficult accessing high quality finishing cattle in Tasmania.* | **Farm size (+)**<br>**Genetics (+)**<br>**Water infrastructure (+)**<br>**Processors branding (+)**<br>**Drainage (-)**<br>*Plans to double the size of the farm/business in the future to enable family to return to the farm (interaction with human capital). Additional plans to improve the genetics of the herd.*<br>*Installed water infrastructure to adapt to increasing variability of rainfall events, particularly less reliable spring rain.*<br>*Acknowledged advantage of processors branding of Tasmanian grass-fed beef.*<br>*Current lack of drainage, with plans to invest in installation in the future to address significant water logging.* | **Access to income/savings (+)**<br>**Corporate investment (-)**<br>**Price volatility (-)**<br>*Current investment in irrigation infrastructure and plans to expand indicate confidence in future access to income/credit.*<br>*For the younger generation it is becoming more difficult to get ahead due to the debt required to compete with corporate investment that has driven up land price.*<br>*Market price volatility is challenging.* |
| **NW2** | **Succession planning (+)** | **Family unit (+)** | **Pasture productivity (+)** | **Water infrastructure (+)** | **Market prices (+)** |

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| | **Long-term view (+)**<br>**Self-efficacy (+)**<br>**Education (+)**<br>**Age (+)**<br>**Perception of climate change (-)**<br>*Father and son managing family farm, with a daughter and two wives involved to a less extent. Self-efficacy is high, with knowledge and skills within complementary roles of family member including Agronomist (son), Vet (daughter) and Accountant (wife).*<br>*Succession plan is well developed.*<br>*With the son returning to the farm within the last 5 years, the 'increase in FTE and energy for the farm has meant an increased focus on strategy and increasing productivity.'*<br>*Lack of climate variability and extreme weather events experienced in coastal location.* | **Social networks (+)**<br>*Family unit work together, seek out information and discuss farm management and adaptation.*<br>*Established in social learning, R&D and governance networks.* | **Soil fertility (+)**<br>**Access to water (+)**<br>**Diversification (+)**<br>*Five years ago started more strategic fertiliser application of 'old English pastures' which greatly increased pasture productivity. Prefers this method of pasture improvement over renovating all old pastures with newer species/cultivars.*<br>*Transitioning into incorporating more alternative species adapted to the dry farm conditions, including cocksfoot and lucerne.*<br>*Introduced some irrigation (not pivots).*<br>*Diversification through the breeding component of the system lowers vulnerability to market fluctuations. Steadily increasing the breeding herd numbers.* | **Solar infrastructure (+)**<br>*Limited water infrastructure installed*<br>*Considering installing solar infrastructure to reduce energy costs and increase climate resilience.* | **Access to income/savings (+)**<br>*Current market prices are high (have previously been challenging) and has long-term demand-supply relationships.*<br>*Diversified income and ensured consistent access through off-farm employment, leasing coastal access to water for abalone farm and considering leasing land to a proposed wind farm and investing in solar infrastructure.* |

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| NW3 | Long-term view (+)<br>Self-efficacy (+)<br>Education (+)<br>Age (+)<br>Perception of climate change (+)<br>*Young couple with Agricultural Science training, specialised knowledge and skills in pasture (husband) and cattle (wife), proactive information seeking and evidence-based decision making. Cost/day calculated and used to assess profitability of different trading options. Climate change has brought about unpredictability, 'an old farming friend said he used to always know what to expect with the seasons, and this can longer be relied on.'* | Family unit (+)<br>Social networks (+)<br>Policy impacts (+)<br>Labour workforce (-)<br>*Couple work together to manage farming system, with extended family involvement in agricultural businesses.*<br>*Established in social learning and R&D networks. Benefited from AgriGrowth Loan Scheme - an initiative of the Tasmanian Government providing low interest loans to Tasmanian farm businesses.*<br>*Currently only couple work on the farm, expansion would increase the workload and pose a challenge for employing additional labour.* | Irrigated pasture productivity (+)<br>Access to water (+)<br>Stocking rate (+)<br>Winter water logging (-)<br>*Irrigated pasture productivity combined with intensive grazing management practices sustain a high stocking rate under careful grazing management.*<br>*Dam on property provides access to water.*<br>*Clay soils become waterlogged during winter.* | Irrigation infrastructure (+)<br>*Traveling gun irrigation infrastructure installed to manage risk associated with variable seasons and high level of trading, enabling maximum pasture production and utilisation that fattens cattle reliably and quickly. Irrigation utilised carefully.* | Access to income/credit (+)<br>Price volatility (-)<br>*Accessed AgriGrowth loan to secure existing farm business, with a plan for future growth through purchasing neighbouring land.*<br>*Market price volatility is challenging and their high level of trading increases vulnerability. However, they strategically buy different grades of cattle to maintain paying low prices with attention to grazing management ensuring they fatten reliably and quickly.* |
| NW4 | Self-efficacy (+)<br>Education (+)<br>Age (+) | Access to information (+) (-)<br>Extension services (-) | Access to finishing cattle (-)<br>Diversification (+)<br>Land capability (+)<br>Unproductive pasture (-) | Irrigation Infrastructure (-)<br>Wallaby fencing (-)<br>Genetics (+) | Corporate investment (-)<br>*For the younger generation it is becoming more difficult to get ahead due to the debt* |

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| | **Perception of climate change (-)**<br>*Climate change is a 'big variable, but it 'hasn't really impacted on us.'* | *Follow market trends and long-term forecasting information provided by MLA. Independently approaches neighbours (e.g. dairy farmers) or advisors to source information.*<br>*Lack of red meat extension officer in Tasmania and the associated on-farm discussion groups to demonstrate fertiliser/grazing management and fencing options that support increased pasture productivity. The existing Circular Head beef group is 'stuff we did 20 years ago…need someone young to challenge and stimulate industry, and question what you do.'* | **Wallaby vermin (-)**<br>*Drought had significant impact on sourcing cattle, and in response have started breeding their own. Diversification through introducing the breeding component of the system lowers vulnerability to market fluctuations – noted a time lag of 2 years.*<br>*Doubled the size of the farm during the last few years, with ongoing focus on clearing land to sow pasture.*<br>*'Only just scratching the surface…want to drive productivity and profitability' with irrigation, improving fertiliser and wallaby fencing.* | *Has not yet invested in irrigation infrastructure, and has noted that across the industry, 'you see irrigation go in, but if they can grow grass first, they would achieve more'.*<br>*Growth from 140 to 6000 cattle over 31 years, with focus on AI to improve genetics for early maturing cattle.* | *required to compete with corporate investment that has driven up land price.* |
| **NW5** | **Long-term view (+)**<br>**Self-efficacy (+)**<br>**Education (+)** | **Social networks (+)**<br>**Access to information (-)**<br>**Extension services (-)**<br>**Social license (-)** | **Land capability (+)**<br>**Improving pasture (+)**<br>**Access to water (+)** | **Farm size (+)**<br>**Irrigation Infrastructure (-)**<br>*Extra-large farm size provides stable employment for* | **Access to income/savings (+)**<br>*Further investment in infrastructure is planned* |

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| | **Perception of climate change (+)**<br>**Succession planning (+)**<br>*Many people have come to the NW from other areas that are MORE impacted by climate change. NW is relatively stable, but early and longer dry autumns are increasingly common.*<br>*Family farm, with significant change when sons came home from education - had labour force to improve strategic management (interaction with social capital).* | *Established in social learning networks.*<br>*Noted an enormous change in extension services offered and lack of a beef officer and active discussion groups in Tasmania. MLA have good programs and research, but extension delivery is lacking.*<br>*'Need to educate those who aren't educating themselves, the system that exists probably favours those who don't need it.' Identified that extension is the greatest improvement we could have in helping develop industry knowledge and skills, 'getting info out and having good educators to give it.'*<br>*Need a 'practical roadmap' to face the combined market, consumer and environmental challenges, with the risk that new* | *Extensive clearing of land to sow pasture in the past, with cheap approach taken because at scale.*<br>*Currently undertaking second round of pasture improvement, with 200 ha in last few years that lifted production by 25%.*<br>*Identified irrigation and dam sites on the property, but currently not economically feasible to irrigate (interactions with physical and financial capital).* | *children without the need for further expansion (interaction with human capital).*<br>*Installing irrigation infrastructure not currently economically feasible.* | *when the current pasture improvements reap further profitability benefits.* |

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| | | *regulations will 'kill industry' if farmers and policy makers don't achieve a common understanding.* | | | |
| **NW6** | **Succession planning (+)**<br>**Long-term view (+)**<br>**Self-efficacy (+)**<br>**Education (+)**<br>**Perception of climate change (+)**<br>*Family farm, with succession planning well developed and two sons in partnership.*<br>*Proactive trialling of different pasture species and establishment methods.*<br>*Climate viewed as a significant challenge, with increasing unpredictability and less reliable Spring rain.*<br>*Acknowledged that NW climate is 'still pretty forgiving, even when Spring doesn't deliver'.* | **Social networks (+)**<br>**Access to information (-)**<br>**Extension services (-)**<br>**Social license (-)**<br>*Established in King Island beef discussion group, which is well facilitated, and well attended by interested producers. Benefited from Pastures Principles course.*<br>*Does not use private consultants.*<br>*Need education for Tasmanian farmers around climate risks and effects on our production systems.*<br>*MLA rebuilding the pasture growth tool would be valuable, and funding on-farm trials.*<br>*Consumer concern not considered a driving force now (in relation to driving regulations around fertiliser* | **Alternative pasture species (+)**<br>**Soil health (+)**<br>**Land capability (-)**<br>*Planting alternative pasture species to suit different soil types (e.g. lucerne on sandy soils) helps decrease vulnerability.*<br>*Have been reducing use of synthetic fertilisers and trialling foliar micronutrient applications – with soil health and maintaining social license in mind.*<br>*Open to installing irrigation but the flat landscape would increase the cost, potentially making it prohibitive (interaction with financial capital).*<br>*Mineral deficiencies associated with sandy soils.* | **Unreliable selling (-)**<br>*Finding the market when cattle are ready to be sold is challenging, as most producers have cattle ready at a similar time. If want to move cattle quickly, then Tas only option. If can afford to wait, then could send to Vic.* | **Cost of production (-)**<br>*High cost of installing irrigation infrastructure due to flat landscape likely to limit investment in irrigation.* |

| | Human | Social | Natural | Physical | Financial |
|---|---|---|---|---|---|
| | | *use), but could in 5-10 years.* | | | |

# Appendix 8.7: Red meat producers survey

*Confidential*



## LPP Nexus Producer Survey

Please complete the survey below.

Thank you!

