Final report

NEXUS Involve & Partner: impacts of biochar supplementation on productivity, profitability and GHG emissions

Project code: P.PSH.2134

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Abstract

Realisation of sectoral net-zero emissions demands development of new technologies that enhance carbon removals while sustainably improving environmental stewardship. The project e trialled biochar as a livestock feed supplement on farm in Tasmania, Australia, given purported benefits associated with biochar in terms of manure and soil organic carbon (SOC) enrichment, animal health, mitigation of enteric and soil methane, and productivity gains. After 14 months, liveweight of the biochar treatment was 5% greater than that of the unsupplemented control, although effects of biochar on manure organic carbon and SOC were *de minimus*. Participatory workshops across Tasmania revealed that industry interests in biochar primarily pertained to animal health and environmental sustainability, including carbon storage. Cost-benefit-mitigation scenario analysis showed that economic returns associated with biochar were more sensitive to liveweight gains, as opposed to enteric methane mitigation or carbon prices. At current carbon prices and biochar costs, our work showed that liveweight gains associated with biochar supplementation would need to be at least 10% to be cost-effective. We contend that use of biochar as a feed supplement comprises a prospective pillar for improving food security while reducing GHG emissions, although further research is required to systematically dissect how such benefit would be best realised.

Executive summary

Background

Nascent anecdotal evidence implies that livestock feed supplementation with biochar may reduce enteric methane, improve liveweight gain and milk quality, reduce soil methane and nitrous oxide, and improve soil carbon through enrichment of manure. To explore the validity of these hypotheses, the project conducted a field experiment in northern Tasmania, Australia, to ascertain effects of *ad libitum* biochar supplementation in Wagyu-cross calves, where measurements of liveweight gain, carbon-enrichment of manure where conducted. Workshops were undertaken across Tasmania to raise awareness of the research findings, to reconcile our findings with industry experiences, to facilitate peer-to-peer learning, and to quantify longitudinal impact of workshop involvement associated with adoption (or abandonment) of biochar feed supplementation.

Objectives

The aims of the project were to:

- Involve and Partner (I&P) with a beef cattle farmer to trial the feeding of biochar to ascertain, through cost-benefit-mitigation analysis, the impact on productivity, profitability and greenhouse gas (GHG) emissions, and soil carbon stocks;
- Undertake three farm workshops across Tasmanian to engage industry to support and extend learnings around the feeding of biochar, and
- Monitor longitudinal adoption and impact arising from workshop involvement by surveying attendees during workshops and interviewing selected participants 8-12 months post-workshop.

Methods

On commencement, 200 calves were separated into biochar and control treatments, based on liveweight and gender. Feeding of a commercial feed-grade biochar to 100 Wagyu-cross calves commenced in April 2022. Animals were weighed six times over the duration of the experiment. Measurements of pasture biomass and botanical composition were undertaken periodically. Measurements taken during the field experiment informed a cost-benefit-mitigation scenario analysis associated with biochar feed supplementation. Three workshops were held during spring and summer 2022/23, one on the I&P farm and two on other farms using biochar in northern Tasmania. These farms had used biochar as a feed supplement for 5 or 10 years, allowing the project to leverage insights from practitioners with long-term experience in using biochar. At the workshops, surveys were completed by attendees and agreed participants were interviewed 8-12 months post workshops. A thematic discourse analysis of the surveys and interviews was conducted.

Primary results

- At the conclusion of the trial, the average liveweight of biochar cohort was 5% heavier than unsupplemented control animals.

- No significant effects of biochar supplementation on manure organic carbon were measured, although this could be due to relatively low numbers of manure samples taken.
- An economic analysis of the biochar-fed animals determined a net profit of approx. $80 above that of the control animals, although based on a higher than average meat price at $4.50/kg LW for premium Wagyu-cross meat, biochar costing $0.10/head/day, equivalent to ~ $2,500/t biochar, without also including any additional costs associated with labour and capital purchase of feeding troughs.
- The cost-benefit-mitigation analysis showed that liveweight gain would need to be greater than 10% for biochar feed supplementation to be cost-effective, assuming carbon prices of $25-$75 per tonne of carbon dioxide equivalents (CO_2e), biochar cost of $2,000 t dry matter (DM) and liveweight valued at $2.75/kg.
- Seventy-two people attended farm workshops. Attendees included producers, industry and government representatives. Awareness, knowledge and skills related to biochar increased substantially between pre-and post-workshops, with the majority of participants stating that they were able to make more informed decisions on the use of biochar as a feed supplement.
- Many workshop attendees showed willingness to use biochar as a feed supplement as a result of attending workshops, driven by motivations to improve soil carbon, animal health and welfare, and mitigate GHG emissions (primarily enteric methane).
- Post-workshop interviews of 23 attendees showed that animal and soil health along with holistic and/or regenerative management were prevailing reasons for exploring biochar use on farm.
- A webinar held November 2023 indicated that 15% of attendees learnt “a great deal”; more than 40% of people indicated they learnt “quite a bit”. Attendee interest in further research primarily related to (1) productivity co-benefits, (2) benefit-cost ratios and (3) soil carbon and carbon trading, although a range of other reasons were raised.

Benefits to industry

The field experiment illuminated several issues associated with feeding biochar in the form we used (loose powder). Workshops on farms who had used biochar as a feed supplement for 5-10 years, illustrating other forms of feed delivery, e.g. mixing powdered biochar in silage, may be more amenable to livestock consumption. We showed that incorporation of salt, while ensuring that biochar remained dry, were amenable to greater intake. Workshop attendees discussed wider benefits associated with their experience with biochar, including lower proportions of dark coloured meat, reduced sheep fly strike, reduced mastitis and lower incidence of parasites. Several barriers associated with adoption were raised, too, such as feeding mechanisms in extensive grazing systems, scalability, cost, suboptimal cost-benefit ratios and regulatory burden. Time commitment required by practitioners – and associated opportunity cost - was a foremost priority when deciding whether or not biochar should be adopted. Despite such barriers, our work suggested that peak adoption ranged from 10-69% depending on perceived environmental benefit, while time to reach peak adoption was relatively expeditious due to the reversibility and trialability associated with feed supplementation.

Future research and recommendations

There are many opportunities for further research and these include; (1) effects of biochar feedstocks (e.g. wood, crop residues etc), and (2) impacts of long-term feed supplementation (at least three years) on liveweight gains, soil organic carbon stocks (mineralisation, rhizodeposition, micro aggregation, occlusion and sequestration), meat and milk quality, enteric methane mitigation and net emissions intensity. Project results imply that biochar feed supplementation improves environmental sustainability and animal welfare, although further research is necessary to dissect this notion.

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1. Background

While growth in agri-food production has underpinned food security hitherto (Coomes et al. 2019), the changing climate, increasingly punctuated by extreme weather events, threatens to undermine contemporary food supply (Bandh et al., 2021; Harrison, 2021; IPCC, 2021). The Food and Agriculture Organization of the United Nations estimates that 11-20% of global greenhouse gas (GHG) emissions are generated by the livestock sector (FAO, 2023; Xu et al., 2021), with 40% of which being derived from beef cattle production (FAO, 2023). These troubling statistics suggest that balancing agri-food needs with continuing climate adaptation and GHG mitigation will be one of the greatest challenges facing humanity in the 21st century (Bilotto et al., 2023; Borsellino et al., 2020; Harrison et al., 2021). Such problems call for the development of sustainable, transdisciplinary, persistent solutions that systematically unravel recalcitrant linkages between production and GHG emissions (Harrison et al., 2016).

Livestock feed additives such as ionophores, methanogenesis inhibitors, essential oils, plant extracts, and organic compounds hold promise (Tseten et al.,2022), but also come with social, animal health and welfare trade-offs (Harrison et al., 2021). Together, these sentiments suggest that the development of sustainable, profitable and socially acceptable emissions mitigation interventions are urgently needed (Taylor et al., 2016), particularly for enterprises based on grazing, as these comprise the majority of Australian livestock production systems (Rawnsley et al., 2019). While biochar often receives attention as a soil amendment [*viz.* Khan et al., 2022], less attention has been given to biochar as a livestock feed supplement. Despite this, nascent evidence suggests that biochar feed supplementation may inhibit CH_4 emissions by altering rumen microbial populations, adsorbing toxins and volatile compounds, increasing rumen surface area and improving animal liveweight gains (Schmidt et al.,2019). Other co-benefits include the ability to adsorb and retain nutrients in dung such as nitrogen and phosphorus, which can otherwise be lost to the environment (Hedley et al., 2021). However, several implementation barriers associated with biochar remain to be resolved. Some of these include practical barriers in feeding, knowledge requirements (e.g. daily recommended dosage of biochar) and safety considerations (Hedley et al., 2021).

The present investment tiralled use of biochar feed supplementation as part of MLA's 'Involve & Partner' (I&P) approach to engagement and extension. This *modus operandi* was adopted to (1) contextualise results with real practicalities associated with feed supplementation on farm, and (2) allow industry to attend, learn from, and engage with, peers while sharing experiences using biochar as a feed supplement. We enumerated the impacts of biochar feed supplementation on liveweight gain, profitability and manure and soil carbon. The trial provided knowledge of biophysical indicators – such as liveweight gain and manure carbon – as well as learnings from workshop attendees. When considering the benefits and barriers to any farm system intervention, it is such participatory feedback that is vital for iteration, planning and successful implementation.

In addition to the field experimentation, a cost-benefit-mitigation scenario analysis was conducted to extricate the economic feasibility of biochar as a feed additive, using a range of market prices for carbon removals, avoidance and biochar costs. This allowed us to extrapolate bespoke findings from the field experiment to a wider range of plausible outcomes, thereby gaining insight into profitability associated with a feasible solution space.

Three workshops were held across northern Tasmania to allow producers, industry, academics and government to visit farms that had long been using biochar as a feed supplement. The aims of these workshops were to promote awareness of the biochar supplementation project including implications for soil carbon, enteric methane and liveweight gain. Attendees were provided with research findings of the I&P farm, as well as experiences from practitioners who had been using biochar for longer periods. We conducted surveys at workshops to assess participant knowledge, attitudes, skills and aspirations to use biochar as a feed supplement on their own properties. Interviews of selected attendees were undertaken near project completion to gauge adoption and impact associated with the workshops.

2. Objectives

1. Collaborated with one Involve and Partner Farm to pilot initial NEXUS adaptations or greenhouse gas mitigations or emergent Livestock Productivity Partnership project(s) recommendations. The adaptation trialled on farm will be Biochar.
2. Measured the impact of biochar supplementation on the growth rate of 200 calves over 15 months and evaluated, through benefit-cost-mitigation analysis, the impact on whole farm GHG and profitability. This included the identification of the price point required to make biochar supplementation a profitable intervention for producers.
3. Modelled the impact of biochar supplementation on whole farm GHG emissions and soil organic carbon.
4. Engaged 20 additional producers and 10 service providers across a series of workshops to support learning around Involve and Partner activity and working through the practicalities of implementing further NEXUS outcomes in the farm context.
5. Monitored the wider impact of the I&P activity by benchmarking of biophysical, economic and social data to measure longitudinal adoption and impact of the project.
6. Monitored the impact of workshop involvement by surveying attendees*. This was conducted in line with MLA's monitoring and evaluation strategy for KASA (knowledge, attitudes, skills and aspirations).

Since we submitted the NEXUS project final report (P.PSH.1219), several nascent peer-reviewed research manuscripts have been realised:

1. Bilotto, F., Christie-Whitehead, K.M., Barnes, N., Harrison, M.T. (2023) Operationalising net-zero with biochar: black gold or red herring? Submitted to *Trends in Food Science and Technology* (Appendix 8.2).
2. Christie-Whitehead, K.M., Barnes, N., Bilotto, F., Turner, L., Hall, A., Harrison, M.T. (2023) Responding to societal change: understanding consumer and producer perceptions of red meat. *Trends in Food Science and Technology* has been accepted for review (Appendix 8.3).
3. Two research papers are in development to further findings from the I&P sub-project and NEXUS project:
   3.1 *Benefits, issues and practical application of biochar on farm*: biochar has been identified as one of the more sustainable ways in which enteric methane abatement could be addressed in the red meat industry, with suggestions that up to 10% enteric methane can be mitigated when biochar is consumed. When this benefit can be completed by co-benefits for soil health and be incorporated within regenerative agendas, biochar becomes an attractive prospect to advance sustainable agriculture. With climate change adaptation and methane reduction being high on the Australian livestock industry agenda, such interventions have received considerable attention from research scholars, industry and government alike. This paper addresses two questions: 'what are the issues around biochar use?' and 'what is required for the most effective and practical implementation of biochar on farm?' Data is drawn from the literature and from interviews with the Nexus I&P to identify practicable use-cases for biochar.

4.2 Farming architypes: Farmer adaption and adoption architypes have been debated *ad nauseum*, although with little consensus to date. There has been recent renewed interest in adaption and adoption as the impacts of climate change take effect, with blame often levelled at red meat farmers for their purported contribution. To compound the problem, social license to operate from consumers is ostensibly dwindling, associated with perceived environmental transgressions of livestock farming, including high water use and emissions. While many farmers are responding by exploring and actioning sustainable practices, we argue that it is necessary to do two things: 1) identify the 'biopower' and 'biopolitics' embedded in the sustainable agriculture movement that requires these changes; 2) identify and match the way farmers understand and speak about these issues to more effectively provide the support and education they need to enact appropriate change. To do this, we conducted a Foucauldian discourse analysis of grey literature concerning sustainable agriculture issues in a broad sense; and interviews with a group of farmers comprising the reference group of the NEXUS project. Our discourse analysis revealed four farmer architypes that may assist the process of change that farmers now must address.

3. Methods

3.1 I&P farm biochar feeding experiment

The I&P farm biochar experiment was undertaken on a beef property near Deloraine Tasmania, and follows regenerative agriculture practices, such as minimal fertiliser inputs, multiple species pastures. On project commencement, 200 Wagyu cross calves (approx. 6 month of age) were randomly allocated into two herds, biochar and control. Once allocated, average liveweight and ratio of male to females was consistent between herds. Feeding of a commercial grade biochar to 100 animals commenced in April 2022 and concluded in early May 2023 (see latter for explanation of why the experiment concluded sooner than planned). Steer and heifer calves were fed this biochar *ad libitum* at intake rates between 0.5-1.0% on a dry matter (DM) basis (30-50 grams/head per day), which equates to $AU0.06-0.10/head per day. Feed-grade biochar used was derived from waste forestry wood produced in Tasmania and contained around 10% natural mineral clay (bentonite) to ameliorate gut imbalances (e.g., acidosis). "Animal ethics approval was sought and obtained from the University of Tasmania's Animal Ethics Committee on 14 January 2022 (review reference A0026293 [A-99527])". Feed-grade biochar passed WHO and Australian Organic Standard (2019) requirements specified for safe animal feed (Australian Organic, 2019). The physical appearance of the product was a black, odourless and granulated compound (1-5 mm) with a density of 226 kg/m^3. This product passed Animal Feed Grade Biochar test standards for heavy metals/contaminants and toxins listed in Code of Practice for the Sustainable Production and Use of Biochar developed by the Australian and New Zealand Biochar Industry Group (ANZBIG, 2021).

Each herd rotationally grazed paddocks (~ 10-12 ha) containing the same species blend of annual and perennial grasses, legumes and herbs such that a paddock grazed by the control herd would be subsequently grazed by the biochar herd the following rotation. This minimised any bias towards either herd grazing pastures with better composition/species mix. Visual assessment of pasture pre-and post-grazing herbage biomass was used throughout the experiment to maintain similar feed availability between groups. This was further strengthened with pre- and post-grazing herbage biomass measurements several times during the field trial using a plate meter (Earle & McGowan, 1979) to complement visual assessment of consistent pasture availability between herds.

Pasture botanic composition (proportions of grasses, legumes, herbs, and weeds) and senescent material were assessed 28 days after the start of the regrowth period in both seasons through hand dissection of five sub-samples (4 m^2 each) per treatment cut to ground level. These animals were weighed six times over the duration of the experiment using a Gallagher W-1 walkover scale. Weights were automatically matched with an animal eID -tag for identification. Scales were zeroed twice during each measurement period. Total carbon content (%) from manure samples collected over two timeframes were collected in autumn and spring 2022 (n = 24 per treatment). Samples were sealed in plastic bags and stored on ice then transferred to the laboratory around 50 km away for immediate testing. Tests were completed by AgVita Laboratory, Spreyton, Tasmania. A t-test was performed to identify differences between mean total carbon content ($p<0.05$). Due to the sale of the land being leased by the I&P producer to undertake this experiment, and after consultation between the I&P farmer, MLA and TIA, the biochar feeding experiment concluded in May 2023.

3.2 Workshops to enable awareness of I&P activities and peer-to-peer learning

Three workshops were held across northern Tasmania during spring and summer 2022/23 (see flyer for the first event in Appendix 8.1 along with the workshop handouts). These were held on the I&P farm (near Deloraine) and on two other farms, one in the northeast of the state (near Ringarooma) and the other in the far northwest of the state (near Marrawah). These other two farms had used biochar as a feed supplement for longer periods (5 and 10 years, respectively). Advertising of the workshops was through communication/email lists within TIA, the Tasmanian Farmers and Graziers Association, Farmer for Climate Action, Natural Resource Managements etc.

The purpose of the workshops was to outline biochar supplementation processes and outcomes, including impacts on GHG emissions, liveweight gain and costs. A range of speakers presented at the workshops including the supplier of the biochar to the I&P farm, TIA representatives discussing the results of the trial and producers who hosted the events. Participants were asked to complete a feedback survey at the start and conclusion of the workshops. Attendees were also asked if they were willing to be contacted (via phone) 8-12 months post workshop to ascertain their reasons for adopting (or abandonment) of using biochar. A descriptive analysis of the surveys and interviews, along with a thematic discourse analysis of the interviews are detailed in the appendices of the present report.

3.3 Biochar feed supplementation scenario analysis for liveweight, GHG emissions and soil organic carbon

In concert with the I&P farm feeding experiment, a modelling study was undertaken. The profit solution space associated with biochar feed supplementation was examined using partial budgets, examining a range of potential liveweight gain by enteric CH_4 reduction scenarios (Table 1). A generalised growth rate pattern for Tasmanian beef cattle was devised from the GrassGro modelling results of the two NEXUS main project case study farms. This data was entered into the Sheep and Beef Greenhouse gas Accounting Framework calculator (SB-GAF; Lopez et al.,2023) to estimate seasonal enteric CH_4 emissions for the control treatment. Calves were fed biochar after being weaned at 7 months until they were sold at 25 months. We conducted a sensitivity analysis using results from the field trial and peer-reviewed literature (Table 1) to determine how profit altered. Based on modelled liveweight (LW), liveweight gain (LWG) and dry matter intake (DMI), we estimated a 0.5% of DMI as biochar (~40-45 grams/head.day). This rate of biochar feeding is in line with results found with the I&P case study farm in addition to published field experimentation showing no benefit of feeding rates > 1% DM on enteric CH_4 reduction (Leng et al.,2012; Winders et al.,2019). A price of $2.75 AUD per kg LW was assumed for additional LW above the control treatment [Heavy Steer Indicator (www.mla.com.au/prices-markets/cattle/heavysteer) as at July 2023]. Based on carbon markets and future projections (CER, 2023; EMBER, 2023), modelled GHG emission removals were credited (i.e., enteric methane (CH_4) reduction and soil organic carbon (SOC) sequestration) with a price range per unit Mg CO_2e abated. The level of C assumed was 91% with 70% remaining by 100 years (Hedley et al., 2021). Thus, of total biochar consumed, around 65% was converted into SOC.

Table 1. Increments used in the sensitivity analysis to examine how perturbation of biochar costs, total GHG emissions abated, potential liveweight change and enteric methane mitigation impacted on profitability.

Variable	Levels	References
Price of biochar (AUD Mg^{-1} biochar)	500, 1000, 1500, 2000	Cotter et al. (2015); Hedley et al. (2021)
Price of Mg CO_2e abated (AUD Mg^{-1} CO_2e)	25, 75, 125	CER (2023); EMBER (2023)
Change on liveweight gain (%)	0, 5, 10, 15	Cotter et al. (2015); Fernandez (2020)
Methane reduction (%)	0, 5, 10, 15	Cotter et al. (2015); Fernandez (2020); Hedley et al. (2021)

3.4 Modelling time to peak adoption and SWOT analysis

The ADOPT (Adoption and Diffusion Outcome Prediction Tool) model (Kuehne et al., 2017) was used to assess the time to reach peak adoption. ADOPT is tailored for forecasting the probable uptake of agricultural innovations within a specific land manager population (Pannell et al. 2006). The 22 input questions required to run the model were informed through discussions with the NEXUS regional reference group (see Appendix 8.2 *Supplementary Material*, Table S1). The majority of participants were motivated by profit and environmental enhancement and conservation. ADOPT inputs included (1) ease of evaluation, (2) availability of advice, (3) skill requirements, (4) observability of trials, (5) initial costs, (6) reversibility of implementation, (7) projected future profit and environmental gains, (8) potential increases in risk, and (9) farm management convenience.

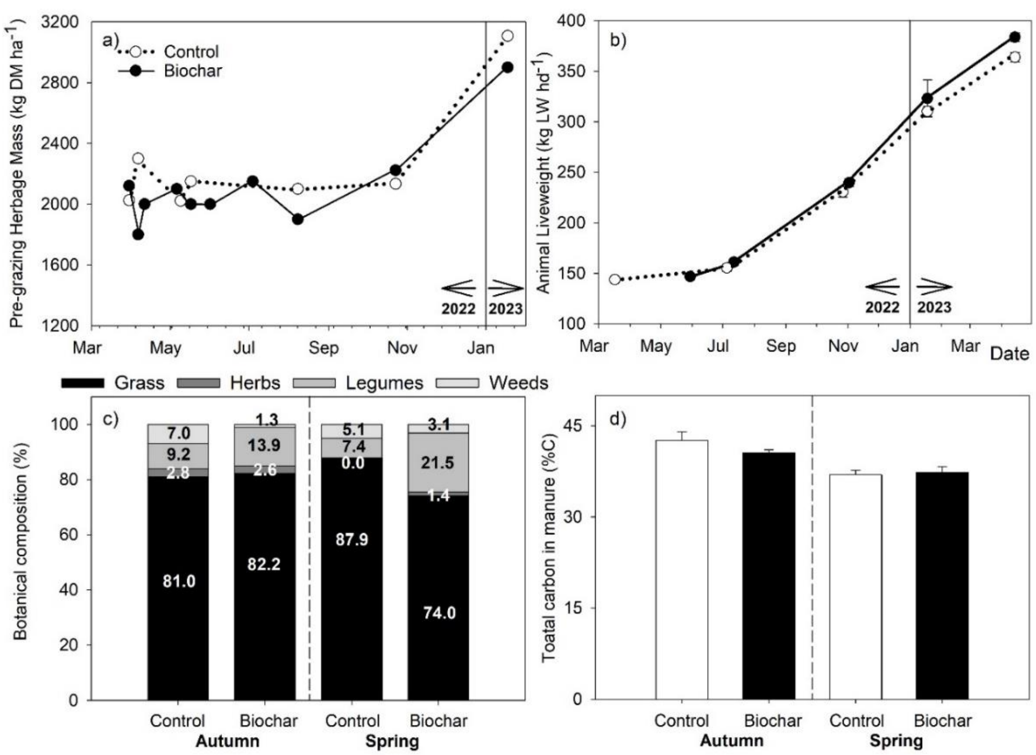
SWOT analyses (Strengths, Weaknesses, Opportunities, and Threats) have hitherto been used as a strategic planning and management technique for businesses to assess decision making. Our SWOT analysis was conducted following Díez-Unquera et al. (2012).

4. Results

4.1 I&P farm trial with biochar feed supplementation

Pre-grazing herbage biomass afforded to the control and biochar treatment were similar (Fig. 1a). Biomass reached a zenith of 3 Mg DM ha^{-1} during late spring and early summer, remaining relatively constant for the remainder of the year at approximately 2 Mg DM ha^{-1}. Grasses, predominantly perennial ryegrass, constituted the primary vegetation group, followed by legumes (Fig. 1c). While there was minor divergence in botanical composition over time (Figure 1c), this relates more to the timing of sampling. The next rotation, the control herd would be grazing this same paddock with a higher legume content, and the biochar herd grazing the lower legume content pastures. Taken together, we found no significant differences between pasture quanta and quality across treatments. Liveweight gain of the control and biochar treatments remained similar for the majority of the trial period (Fig. 1b). However, the gradual increase of LWG generated a significant 5% gain (+20 kg hd^{-1}) for the biochar treatment on the final measurement (Fig. 1b). Carbon content of manure was similar between herd prior to access to biochar (Autumn sample period) and varied more seasonally compared with between treatments (Fig. 1d; 3-6% variation across seasons).

Figure 1. Results from farm experiments with cattle fed biochar ad libitum at Deloraine, Tasmania, Australia.



Results from farm experiments with cattle fed biochar ad libitum at Deloraine, Tasmania, Australia *figure 1*. (a) pre-grazing herbage mass in the grazed paddocks (kg DM/ha), (b) mean animal liveweight (kg/head) from grazing steers fed with biochar or no biochar (control), (c) botanical composition (%), (d) mean total carbon content of manure collected in autumn and summer 2022. Error bars depict standard error of the mean. Each herd rotationally grazed paddocks (~10-12 ha) containing the same species blend of annual and perennial grasses, legumes and herbs such that a paddock grazed by the control herd would be subsequently grazed by the biochar herd the following rotation. This minimised any bias towards either herd grazing pastures with better composition/species mix.A cost-benefit analysis of the farm experiment showed that the biochar animals gained an additional 26 kg LW over the control herd. This extra LW was valued at $4.50/kg (price quoted by the I&P farmer), based on the premium price they receive for Wagyu cross animals. Thus, the income generated by feeding biochar was valued at $8,892. Information supplied to us by the manufacturers of the biochar valued the biochar costing $0.10/head/day, resulting in a cost of $2,774 over the 12-month period. The net profit was valued at $6,118, equivalent to a net profit, above that of the control herd, of $80/animal (excluding any additional costs associated with feeding biochar such as increased labour, capital cost of purchasing feeding out equipment etc.).

4.2 Workshops to support awareness and peer-to-peer learning associated with I&P activities

Three workshops were undertaken across spring and summer of 2022/23. The first was held on the I&P farm, the second on a dairy farm in the north-east of the state and the third on a beef farm in the north-west of the state. All workshops were conducted on farms that have used biochar as a feed supplement, with the latter two having fed biochar for several years, and thus further along the mitigation journey compared with the I&P farm. Attendees totalled 72 across all three workshops, with a blend of producers, industry, government and academic representatives (Fig. 2). Workshop participants came from a range of regions across the State, with two producers from Flinders Island attending the third workshop, displayed as ‘Other’ in Fig. 3. There were also managers of multiple 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 2). The smallest property size was 2 ha which was running 6 sheep, and the largest property size was 4,200 ha which was running around 8,000 cattle and 3,000 sheep. Of the 72 people that attended a workshop, 32 people completed a feedback form.

Figure 2. Workshop participant distribution across sectors.

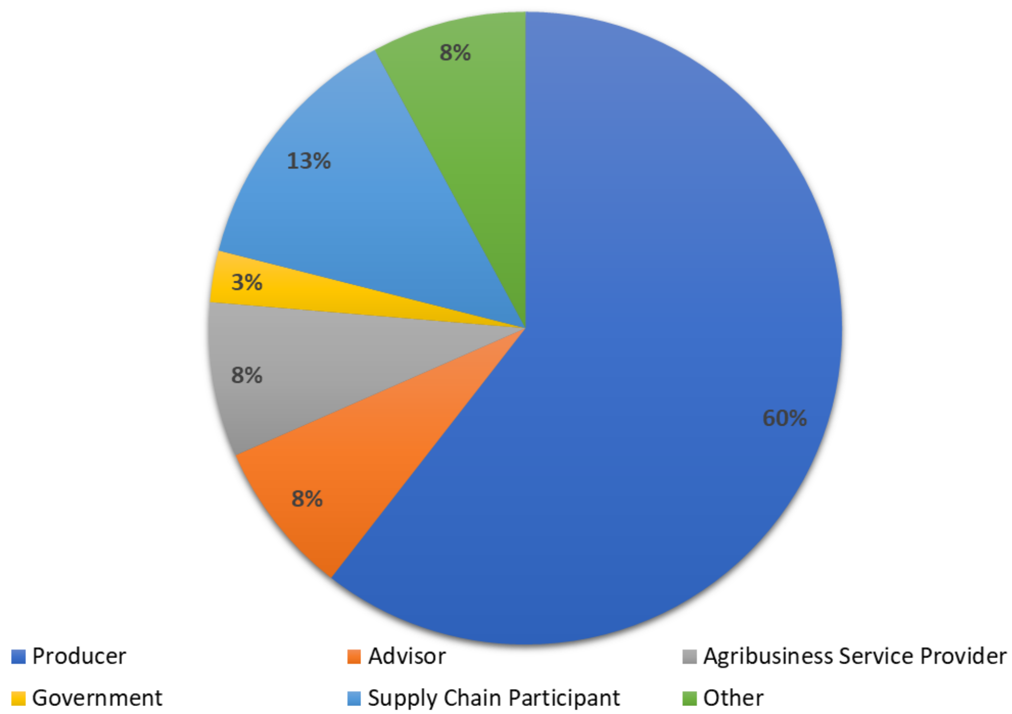


Figure 3. Number of participants from each production region that completed the survey after attending one of the three biochar workshops.

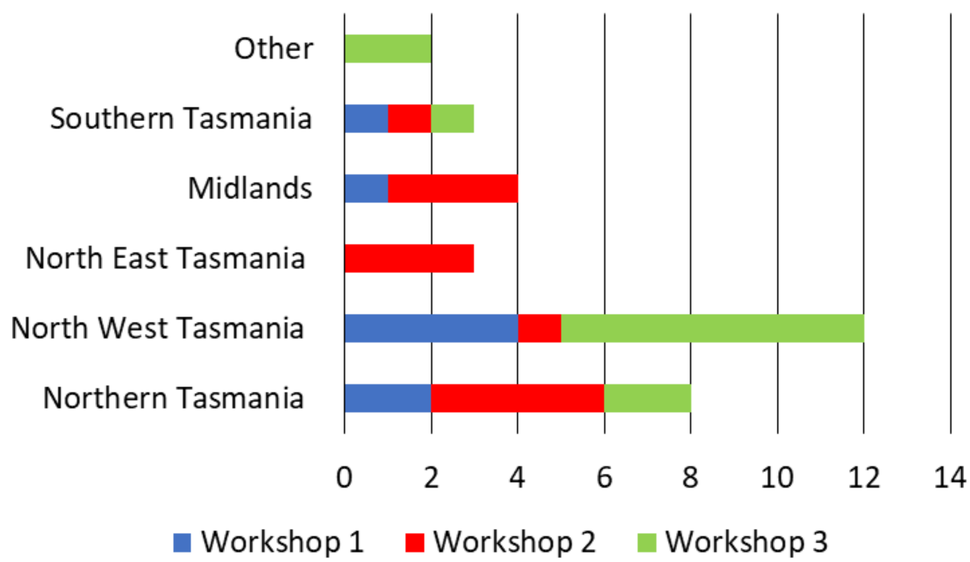
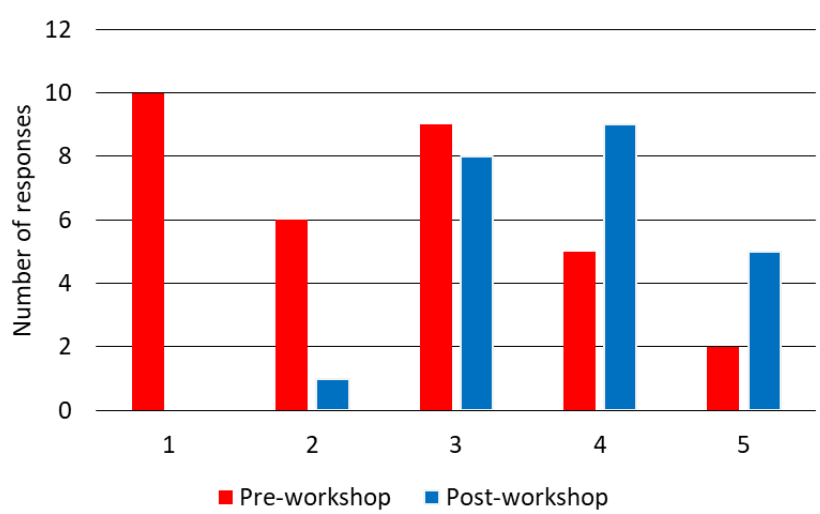


Table 2. Total property area, head of cattle and sheep managed by survey participants from the three biochar workshops.

	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

Awareness, knowledge, skills and attitudes related to biochar increased substantially between pre-and post-workshops, with the majority of participants indicating that they were now more able to make informed decisions on the provided topics relating to biochar (e.g. how to use on farm, the benefits and issues in using biochar etc). The majority of survey participants (> 80%) indicated a willingness to use biochar as a feed supplement after attending the workshops, primarily to assist in improving soil carbon and animal health, while reduce GHG emissions (enteric methane). Survey participants were asked to provide a rating of 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. 4. Knowledge ratings of 3 and below was higher pre-workshop compared to post-workshop ratings. 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.

Figure 4. 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.

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. 5). Only one person indicated that they were not comfortable making an informed decision on the forms of biochar available in agriculture. After attending one of the field days, 21 participants indicated that they intend to use the biochar as a feed supplement, with 9 unsure. The two main reasons for this intention were to improve both animal health and soil carbon (Fig. 6). 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. 6). Plates 1 to 7 are photos taken across the three workshops.

Figure 5. Participants were asked if they were able to make more informed decisions on topics relating to biochar after attending the workshops.

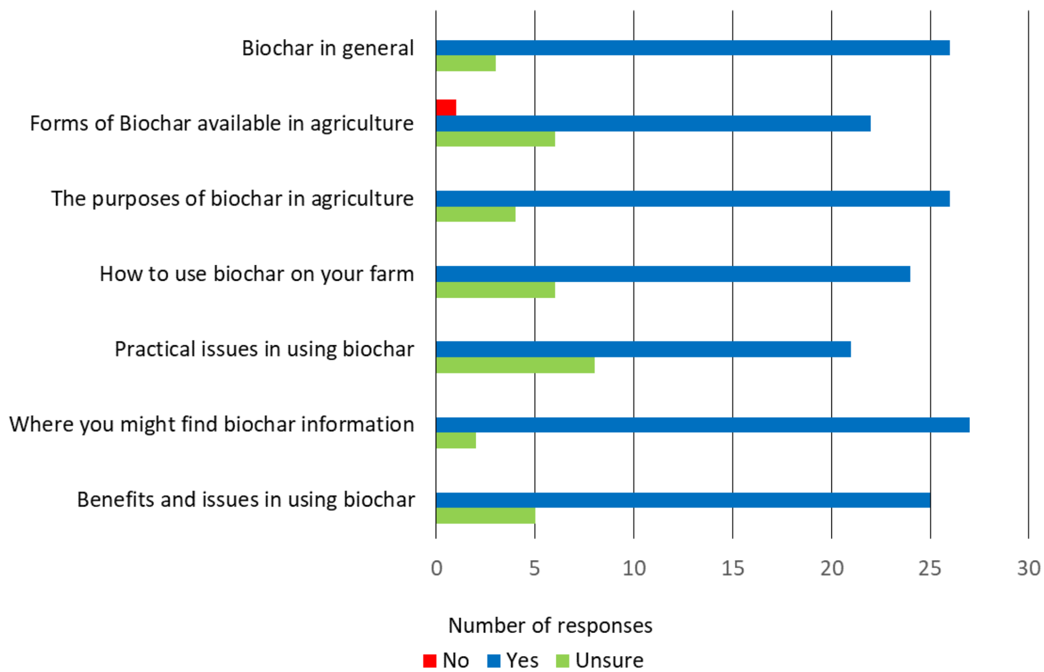


Figure 6. Participants were asked to assess the main reasons for their intention to use biochar after attending the workshop.

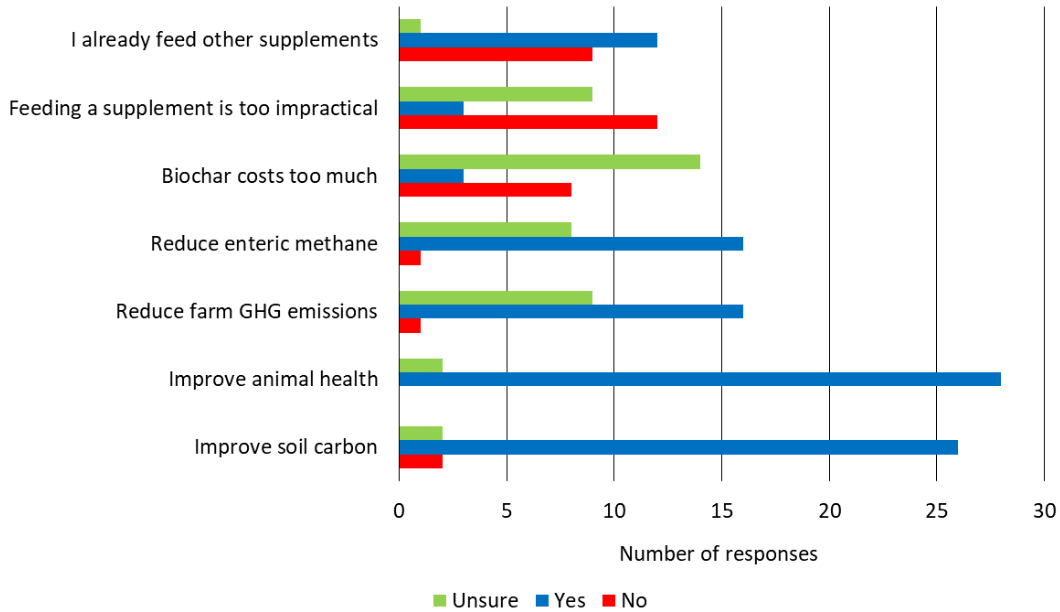


Image 1. Attendees at the first Involve and Partner biochar field day, November 2022, held on the Involve and Partner farm, shown inspecting a mob of Wagyu cross cattle being fed biochar.

Image 2. Biochar treatment animals grazing a multi-species pasture at the first Involve and Partner biochar field day, November 2022.

Image 3. Mobile biochar feed wagon at the first Involve and Partner biochar field day, November 2022.

Image 4. Attendees viewing milking herd at the second Involve and Partner biochar field day, December 2022. The dairy cows are fed biochar combined into the pellet fed in the dairy during milking.

Image 5. Calves at the second Involve and Partner biochar field day, December 2022.