Nexus Project Producer Survey

We invite you to participate in this survey of the Tasmanian red meat industry, that will help the Nexus Project provide relevant recommendations around future extension and skill development requirements. Moving forward, the red meat industry will adapt to a changing climate, respond to the changing views of consumers, and increase its focus on environmental sustainability and animal welfare. We recognise that understanding the people in your operation - including your labour force, how you access information and plan for the future - is key to MLA and other industry stakeholders developing relevant support. We ask that someone in a decision-making role (i.e. Owner or Manager) please answers the survey questions.

By submitting this survey, you are consenting to participate in the project and contribute anonymous data that may be published. All survey responses will be treated in confidence and will be stored in a password protected server on the University of Tasmania network. All the research data will be retained securely for five years in line with relevant policy.

Participants will be non-identifiable if they choose not to record their name and contact details in the survey they submit. Participants will only be able to withdraw data after submitting the survey if they have provided their name on the materials that are submitted.

This study has been approved by the Tasmania Social Sciences Human Research Ethics Committee. If you have concerns or complaints about the conduct of this study, you can contact the Executive Officer of the HREC (Tasmania) Network on (03) 6226 2975 or email ss.ethics@utas.edu.au The Executive Officer is the person nominated to receive complaints from research participants. You will need to quote 17705.

All questions are optional, and the survey will take between 15-20 minutes to complete.

Click next to start the survey.

| | |
|---|---|
| 1. What region is your farm based in? If you have multiple farms, pick the one applicable to your primary production property that is used for red meat production. | ○ West Coast<br>○ North West Coast<br>○ Central North Coast<br>○ Launceston/Tamar<br>○ Northern Midlands<br>○ Southern Midlands<br>○ Derwent Valley<br>○ North East<br>○ East Coast<br>○ Tasman Peninsular<br>○ Hobart/South<br>○ King or Flinders Islands |
| 2. What age range do you fall within? | ○ 15-19<br>○ 20-29<br>○ 30-39<br>○ 40-49<br>○ 50-59<br>○ 60-69<br>○ 70-79<br>○ 80 and over |
| 3. What gender do you identify as? | ○ Male<br>○ Female<br>○ Other<br>○ Prefer not to answer |

| | |
|---|---|
| 4. What is the approximate size of your property (hectares) | ______________________ |
| 5. What is the approximate size of your grazing area (ha) - improved pasture | ______________________ |
| 6. What is the approximate size of your grazing area (ha) - native/natural pasture | ______________________ |
| 7. Do you trade lambs? | ◯ Yes<br>◯ No |
| If yes to trading lambs, how many did you sell in 2020-21? (Approximate) | ______________________ |
| 8. Does your production system include ewes lambing? | ◯ Yes<br>◯ No |
| If yes to ewes lambing, how many do you expect to lamb in the 2021-22 season? (Approximate) | ______________________ |
| 9. Do you finish beef cattle? | ◯ Yes<br>◯ No |
| If yes to finishing beef, how many cattle do you expect to sell in 2021-22? (Approximate) | ______________________ |
| 10. Does your production system include cows calving? | ◯ Yes<br>◯ No |
| If yes to cows calving, how many do you expect to calve down in the 2021-22 season? (Approximate) | ______________________ |
| 11. What percentage of your whole farm operation would red meat constitute (in terms of revenue, with the balance percentage being wool, dairy, grain growing, horticulture etc.)? | ◯ Less than 25%<br>◯ 25-50%<br>◯ 51-75%<br>◯ More than 75% |
| 12. Looking ahead 5 to 10 years, which option best describes your approach to red meat production? | ◯ Maintaining<br>◯ Increasing<br>◯ Decreasing<br>◯ Unsure |
| If maintaining, specify whether | ◯ Maintaining both beef and/or lamb production at same levels<br>◯ Decreasing lamb and increasing beef to maintain production<br>◯ Increasing lamb and decreasing beef to maintain production |
| If increasing, specify whether | ◯ Increasing lamb production<br>◯ Increasing beef production<br>◯ Increasing both lamb and beef production |

| | |
|---|---|
| If decreasing, specify whether | ◯ Decreasing lamb production<br>◯ Decreasing beef production<br>◯ Decreasing both lamb and beef production |
| 13. Please select the information seeking approaches that you typically engage with (check all that apply) | ☐ Attending Red Meat Updates<br>☐ Member of a red meat producer group<br>☐ Participating in training courses run through private consultancies<br>☐ Engaging a private consultant for my farming operation<br>☐ Talking with my neighbours and other farmers<br>☐ Searching for targeted information online<br>☐ Getting advice from my agribusiness/retailer representatives<br>☐ Member of online social media groups<br>☐ Reading research papers<br>☐ Participating in research trials<br>☐ Other |
| If other, please specify. | ________________________________ |
| 14. What generation of your family are you to have farmed this property? | ◯ First generation to farm this property<br>◯ Second generation to farm this property<br>◯ Third generation to farm this property<br>◯ Fourth generation to farm this property<br>◯ Fifth generation or more to farm this property |
| 15. How likely do you think it is that the next generation in your extended family will farm this property? | Very unlikely — Neutral — Very likely<br>*(Place a mark on the scale above)* |
| 16. In your situation, is succession planning likely to enable (i.e. positively influence) or constrain (negatively influence) how you develop your farming operation in the future? | Constrain future development — Neutral/unsure — Enable future development<br>*(Place a mark on the scale above)* |
| 17. Currently, how many PAID family members (including yourself) work on your farm? | __________________________ |
| 18. Currently, how many UNPAID family members (including yourself) work on your farm? | __________________________ |
| 19. Currently, how many people who are not family, work on your farm? | __________________________ |
| 20. What are the main roles for PAID family members on your farm? | ☐ Manager<br>☐ 2IC<br>☐ Farm hand<br>☐ Shearer<br>☐ Other |

| | |
|---|---|
| 21. What are the main roles for UNPAID family members on your farm? | ☐ Manager<br>☐ 2IC<br>☐ Farm hand<br>☐ Shearer<br>☐ Other |
| 22. What are the main roles for non-family members on your farm? | ☐ Manager<br>☐ 2IC<br>☐ Farm hand<br>☐ Shearer<br>☐ Other |
| 23. Do you expect to be recruiting staff to work in your enterprise during the next 2 years? | ◯ Yes<br>◯ No |
| If yes, how many new staff are you likely to recruit during the next 2 years? | ______________________ |
| Can you please identify the main roles you are likely to recruit? Select all that apply. | ☐ Manager<br>☐ 2IC<br>☐ Farm hand<br>☐ Shearer<br>☐ Other |
| 24. What method do you MOST OFTEN use to find suitable employees? Please pick no more than 3. | ☐ Advertise in local and regional newspapers<br>☐ Advertise in the Tas Country or other agricultural newspaper<br>☐ Ask government funded employment agencies, e.g. WISE Employment, MAX Employment<br>☐ Use online job search and advertising websites, e.g. SEEK<br>☐ Use farm consultants or specialist farm employment groups<br>☐ Use private employment services<br>☐ Use Facebook or other social media<br>☐ Gumtree<br>☐ Word of mouth<br>☐ Other |
| If other, please provide details. | ______________________ |
| 25. How much of an issue is staff turnover on your farm? | Not an issue — Minor issue — Major issue<br>*(Place a mark on the scale above)* |
| 26. How much of an issue is staff turnover on farms in the red meat industry in Tasmania in general? | Not an issue — Minor issue — Major issue<br>*(Place a mark on the scale above)* |
| Would you like to add any comments about staff turnover on your farm or the red meat industry more generally? | ______________________ |

27. In the next 5 to 10 years, what is likely to happen to the number of PAID people (family and non-family) working on your farm?

- ◯ Decrease
- ◯ Stay about the same
- ◯ Increase

28. In the next 5 to 10 years, what is likely to happen to the number of UNPAID people (family and non-family) working on your farm?

- ◯ Decrease
- ◯ Stay about the same
- ◯ Increase

29. Do you believe the labour workforce is likely to enable (positively influence) or constrain (negatively influence) how you develop your farming operation in the future?

Constrain future development — Neutral/unsure — Enable future development

*(Place a mark on the scale above)*

An important part of the Nexus Project is exploring potential adaptation pathways in response to the changing climate, through biophysical modelling and economic analyses. These adaptation pathways include incremental changes through to transformational changes within red meat production systems, with some pathways focusing on moving towards carbon neutrality, and others on diversification. As the owner/managers of red meat production systems who are making decisions and changing on-farm practices, we are interested in your views on climate change, matching feed supply to feed demand, irrigation investment and other potential changes (looking back and looking forward).

30. Which option best describes your perspective on the changing climate:

- ◯ The climate is not changing significantly
- ◯ The climate is changing, but does not affect the way I manage my farming operation now or in the future
- ◯ The climate is changing, but I am unsure what I need to do on-farm to respond to it
- ◯ The climate is changing, and I am already adapting to it in the way I manage my farming operation
- ◯ I would like to know more about how the climate is changing, so that I can better make future management decisions
- ◯ None of the above

If none of the above, please provide further details.

__________________________________________

31. How would you currently rate how well you match feed supply to feed demand?

Not very well — Neutral/average — Extremely well

*(Place a mark on the scale above)*

| | |
|---|---|
| 32. Which option best describes your perspective on developing knowledge and skills around matching feed supply to feed demand? | ◯ I am doing it well enough to get by for now<br>◯ I have already developed my knowledge and skills in this area, or am currently working on this area<br>◯ I would like to increase my knowledge and skills but am unsure where to access information and training<br>◯ I would like to increase my knowledge and skills, and know information and training are available, but I currently have other areas that are higher priority<br>◯ I have room to improve matching feed supply to feed demand, but am not convinced the improvement will make a significant enough difference to profitability for me to invest my time in training<br>◯ None of the above |
| If none of the above, please provide further details. | __________________________________ |
| 33. Do you currently undertake physical pasture measuring in regard to the following (check all that apply) | ☐ Ground cover<br>☐ Pasture composition<br>☐ Pasture growth rates<br>☐ Pasture cover / pasture availability<br>☐ None of the above<br>☐ Other |
| 34. How would you rank the level of impact from feral and native browsing competition on your grazing enterprise both economically and environmentally? | No impact — Neutral/medium impact — Significant impact<br>*(Place a mark on the scale above)* |
| 35. Does the impact from feral and native browsing competition limit the productivity success of future management going forward? | ◯ Yes<br>◯ No |
| 36. Do you currently have irrigated pasture? | ◯ Yes<br>◯ No |
| If yes, how many hectares of pasture do you currently irrigate (approx) | ____________________________ |
| 37. Do you currently have irrigated cropping with the purpose of red meat production? | ◯ Yes<br>◯ No |
| If yes, how many hectares of cropping do you irrigate (approx) | ____________________________ |
| 38. What kind of irrigation infrastructure to you currently have? | ☐ Centre pivots<br>☐ Linear travel<br>☐ Solid set<br>☐ Hard hose<br>☐ Other |
| 39. Are you planning to increase your irrigation capacity during the next 5 to 10 years? | ◯ Yes<br>◯ No |

| | |
|---|---|
| If yes, will increasing your irrigation capacity rely on you | ◯ Purchasing more water<br>◯ Investing in more irrigation infrastructure<br>◯ Both purchasing more water and investing in infrastructure<br>◯ Other |
| If no, which of the following factors contribute to your decision not to increase irrigation capacity? | ☐ Limited or no access to water<br>☐ Cost of purchasing more water<br>☐ Cost of investing in more irrigation infrastructure<br>☐ None of the above<br>☐ Other |
| 40. Have you managed feed intensively under irrigation before? | ◯ Yes<br>◯ No |
| 41. Please indicate which of the following changes you have made during the last 5 to 10 years on your farm | ☐ Adjusted seasonal stocking rate to better fit feed demand to the changed pattern of feed supply<br>☐ Increased the extent of deeper-rooted legumes in your perennial pastures<br>☐ Actively worked on improving soil fertility through addition of PKS fertilisers<br>☐ Planted trees with the intention of reaping environmental benefits<br>☐ Purchased an additional block of arable land<br>☐ Purchased carbon offsets<br>☐ Diversified by introducing a new enterprise to your farming system<br>☐ Invested in irrigation water and/or infrastructure<br>☐ Explored dairy beef as a potential production pathway<br>☐ None of the above |