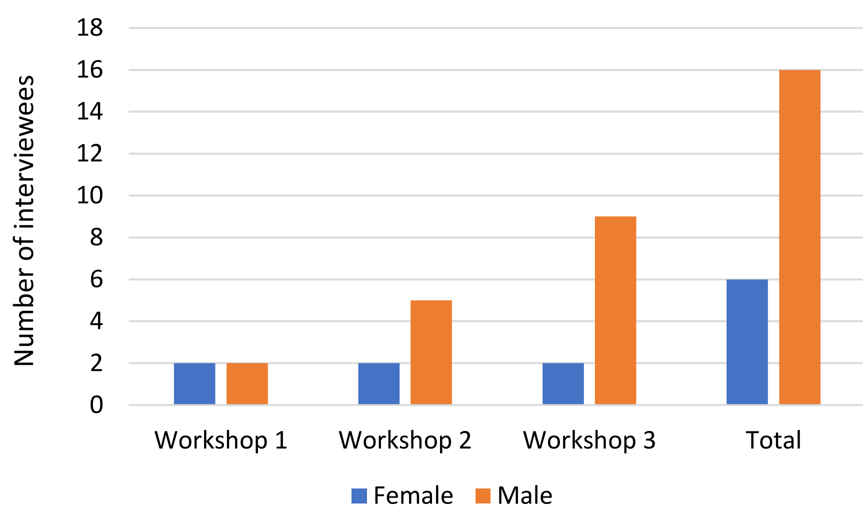
Image 6. Workshop at the third Involve and Partner biochar field day, February 2023, listening to Matthew Harrison discuss the results of the Involve and Partner biochar study.

Image 7. Attendees at the third Involve and Partner biochar field day (February 2023) in Marrawah had the opportunity to have a tour of the Greenham Tasmania 'Westmore' property. Here, attendees inspect a mob of Wagyu cross cattle that had been supplemented with biochar.

4.3 Post workshop interviews

At the three workshops, attendees were given the option to provide their contact details to allow a follow up phone interview post workshop. These interviews occurred between 8 and 12 months after the workshops (mostly in October 2023). The phone interviews were used to gain an understanding of adoption associated with (and impact of) the workshops, with particular attention paid to the knowledge, attitudes, skills and aspirations of participants. Of the 32 people who participated in the post workshop survey, 23 phone interviews were conducted. The remaining 9 people either did not provide their contact details on the post workshop survey, could not be contacted using the details they provided or declined to be interviewed. Of the people that participated, 16 participants identified as producers (69% of interviewees), 5 participants were involved in the biochar production industry (22% of interviewees) and 2 identified as being industry/community (9% of interviewees). One of the interviewees self-identified as an Indigenous Elder. This interviewee had a wide range of grazing experience and knowledge of the importance of cultural burning. Two females from each of the three workshops were interviewed for a total of 6 females (Fig. 7). There were 2, 5 and 9 males interviewed from the first, second and third workshops respectively (Fig. 7).

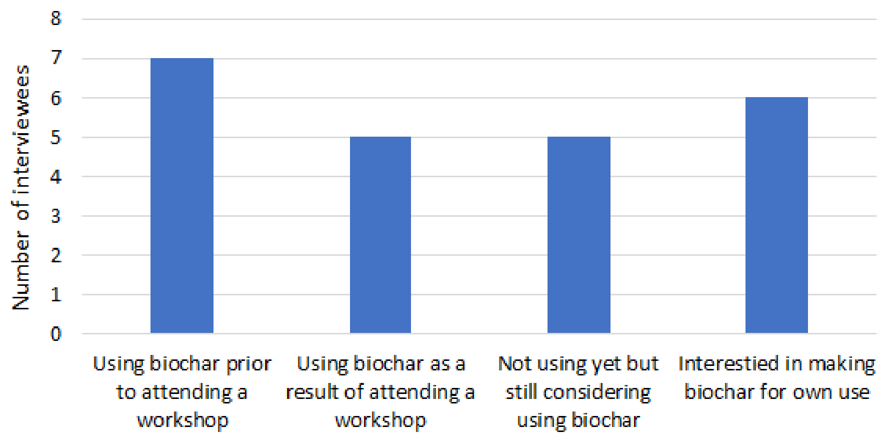
Figure 7. Post workshop interviewee demographics.



The post workshop livestock producers were predominantly beef producers (~ 60%), followed by sheep producers (~ 15%), with one dairy farmer and other beef and sheep producer, in addition to 4 industry representatives. The post workshop surveys showed that between 22 and 27 participants felt they were able to make more informed decisions relating to biochar after attending the workshops. Only one person indicated they were not comfortable making an informed decision to use biochar.

The interviews showed that 7 people were already using biochar prior to attending a workshop, 5 people began using biochar after attending a workshop and 5 people had not started using biochar but were 'still getting around to it' (Fig. 8). These 10 people are clear evidence of impact associated with the workshops. This equates to around 52% of respondents using biochar on farm at the 12 month follow up compared to the post workshop survey data that revealed 66% of survey participants were using or were intending to use biochar. Some interviewees acknowledged they still intended to use biochar and time and other constraints were prohibiting initiation. One producer who was waiting for technical product information from the biochar supplier and one producer planned to conduct their own feed trial with steer calves.

Figure 8. Producer propensity to adopt biochar gathered in interviews 8-12 months post workshop.



4.3.1. Biochar knowledge, attitudes, skills and aspirations

The following relates to the benefits, issues and processes of using biochar and innovations that were compiled as part of interviews via phone and with the I&P farm manager.

A. Knowledge and skills

<u>Learnings</u>

While the purpose of the I&P project related to the use of biochar as a mechanism for productivity, producers attended the workshops for several reasons. Producers were looking at biochar as one part of a holistic farming approach. They also wanted more research with different aspects of biochar to be confident of not wasting their time and money on something they were unsure was of, particularly in terms of its value on a commercial scale (discussed further below in Attitudes). This was exemplified by comments such as:

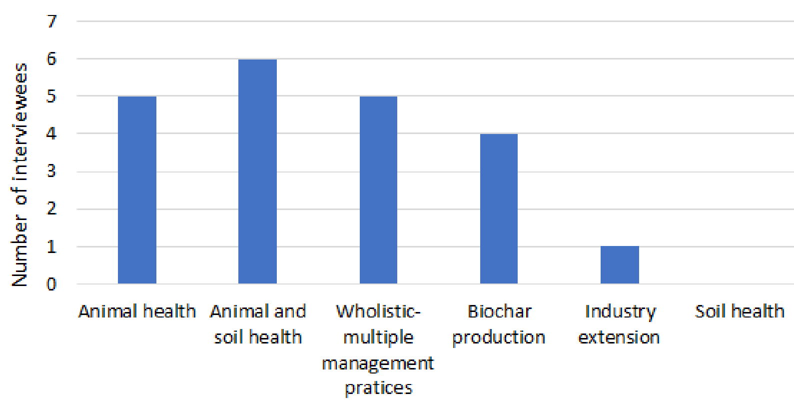
> *The science is not there to back up the claim, and it's gonna be very tough to promote a product when the science is not in on it yet.*

In the post survey feedback forms, it was identified that one of the two main reasons that producers would look to using biochar supplementation after attending one of the workshops was to improve animal health and soil carbon (Fig. 9). Producers were most interested in the animal and soil benefits of implementing biochar supplementation, however, it was also commonly stated that producers were interested in a holistic management approach, that is, they were interested in how biochar could form a part of a wholistic management system to synergistically improve both animal and soil health (Fig. 9). None of the producers interviewed were focused on the benefits of biochar for soil health alone (Fig. 9).

> *Initially, it was for animal health. But then yeah you sort of start looking into it more and you realise oh well it actually has a benefit for the soil as well because you know like all that manure is inoculated with it, if you know what I mean.*

> *Like a whole system process, not just the animals but it's also the soil that it's helping balance out everything.*

Figure. 9. Producer motivations for biochar adoption gathered in interviews 8-12 months post workshops.



Benefits

Producers believed that biochar had a number of benefits. They spoke of its use to decrease toxins and/or pathogens in soil and animals.

> *Oh, all the bad bugs that were in their stomach are gone and they're just living off the good things now.*

> *We don't put it out all the time, cause we've seen that they're not exactly needing it all, cause pretty much what we're doing it for is just to reduce the toxin load and flush them out.*

> *Anecdotally, I agree. I think it does have animal health benefits largely to do with the fact that I've run cattle in the central highlands, and I'll actually see cattle target charcoal and I imagine it's for health reasons, parasites or whatever it may be*

Producers had knowledge of biochar being used to improve gut health and methane reduction.

> *better rumen function in the animals. I mean better utilisation of the nutrient and the fibre and everything they eat.*

> *It helps the pH of the cattle's stomach, so it's going to be a benefit health wise for the animal.*

In terms of soil health, producers using biochar spoke of biochar's impact in decreasing or working towards eliminating their need for using nitrogen fertilisers but were unsure of its effectiveness.

> *Unsure about it all and not it's saying that there's a lot of benefit to me, even though I think the product would be good down the track, but I just couldn't see the benefit to me in my [circumstances] as a replacement sort of artificial fertilisers.*
>
> *We're obviously going down the track of there's no synthetic fertilisers, sprays, you know. All natural.*

It was frequently stated by producers that they believed that biochar could not be a single fix for a problem but would rather complement other holistic management strategies. Most spoke of the long-term benefits as opposed to taking the 'silver bullet' approach.

> *Biochar is a piece of the puzzle biologically for the environment.*
>
> *Because we're in organics, every little thing helps, and this is just one of those little things that help us*
>
> *I'm interested in biochar more for the animal health. I'm assuming its gonna take a lot of years before you started to see the benefit in the soil. Short term animal health and long-term soil health*
>
> *In this space it's not about just having a silver bullet and saying go and use this and you'll have X amount of dry matter. You've got to want to do it and you've got to understand the whole holistic approach as to why you're actually doing it……It's not just about saying "Oh well, yep, we'll feed char" and that's gonna solve all our environmental problems. They've actually got to have …. A light bulb moment where they go "Yep this is what we're doing".*

Those using biochar had noted:

- There were reductions in sheep fly strike and a reduction of maggots in the soil,
- It was good for the treatment for mastitis,
- It acted to increase dung beetles and worms and the follow-on soil benefits,
- Shiny coats on cattle – as an indicator of good health,
- There was a reduction in ringworm lesions,
- Reduction in dark cutters (ie percentage dark coloured meat, which can be economically downgraded),
- The most significant change was in the consistency of animal manure, this meant less crutching for sheep and cattle's improved health, especially when on green feed.

<u>Issues</u>

There were four main issues that farmers identified in the use of biochar:

1. The form the biochar is sold in

2. Cost/benefits
3. Time it takes for use
4. Concerns over long term impacts

From the data collected it should also be noted that these issues could flag further developments and opportunities that could happen within, and to the benefit of, the biochar industry, supporting the use of biochar. Producers expressed concern about:

1. The form of biochar
   The biochar used in the trial came in a powdered form. This was seen as problematic for the majority of the users including the I&P producer and producers who either started using biochar after attending the workshops or those who had already been using biochar prior to the workshops. Feed mechanisms were not ‘easy’ for the powdered form of biochar and therefore was seen as time consuming to use and resulted in incidental loss of biochar and additional costs for equipment/additional supplements appropriate to feeding out or administering the biochar.

   It sounds very good in theory, but it just didn’t work. I didn’t think it was practical. I think if we could get it into grain or something like that it would be wonderful.

   We don’t feed it out in any type of dry lick or anything like that. It just becomes too much of a hassle when you’ve got 14 to 15 mobs, and if one guy forgets to shift it… then it just gets behind. So, it’s better off being in the mixing wagon.

   Producers came up with some creative options as to how to feed biochar in this form but most of these options then added costs to what they saw as an already expensive product. From this experience producers also came up with other suggestions concerning the form biochar would be helpful in, for ease of use, especially in a large-scale farm context (see below in Innovations for examples).

2. The cost/benefit of biochar use at a farm scale

   The financial cost of biochar was seen as prohibitive, particularly on a large scale. Smaller scale use, for example, treating horses and dogs and a few sheep, use on a hobby farm, use as a garden fertiliser, was not seen as an issue and in fact, these contexts were used as evidence of the usefulness of biochar in animal health by many producers. However, the possible cost benefit was still questioned at scale. They believed that on the larger scale of their farms, it was not cost effective for the benefits they perceived would/would not be achieved.

   I think the biggest problem that we all seem to be up against is getting the cost down. It’s just too expensive to use in bulk, which is what you need for the farming industry.

   What are the limitations? Cost?

   I was interested to see whether there could be a business model made out of it, and when I looked at the price of the product it’s quite expensive and I think if you can get the cost down it going to be a lot more acceptable for people to purchase.

the way cattle prices are at the moment, we can't afford to throw money away [this quote was in terms of the lick solidifying when it got wet]

I never really got a solid costing on what it was going to cost me to use it.

There are so many farmers that just keep saying all these adaptions you're asking us to do… who's going to be doing this? And where's the money coming from?

Fair enough for a veggie garden, stuff like that. If it can be good like for a bigger enterprise, I'm not sure.

Equipment – Specific equipment was required to use the biochar, adding set up costs (see more examples below in Innovations). Tractors/forklifts were required to move bulker bags, although this was common on-farm machinery, and a mechanism to unload a measured amount. Manual bucketing of the biochar from the bulker bags to a transporting container to take to paddocks was common. Once in paddocks a feeding mechanism was required. Open troughs were trialled on the I&P farm as they were the cheapest delivery mechanism. This was unsuccessful when the biochar was lost when moving it around the farm.

You can lose a bit of biochar if you go over a rock or something and it gets a bit tricky.

Or was exposed to the weather. In Tasmania with high rainfall and wind, the biochar was either wet and went hard and was then not consumable, or dry and blew away.

It gets wet and then it's no good at all.

That's the only limitation. It's not waterproof.

They don't like it when it's wet, which is the case with most supplements.

They didn't want to deal with it…. the char was wet then…. It would get wet and dry, and it would be a dead flat rock hard…. So, I'd go and mix it up. But it was still wet.

Further biochar losses happened when moving troughs from paddock to paddock as they would tip, spilling biochar. These had to be filled daily. On the I&P farm, a covered mobile feeder was trialled – this prevented wind and most of the rain damage but made moving between paddocks more time consuming. It could also be filled once out of the bulker bag rather than the daily filling of troughs, saving time. Some producers experimented with cutting the sides out of 1000 litre water bins to similar effect.

Most farmers reported having to mix the biochar with other additives to get their livestock to begin feeding. Those with sheep added biochar to grain rations. As cattle destined to the Never Ever Program (the Greenham's abattoir accreditation program that many beef producers in Tasmania sell into) are not allowed access to grain, some farmers spread the biochar though silage to feed out. Both sheep and cattle producers also combined the biochar with salt or molasses to encourage consumption by stock. All of these options increased costs unless it was already happening at certain times of the year (e.g., grain to fatten lambs or silage over winter to cattle).

With all of these mechanisms, biochar dosage, or "who got what", was unknowable and unmeasurable unless it was being used in something like a dairy feed ration or the drench discussed in the Innovations section below. Producers used estimates but were aware that this was only a broad understanding of what was consumed in the reality of a paddock.

Despite the cost/benefit perception, those who participated in the follow up interviews were still willing to trial biochar for themselves and some had already begun use.

3. Cost was also measured in time by the producers who were using biochar – this related closely to the form (as a powder) that the biochar was currently available in. In this form the biochar became time consuming to use and added another dimension to the day that had to be accounted for in terms of labour.

    You know, any other products that…. or anything that you want a farmer to adopt…. you have to take a job away. You know, as soon as you start adding jobs it becomes very difficult and hard to justify cause we're busy enough as it is. So, unless it's making you, you know, serious, serious weight gain….

    This relates to opportunity cost – what is the benefit of feeding biochar versus the benefit of the task that has been negated. This opportunity cost is a key consideration for all farming systems interventions.

    Limitations? The time factor in feeding it if they're going to feed it dry.

    It's extra handling and work.

    Administering it was hard…. administration and the controlled administration of it. And accessibility in Tasmania.

4. Other issues raised by producers came from workshop presentations that addressed some of the research about contested understandings of biochar use.

   Some producers expressed concern over the long-term impacts of biochar use, addressing in particular the research speaking to the development of carcinogens during production. The processing of biochar via a fast pyrolysis process produces polycyclic aromatic hydrocarbons which make the biochar carcinogenic (Odinga et al., 2021) and could have implications for use with animals, particularly for breeding stock. However, the Tasmanian biochar manufacturers interviewed are currently working on setting biochar standards across the industry to counter this possibility, and are working to have processing (i.e., fast or slow pyrolysis) as part of labels on biochar products. These industry standards are still being developed.

   Biochar acts as an extremely effective carbon sink and is therefore excellent for carbon sequestration (Gruss et al., 2019; Schmidt et al., 2020). However, this has two implications for Tasmania. In places like northwest Tasmania, with permanent pastures, soil carbon can already be relatively high so the ability of biochar to sequester carbon is unlikely to have significant impact.

While being a great carbon sink, biochar is also a very good oxygen sink. This is problematic as depleting oxygen supplies for a world that relies on oxygen for survival needs careful attention (Ho, 2010). Therefore, large scale biochar production is not being encouraged unless the oxygen sink effect can be addressed. This suggests that small scale on farm biochar production is an encouraging direction.

Two other issues raised in the literature but not address by producers is that biochar is effective at trapping contamination such as heavy metals (Gruss et al., 2019). The use of biochar in the soil can then affect soil microbes in the soil biome if highly 'contaminated' biochar is used. Again, industry standards, which are currently being developed, will help with this but will not regulate biochar producers outside that system. The second issue relates to food security. While in most research, biochar is argued to support food security (e.g., Murtaza et al., 2023), in the US there is a concern that producers will swap food crops for biochar crops because it is currently more profitable. If crop production moves in this direction, i.e., from human-grade food production towards biochar production, food security is argued to be at risk (Levitan, 2010).

Innovations

Producer ingenuity was often demonstrated. A number of suggestions and innovative developments occurred in their attempts to use biochar in its current powdered form and was obvious in their suggestions for alternate forms. Producers also had suggestions for innovation in the biochar industry.

Delivery mechanisms

Producers suggested that alternative feed mechanisms were needed to overcome the weather and loss implications presented when feeding powdered biochar using open troughs. This included the use of a mobile feeder that could be bulk filled and easily moved between paddocks with livestock. However, this was an expensive set up option. Suggestions were also made for the conversion of bins (referring to a 1000 litre plastic water container in a metal frame) by cutting out one of the sides and using as a feeder that could be dragged between paddocks. Placement of the bins in paddocks needed to be considered so that the opening faced away from the prevailing weather.

One of the major Tasmanian stock feed companies had also purchased biochar and producers could request for biochar to be mixed through other feed rations such as grain, pellets or minerals. This was particularly helpful for sheep and dairy farmers who feed rations to stock.

Feeding out biochar with grain, silage, salt or molasses was recommended, particularly when introducing livestock to biochar was commonly mentioned. Once feeding was established, the animals would 'self-medicate', *ad libitum*.

> *So, feeding it out we have got a big mixer wagon with pit silage and so…. We're putting a 30-litre drum's worth of biochar thought the feed on each mix.*

One producer had purchased a pelletizer to convert the powder into pellets to be able to more easily feed out to his cattle. Another family trialled making a drench from the biochar mixed with yoghurt and apple cider vinegar to produce a 'liquid form'.

> *So, Mum mixed up apple cider vinegar, biochar and yogurt* [In relation to administering as a kind of a drench]

They had a special drench gun as commonly available drench guns would clog. This process required drenching every 2 months and each sheep/lamb had to have its own dose drawn up in the gun, making it a time-consuming process. However, these farmers saw benefits for their sheep so continued the process. They also saw benefits in knowing the exact dosage each animal received rather than the hit and miss of other mechanisms and reported reductions in fly strike and reduced stock losses from lambing to weaning.

Other suggestions for alternative delivery mechanisms were made but not necessarily trialled. These ideas included combining biochar into a lick block with other necessary minerals; or adding it to weather bags.

> *It would make more sense if it was in their mineralized … with something like copper and selenium and magnesium…dolomite…. All those things mixed up that was a mineral lick.*

> *I was thinking more along the lines of a salt lick or, you know, a molasses block or something like that.*

> *Since attending the workshop I've been mixing biochar with molasses and feeding on the hay – the calves seem to be attracted to the hay more than the cows are.*

> *We actually use it as we've got an ad lib feeder that goes around the paddock with the cows, and we have it as one of the things that's in the supplement station so they can take it when they want it.*

<u>Circular Economy</u>

There was a noticeable number of producers interested in making their own biochar, either for use as an animal supplement or as part of a business plan to deal with waste products including timber and gorse, on farm, in a 'circular economy'.