**42. Please indicate how likely you are to make the following changes within the next 5-10 years**

| | Very unlikely | Unlikely | Neutral | Likely | Very likely |
|---|---|---|---|---|---|
| Adjusting seasonal stocking rate to better fit feed demand to the changed pattern of feed supply | ◯ | ◯ | ◯ | ◯ | ◯ |
| Increase the extent of deeper-rooted legumes in your perennial pastures | ◯ | ◯ | ◯ | ◯ | ◯ |
| Actively work on improving soil fertility through addition of PKS fertilisers | ◯ | ◯ | ◯ | ◯ | ◯ |
| Plant trees with the intention of reaping environmental benefits | ◯ | ◯ | ◯ | ◯ | ◯ |
| Purchase an additional block of arable land | ◯ | ◯ | ◯ | ◯ | ◯ |
| Purchase carbon offsets | ◯ | ◯ | ◯ | ◯ | ◯ |

| | | | | | |
|---|---|---|---|---|---|
| Diversify by introducing a new enterprise to your farming system | ○ | ○ | ○ | ○ | ○ |
| Invest in irrigation water and/or infrastructure | ○ | ○ | ○ | ○ | ○ |
| Explore dairy beef as a potential production pathway | ○ | ○ | ○ | ○ | ○ |

43. In the future, are you interested in hosting an on-farm demonstration of legumes that have been shown to have production potential in either the Midlands or North West region (the latter focusing on waterlogging tolerance?

○ Yes ○ No

If yes, please consider contacting Rowan Smith (Pasture Researcher with the Tasmanian Institute of Agriculture) to express your interest. Email Rowan.Smith@utas.edu.au

Thank you for your participation!

# Appendix 8.8: Social research addressed in the Tasmanian red meat survey

Social research enquiries addressed in the Tasmanian red meat survey, with supportive statements from preliminary data collection and implications for future extension.

| Social research enquiry | Supportive statements and extension implications |
|---|---|
| What do red meat industry segments currently comprise in Tasmania, in terms of: owner/manager demographics, farm shape and scale, extent of red meat production?<br>What is the planned growth of Tasmanian red meat production?<br>What are the information seeking approaches of red meat producers? | RRG members and interviewees were predominantly innovative producers from large scale operations, and less is known about other industry segments.<br>Producer perceptions, plans, information seeking patterns and therefore extension needs may vary between industry segments.<br>*One producer emphasised that, "We need to educate those who aren't educating themselves, the system that exists probably favours those who don't need it."* |
| What is the shape (infrastructure type) and scale (total and proportion ha) of irrigation in Tasmanian red meat production?<br>What is the planned growth of irrigation in Tasmanian red meat operations?<br>What are the barriers and enablers to increasing irrigation capacity in Tasmanian red meat operations? | Investing in irrigation water and/or infrastructure is an adaptation opportunity for Tasmanian red meat farming systems to reduce risk.<br>This social research enquiry will establish the extent of irrigation investment likely to occur, the factors limiting future expansion (physical and financial capacity), and what extension support (social capacity) is required to build producer knowledge and skills (human capacity) required to manage pastures intensively under irrigation.<br>*Interviewees reported that scaling up irrigation has provided confidence to increase stocking rate.*<br>*They highlighted the need to learn how to manage the animal health implications (e.g. nutrient imbalances, metabolic issues and increased lamb mortality) associated with increased stocking rate and intensively grazing monocultures under pivots.* |
| What is the current Tasmanian red meat producer demand for improving knowledge and skills around matching feed supply to feed demand? | This line of social research enquiry helps establish the appetite of producers for improving their pasture management practices, and therefore how to target and market the associated extension services.<br>*Interviewees highlighted that there are little publicly available extension information and resources, and that this translates to a lower baseline in industry knowledge and practice change, particularly around pasture management. One interviewee commented that, "A large proportion of industry do not know how to source and interpret independent information."*<br>*Interviewees noted the lack of red meat extension officers in Tasmania and the associated lack of on-farm discussion groups and trials to demonstrate fertiliser/grazing management and fencing options that support increased pasture productivity.* |

| | |
|---|---|
| | *Discussions in RRG Meeting 2 highlighted the importance of 'going back to basics' with the current cohort of red meat producers, with a particular focus on grazing management and feed budgets.* |
| What is the extent of intergenerational red meat farming in Tasmania?<br>Are adaptation and transformation of Tasmanian red meat farming systems currently constrained or enabled by succession planning? | *Within the families of RRG members and interviewees, educated children are returning to large scale family farms and driving change with a future focus. One RRG member commented that, "An increase in FTE and energy for the farm has meant an increased focus on strategy and increasing productivity".*<br>This line of social research enquiry will explore the wider industry's experience in relation to succession planning, acknowledging that the RRG members and interviewees are predominantly innovative producers with large scale operations.<br>Many intergenerational red meat farming families benefited from a succession planning project in the 1990s. Is succession planning support required in the 2020s to enable confident commitment to future development? |
| What is the current shape (roles) and scale (numbers) of employment on Tasmanian red meat operations?<br>How is adaptation and transformation of Tasmanian red meat farming systems currently constrained by labour workforce challenges? | *Data from the interviews and RRG meetings revealed that there is a lack of reliable and skilled labour, with increased workforce skills development identified as a requirement to support increasingly intensive red meat farming. These views were also expressed in SALRC South East Vic & Tas Regional Committee Meeting in May 2021.*<br>A suite of survey questions therefore focuses on current and planned employment in Tasmanian red meat operations, with a focus on recruitment processes within the next 2 years. The issues of staff turnover will be quantified, and the extent to which labour challenges are perceived to influence future development. |
| What are red meat producers' perspectives on the changing climate? This was directly asked through the following question:<br><br>Which option best describes your perspective on the changing climate? (select one option)<br>• The climate is not changing significantly<br>• The climate is changing, but does not affect the way I manage my farming operation now or in the future<br>• The climate is changing, but I am unsure what I need to do on-far, to respond to it<br>• The climate is changing, and I am already adapting to it in the way I manage my farming operation<br>• I would like to know more about how the climate is changing, so that I can | Red meat producers' perspectives about the changing climate are a dimension of human capacity that directly influences their decision making and approaches to future development. Extension messaging needs to be responsive to the prevailing experiences and perspectives of red meat producers, and these perspectives may vary with region and scale of operation.<br>*The preliminary analysis revealed that interviewees and RRG members were experiencing increasing climate variability, with a general attitude of 'we can and will adapt'.*<br>*Less impact of climate change on farming was noted in the North West than in other Tasmanian regions and nationally. This is drawing investors to the region and driving up land prices (interaction with financial capital).* |

| | |
|---|---|
| better make future management decisions<br>• None of the above | |
| What adaptations and transformations have Tasmanian red meat producers made to their farming systems during the last 5 to 10 years? This was asked directly asked through the following question:<br><br>Please indicate which of the following changes you have made during the last 5 to 10 years on your farm. (select one or more options)<br>• Adjusted seasonal stocking rate to better fit feed demand to the changed pattern of feed supply<br>• Increased the extent of deeper-rooted legumes in your perennial pastures<br>• Actively worked on improving soil fertility through addition of PKS fertilisers<br>• Planted trees with the intention of reaping environmental benefits<br>• Purchased an additional block or arable land<br>• Purchased carbon offsets<br>• Diversified by introducing a new enterprise to your faming system<br>• Invested in irrigation water and/or infrastructure<br>• Explored dairy beef as a potential production pathway<br>• None of the above | This question will provide a direct indication of industry development to date, in some key areas of incremental and transformational adaptation that are being modelled in the Tasmanian NEXUS project. Differences between regions and industry segments are of interest. |
| How likely are Tasmanian red meat producers to adapt and transform their farming systems during the next 5 to 10 years? This was established by providing the same set of statements above, with a Likert scale comprising of Very unlikely, Unlikely, Neutral, Likely, Very likely, and asking participants to select an option for the Likert scale for each statement. | This question will reveal the direction and extent of planned development by Tasmanian red meat producers, in some key areas of incremental and transformational adaptation that are being modelled in the Tasmanian NEXUS project. Differences between regions and industry segments are of interest and will help targeting of future extension efforts. Where there are consistent negative responses, further investigation could explore the underlying constraints. |

# Appendix 8.9: Consumer attitudes towards eating and farming of red meat

# The Tasmania Project

## Attitudes towards eating red meat

*Summary of findings from the fourth general survey (29 Apr – 12 May 2021)*

Report number: 48
Authors: Libby Lester, Sebastian Kocar, Ella Horton
Date: 7 July 2021

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# Key Findings

Findings from the Fourth General Survey of The Tasmania Project (TTP4) show that about four in five respondents (82%) eat red meat.

There are notable differences between sociodemographic groups, with the following respondents more likely to eat meat:

- Men (89% vs 79% women)
- 65 years or older (84% vs 81% all other age groups)
- without a university degree (89% compared to 79% with a uni degree)
- residing outside of Greater Hobart (86% compared to 79% from Greater Hobart)
- living in households with children (88% compared to 80% without children)
- living in households with annual income > $100,000 (87% vs 82% < $100,000)

The survey identified a range of interesting findings in relation to attitudes towards production, sourcing and consumption of red meat.

- Red meat is an important source of nutrition in two thirds of respondents' diets, but three in five respondents eat less meat now than they did five years ago.
- About 60% of respondents have become more interested in animal welfare and environmental management practices.
- Females are more interested in animal welfare (59%F, 46%M (strongly) agreed) and environmental management aspects of red meat production and sourcing than males (63%F, 51%M (strongly) agreed). Guaranteeing a fair price to farmers (85%F, 76%M answered (very) important) and the local production of red meat is also of greater importance to females compared with males.

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## Methodology

Data for TTP4 were collected between 29 April and 12 May 2021 using an online survey questionnaire.

An email invitation with a link to the survey was sent to about 3500 Tasmanian residents who had registered to be involved in The Tasmania Project.

An invitation to the survey was also shared on social media and via a range of community, government and business contacts.

A total of 1176 full responses were collected.

| Variable | n | % |
|---|---|---|
| **Gender** | | |
| Female | 718 | 66.7 |
| Male | 345 | 32.1 |
| Prefer not to say/self describe | 8 | 0.7 |
| **Age** | | |
| 18-24 years | 24 | 2.3 |
| 25-44 years | 189 | 17.9 |
| 45-64 years | 477 | 45.1 |
| 65+ years | 367 | 34.7 |
| **Education** | | |
| High School | 125 | 11.6 |
| (Advanced) Diploma, Certificate | 213 | 19.8 |
| Bachelor's degree or more | 736 | 68.5 |
| **Region** | | |
| Greater Hobart | 533 | 45.3 |
| Launceston | 106 | 9.0 |
| Rest of Tasmania | 537 | 45.0 |
| **Household composition** | | |
| Couple without children | 470 | 44.2 |
| Parents with pre- or school-aged children | 152 | 14.3 |
| Parent/s with adult children | 123 | 11.6 |
| One-person household | 219 | 20.6 |
| Other household composition | 100 | 9.4 |
| **Household income (annual)** | | |
| <$60,000 | 378 | 39.5 |
| $60,000 - <$100,000 | 269 | 28.1 |
| $100,000+ | 310 | 32.4 |

**Table 1:** TTP4 respondents by sociodemographic variables

Respondents to TTP4 were largely female (about two-thirds), aged 45 years and over (almost four-fifths), highly educated (more than two in three respondents had a Bachelor's degree or higher) and residents of Greater Hobart (more than half of all respondents).

A significant proportion of respondents were living in households consisting of couples without children (44%), and almost two in five respondents were from households with a total annual income of less than sixty thousand dollars.

## Eating red meat

Respondents were asked a series of questions about eating red meat and their attitudes towards production, sourcing and consumption. First, we asked if they ate red meat such as lamb of beef.

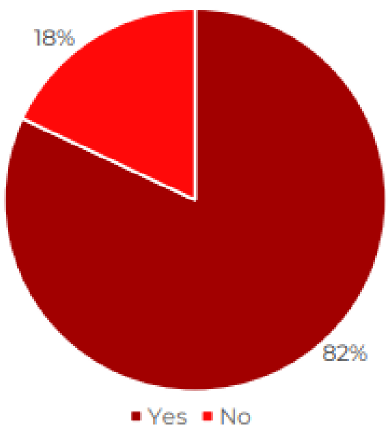


**Figure 1:** Do you eat red meat (e.g., lamb or beef)?

The results show that about four in five respondents eat red meat and 18% do not eat red meat at all. To determine who is more (or less) likely to eat red meat, we compared red meat eating habits across various sociodemographic groups.

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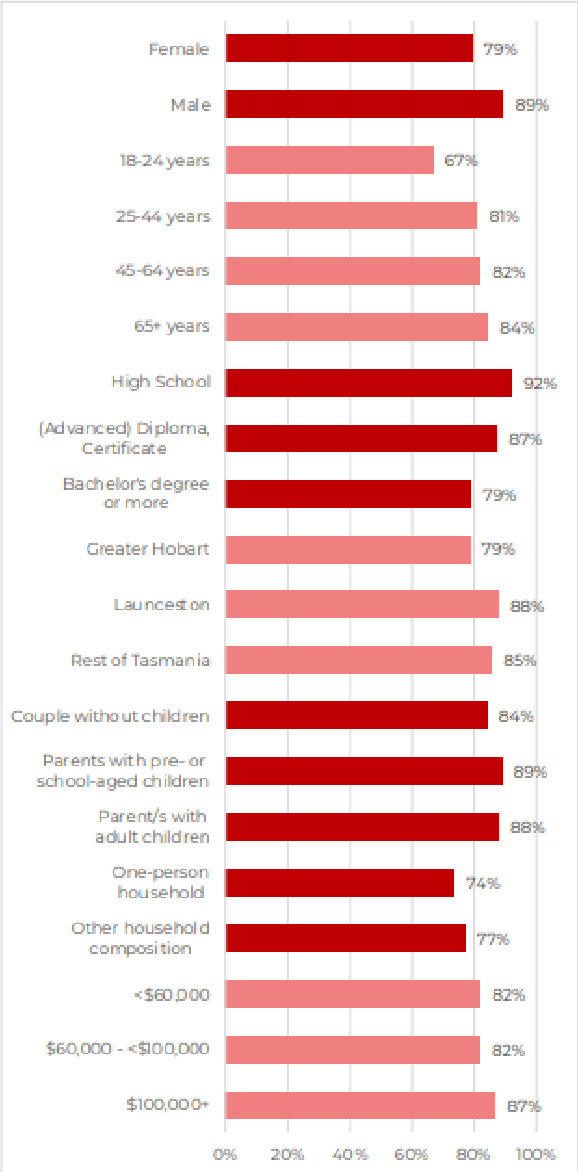


**Figure 2:** Meat eating habits by sociodemographic variables

Both the multivariate analysis results and the descriptive results (shown in figure 2) indicate that males are more likely to eat red meat than females (89%; 79%) and the oldest respondents (65+ years) are more likely to eat meat than younger respondents (84%, 67-82%).

Education is also a predictor of red meat eating habits. The most educated respondents (those with a Bachelor's degree or higher) are less likely to eat red meat than respondents with lower levels of education (79% compared with 87% of respondents whose highest level of education is an advanced diploma or certificate and 92% whose is completing high school).

Some regional differences can also be observed, with respondents from Greater Hobart less likely to eat red meat (79%) compared with respondents from Launceston (88%) and other parts of Tasmania (85%).

There were minimal differences observed in red meat eating habits between respondents from households with different compositions, with the only statistically significant difference found between households with and without children. These results suggest that living with children increases the likelihood of eating red meat.

Total annual household income also showed an effect on the likelihood of eating red meat, whereby respondents living in households with higher income (that is, $100,000 or more per annum) are more likely to eat red meat than those on lower incomes.

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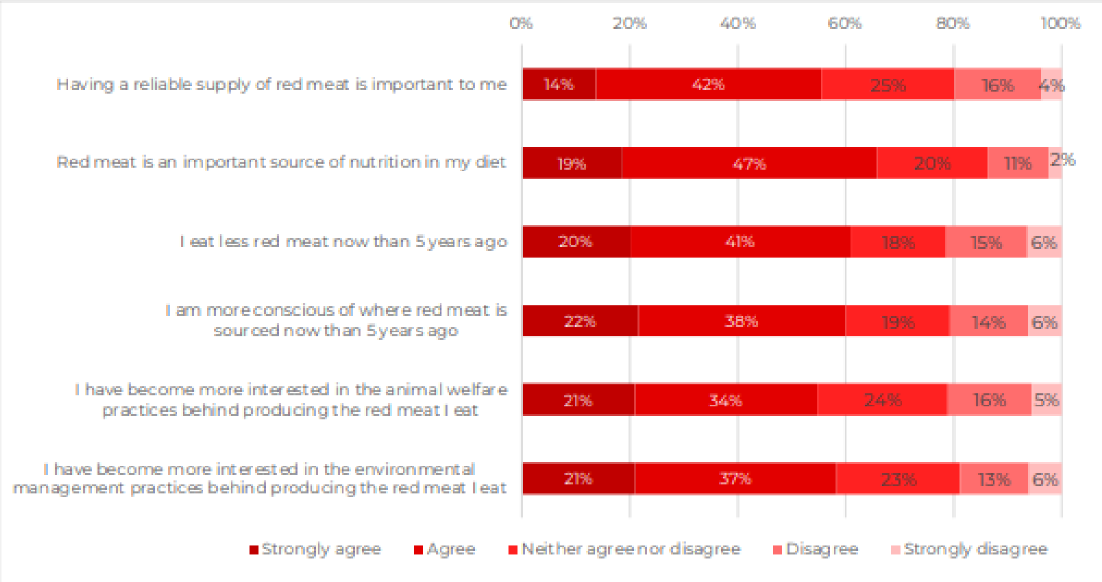


**Figure 3:** Respondents' attitudes towards the production and consumption of red meat

## Attitudes towards red meat

In TTP4, we asked respondents about their attitudes towards the consumption and production (see figure 3).

The results show that there is fairly consistent agreement with different statements on the importance of red meat in respondents' diet and on various practices behind producing the red meat they eat.

About three in five respondents strongly agree with the following statements:

1. *Having a reliable supply of red meat is important to me*
2. *I eat less red meat now than 5 years ago*
3. *I am more conscious of where red meat is sourced now than 5 years ago*
4. *I have become more interested in the animal welfare practices behind producing the red meat I eat*
5. *I have become more interested in the environmental management practices behind producing the red meat I eat.*

An even higher proportion of respondents (about two in three) agree that red meat is an important source of nutrition in their diet.

There are notable differences between socioeconomic groups in their attitudes towards production and consumption of red meat. Females and residents of Greater Hobart tend to agree less that having a reliable supply of red meat is important to them, and that red meat is an important source of nutrition in their diet.

Females, residents of Greater Hobart (compared to other parts of Tasmania), and respondents with the lowest household income (<$60,000 per annum compared to higher income groups) were more likely to report eating less meat now than 5 years ago.

Respondents with the highest education and females are more likely to agree that they have become more conscious of where red meat is sourced and more interested in animal welfare and environmental management practices behind producing the red meat they eat compared to males and respondents without a university degree.