> *I was even thinking about buying a big mobile biochar maker.*

> *So, if you're going to encourage farmers to use biochar, they need to be able to make it themselves, maybe collectively own systems so they can do it together, or do it, you know, hire around the equipment.*

This was seen as a cost-effective way of using it for animal supplementation and may have been influenced by the cost of supplementing biochar, which was repeatedly flagged as a potential limitation for widespread uptake in the follow up interviews.

On a broader scale, there were suggestions to establish local groups who could purchase biochar production equipment that could then be shared/hired within the local areas. This could also deal with farm waste at a local level. The biochar product, they suggested, could then be given to/bought back by local producers for use on farm for either soil improvement or animal health, or for those wanting to take a more wholistic approach to their farm management.

Another producer had seen connections between biochar production and a way to deal with a Tasmanian endemic weed problem, i.e., gorse removal. He had purchased a biochar kiln and was experimenting with removing gorse from farms and forests and using it as the base for biochar. He owned a small farm and was planning to use this as a way of supplementing farm income.

> *I'm currently working on perfecting the manual harvesting/cutting, letting it dry out and making biochar from gorse. I'm finding that the less soil disturbance from manual harvesting compared to mechanical harvesting is meaning that there is less gorse re-growth. I'm currently looking at turning this into a business.*

This was another 'circular economy' innovation that dealt with a weed problem and created off farm income for a small farm despite still being in an experimental phase. This producer was also enthusiastic about doing this type of activity to help reduce the price of biochar to make it more commercially viable for larger scale use.

Seasonal use of biochar

> *Sometimes they eat a lot and other times they don't touch it at all.*

The issue of unknown dosages was not seen as a problem by producers.

> *We set up a trail camera so we could see the cattle that were coming, and it looked like the majority of them were getting a feed, but it's hard to say.*
>
> *They can access it whenever they like.*

This understanding seemed to link with their understanding of stock as 'knowing' when they needed/required biochar (and other minerals or feed) and regulating their own consumption.

> *You know, I'm a big believer of cattle knowing what they need, knowing what they want.*
>
> *Maybe it's something that they're compensating for.*
>
> *They're not making the decision [when you feed biochar with salt] …. You're forcing the cattle… like they know better than we know what they need. Like we're deciding whether we need to feed straw or not, but if you put straw out there and they all go lie in it, then you know that they don't want it. But if they eat it, then they need more roughage. I like the idea of having… creating like a free will.*
>
> *I think the cattle are looking for it at the moment. I haven't put it out….so that's telling me something. They're walking a lot and that's telling me maybe they want it.*

Therefore, the producers were not overly concerned about 'correct' dosages. However, in acting on this more *ad libitum* approach what they noticed was that stock seemed to consume biochar at specific times of the year.

> *Sometimes [biochar consumption] was a little bit more, like say early spring when the feed still hasn't sort of made-up quality. They'll eat more [biochar] than when, you know, the feed is starting to harden off.*

It's pretty simple and it makes a lot of sense to me. Basically, when we have high growth periods (of pasture), so in spring and autumn…. so, then they are hitting the char. Just coming into autumn we're having another growth period, and they were absolutely smashing the char, also there was salt involved, but they were eating the char significantly then. And then as winter came along and we started feeding straw to them, yeah, they came off it. The didn't want to deal with it, but the char was wet then too…. We moved on to the feeder that kept it dry. That was just around the start of spring and at the same time they absolutely smashed it. I can't remember the exact amount, but they finished a bag in like …. a month. ….. Then they went off it coming into summer because we had a lot of dry grass around.

I think it's getting fibre is what they want. Because there is a lot of water in the grass and endotoxins in the rye grass and when it is that very green and lush stage, and that's all they eat. It's like if you and I ate Snickers bars, you know, and we need that broccoli, we need the roughage in our stomach to clean us out. So, I think that's what they were chasing. That's the only thing that makes sense to me unless the toxin thing was the main reason.

When the season changed, and we lost a lot of pasture growth, they dropped right off.

When we were feeding straw then they pretty much went completely off it, and they didn't want anything to do with it.

This seasonal cycle of spring and autumn 'self-medication' by cattle would be an interesting follow up study.

B. Attitudes

Three understandings became prominent over the course of the workshops. The primary understanding concerned 'having more research', the other was about the waste of biochar in feeding out. A third understanding was about the time/cost benefit of using biochar. However, this was dealt with above so isn't repeated here.

<u>More knowledge required</u>

At each workshop, producers had the opportunity to experience how biochar was used on the host farms during a farm tour. They were also presented with research about biochar and its use and had time to ask questions of the biochar manufacturers, the researchers and the host farmers and each other any questions they might have – noting there were other producers already using biochar that willingly shared their experiences at the workshops. From the workshop survey, many of the respondents indicated that they would like more knowledge of biochar and how to use it before they would invest in the time and money needed to implement its use on farm.

The science is not there to back up the claim, and it's going to be very tough to promote a product when the science is not in on it yet.

As was presented in the workshops and provided in handouts, there is copious research on the topic of biochar and its use, which can be found online (see Appendix 8.1 for Workshop Handout which contains a summary literature review and links). A very small proportion of the current research was explained in the workshops and online links provided in the handout which could be accessed when appropriate for the producer. This would suggest that it is not the amount of research that is actually the issue but the accessibility of the research in a format that producers are comfortable in using that is problematic. It appeared that what producers were also looking for was repeated exposure to others using biochar, who had worked through the issues and could guide people through the solutions they had come up with.

C. Attitudes evidencing impact of this research

There was clear evidence of the impact of this work. For example, workshop participants were very supportive of the information presented and the farm tours to gain firsthand experience on how they might use biochar themselves.

> *I wouldn't have started using it if I hadn't gone to the workshop.*
>
> *I thought the workshop was fairly thought provoking.*
>
> *it was good touring around [the farm], I thought. That was absolutely wonderful.*

The request for 'more research' seemed to be about allaying their fears that biochar use was more common practice, and they wanted the research to show them they were not going to be throwing away money on an 'unproven' solution when there was 'no evidence' that it did anything other than the anecdotal reports they had heard.

> *But I was just like, you know, hippies, and organic farmers used to put under their plants. I just thought it was something that they used in gardening, and I didn't really get why.*

They wanted to see 'how', and they wanted to see it function on larger farm sites.

> *I think it's about getting the myths and the truths out there.*
>
> *if you're a farmer and you just wanted to see results, there needs to be more than a 10% result to actually be able to see it.*
>
> *I would like to just try a mob of steers with it and just monitor how they went in comparison with other groups of stees on similar nutritional intake conditions.*

<u>Waste vs incidental benefits</u>

One attitude that was commonly identified throughout the data concerned the waste that occurred when feeding out biochar.

> *If I knock over the feeder and have to pick it up…*
>
> *You know I could lose a litre a day by cattle knocking it out and stuff like that.*

However, one larger commercial biochar user saw this in a different light. He was mixing the biochar through silage before feeding out. The perceived loss in feeding this way could be assumed to be even greater than feeding out using a covered feeder given the overall perception of waste as not being cost effective. However, the producer saw the benefits of biochar as having a more wholistic role across the farm and included soil health as well as animal health.

> *And the cattle were either consuming it or it was sort of hitting the ground as is. Ideally, you'd like it to go through the animal because it's probably multiple benefits, one being that the animal, you know, if it is feeling a bit unwell or got a slightly acidic gap, …. It's going to help to clean out any toxins … and equalise their system. And then squirt it out the other end and obviously it's going into the soil and staying there and doing its job….*

Therefore, the 'waste' of biochar was seen differently in this context. The biochar falling through silage when feeding was still getting into the soil despite not having gone through the animals first and was therefore still benefiting whole farm production through soil improvement. They also spoke of seeing the advantages (and therefore cost recovery) in such things as the reduction of dark cutters and increased animal health.

> *There's no data set that I can go "yep that data tells me that char works", you know. Anecdotally now the kill cattle and their dark cutting percentages was pretty good through those winter months* – this was when biochar was being fed out with silage.

This difference in understanding seemed to come from producers' different purposes for using biochar. For example, producers wanting to address animal health only, were more inclined to see the 'waste' as it was not meeting their cost/benefit needs. Whereas the producer described here was more focused on a holistic farm approach in his use of biochar, and so could see that while the animals might not get the benefit of the biochar the soil still would and so was focused on the benefits rather than the waste.

D. Aspirations

Overall, those who began biochar use were aiming to do a number of things in taking up the use of biochar. The aspirations of producers were demonstrated through their innovative application of biochar on farm to overcome the issues they encountered. Across all the data and from all aspects of this report, aspirations included:

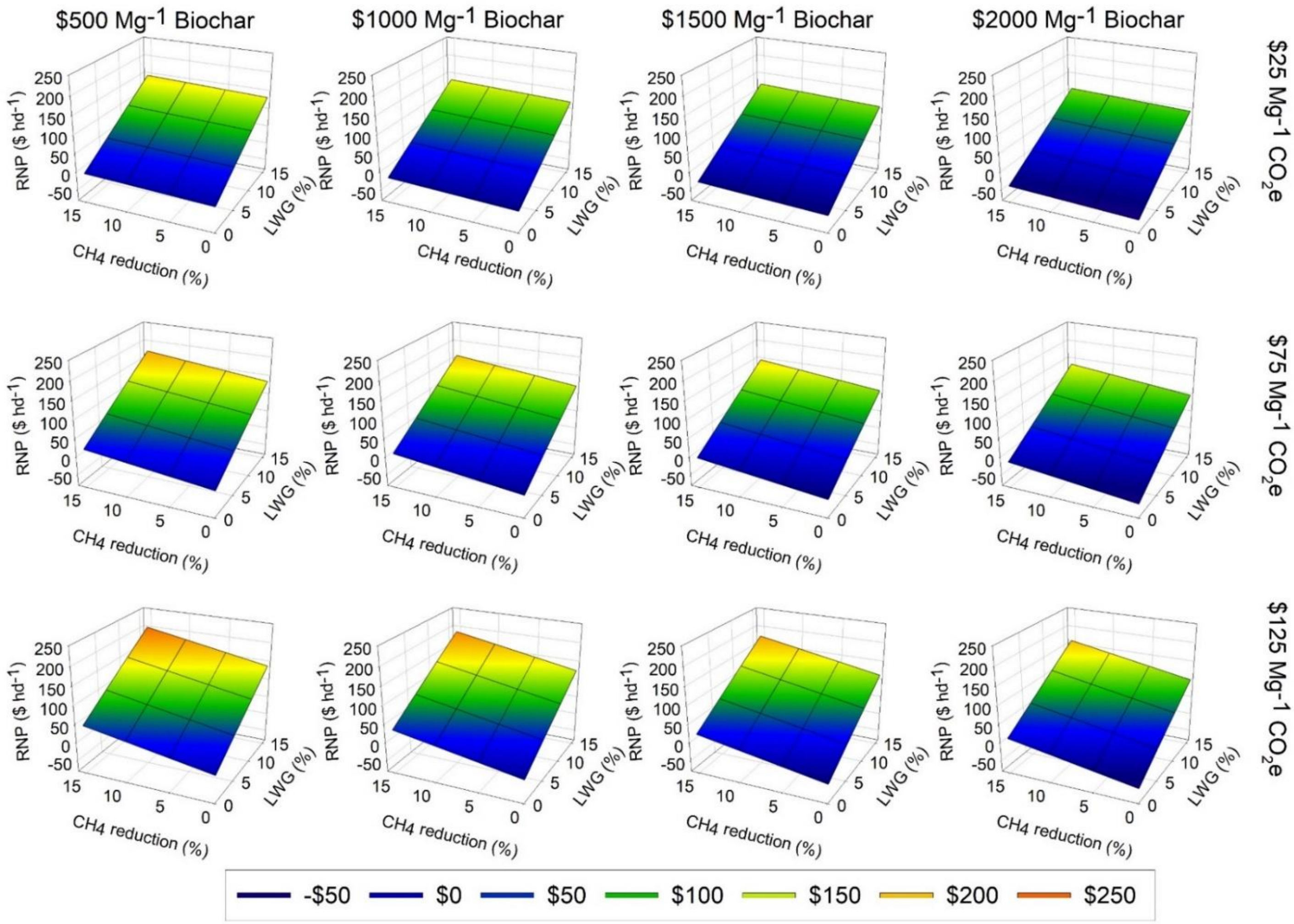
1. Use of biochar as a tool to build a holistic approach to farm management that combined science and sustainability. Specific use targeted the reduction of chemical use in the farming system for example, less drenching, fertilising and spraying.
2. Use of biochar for the health of animals, particularly in reducing illness, methane reduction, and dealing with toxins/pathogens.
3. Pelletising – one producer had found the powdered form problematic and so bought a pelletiser and was working on how to change the biochar powder into a pelletised form for easier use.
4. Developing healthy soils by increasing carbon in soil.
5. Developing circular economies. Two examples of this arose. Firstly, the development of circular economies individual on farms, to both deal with farm waste and/or deal with perceived costs of biochar. Or secondly, as a community /cooperative of local farmers/others willing to work together to produce their own biochar from farm/local waste (e.g., Tasmanian forestry).
6. Establishing biochar businesses as a way to gain 'off farm' income. For example, using gorse (weed) to produce biochar for sale.
7. Wholistic approaches to farm management could be supported by the use of biochar as one part of building a larger picture around soil health, animal health and other 'wholistic', sustainable practices.

4.4 Scenario analysis of how biochar supplementation impacts on liveweight, GHG emissions and soil organic carbon

Our scenario analysis showed that at lower cost per unit of biochar cost and higher carbon pricing, an expected greater potential for improving LWG and reducing enteric CH_4 emissions may result in a higher relative net profitability per head (Fig. 10, Appendix 8.2 supplementary material Tables S2-S5). When aiming for a projected 15% increase in LWG, the incorporation of biochar into the diet was highly profitable (exceeding $100 per head), reaching its maximum point when a 15% reduction in CH_4 emissions was attained (Fig. 10). This favourable outcome was amplified by a high carbon credit valuation of $125 per Mg CO_2e abated and a low biochar price of $500/ Mg (Fig. 10). However, economic losses were incurred when carbon prices fell to $25 per Mg CO_2e abated and no improvement in LWG was realised (Appendix 8.2 supplementary material Tables S2-S5), regardless of income derived from GHG emission reductions (i.e., SOC sequestration and CH_4 reduction). Assuming that the Australian Government sets a carbon credit cap at $75 per Mg CO_2e abated (CER, 2023), the economic viability of biochar could be ensured if a minimum 5% improvement in LWG was realised. Otherwise, biochar supplementation would only be profitable if the cost of biochar was significantly below $2,000/ Mg, assuming substantial reductions in enteric CH_4 emissions could also occur (Fig. 2).

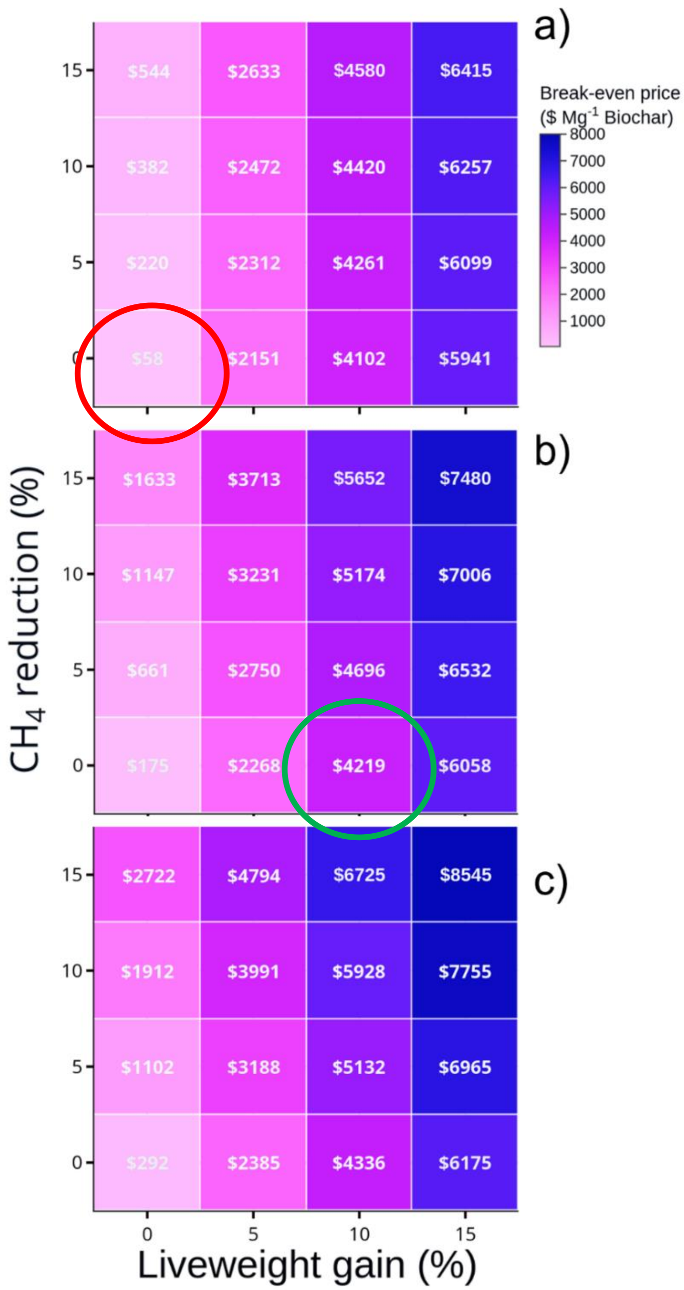
To determine an isometric (break-even) cost of biochar, we evaluated how income was influenced by LWG, biochar cost and carbon price. The variation in liveweight gain and enteric CH_4 reduction becomes important when determining the minimum cost when incorporating biochar into the system (Fig. 11). For example, if feeding biochar resulted in no change in LWG and enteric CH_4 emissions, and thus only the increase in carbon into the soil through manure deposition was valued at $25 per Mg, the biochar would need to cost < $58/ Mg to remain profitable (red circle in Fig. 3a). In contrast, if feeding biochar resulted in a 10% improvement in LWG, but still no reduction in enteric CH_4 (or the reduction could not be quantified and thus assumed zero change), although the increase in soil carbon could be justified and valued at $75/ Mg, the biochar could cost as much as $4,219/Mg to remain profitable (green circle in Fig. 3b). Improvements in LWG have a more significant impact on the break-even cost than enteric CH_4 reduction. For example, with a carbon price of $125/t Mg abated (Fig. 3c), the difference in break-even cost between 0 and 15% improvement in LWG, with 0% change in enteric CH_4, is $5,883, whereas the difference in break-even cost between 0 and 15% reduction in enteric CH_4, with 0% change in LWG, is $2,430. We also modelled a relatively low price for additional LWG, at $2.75/kg LW and thus if market prices for livestock are greater than this, the break-even cost for biochar would increase further, making the feeding of biochar more attractive.

Figure 10. Partial budgeting for use of biochar as a feed supplement



Relative net change in profitability (RNP, $/hd) is shown as a function of biochar cost (columns, $/Mg), price of carbon removals (rows, $/ Mg CO_2e abated), percentage liveweight change (LWG, %), and percentage reduction in methane emissions (CH_4 reduction, %) in figure 10.