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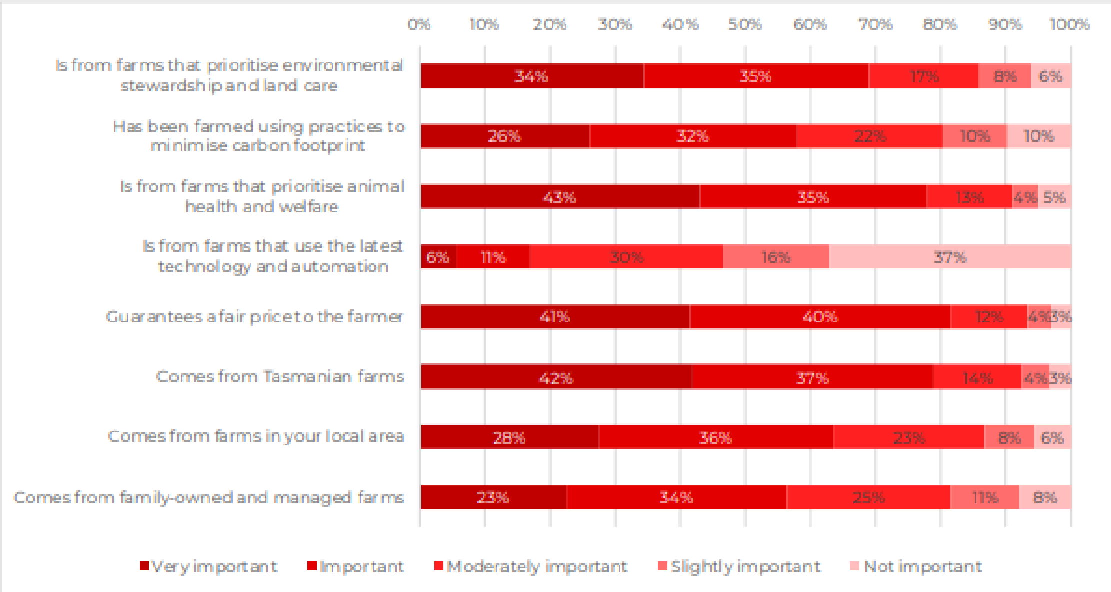


**Figure 4:** What is important to respondents in relation to sourcing red meat

## Sourcing red meat

Respondents were asked about the importance of a range of factors in relation to sourcing red meat (see Figure 4). The following factors were identified as the most important:

- Guarantees a fair price to the farmer (important or very important to 81% of respondents)
- Comes from Tasmanian farms (important or very important to 79% of respondents)
- Is from farms that prioritise animal health and welfare (important or very important to 78% of respondents)
- Is from farms that prioritise environmental stewardship and land care (important or very important to 69% of respondents)

Interestingly, sourcing red meat from farms that use the latest technology and automation was only important or very important to only 17% of respondents.

Comparative analysis of the importance of different sources of red meat to different sociodemographic groups shows interesting results. These are generally consistent with results previously reported regarding eating red meat and attitudes towards production and consumption (from Figures 2 and 3):

- Various factors in relation to sourcing red meat, including those associated with the environment, animal welfare, fair price, and local production., were of greater important to females than males.
- Environmental aspects of red meat production were of greatest importance to respondents with a university degree than those with lower levels of formal education.
- Factors relating to the environment, ensuring a fair price, to the farmer and sourcing meat from family-owned and managed farms are more important to respondents from households without children than those living with either pre-school, school-aged, or adult children.
- The oldest respondents (65+ years) reported lower importance for sourcing red meat from family-owned and managed farms than other age groups.

# Appendix 8.10: Consumer attitudes towards dairy, red meat and seafood


# The Tasmania Project

## Attitudes towards dairy, red meat and seafood

*Summary of findings from the fourth general survey (29 Apr – 12 May 2021)*

Report number: 49
Authors: Libby Lester, Sebastian Kocar, Ella Horton
Date: 5 July 2021

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# Key Findings

Findings from the Fourth General Survey of The Tasmania Project (TTP4) show that more respondents eat dairy (95%) than red meat (82%) and seafood (77%). About two in three respondents eat red meat, dairy and seafood as part of their diet.

For respondents who consume these food types, dairy seems to be the most important in respondents' diet, followed by seafood and red meat.

While the most common places to buy food in Tasmania are major (89%), minor or independent supermarkets (72%), 56% of respondents grow their own food, 30% buy it at local farmers markets, and 18% buy it from the farm gate or wharf.

In the last five years, more respondents reduced their consumption of red meat than dairy or seafood. In this same period, most respondents indicate they have become more conscious of where red meat, dairy and seafood are sourced, and more interested in the animal welfare practices and environmental management practices associated with production.

The most important factors for respondents when buying red meat, dairy and seafood are:

- a fair price to the farmer/fisher is guaranteed
- they come from Tasmanian farms/fishers,
- they come from farms that either prioritise animal health and welfare or environmental stewardship and land care.

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## Methodology

Data for TTP4 were collected between 29 April and 12 May 2021 using an online survey questionnaire.

An email invitation with a link to the survey was sent to about 3500 Tasmanians who had registered to be involved in The Tasmania Project. An invitation to the survey was also shared on social media and by a range of community, government and business contacts. A total of 1176 full responses were collected.

Respondents to TTP4 were largely female (about two-thirds), aged 45 years and over (almost four-fifths), highly educated (more than two in three respondents had a Bachelor's degree or higher) and residents of Greater Hobart (more than half of all respondents).

A significant proportion of respondents were living in households consisting of couples without children (44%), and almost two in five respondents were from households with a total annual income of less than sixty thousand dollars.

Almost 70% of respondents have lived in Tasmania for more than 15 years and approximately 20% of respondents have lived in the state between 6 and 15 years. Only about 1 in 10 respondents moved to Tasmania in the last 5 years.

| Variable | n | % |
|---|---|---|
| **Gender** | | |
| Female | 718 | 66.7 |
| Male | 345 | 32.1 |
| Prefer not to say/self describe | 8 | 0.7 |
| **Age** | | |
| 18-24 years | 24 | 2.3 |
| 25-44 years | 189 | 17.9 |
| 45-64 years | 477 | 45.1 |
| 65+ years | 367 | 34.7 |
| **Education** | | |
| High School | 125 | 11.6 |
| (Advanced) Diploma, Certificate | 213 | 19.8 |
| Bachelor's degree or more | 736 | 68.5 |
| **Region** | | |
| Greater Hobart | 533 | 45.3 |
| Launceston | 106 | 9.0 |
| Rest of Tasmania | 537 | 45.0 |
| **Household composition** | | |
| Couple without children | 470 | 44.2 |
| Parents with pre- or school-aged children | 152 | 14.3 |
| Parent/s with adult children | 123 | 11.6 |
| One-person household | 219 | 20.6 |
| Other household composition | 100 | 9.4 |
| **Household income (annual)** | | |
| <$60,000 | 378 | 39.5 |
| $60,000 - <$100,000 | 269 | 28.1 |
| $100,000+ | 310 | 32.4 |

**Table 1:** TTP4 respondents by sociodemographic variables

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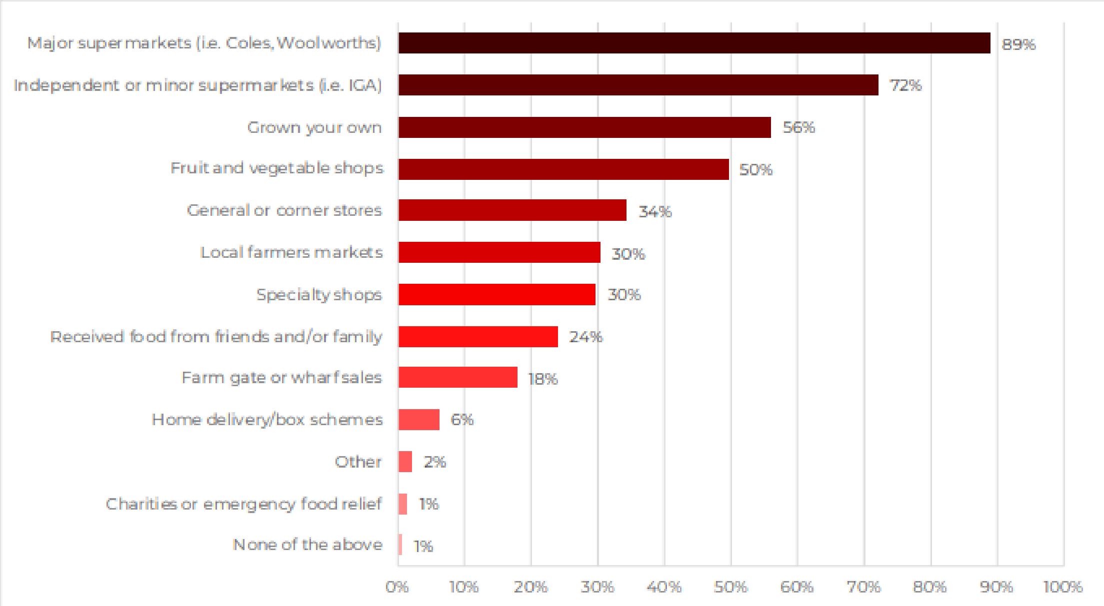


**Figure 1:** In the last 30 days, have you eaten food sourced from the following? Select all that apply.

## Sourcing food

When asked where they had sourced their food in the last thirty days (see Figure 1), most respondents indicated that they buy food from major supermarkets, such as Woolworths and Coles (89%), and independent or minor supermarkets, such as IGA (72%). More than one half of respondents grow their own food (56%) and exactly half buy food from fruit and vegetable shops.

It was far less common for respondents to buy food from the farm gate or wharf (18%), have food delivered to their home (6%) or get food from charities or emergency food relief (1%).

There are several interesting differences in how certain sociodemographic groups source their food. These are that:

- women are less likely to eat food from major supermarkets than men;
- respondents younger than 45 years are more likely to receive food from friends and/or family than older respondents;
- more educated respondents are more likely to grow their own food, to receive food from friends and/or family, or to eat food from local farmers markets;
- respondents with the lowest household income (<$60,000 per annum) are less likely than those on higher incomes to eat food from independent or minor supermarkets, general and corner stores, specialty shops, and local farmers markets, but more likely to receive food from friends and/or family; and
- respondents who have lived in Tasmania for 15 years or less are more likely to eat food from local farmers markets, while respondents who have lived in Tasmania for 5 years or less are more likely to source food from a farm gate or wharf.

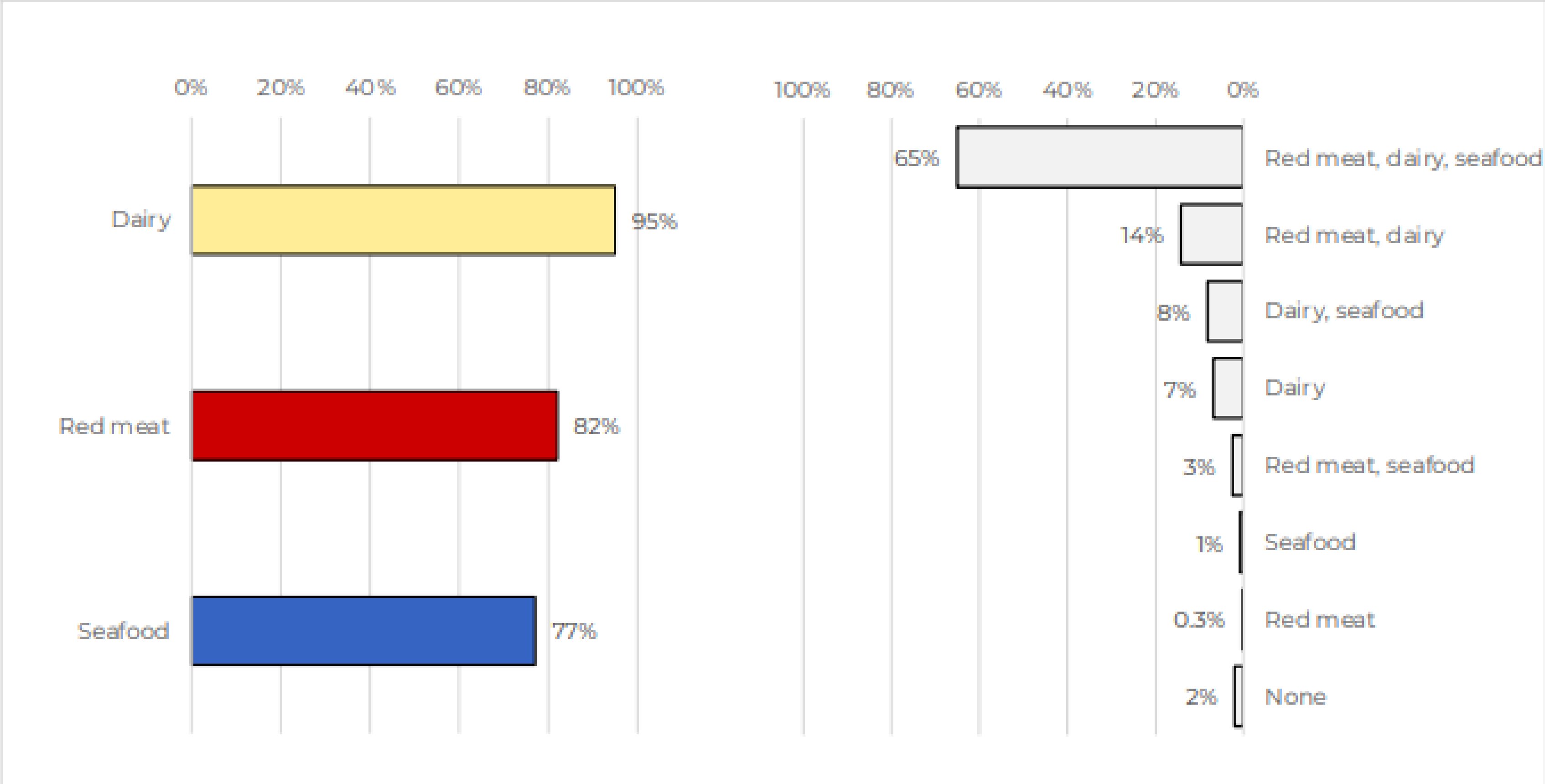


**Figure 2:** Respondents' consumption of red meat, dairy and seafood (left) and consumption of various combinations of the food types (right)

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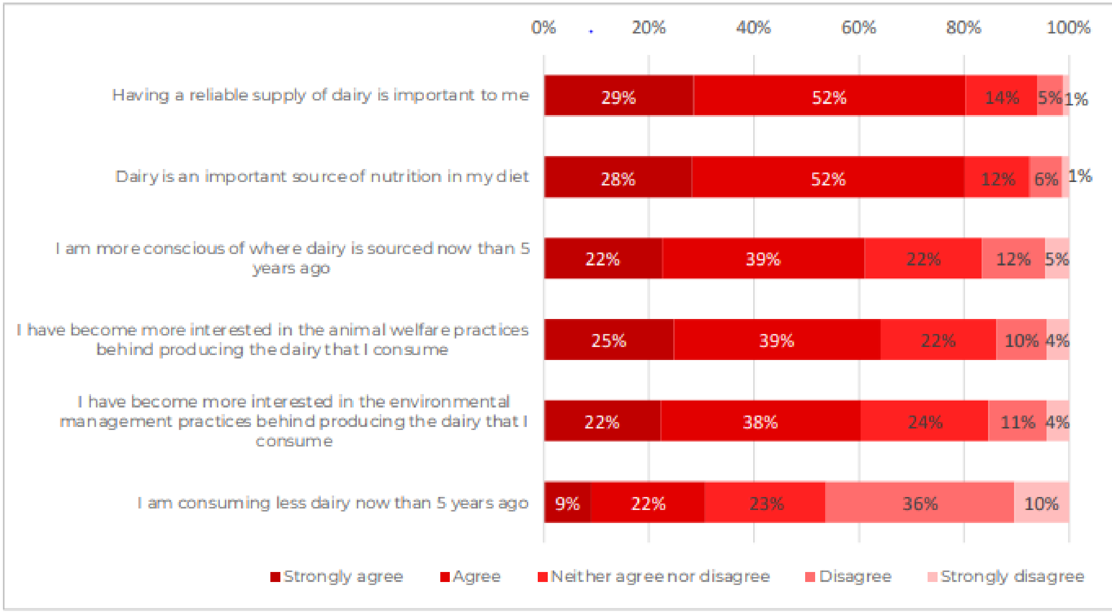


**Figure 3**: Respondents' attitudes towards the production and consumption of dairy

## Attitudes towards eating dairy

In TTP4, we asked respondents about their attitudes towards the consumption and production of dairy (see figure 3).

The results show a high level of agreement with the following statements that relate to the importance of dairy in their diet:

- *having a reliable supply of dairy is important to me* (81% either agree or strongly agree)
- *dairy is an important source of nutrition in my diet* (80% either agree or strongly agree)

About three in five respondents either agree or strongly agree that they are more conscious of where dairy is sourced than they were five years ago, and that they are becoming more interested in the animal welfare and environmental management practices behind the production of dairy they consume. Approximately one in three respondents indicate they consume less dairy now than five years ago.

Comparative analysis of the sociodemographic groups showed minor differences in their attitudes towards the production and consumption of dairy.

Women and respondents from households with young/younger children are more conscious of where dairy is sourced and have become more interested in the animal welfare and environmental management practices behind producing the dairy that they consume compared with men and other types of households

Respondents with a university degree have become more interested in the environmental management practices behind producing the dairy they consume compared to those with lower levels of formal education.

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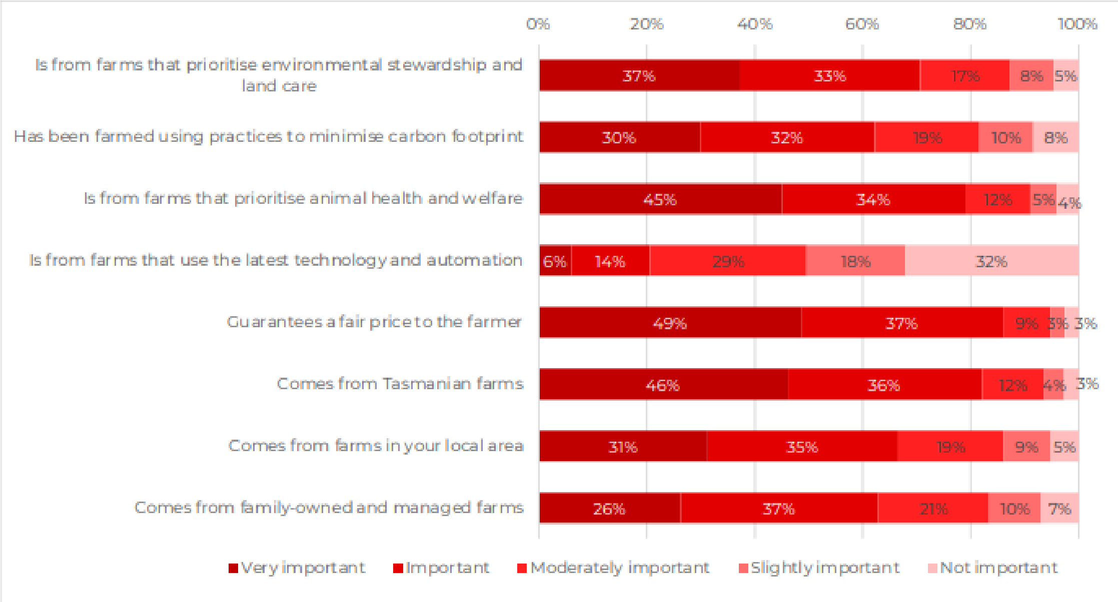


**Figure 4:** What is important to respondents in relation to sourcing of diary

## Sourcing dairy

Respondents were asked about the importance of a range of factors in relation to sourcing dairy (see Figure 4).

The following factors were identified by respondents as the most important (which are, interestingly, almost identical to the results of the same questions asked about sourcing red meat):

- Guarantees a fair price to the farmer - important or very important to 86% of respondents.
- Comes from Tasmanian farms - important or very important to 82% of respondents.
- Is from farms that prioritise animal health and welfare – important or very important to 79% of respondents.
- Is from farms that prioritise environmental stewardship and land care – important or very important to 70% of respondents.

Sourcing dairy from farms that use the latest technology and automation was important or very important to fewer respondents (20%).

Comparative analysis of the importance of different sources of dairy to different sociodemographic groups shows several interesting findings.

Compared to men, women reported greater importance of a number of factors related to the sourcing of dairy, including those associated with the environment and animal welfare, a fair price for farmers and local production.

Respondents with higher levels of formal educated reported greater importance of environmental aspects of dairy production compared with those who do not have a university degree. The same is true of residents of Greater Hobart compared to residents of other Tasmanian regions.

Respondents aged between 45 and 64 years reported greater importance of sourcing dairy from Tasmanian farms and from family-owned and managed farms compared with those aged 65 years and above.