Figure 11. Break-even cost of biochar as a livestock feed supplement

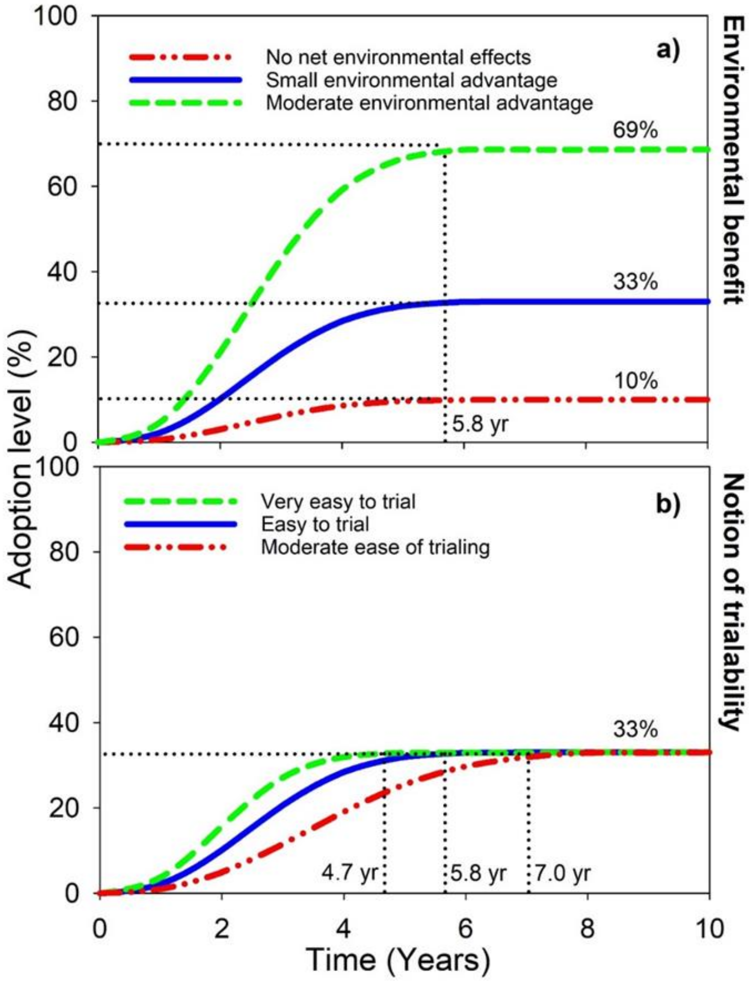


Break-even cost of biochar as a livestock feed supplement as influenced by liveweight gain (LWG, %) and reduction in methane emissions (CH_4 reduction, % relative to zero biochar control) in figure11. Biochar costs less than the value shown in the cell would realise profit. Panels depict alternative carbon prices: (a) $25 Mg CO_2e, (b) $75 Mg CO_2e and, (c) $125 Mg CO_2e abated. For example, for nil liveweight gain and methane mitigation and carbon price of $25/Mg CO_2e abated, biochar cost would need to be less than $58/Mg to realise profit (red circle). In contrast, for a liveweight gain of 10%, no methane mitigation, and carbon price of $75/ Mg CO_2e abated, biochar costs less than $4,219/Mg would be profitable (green circle).

4.5 Potential adoption and SWOT analyses

The projected adoption rate of biochar as a dietary additive varied as a function of perceived environmental benefits and practical implementation (Fig. 12, See Appendix 8.2 Supplementary material Figs. S1 and S2). A moderate level of environmental benefits would elevate peak adoption to nearly 70% (Fig. 12a). The time required to reach the peak adoption rate for biochar feeding was primarily influenced by trialability (See Appendix 8.2 Supplementary material Fig. S2). The peak adoption rate (33% of the population) was achieved approximately 5.8 years after adoption (range 5-7 years; Fig. 12b). The interviews and discussions conducted with participants from the biochar workshops and regional reference group highlighted the strengths, weaknesses, opportunities and threats associated with using biochar as a feed additive (Box 1). Further details are provided in Appendix 8.2 Supplementary material Table S1.

Figure 12. Adoption rates associated with use of biochar as a feed supplement on beef cattle.



Adoption rates associated with use of biochar as a feed supplement on beef cattle farms in Tasmania as influenced by (a) environmental advantage (peak adoption level) and (b) trialability (time to peak adoption) in figure 12.

Figure 13. Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis of feeding biochar in beef cattle systems.

Box 1. Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis of feeding biochar in beef cattle systems

Strengths (S)

- Free will and multiple delivery forms of feed-grade biochar.
- It is a long-lasting C sink and mixed with salt can help enrich soil that is deficient in certain minerals (e.g., cu, se, co).
- Good health indicators.
- Easily trialable.

Weaknesses (W)

- Time of handling and new skills.
- Expensive.
- Biochar production involves variable feedstock and a pyrolysis process, resulting in variable constituents that influence its potential properties and could be carcinogenic if not regulated.
- Uncertainty in the reduction of GHG emissions (it needs more research and it requires life cycle assessments).

Opportunities (O)

- May suit feedlot and dairy systems (feeding Total Mixed Rations).
- Carbon market.
- Co-benefits (e.g, soil health, fertiliser effect and accumulation of SOC, reduction of nitrous oxide emissions).
- Circular economy (e.g., waste from forestry sector, renewable energies, displacements of fossil fuels).

Threats (T)

- Competence with other feed additives.
- Consumer's decision making.
- The 'biochar industry' needs to be regulated by certification schemes (e.g., scale, type of pyrolysis used, feedstock, quality of charcoal).
- Food security issues by land use competition (*viz.* Shahpari et al. 2021) and caution about the amount of biomass diverted to biochar production.

4.6 End of project stakeholder engagement event

A webinar was held on Tuesday 21 November 2023 to converse biophysical, economic and environmental learnings from the project. The webinar received 350 registrations and, since posting online (7 days ago at time of writing), has been viewed 440 times. The webinar is available here: https://www.youtube.com/watch?v=3PFALaN7RMg

Real time polls held within the webinar indicated that attendees came from all States and territories of Australia, even some from overseas and were from a range of occupations, including farming, industry, government and research (Fig. 13).

Around 15% of attendees indicated that they learnt "a great deal" during the webinar, with more than 40% of people indicating that they learnt "quite a bit" (Fig. 14). More than 50% of people expressed interest in the farm results, farmer feedback and cost-benefit-mitigation scenario analysis. Attendees interest in further information and research primarily related to (1) productivity co-benefits, (2) benefit-cost ratios and (3) soil carbon and carbon trading, although a range of other reasons were raised (Fig. 14).

Figure. 14. Key demographics of attendees to the biochar webinar.

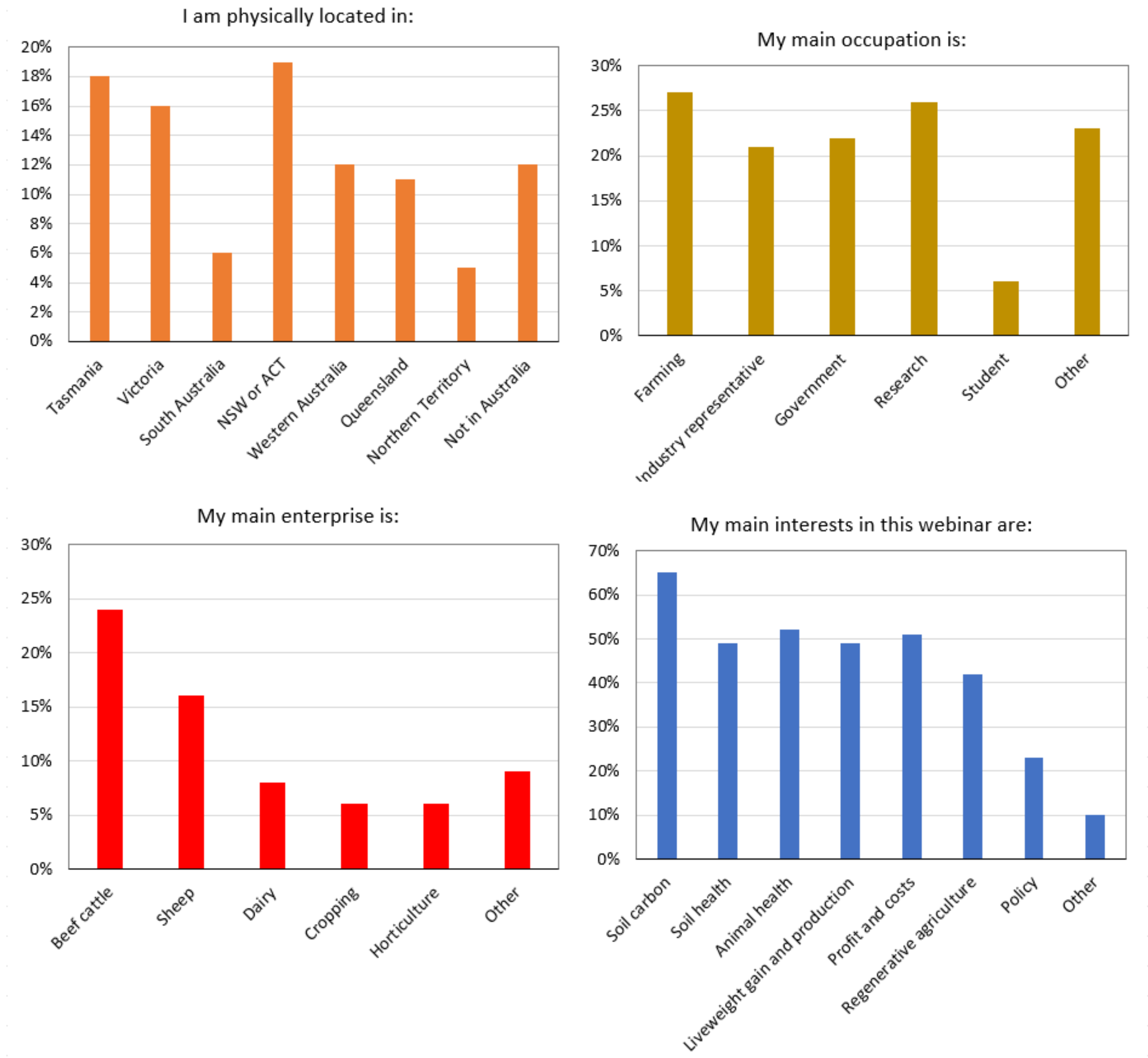
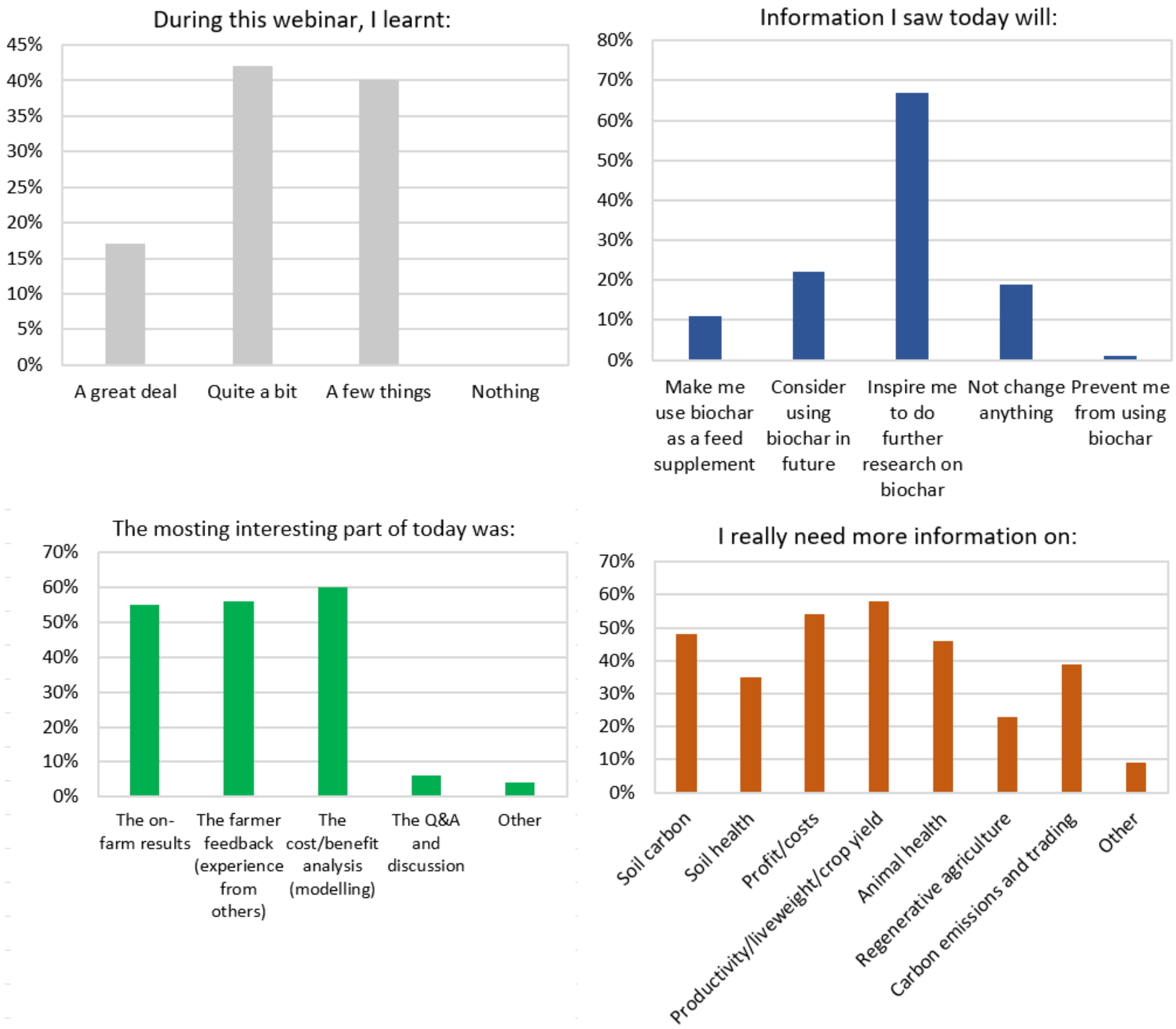


Figure. 15. Post-webinar survey of attendees to the biochar webinar.



5. Conclusions

5.1 Key findings and benefits to industry

5.1.1. I&P farm biochar feeding experiment

- Biochar supplementation increased liveweight gain by ~ 5% compared to the non-biochar fed animals.
- There were no significant differences in the carbon content of manure sampled between cohort of animals.
- The case study farmer suggested that biochar supplementation resulted in earlier appearance of winter coats and less manure scouring, implying animal health benefits.

5.1.2. Workshops on farms feeding biochar

- Attendance at workshops was highly valued, as such media provide first-hand opportunities to experience how biochar was implemented in a commercial context. Workshops provided peer-to-peer learning opportunities for producers, industry representatives, researchers and government attendees.
- Workshop participants primarily attended for four reasons: animal health, the nexus between animal and soil health, soil carbon/carbon trading, and need for knowledge associated with practical implementation within holistic management practices.

5.1.3. Post-workshop interviews

- Twenty-three workshop attendees were interviewed by phone 8-12 months after the workshops.
- Seven of the 23 attendees were already feeding biochar prior to the workshops, with a further five attendees having commenced feeding biochar post-workshops. This is a clear indication of adoption and impact of this research.
- Perceived benefits of biochar feed supplementation ranged from medicinal benefits and gut health to broader sustainability motivations such as reducing need for synthetic fertilisers from farm management practices.
- Producers raised four key areas of concern: the form biochar was available in (powdered in the present study); cost for benefit ratios; time requirements, and concerns over the long-term impacts of biochar. These issues present opportunities for the biochar industry to explore and benefit from the innovation and entrepreneurship of producers to overcome the practical and economic challenges associated with use of biochar.
- Producer-led innovations related to delivery mechanisms required for biochar to be practicable, use of biochar within a circular economy, local communities and industry.
- Our study suggests that biochar feed supplementation may benefit animal health during particular seasons in Tasmania that coincide with high green feed quanta. This implies that use of biochar could be limited to specific feeding rotations or when animal health issues

arise, rather than constant feeding. In this way, strategic use may help producers reduce cost and overcome time constraints. Further research is required in this space.
- Attendees frequently called for more research. Producers indicated they wanted tangible, face to face, contextualised, practical exposure to others using biochar. Our workshops and webinar partially fulfilled this dearth, although end-users engaged indicated that much more is called for in this endeavour (see further research section).

5.1.4. **Cost-benefit-mitigation scenario analysis**

- At current carbon prices (\$25-75/t CO_2e) and biochar costs, liveweight gains of juvenile animals would need to be at least 10% greater than unsupplemented controls.
- We showed that profit per animal was generally more sensitive to liveweight gains rather than to enteric methane mitigation, suggesting that biochar eliciting a productivity co-benefit may yield greater economic returns than biochar which causes greater relative mitigation of enteric methane.
- While current carbon prices and liveweight gains suggest that use of biochar as a feed supplement was not economical, carbon prices of \$75/t CO_2e coupled with enteric methane mitigation of 10% or more were profitable, suggesting that biochar feed supplementation could be more attractive if carbon and/or livestock prices increase in future.

5.1.5. **End of project webinar**

- A webinar held 21 November 2023 indicated that 15% of attendees learnt "a great deal"; more than 40% of people indicated they learnt "quite a bit". Attendee interest in further research primarily related to (1) productivity co-benefits, (2) benefit-cost ratios and (3) soil carbon and carbon trading, although a range of other reasons were raised. Almost 70% of people attending indicated the webinar had inspired them to do further research on biochar.

5.2 Benefits to industry

Many benefits associated with biochar feed supplementation were raised by end-users (for details, see Box 1, Appendix 8.2). Briefly, selected benefits, and barriers to adoption promulgated during workshops and producer interviews included:
- Carbon removal potential via mitigation of enteric methane, manure methane and nitrous oxide
- Ability to improve soil carbon stocks, soil health and ecosystem functioning
- Potential fit with circular economy and regenerative agendas
- Relatively ease of trialling and reversibility
- Scalability and cost were noted as a challenge
- Time commitment, and displacement of existing duties were perceived as key challenges. The opportunity cost associated with use of biochar would need to outweigh that of another existing chore. This sentiment applies to all farming systems interventions.
- Regulation and changing legislation were perceived as barriers to adoption.

6. Future research and recommendations

Many prospective opportunities worthy of deeper investigation were uncovered. In particular, industry engaged recommend further research on:

(1) Effects of biochar feedstocks (e.g. wood, crop residues etc), as peer-reviewed literature indicates a large disparity in liveweight gains associated with differing feedstocks and

(2) Impacts of long-term feed supplementation (at least three years) on

- Liveweight gains,

- Cost-benefit ratios,

- Soil organic carbon stocks (including mineralisation, micro aggregation, occlusion, rhizodeposition and sequestration; *viz.* Weng et al. 2022),

- Meat and milk quality, including dark cutting meat and microbial content of milk,

- Enteric methane mitigation and net emissions intensity, which hitherto have been largely unexplored.

Our results imply that biochar feed supplementation can improve sustainability (via collective impacts of the above), although further research is necessary to systematically dissect this notion. Stakeholders engaged through the project indicated very high interest in biochar, suggesting that investment in this endeavour would be cost-effective.

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8. Appendix

8.1 Workshop flyer and handouts

Biochar Workshop 1

NEXUS PROJECT

The NEXUS Project (supported by TIA and MLA Donor Company) is hosting a series of Biochar Workshops at three northern Tasmanian locations over the coming months: in the North (Dunorlan), North West (Marrawah), and North East (Ringarooma).

The program will be the same at each workshop.

DATE Friday 28 October 2022, 10am – 12.30pm, TasAgCo, 35 Sadlers Rd, Dunorlan

Morning tea and lunch provided

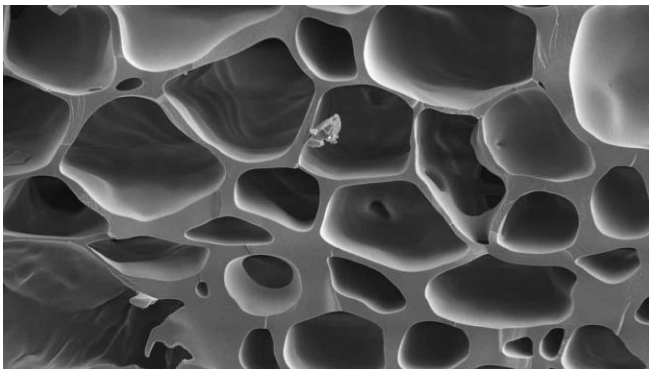
RSVP Register to nicoli.barnes@utas.edu.au by Tuesday, 25 October

UNIVERSITY of TASMANIA
TIA
Tasmanian Institute of Agriculture

mla
MEAT & LIVESTOCK AUSTRALIA

CRICOS 00586B

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 Package Tour Pre workshop data capture	Nici Barnes – TIA
10:45-11:00	Biochar Involve and Partner Project	Matt Harrison - TIA
11:10-11:25	Biochar	Biochar providers
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:

TIA is a joint venture of the University of Tasmania and the Tasmanian Government

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
- 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).

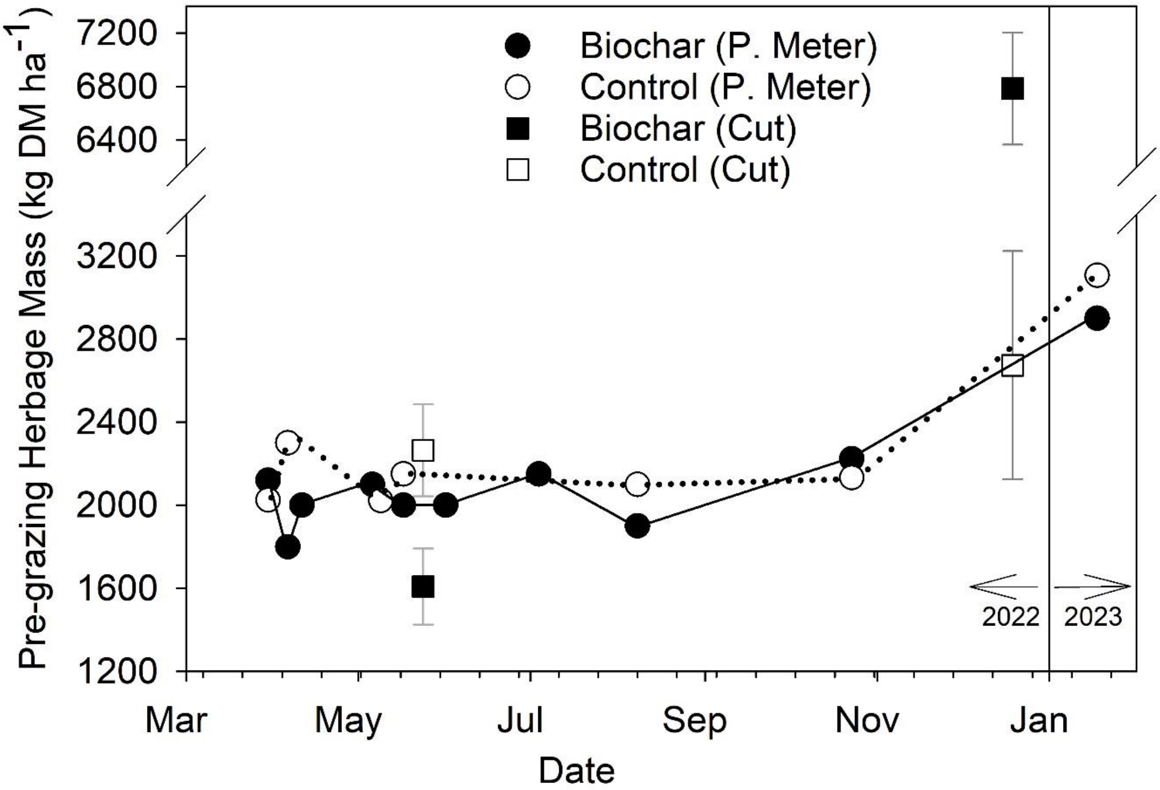


Fig. 1: Pre-grazing herbage mass of the control and biochar treatments has been similar over the duration of the experiment. Comparison of plate meter samples and hand cuts indicated little difference in methods for measuring pasture biomass.

- 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).

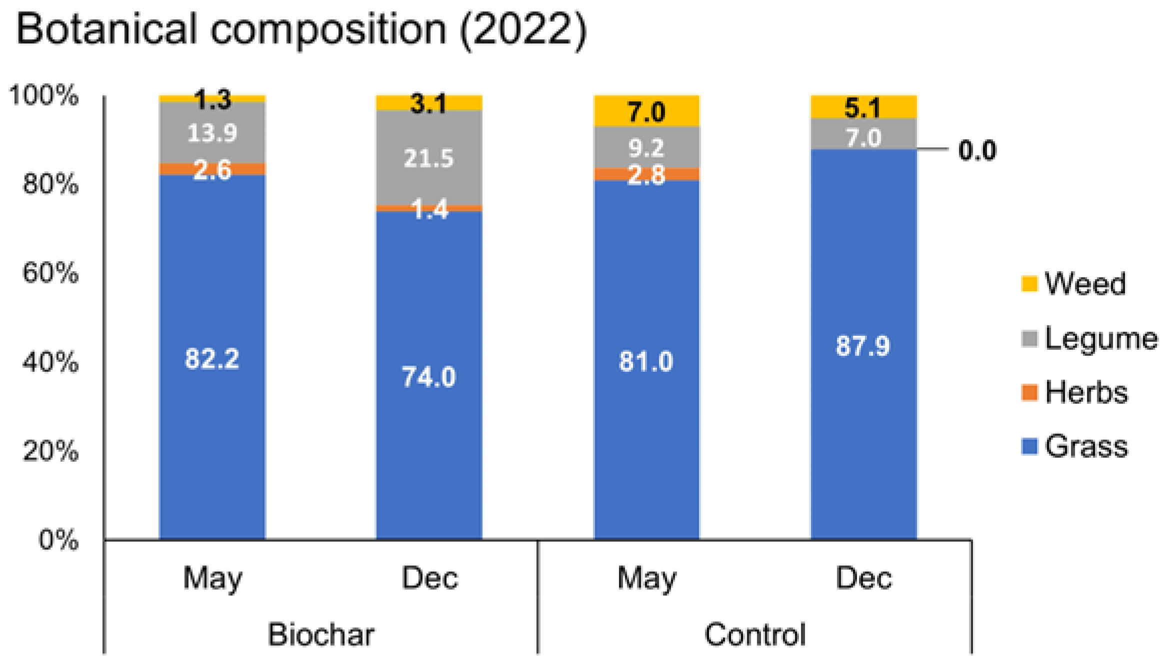


Fig. 2: Botanical composition in May and December 2022 of the control and biochar treatment groups.

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

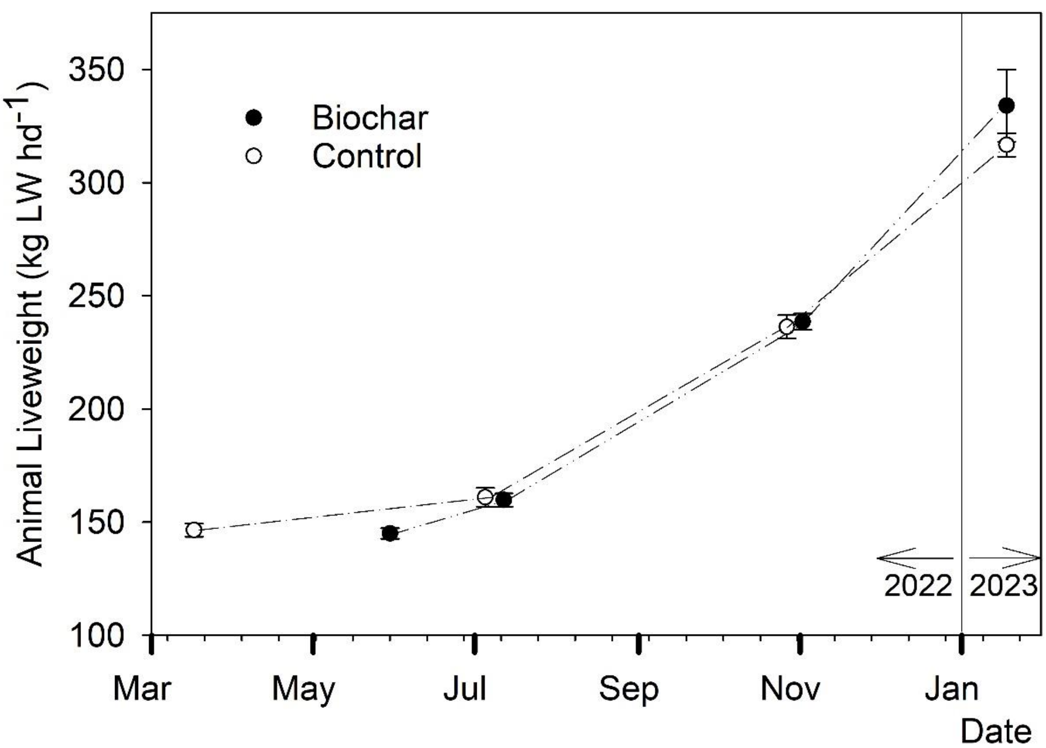


Fig. 3: Liveweight of the control and biochar cohorts over the duration of the experiment.

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).

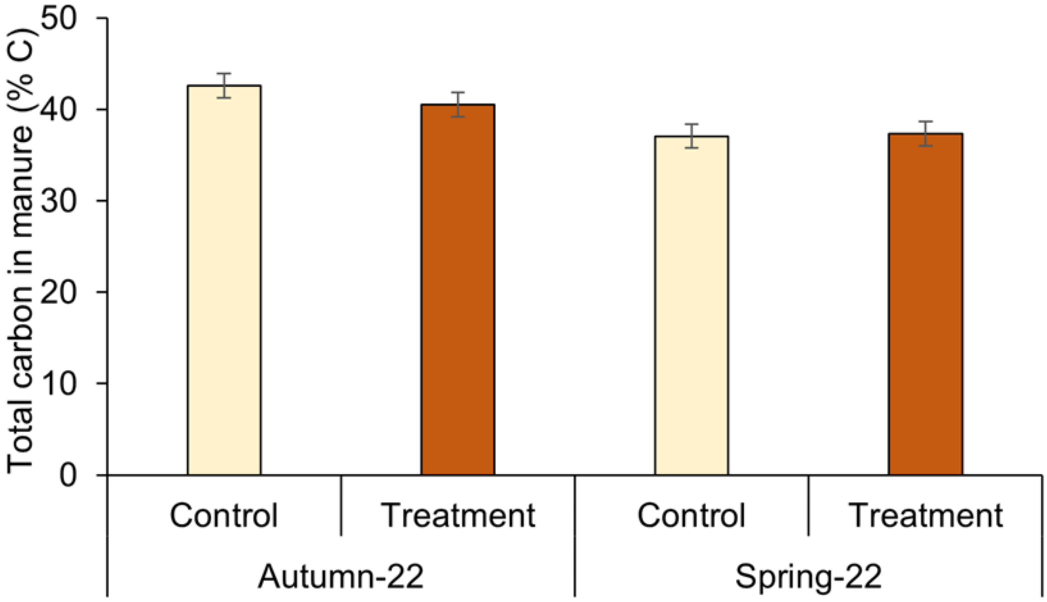
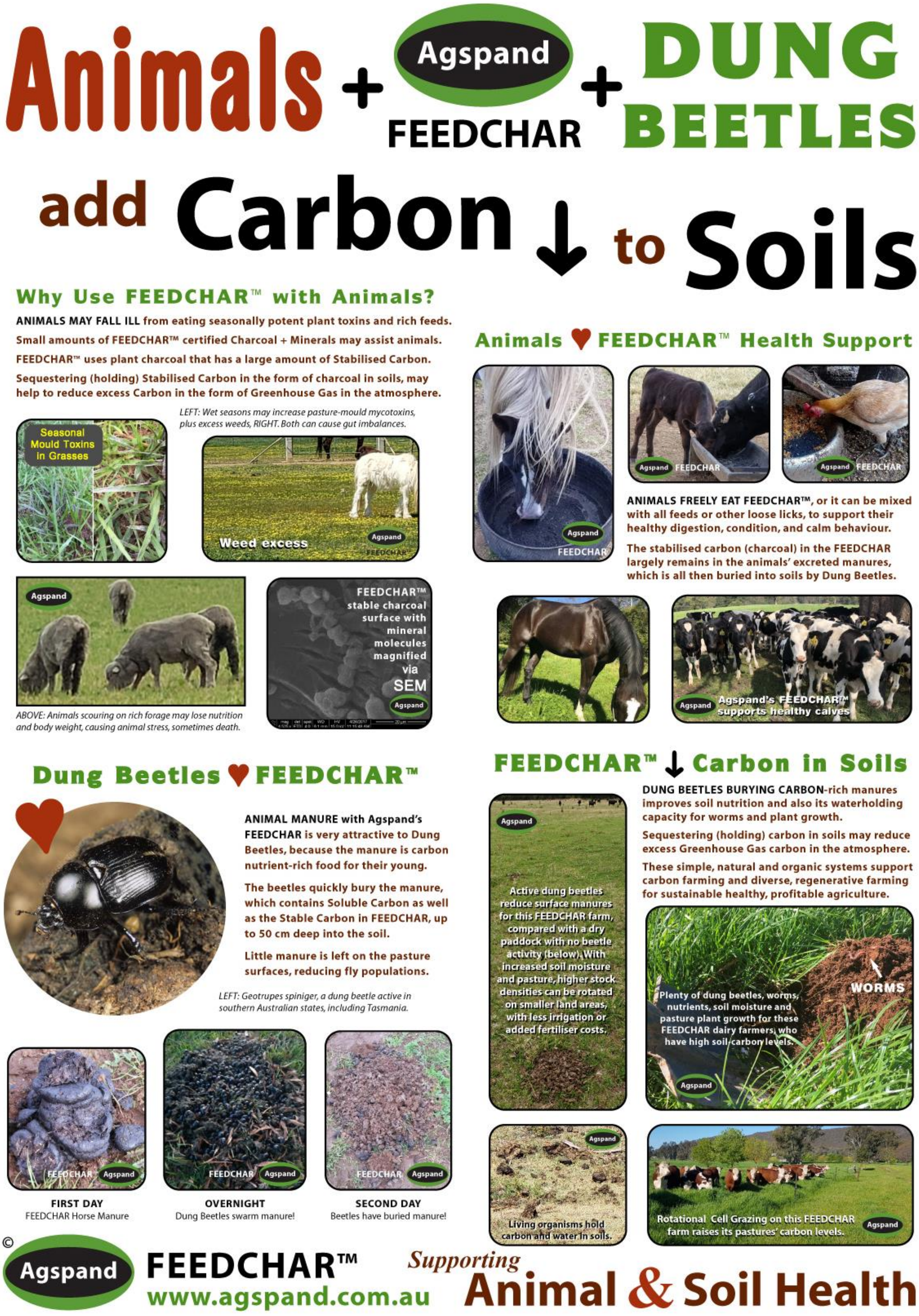


Fig. 4. Carbon control in manure for the control and biochar cohorts in autumn and spring 2022.



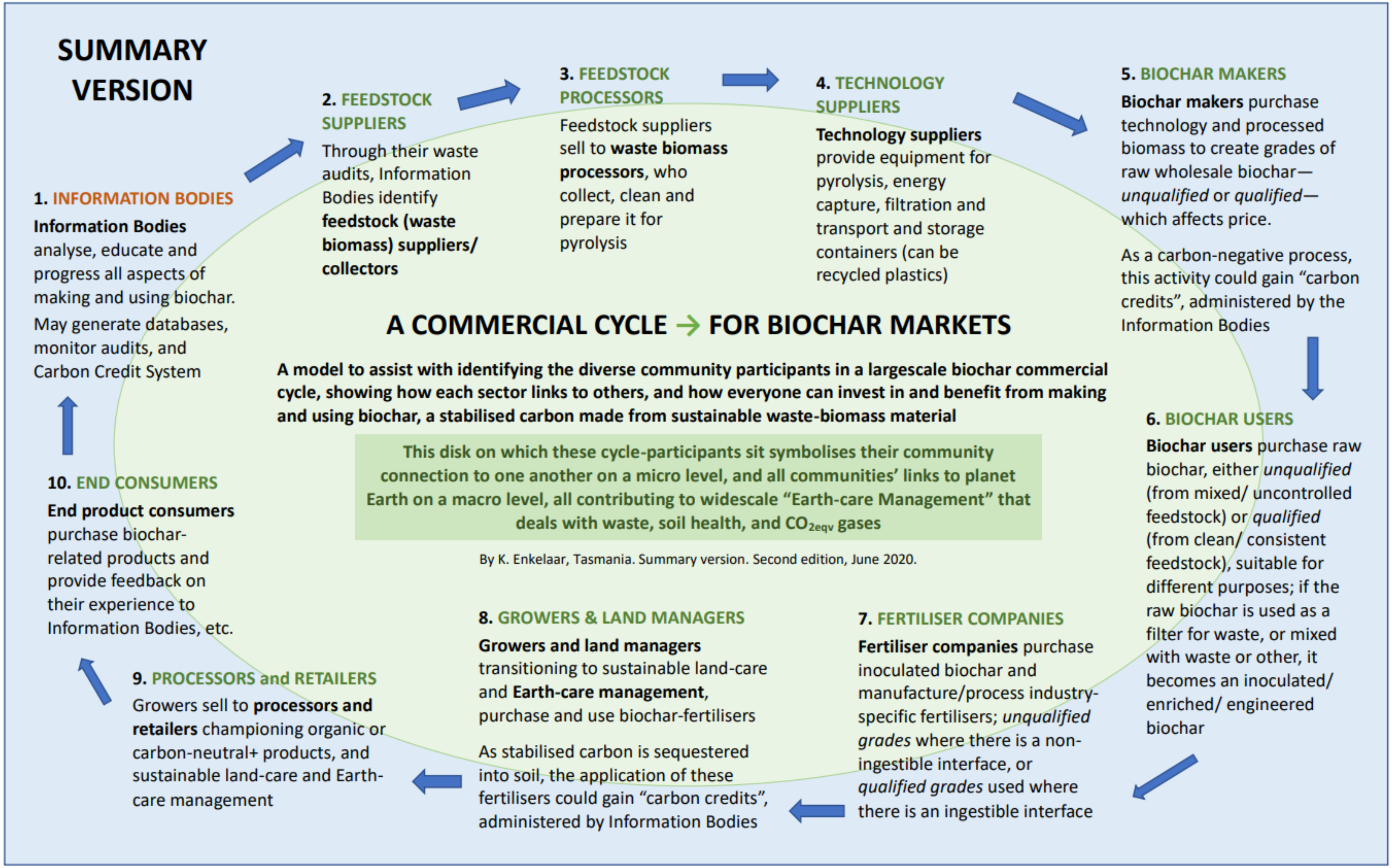
A COMMERCIAL CYCLE → FOR BIOCHAR MARKETS

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

https://www.sciencedirect.com/science/article/pii/S0341816221001430

https://www.sciencedirect.com/science/article/pii/S0167880917300087

https://www.sciencedirect.com/science/article/pii/S0929139316303687

https://www.mdpi.com/2076-3417/9/17/3494

https://www.sciencedirect.com/science/article/pii/S0304389415300170

https://www.mdpi.com/2073-4441/12/10/2847

https://www.sciencedirect.com/science/article/pii/S0167880915301651

https://www.sciencedirect.com/science/article/pii/S0301479718309538

https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-b96be06a-6a9d-4314-a2d8-1890b14bbaed

https://www.scirp.org/journal/paperinformation.aspx?paperid=73077

https://www.mdpi.com/1420-3049/26/18/5584

http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S0120-548X2020000200327

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 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

Nici

8.2 Operationalising net-zero with biochar: black gold or red herring?

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Abstract

Nascent anecdotal evidence implies that livestock feed supplementation with biochar may reduce enteric methane, improve liveweight gains (LWG) and improve soil carbon through enrichment of manure. Here we dissect this hypothesis using a transdisciplinary participatory approach. We show that steers fed with biochar *ad libitum* increased LWG relative to unsupplemented controls (5% improvement after 14 months). At carbon prices of \$25-75 Mg^{-1} CO_2-e and \$2,000 Mg^{-1} biochar, LWG would need to be at least 5% greater to be profitable. Profit per animal was more sensitive to LWG compared with enteric methane mitigation, suggesting greater economic value in pursuing types of biochar that elicit a productivity co-benefit, rather than biochar for mitigation of enteric methane. Our modelling of industry adoption showed that peak adoption of biochar was 10-69% over 5-7 years, depending on perceived environmental benefits and ease of trialing. The participatory approach with farmers revealed multiple strengths (e.g. animal health co-benefits and recalcitrant properties in the soil), weaknesses (cost, knowledge requirements), opportunities (carbon markets) and threats (potential antagonism with other feed additives, regulation) associated with biochar feed supplementation. We contend that livestock feed supplementation with biochar comprises a prospective pillar towards reducing agri-food GHG emissions in a sustainable way.