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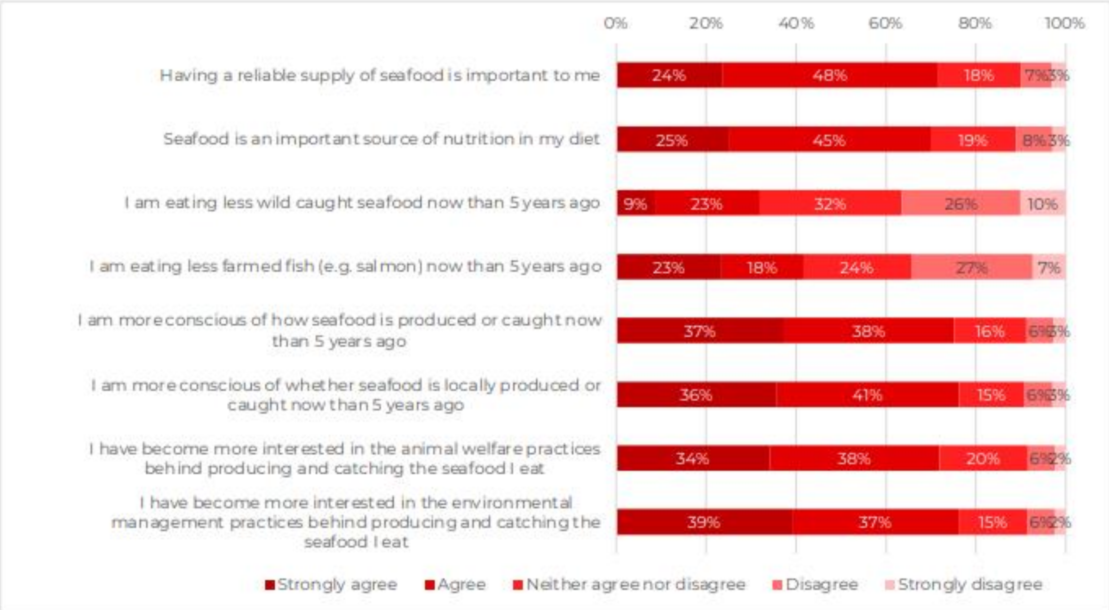


**Figure 5:** Respondents' attitudes towards the production and consumption of seafood

## Attitudes towards eating seafood

Respondents were asked about their attitudes towards the consumption and production of seafood (see figure 3). The results show fairly consistent agreement between statements on the importance of seafood in respondents' diet and in relation to a rane of factors associated with producing the seafood they eat.

About three in four respondents agree or strongly agree with the following statements:

1. *Having a reliable supply of seafood is important to me*
2. *Seafood is an important source of nutrition in my diet*
3. *I am more conscious of where seafood is produced or caught now than 5 years ago*
4. *I am more conscious of where seafood is locally produced or caught now than 5 years ago.*

About the same proportion of respondents have become more interested in the animal welfare practices (72%) and the environmental management practices behind producing and catching the seafood they eat (76%). Between 32% and 41% of respondents (wild caught and farmed fish respectively) eat less seafood now than they did 5 years ago.

The results show some notable attitudinal differences between sociodemographic groups:

- having a reliable supply of seafood was more important to the oldest respondents (65 years and above) than other age groups;
- women are more conscious of where seafood is produced or caught and eat less seafood now than they did 5 years ago compared with men;
- females, those with higher education levels, and residents of Greater Hobart have become more interested in animal welfare practices and/or the environmental management practices behind producing and catching the seafood that they consume;
- households with the lowest income eat less seafood now than they did 5 years ago.

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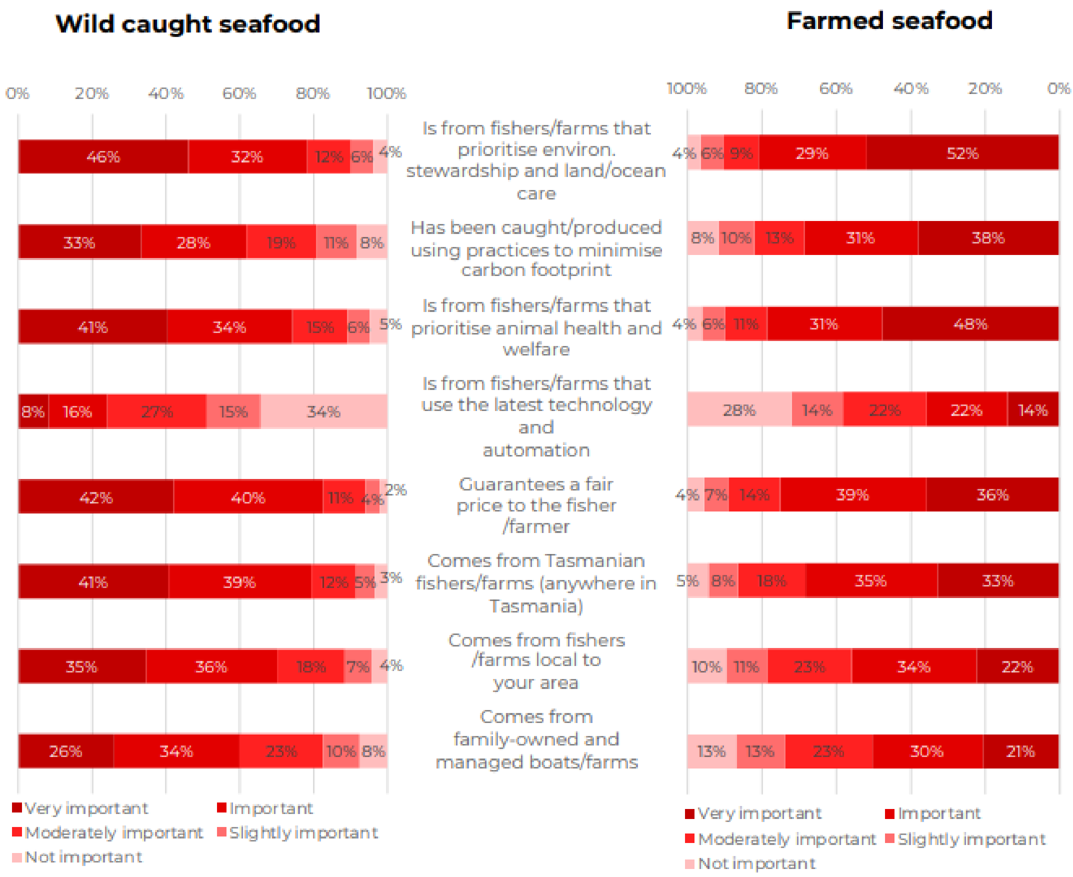


**Figure 6:** Respondents' priorities on sourcing of wild caught seafood (left) and farmed seafood (right)

## Sourcing seafood

Respondents were asked about the importance of different sources of both wild caught and farmed seafood (see Figure 6).

Factors that are the most important for seafood (wild caught or farmed) are also the most important factors for sourcing red meat and dairy. The % of respondents who answered important or very important for each statement is in brackets.

- guarantees a fair price to the fisher (82%) or farmer (75%);
- Is from fishers (78%) or farms (81%) that prioritise environmental stewardship and land care.
- Is from fishers (75%) or farms (79%) that prioritise animal health and welfare.

While there are little overall differences in priorities on sourcing wild caught seafood relative to farmed seafood, local (or family-owned) sourcing is notably more important to respondents when buying wild caught seafood than when buying farmed seafood.

Additional comparative analysis has shown that, in comparison to men, women reported greater importance of factors associated with the environmental impact, animal welfare, price and local production/catching of seafood. Local production is much less important to the youngest respondents (18-24 years of age).

## Appendix 8.11: Communications and extension activities

The following activities occurred over the NEXUS project to engage producers and industry stakeholders (2020-2023):

- Seven meetings of a Regional Reference Group Input to an annual presentation at Livestock Productivity Partnership team meetings, with two face to face meetings in 2020 (including a visit to one of the case study farms at Campbell Town), two meetings in 2021 (Zoom meetings due to COVID restrictions), and two meetings in 2022 (Face-to-face meeting, including a visit to the other case study farm at Stanley, and one online meeting), and one final project online meeting in early 2023.

- Over the duration of the NEXUS core project, a range of presentations, webinars, conferences, radio interviews and popular press articles have been undertaken by the project team. While not all directly related to the NEXUS project, and two case study farms, they encompass aspects related to the NEXUS project.

- A detailed list of activities is shown in Table 1.

**Table 1: Communications and extension engagement conducted in the NEXUS project. Total direct engagement through workshops, field days, webinars, discussion groups or conferences to March 2023 was 3,920 people. Assuming that only 1% of newspaper or radio listeners either read or see NEXUS content published, indirect engagement was conservatively estimated at 168,920.**