Keywords

Microbiome, nature based-technology, Environmental social governance, carbon market, adoptability, social license

1. Introduction

While growth in agri-food production has underpinned food security hitherto (Coomes, Barham, MacDonald, Ramankutty, & Chavas, 2019), the changing climate, increasingly punctuated by extreme weather events, threatens to undermine contemporary food supply (IPCC, 2021; Harrison 2021). The Food and Agriculture Organization of the United Nations estimates that 11-20% of global greenhouse gas (GHG) emissions are generated by the livestock sector (FAO, 2023; Xu et al., 2021), with 40% of which being derived from beef cattle production (FAO, 2023). These troubling statistics suggest that balancing agri-food needs with continuing climate adaptation and GHG mitigation will be one of the greatest challenges facing humanity in the 21st century (Bilotto et al., 2023a; Harrison et al., 2021; Liu et al.,2021). Such wicked problems call for the development of sustainable, transdisciplinary, persistent solutions that systematically unravel the linkage between production and GHG emissions (Harrison, Cullen, Tomkins, McSweeney, Cohn, & Eckard, 2016).

Even though Australia has one of the most variable climates in the world (King, Pitman, Henley, Ukkola, & Brown, 2020) and is increasingly impacted by extreme weather (Abram et al., 2021; Chang-Fung-Martel, Harrison, Brown, Rawnsley, Smith, & Meinke, 2021; Wasko et al., 2021), the nation is the largest exporter of sheep meat and third largest exporter of beef meat in the world (MLA, 2022; USDA, 2022). Australian beef cattle production and processing constitute 88% of total GHG emissions within the Australian red meat industry, with 79% of these emissions being derived from CH_4 enteric fermentation (Ridoutt, 2022). While feed additives such as ionophores, methanogenesis inhibitors, essential oils, plant extracts, and organic compounds hold promise (Tseten, Sanjorjo, Kwon, & Kim, 2022), feed additives may also come with social, animal health and welfare trade-offs (Harrison et al., 2021). Together, these sentiments suggest that the development of sustainable, profitable and socially acceptable emissions mitigation interventions are urgently needed (Taylor et al., 2016), particularly for enterprises based on grazing, as these comprise the majority of Australian livestock production systems (Rawnsley et al. 2019).

While biochar often receives attention as a soil amendment [*viz.* Khan et al. (2022)], less attention has been given to biochar as a livestock feed supplement. Despite this, nascent evidence suggests that biochar feed supplementation may inhibit CH_4 emissions by altering rumen microbial population, adsorbing toxins and volatile compounds, increasing rumen surface area and improving animal liveweight gains (Schmidt, Hagemann, Draper, & Kammann, 2019). Other co-benefits include the ability to adsorb and retain nutrients in dung such as nitrogen and phosphorus, which can otherwise be lost to the environment (Hedley, Camps-Arbestain, McLaren, Jones, & Chen, 2021). However, several implementation barriers associated with biochar remain to be resolved. Some of these include practical barriers in feeding, knowledge requirements (e.g. daily recommended dosage of biochar) and safety considerations (Hedley et al., 2021). It remains to be seen whether feed-grade biochar (biochar approved as a livestock feed additive) yields beneficial outcomes (‘black gold’) or is ultimately maladaptive (‘red herring’). Here we employed a transdisciplinary approach, involving participatory dialogue with a 'regional reference group' (RRG) comprising industry experts and farmers; on-farm field trials, farm workshops, cost/price scenario analysis, and prospects for long-term industry adoption of biochar using principles of diffusion of innovation. Specifically, we aimed to (1) measure the biophysical impact of biochar supplementation on pasture biomass, botanical composition, liveweight gain, and manure carbon content in a commercial farm environment, (2) model livestock production and net GHG emissions, (3) quantify the impact on whole-farm profitability, accounting for carbon offsets, and variation in market prices, (4) explore ease of adoption and long-term adoption potential, and (5) explore the wider social perceptions, including strengths, weaknesses, opportunities and threats (SWOT analysis).

2. Materials and Methods

2.1. Overview

This was very much a holistic transdisciplinary study, including numerical modelling, on-farm trials, discussion groups, social research and long-term adoption analysis. A field trial on a commercial farm was conducted to obtain credible insights for the regional reference group critique. The modelling encompassed multiple biophysical and economic models to simulate changes in pasture and livestock productivity, net greenhouse gas (GHG) emissions and profitability. The whole-farm model, GrassGro® (version 3.3.10), was used to simulate daily pasture and livestock production, while net GHG emissions were calculated using the Sheep Beef-Greenhouse Accounting Framework (SB-GAF version 1.4). Various social analyses were invoked to explore social and practical implications of biochar feed supplement adoption, including adoption barriers, social license to operate and new skills required. Model results and inputs were refined based on iterative feedback from the regional reference group to ensure credibility and legitimacy of the results [further details are given in Bilotto et al. (2023a,b). A reflexive thematic analysis (Braun & Clarke, 2019) was used to explore ideas that framed workshop participant motivations for use of biochar in their farm management system (profit, environmental, risk, etc.) and to elicit advantages, complexity and learnability of the intervention. Data obtained from biophysical modeling, farmer perceptions and feedback collected during interviews were used as inputs for the ADOPT model to estimate the potential long-term industry adoption of biochar [*viz*. James and Harrison (2016)]. This data was framed using a SWOT analysis (strengths, weaknesses, opportunities and threats) associated with adoption of biochar feed supplementation. Further details are shown below and in Fig. 1.

Fig. 1. General overview of the study

2.2. Type of biochar used

Feeding of the commercial feed-grade biochar (premium safety grade as feed additive) commenced in March 2022 and concluded in May 2023. Feed-grade biochar used was derived from waste forestry wood produced in Tasmania and contained around 10% natural mineral clay (bentonite) to ameliorate gut imbalances (e.g., acidosis). Feed-grade biochar passed WHO and Australian Organic Standard (2019) requirements specified for safe animal feed (Australian Organic, 2019). The physical appearance of the product was a black, odourless and granulated compound (1-5 mm) with a density of 226 kg m^{-3}. This product passed Animal Feed Grade Biochar test standards for heavy metals/contaminants and toxins listed in Code of Practice for the Sustainable Production and Use of Biochar developed by the Australian and New Zealand Biochar Industry Group (ANZBIG, 2021). Steer and heifer calves were fed this biochar *ad libitum* at intake rates between 0.5-1.0% on DM basis (30-50 g hd^{-1} d^{-1}), which equates to $AU0.06-0.10 hd^{-1} d^{-1}. Further chemical characteristics of the biochar are shown in Table 1.

Table 1. Chemical characteristics of feed-grade biochar used as feed supplement

Parameter	Value	Method
pH	8.97	Rayment & Lyons 2011 – 4A1 (1:10 Water)
Electrical Conductivity (dS/m)	0.38	Rayment & Lyons 2011 – 3A1 (1:10 Water)
Ash (%)	2.3	
Volatile Matter (%)	97.7	
SSA (m_2/g)	264.8	
Total Sulfur (%)	<0.01	Rayment & Lyons 2011 – 17C1 Aqua Regia
Total Hydrogen (%)	1.92	
Total Oxygen (%)	4.62	
Total Carbon (%)	91.0	LECO Trumac Analyser-Inhouse S15b
Total Nitrogen (%)	0.2	Inhouse S4a (LECO Trumac Analyser)
Total Phosphorus (%)	<0.01	
Total Potassium (%)	0.06	Rayment & Lyons 2011 – 17C1 Aqua Regia
Total Magnesium (%)	0.05	
Total Calcium (%)	0.17	
$CaCO_3$-eq (%)	1.33	AS4454:2012
Hydrogen/Organic Carbon Ratio	0.02	Calculation - Hydrogen/Total Organic Carbon
Oxygen/Organic Carbon Ratio	0.05	Calculation - Oxygen/Total Organic Carbon

2.3. Measurement of pasture biomass and botanical composition

Pre- and post-grazing herbage biomass was measured several times during the field trial using a plate meter (Earle & McGowan, 1979). In line with operations of the commercial farm, pasture quality and similar grazing pressure was maintained across treatments such that pre-grazing biomass did not exceed 3,000 kg DM ha^{-1} and post-grazing biomass was not less than 1,200 kg DM ha^{-1} (Chapman, 2016). Pasture botanical composition (proportions of grass, legumes, herbs, and weeds) and senescent material were assessed 28 days after the start of the regrowth period in both seasons through hand dissection of five sub-samples (4 m^2 each) per treatment cut to ground level.

2.4. Liveweight

Sixty Wagyu-cross calves were used to rotationally graze paddocks for each treatment (control and biochar). These animals were weighed six times over the duration of the experiment using a Gallaghar W-1 walkover scale. Weights were automatically matched with animal ear-tag for identification. Scales were zeroed twice during each measurement period.

2.5. Carbon content in manure

Total carbon content (%) from manure samples collected over two timeframes were collected in autumn and spring 2022 (n = 24 per treatment). Samples were sealed in plastic bags and stored on ice then transferred to the laboratory around 50 km away for immediate testing. Tests were completed by AgVita Laboratory, Spreyton, Tasmania. A t-test was performed to identify differences between mean total carbon content ($p<0.05$).

2.6. Strengths, weaknesses, opportunities and threats (SWOT) analysis

SWOT analyses (Strengths, Weaknesses, Opportunities, and Threats) have hitherto been used as a strategic planning and management technique for businesses to assess decision making. Our SWOT analysis was conducted following Díez-Unquera et al. (2012).

2.7. Modelling pasture and livestock production

The GrassGro® model (version 3.3.10) was used to longitudinally integrate the effects of multiple biophysical variables (climate, soils, pastures and livestock; farm management including soil fertility, paddock layout, grazing rotations, stocking rates) on pasture and livestock production (Moore, Donnelly, & Freer, 1997). GrassGro® has shown value in investigating the impacts of climate change on livestock productivity and profitability in pasture-based industries across regions including Australia (Bilotto et al., 2023b; Cullen, Eckard, Timms, & Phelps, 2016), North America, and Northern China (Duan, et al., 2011; Lynch, Cohen, Fredeen, Patterson, & Martin, 2005). The model deterministically computes a range of variables on a daily basis, including soil moisture, pasture growth, and quality metrics such as crude protein (%CP) and dry matter digestibility (%DMD) for each pasture species, paddock and farm. The model also computes sward attributes, pasture cover, persistence, availability, intake, supplementary feed requirements, liveweight change and the carry-over effects of feed from one year to the next. Initialisation and parameterisation of the model are described in Bilotto et al. (2023a,b).

2.8. Greenhouse gas emissions

The Sheep-Beef Greenhouse Accounting Framework [SB-GAF version 1.4, Dunn, Wiedemann, and Eckard (2020)] was used to compute net GHG emissions. SB-GAF employs Intergovernmental Panel on Climate Change methodology to compute farm net GHG emissions following Australian National Greenhouse Gas Inventory guidelines with animal liveweights, pasture quality and LWG inputs derived from GrassGro simulations. SB-GAF converts CH_4 and N_2O emissions into CO_2 equivalents (CO_2e) using 100-year global warming potentials of 28 and 265, respectively. Results include net farm emissions (Mg CO_2e annum^{-1}) and emissions intensity (Mg CO_2e Mg^{-1} product). Emissions allocation to meat production is guided by protein mass ratio following Wiedemann, Ledgard, Henry, Yan, Mao, and Russell (2015).

2.9. Modelling time to peak adoption

The ADOPT (Adoption and Diffusion Outcome Prediction Tool) model (Kuehne et al., 2017) was used to assess the time to reach peak adoption. ADOPT is tailored for forecasting the probable uptake of agricultural innovations within a specific land manager population (Pannell, Marshall, Barr, Curtis, Vanclay, & Wilkinson, 2006). The 22 input questions required to run the model were informed through discussions with the regional reference group (see *Supplementary Material*, Table S1). The majority of participants were motivated by profit and environmental enhancement and conservation. ADOPT inputs included (1) ease of evaluation, (2) availability of advice, (3) skill requirements, (4) observability of trials, (5) initial costs, (6) reversibility of implementation, (7) projected future profit and environmental gains, (8) potential increases in risk, and (9) farm management convenience.

2.10. Cost-mitigation scenario analysis

We examined the economic feasibility of biochar feed supplementation using partial budgets informed by our biophysical modelling. Young stock (steers and heifers) were fed with biochar after being weaned at 7 months until they were sold at 25 months. We conducted a sensitivity analysis using results from both the field trial and peer-reviewed literature (Table 2) to determine how profit changed. Based on modelled LW, LWG and DMI, we estimated a 0.5% of DMI as biochar (~30-40 g hd^{-1} d^{-1}). A price of 2.75 AUD kg^{-1} was assumed for LW above the control treatment [Heavy Steer Indicator | Meat & Livestock Australia (http://mla.com.au)]. Based on carbon markets and future projections (CER, 2023; EMBER, 2023), modelled GHG emission removals were credited (i.e., enteric CH_4 reduction and SOC sequestration) with a price range per unit Mg CO_2e abated. The level of C assumed was 91% as per Table 1 with 70% remaining by 100 years (Hedley et al., 2021). Thus, of total biochar consumed, around 65% was converted into soil organic carbon (Eq. 1-3).

Table 2. Lower and upper bounds used in the sensitivity analysis to examine perturbation of biochar prices, total GHG emissions abated, potential liveweight change and enteric methane mitigation

Variable	Levels	References
Price of biochar (AUD Mg^{-1} Biochar)	500, 1000, 1500, 2000	Cotter, Glass, Black, Madden, and Davison (2015); Hedley et al. (2021)

Price of Mg CO_2e abated (AUD Mg^{-1} CO_2e)	25, 75, 125	CER (2023); EMBER (2023)
Change on liveweight gain (%)	0, 5, 10, 15	Cotter et al. (2015); Fernandez (2020)
Methane reduction (%)	0, 5, 10, 15	Cotter et al. (2015); Fernandez (2020); Hedley et al. (2021)

$$\Delta \text{SOC (Mg SOC hd}^{-1}) = \frac{\text{Biochar fed per head (kg hd}^{-1})}{1000} \times 0.91 \times 0.70$$ **Equation (1)**

ΔSOC is the SOC change in Mg per head for lifetime,

0.91 is the C concentration assumed for biochar (Table 1),

0.70 is the biochar C lasting more than 100 years.

1,000 is a conversion factor from kg to Mg.

$$\Delta \text{Profit (AUD hd}^{-1}) = \Delta \text{LWG (kg hd}^{-1}) \times 2.75 + [\Delta \text{SOC } \times 3.67 + \Delta \text{CH}_4 \text{ reduction (CO}_2\text{e hd}^{-1})] \times \Delta \text{CCP} - \frac{\text{Biochar fed per head (kg hd}^{-1})}{1000} \times \Delta \text{Biochar price (AUD Mg Biochar}^{-1})$$ **Equation (2)**

ΔLWG is liveweight gain in kg per head for lifetime applying the factor levels selected from Table 2,

2.75 is the price for additional liveweight in kg above the control treatment,

3.67 is a conversion factor for SOC change into CO_2e estimated in Equation (1),

ΔCH_4 reduction is the variation is methane emissions (CO_2e) selected in the sensitivity analysis from Table 2,

ΔCCP is the carbon credit price (AUD Mg^{-1} CO_2e abated),

ΔBiochar price is the variation in biochar price per Mg fed selected from Table 2,

1000 is a conversion from kg to Mg.

$$\Delta \text{Break} - \text{even price (\$ Mg}^{-1} \text{ Biochar)} = \frac{\Delta \text{LWG (kg hd}^{-1}) \times 2.75 + [\Delta \text{SOC } \times 3.67 + \Delta \text{CH}_4 \text{ reduction (CO}_2\text{e hd}^{-1})] \times \Delta \text{CCP}}{\text{Biochar fed per head (kg hd}^{-1})} \times 1{,}000$$ **Equation (3)**

3. Results

3.1. Key biophysical factors measured in the on-farm biochar trial

Pre-grazing herbage biomass afforded to each treatment were similar (Fig. 2a). This biomass reached its peak of 3 Mg DM ha^{-1} during late spring and early summer, remaining relatively constant for the remainder of the year at approximately 2 Mg DM ha^{-1}. Grasses, predominantly perennial ryegrass (data not shown), constituted the primary vegetation group, followed by legumes (Fig. 2c). While there was minor divergence in botanical composition over time (Fig. 2c), LWG of the control and biochar treatments remained similar over the duration of the experiment (Fig. 2b). Taken together, these results indicate no significant differences between the pasture quantum and quality available across treatments. However, the gradual increase of LWG generated a significant 5% gain (+20 kg hd^{-1}) for the biochar treatment on the final measurement (Fig. 2b). Carbon content of manure varied more seasonally compared with between treatments (Fig. 2d; 3-6% variation across seasons).