| Date | Where | Who presented | What presented | Dir. engage | Ind. engage/ week | Break-down of attendees | Additional information |
|---|---|---|---|---|---|---|---|
| 15-Oct-2020 | Pipers River, TAS | Karen Christie, Peter Ball | Outline of NEXUS Project | 30 | | Farmers | |
| 03-Dec-2020 | Campbell Town, TAS | Matt Harrison, Peter Ball, Rowan Smith | Overview of Case Study Farm, legume trial | 15 | | Service providers, some farmers | |
| 25-Feb-2021 | Notley Valley Farm, TAS | Karen Christie | Biochar discussion group | 70 | | Farmers, high school students | |
| 25-Feb-2021 | Moores Hill Winery, TAS | Karen Christie | NEXUS results in discussions | 45 | | Farmers, industry representatives | |
| 25-Apr-2021 | Guardian Newspaper | Matt Harrison | Scientist source for article content | | 2,900,000 | Australian public | Here |
| 21-May-2021 | Mount Pleasant, TAS | Lydia Turner | Overview of the NEXUS Project | 18 | | Farmers, researchers | |
| 01-Jun-2021 | Online webinar | Brendan Cullen | Overview of NEXUS activities to LPP group | 80 | | Scientists and consultants | |
| 01-Jun-2021 | Griffith NSW, online | Matt Harrison | Pathways to carbon neutral | 110 | | Farmers, advisors, businesses | |
| 01-Aug-2021 | South Australia, online | Matt Harrison | Pathways to carbon neutral | 290 | | Researchers, farmers, policy makers | |
| 01-Sep-2021 | Launceston, online | Matt Harrison | Pathways to carbon neutral | 230 | | Farmers, policy makers, researchers | |
| 01-Sep-2021 | Launceston | Dominique Bowen Butchart | Poster presentation | 230 | | Farmers, policy makers, researchers | |
| 01-Sep-2021 | Launceston | Demlie Zelelew | Poster presentation | 230 | | Farmers, policy makers, researchers | |
| 01-Oct-2021 | ABC radio | Matt Harrison | Climate adaptation of red meat enterprises | | 631,000 | General public, Australia wide | Here |
| 05-Oct-2021 | Sandy Bay, Hobart | Daniel Bosveld | Climate adaptation of red meat enterprises | 30 | | Academics and students | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 15-Oct-2021 | Zoom | Karen Christie, Bill Malcolm, Matt Harrison | Climate adaptation of red meat enterprises | 20 | | Farmers, policy makers, researchers | |
| 07-Nov-2021 | ABC Landline, ABC TV news | Matt Harrison | Climate adaptation of red meat enterprises | | 5,069,000 | Free to air TV | ABC Landline |
| 09-Nov-2021 | Deloraine, TAS | Karen Christie, Dominique Butchart, Rowan Eisner | Participation in carbon markets | 28 | | Farmers and service providers | |
| 18-Nov-2021 | Online webinar | Karen Christie, Richard Eckard | Why we estimate GHG emissions, tools used | 38 | | Government staff | Soils DG - Carbon Tools Presentation |
| 19-Nov-2021 | TIA newsletter | Matt Harrison | Biochar feeding trial, pathways to net zero | 160 | | Academics, extension officers | |
| 23-Nov-2021 | Campbell Town, TAS | Simon Foster | Future 2050 temperatures and rainfalls | 70 | | Farmers, service providers | |
| 23-Nov-2021 | Campbell Town, TAS | Simon Foster | Impacts of 2050 climates on pasture in Tas | | 631,000 | Australian public | |
| 12-Dec-2021 | Online - global | Brendan Cullen | GHG emissions mitigation in NEXUS project | 400 | | Scientists, industry, policy-makers | Here |
| 09-Mar-2022 | Online global | Matt Harrison | Effects of climate change on Tas, on soil carbon | | 190,000 | Australian public | Here |
| 18-Mar-2022 | Online and in print | Matt Harrison | Steps towards carbon neutrality | | 40,000 | Tasmanian public | Here |
| 06-Apr-2022 | Online - global | Matt Harrison, Karen Christie, Rowan Eisner | Introduction to carbon farming | 122 | | farmers, advisors, academics | |
| 12-May-2022 | Online - global | Nicoli Barnes | Biochar Project and Red Meat Producers Survey | | 631,000 | Australian public | Here |
| 19-May-2022 | Stanley, TAS | Matt Harrison, Franco Bilotto, Karen Christie, Nicoli Barnes | Farmer priorities on RD&E climate adaptation | 12 | | Project team | |
| 05-Jun-2022 | Online - global | Franco Bilotto | Effects of adaptation/mitigation on production | 460 | | Researchers, industry, policy-makers | Here |
| 13-Jun-2022 | Canada and online | Matt Harrison | GHG emissions, results of TCN and LHF | 40 | | Scientists and policy-makers | Here |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 15-Jun-2022 | WA farmers (online) | Matt Harrison | Impacts of extreme climatic events on ag | 60 | | Leading farmers in WA | |
| 22-Jun-2022 | Radio national | Matt Harrison | Improving biodiversity, natural capital on farm | | 631,000 | People with a regional interest | Here |
| 22-Jun-2022 | Weekly Times newspaper | Matt Harrison | Additionality, soil carbon markets | | 190,000 | Farmers, researchers, industry | Here |
| 23-Jun-2022 | 2GB radio Sydney | Matt Harrison | Additionality, soil carbon markets | | 677,000 | Farmers, researchers, industry | Here |
| 24-Jun-2022 | ACE Radio Regional Victoria | Matt Harrison | Additionality, soil carbon markets | | 3,270,000 | Farmers, researchers, industry | Here |
| 13-Jul-2022 | Email | Matt Harrison | Changing red meat sector GHG emissions | 1 | | EU policy-makers, Belgian public | |
| 29-Jul-2022 | Launceston | Nicoli Barnes | Farmer survey on RD&E priorities | 400 | | Farmers, industry, Tas government | |
| 24-Aug-2022 | ABC Radio | Nicoli Barnes | NEXUS project overview | | 631,000 | Farmers | Here (approx.. 38 minutes in) |
| 26-Aug-2022 | Online | Matt Harrison | Soil carbon measurement technology | | 2,192 | Australian public | Here |
| 08-Sep-2022 | Online | Matt Harrison | NRM Regional Australia | 30 | | NRM and associates | |
| 27-Sep-2022 | Online | Matt Harrison, Steven Bray | Q&A session on soil carbon markets | 35 | | Farmers, industry, consultants | |
| 21-Oct-2022 | Online | Matt Harrison | Soil carbon measurement, trading, markets | 180 | | Bank staff | |
| 28-Oct-2022 | Phone | Nicoli Barnes | Social research aspect of biochar workshops | | 631,000 | ABC Country Hour audience | |
| 04-Nov-2022 | Webinar | Matt Harrison | Soil carbon measurement, trading, markets | 400 | | Global | Here |
| 04-Nov-2022 | Newsprint | Karen Christie | How climate change will affect society | | 40,000 | Farmers, service providers | |
| 10-Nov-2022 | Newsprint | Karen Christie | How climate change will affect society | | 2,000 | Farmers | |
| 18-Nov-2022 | Deloraine, TAS | Matt Harrison, Nici Barnes, Steve Sullings | Biochar impact on GHG emissions, liveweight | 20 | | Farmers, NRM, consultants | |
| 01-Dec-2022 | Ringarooma, TAS | Nicoli Barnes, Steve Sullings, Karen Enkelaar, Stuart Nailor | Biochar impact on GHG emissions, liveweight | 20 | | Farmers, industry representatives | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 18-Jan-2023 | Newsprint | Matt Harrison | Soil carbon farming, markets, sampling | | 483,333 | General public, Australia wide | Here |
| 10-Feb-2023 | Newsprint | Nicoli Barnes | Biochar impact on GHG emissions, liveweight | | 40,000 | General public, Tasmania | |
| 15-Feb-2023 | Marrawah, TAS | Matt Harrison, Nici Barnes, Steve Sullings, Karen Enkelaar, Aiden Coombe | Biochar impact on GHG emissions, liveweight | 32 | | Advisors, supply chain participants | |
| 25-Feb-2023 | Newsprint | Matt Harrison | Costs of attaining carbon neutrality | | 190,000 | Farmers, researchers, industry | Here |
| 03-Mar-2023 | Online | Project team | Profitable climate change adaptations | 14 | | Farmers, advisors, researchers | |
| 01-Jun-2023 | Online | Matt Harrison | Raising awareness about national NEXUS Project | | 12,500 | | |

**Total direct engagement = 3,920 people**

**Total indirect engagement (assuming only 1% of all newspaper readers or radio listers either read or hear our content) = 168,920**

# Appendix 8.12: Impact of NEXUS modelling, social research and engagement

**Table 1:** Values and references used to estimate NEXUS impact on liveweight gain, income, and carbon sequestration. Average impact over the course of NEXUS is conservatively estimated at 333,000 tonnes $CO_2$-eq over 227,000 hectares, improving farm gate revenue by $11.7M.

| Indicator | Value | Reference and/or notes |
|---|---|---|
| People directly engaged in NEXUS | 3,920 | See Appendix 8.11. |
| People indirectly engaged in NEXUS | 168,815 | See Appendix 8.11. |
| Total people engaged due to NEXUS | 172,735 | Calculated |
| Farm profit at full equity in 2021-22 | $225,000 | https://www.agriculture.gov.au/abares/research-topics/surveys/farm-performance |
| Area of farm impacted due to NEXUS | 1% | https://www.agriculture.gov.au/abares/research-topics/surveys/farm-performance |
| Number of broadacre farms in Australia | 50,365 | https://www.agriculture.gov.au/abares/research-topics/surveys/farm-performance |
| Broadacre farm area in ha | 26,000,000 | https://www.abs.gov.au/statistics/industry/agriculture/agricultural-commodities-australia/latest-release |
| Average farm area in ha | 516 | Calculated |
| Total annual grain production tonnes | 62,000,000 | https://www.treasury.sa.gov.au/economy,-taxes-and-rebates/economic-briefs/abares-crop-reports/ABARES-Crop-Report,-June-2022.pdf |
| Average yield per farm t/ha | 2.4 | Calculated |
| Grazing of modified pastures in hectares | 41,410,000 | https://www.agriculture.gov.au/abares/products/insights/snapshot-of-australian-agriculture-2022#previous-reports |
| Grazing of native vegetation in hectares | 283,370,000 | https://www.agriculture.gov.au/abares/products/insights/snapshot-of-australian-agriculture-2022#previous-reports |
| Agricultural businesses in Australian in 2019-20 | 87,800 | https://www.agriculture.gov.au/abares/products/insights/snapshot-of-australian-agriculture-2022#previous-reports |
| Livestock businesses in Australia in 2019-20 | 56,192 | https://www.agriculture.gov.au/abares/products/insights/snapshot-of-australian-agriculture-2022#previous-reports |
| Average livestock business size in hectares 2019-20 | 5,780 | https://www.agriculture.gov.au/abares/products/insights/snapshot-of-australian-agriculture-2022#previous-reports |
| **Area of livestock businesses impacted by NEXUS in hectares** | **226,569** | **Calculated from above** |
| Improved soil carbon storage in tonnes per hectare due to NEXUS | 0.2 | Discussions with experts |
| Improved vegetation carbon in tonnes per hectare due to NEXUS | 0.2 | Discussions with experts |
| Improved soil carbon storage in tonnes due to NEXUS | 90,628 | Calculated |
| **Improved carbon storage in tonnes CO2-equivalents due to NEXUS** | **332,604** | **Calculated from above** |
| Average cattle herd in Australia | 25,200,000 | https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/cattle-projections/feb2021-mla-australian-cattle-industry-projections.pdf |
| Average sheep flock in Australia | 65,000,000 | https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/sheep-projections/mla-june-update-sheep-industry-projections-2021.pdf |

| | | |
|---|---|---|
| Total sheep meat production in Australia in tonnes cwt | 650,000 | https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/sheep-projections/mla-june-update-sheep-industry-projections-2021.pdf |
| Total beef meat production in Australia in tonnes cwt | 2,100,000 | https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/cattle-projections/feb2021-mla-australian-cattle-industry-projections.pdf |
| Average cattle carcase weight in kg/head | 301 | https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/cattle-projections/feb2021-mla-australian-cattle-industry-projections.pdf |
| Average sheep carcase weight in kg/head | 25 | https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/sheep-projections/mla-june-update-sheep-industry-projections-2021.pdf |
| Average number of beef cattle per farm | 448 | Calculated |
| Average number of sheep per farm | 1,157 | Calculated |
| Improvement in sheep meat production due to NEXUS in tonnes cwt | 1,134 | Calculated |
| Improvement in cattle meat production due to NEXUS in tonnes cwt | 439 | Calculated |
| **Total improvement in meat production due to NEXUS in tonnes cwt** | **1,573** | Calculated |
| Price of lamb carcase weight in $/kg cwt | $ 7.50 | https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/sheep-projections/mla-june-update-sheep-industry-projections-2021.pdf |
| Price of beef carcase weight in $/kg cwt | $ 7.42 | https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/cattle-projections/feb2021-mla-australian-cattle-industry-projections.pdf |
| Income from sheep meat production due to NEXUS in $ | $ 8,502,100 | Calculated |
| Income from cattle meat production due to NEXUS in $ | $ 3,261,039 | Calculated |
| **Total income from livestock meat production due to NEXUS in $** | **$ 11,763,139** | Calculated (sum of sheep and beef) |