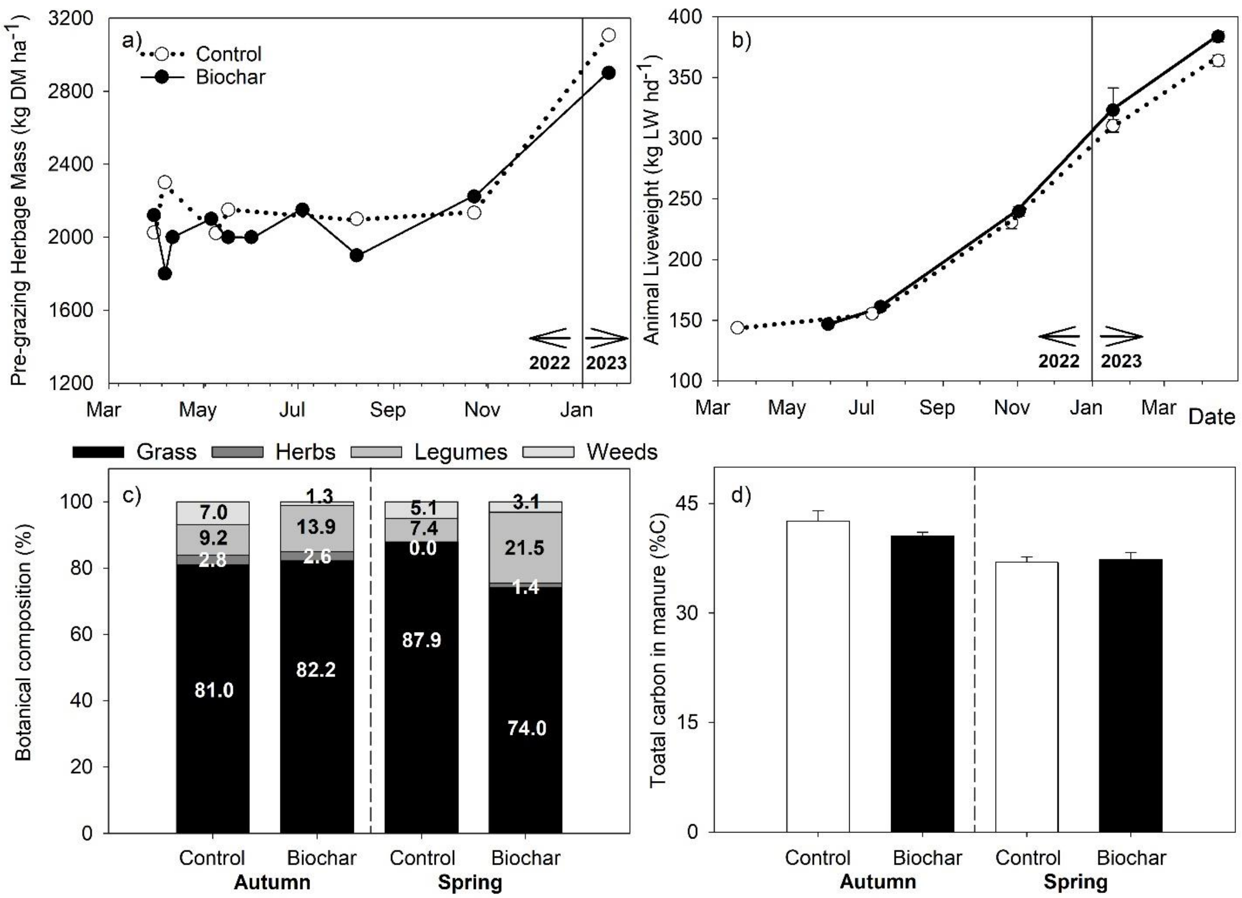

Fig. 2. Results from farm experiments with cattle fed biochar *ad libitum* at Deloraine, Tasmania, Australia. (a) pre-grazing herbage mass in the grazed paddocks (kg DM ha^{-1}), (b) mean animal liveweight (kg hd^{-1}) from grazing steers fed with biochar or no biochar (control), (c) botanical composition (%), (d) mean total carbon content of manure collected in autumn and summer 2022. Error bars depict standard error of the mean.

3.2. Partial budget and break-even price for biochar as feed additive

Our sensitivity analysis showed that at a lower cost per unit of biochar and higher carbon pricing, an expected greater potential for improving LWG and reducing enteric CH_4 emissions may result in a higher relative net profitability per head (Fig. 3, Tables S2-S5). When aiming for a projected 15% increase in LWG, the incorporation of biochar into the diet was highly profitable (exceeding $100 per head), reaching its maximum point when a 15% reduction in CH_4 emissions was attained. This favourable outcome was amplified by a high carbon credit valuation of $125 Mg CO_2e and a price of $500 Mg^{-1} biochar (Fig. 3). However, economic losses were incurred when carbon prices fell to $25 Mg^{-1} CO_2e and no improvement in LWG was realised (Tables S2-S5), regardless of income derived from GHG emission reductions (i.e., SOC sequestration and CH_4 reduction). Assuming that the Australian Government sets a carbon credit cap at $75 Mg CO_2e (CER, 2023), the economic viability of biochar could be ensured if a minimum 5% improvement in LWG was realised. Otherwise, biochar supplementation would only be profitable if the cost of biochar was significantly below $2,000 Mg^{-1} assuming substantial reductions in enteric CH_4 emissions could also occur.

To determine an isometric (break-even) price of biochar, we next evaluated how income was influenced by LWG, biochar cost and carbon price. The variation in enteric CH_4 reduction therefore becomes important when determining the minimum price to pay when incorporating biochar into the system (Fig. 4). Carbon prices (Australian Carbon Credits Units) from $25-75 Mg^{-1} CO_2e yield attractive margins, from $151 to $1713 per Mg of biochar (Fig. 4a and 4b). Assuming no improvement in LWG, a high price ($125 Mg^{-1} CO_2e) for carbon offsets and enteric CH_4 reductions exceeding 10% would cover and justify prices of biochar higher than $2,000 per Mg (Fig. 4c).

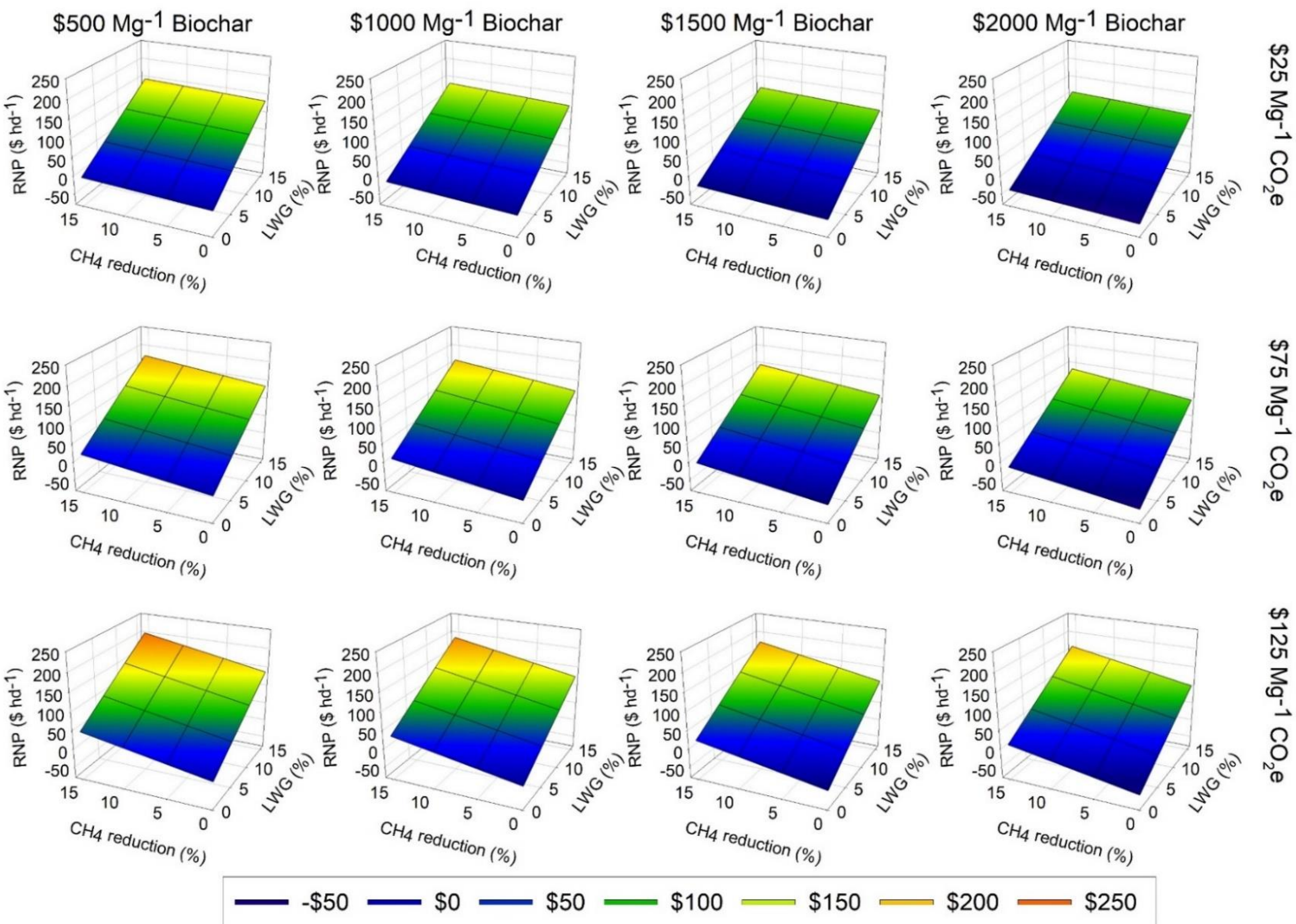

Fig. 3. Partial budgeting for use of biochar as a feed supplement. Relative net change in profitability (RNP, $ hd^{-1}) is shown as a function of the price of biochar (columns, $ Mg^{-1}), price of carbon removals (rows, $ Mg CO_2e), percentage liveweight change (LWG, %), and percentage reduction in methane emissions (CH_4 reduction, %).

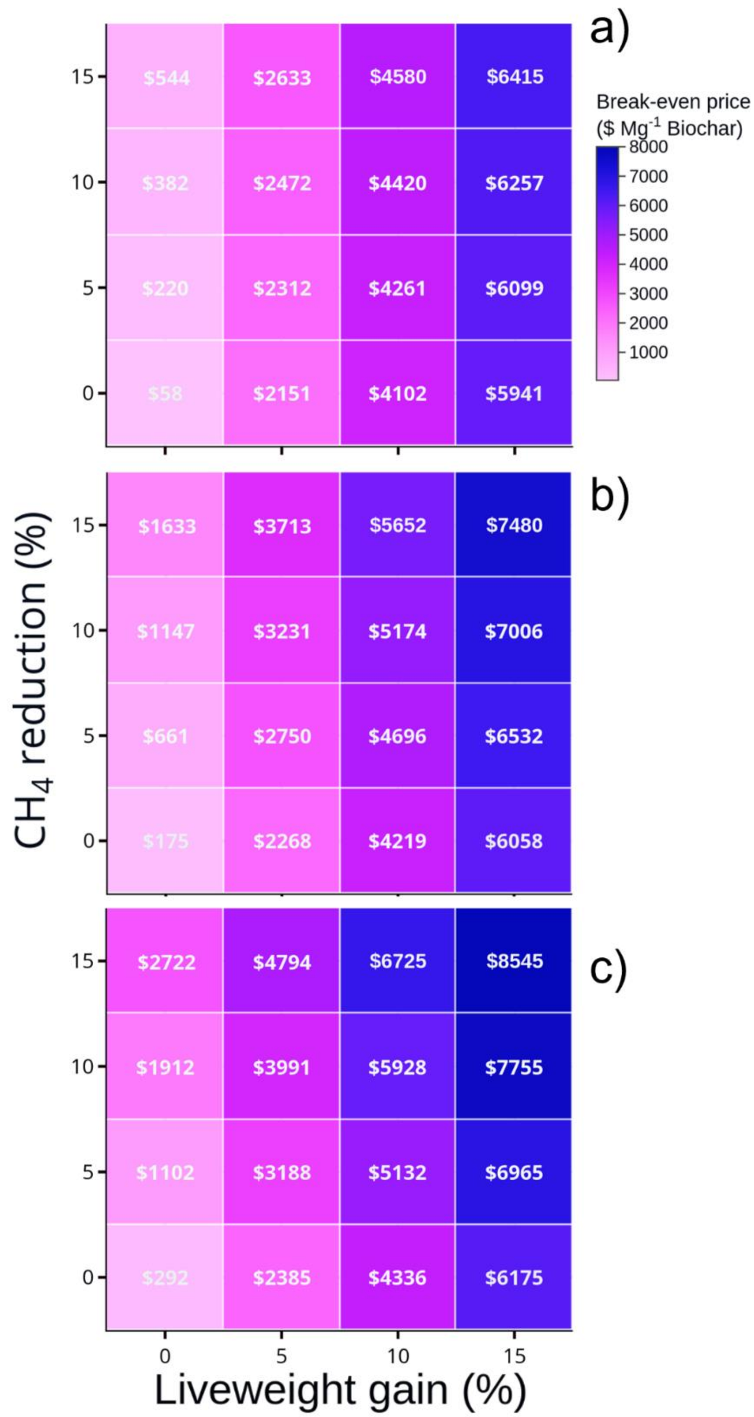

Fig. 4. Break-even price of using biochar as a livestock feed supplement as influenced by liveweight gain (LWG, %) and reduction in methane emissions (CH_4 reduction, % relative to zero biochar control). Panels depict alternative carbon credit prices: (a) \$25 Mg CO_2e, (b) \$75 Mg CO_2e and, (c) \$125 Mg CO_2e. For example, for a liveweight gain and methane mitigation of zero with a carbon price of \$25 Mg CO_2e, a biochar cost of more than \$58 Mg^{-1} would result in loss of income (negative profit).

3.3. Potential adoption and SWOT analysis

The projected adoption rate of biochar as a dietary additive varied as a function of perceived environmental benefits and practical implementation (Fig. 5, S1 and S2). A moderate level of environmental benefits would elevate peak adoption to nearly 70% (Fig. 5a). The time required to reach the peak adoption rate for biochar feeding was primarily influenced by trialability (Fig. S2). The peak adoption rate (33% of the population) was achieved approximately 5.8 years after adoption (range 5-7 years; Fig. 5b). The interviews and discussions conducted with participants from the biochar workshops and regional reference group highlighted the strengths, weaknesses, opportunities and threats associated with using biochar as a feed additive (Box 1). Further details are provided in the *Supplementary* Materia, Table S1.

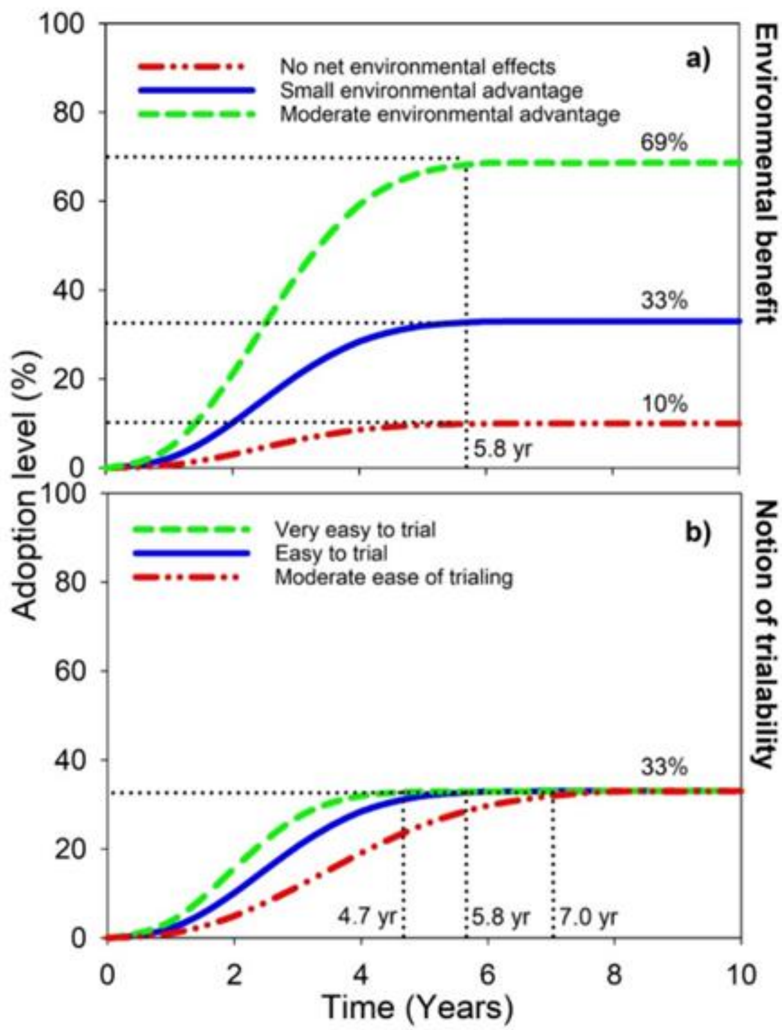

Fig. 5. Adoption rates associated with use of biochar as a feed supplement on beef cattle farms in Tasmania as influenced by (a) environmental advantage (peak adoption level) and (b) trialability (time to peak adoption).

Box 1. Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis of feeding biochar in beef cattle systems

Strengths S

- Free will and multiple delivery forms of feed-grade biochar.
- It is a long-lasting C sink and mixed with salt can help enrich soil that is deficient in certain minerals (e.g., cu, se, co).
- Good health indicators.
- Easily trialable.

Weaknesses W

- Time of handling and new skills.
- Expensive.
- Biochar production involves variable feedstock and a pyrolysis process, resulting in variable constituents that influence its potential properties and could be carcinogenic if not regulated.
- Uncertainty in the reduction of GHG emissions (it needs more research and it requires life cycle assessments).

Opportunities O

- May suit feedlot and dairy systems (feeding Total Mixed Rations).
- Carbon market.
- Co-benefits (e.g, soil health, fertiliser effect and accumulation of SOC, reduction of nitrous oxide emissions).
- Circular economy (e.g., waste from forestry sector, renewable energies, displacements of fossil fuels).

Threats T

- Competence with other feed additives.
- Consumer's decision making.
- The 'biochar industry' needs to be regulated by certification schemes (e.g., scale, type of pyrolysis used, feedstock, quality of charcoal).
- Food security issues by land use competition (*viz.* Shahpari et al. 2021) and caution about the amount of biomass diverted to biochar production.

4. Discussion

4.1. Impacts of biochar supplementation on liveweight gain, methane mitigation, and enterprise profit

We found a significant increase in LWG for the biochar treatment after around 14 months. Given that pasture biomass and composition were relatively similar across treatments, these differences may be attributed to biochar consumption. Schmidt et al. (2019) suggested that biochar alters rumen microbiota, with supplemented animals being more efficient in breaking down forage, leading to enhanced animal performance. Calvelo Pereira, Muetzel, Camps Arbestain, Bishop, Hina, and Hedley (2014); Schmidt, et al. (2019) demonstrated that biochar had no negative effects on *in vitro* rumen activity and, when used as dietary supplement for livestock, catalysed volatile fatty acid production with positive effects on animal growth of cattle (LWG, feed conversion ratio, and nutrient intake). Given these effects, it is plausible that LWG of the biochar treatment observed here would have been greater had the experiment continued for a longer time.

The association between feeding biochar and LWG may indicate a potential reduction in emissions intensity (via reduced enteric CH_4 per unit of product and per head of cattle). Derivative feedstocks (raw material to produce biochar) vary in efficacy on plant yields when used as fertilisers or liming agents (Khan et al., 2022) depending on season and production system (Bilotto et al., 2023a,b). This suggests that the type of biochar may influence potential methane production. It is also possible that methane mitigation varies depending on how seasonal climatic conditions, nutrition and abiotic stress impact on pasture growth (Langworthy et al., 2018; Singhal et al., 2023). Terry et al. (2019) reported no effect of biochar supplementation on CH_4 production for cattle fed a barley-silage diet at one of three doses (0.5%, 1.0%, or 2.0% DMI), using biochar derived from pine tree wood. In contrast, Al-Azzawi, Bowtell, Hancock, and Preston (2021) achieved a much larger 30-40% reduction in CH_4 emissions from dairy cows by supplementing with 0.5% DMI of high-activity microporous powdered activated biochar. Fernandez (2020) suggested that methods applied by Al-Azzawi et al. (2021) may have overestimated CH_4 reduction and suggested that standardised methods for comparing across studies would be necessary. Furthermore, extending the trial duration into a long-term experiment and ensemble modelled could be used to further evaluate SOC dynamics (Mackay, Vibart, McKenzie, Costall, Bilotto, & Kelliher, 2021; Sándor et al., 2020). We add that pasture biomass and digestibility have a large bearing on liveweight gains and vary seasonally (Phelan, Harrison, Kemmerer, & Parsons, 2015; Taylor, et al., 2016), and thus should be a key factor in formulating standardised comparisons of GHG mitigation across studies.

We used a scenario analysis of carbon price, biochar cost and LWG to determine economic prospects for biochar supplementation under a range of biophysical and/or economic conditions. The combination of a 5% improvement in livestock production, with no changes in CH_4 emissions, along with carbon price of 75 AUD Mg^{-1} CO_2e implies that biochar costs would need to be less than 225 AUD Mg^{-1} (<22.5 cents kg^{-1} biochar) to be affordable for beef producers. Assuming current biochar costs of around 2000 AUD Mg^{-1} and current carbon credit prices around 40 AUD Mg^{-1} CO_2e [noting that carbon prices are highly variable, ranging between 30 and 60 AUD Mg^{-1} in 2022 alone; (CER, 2023)], LWG would need to increase by 5% with concurrent mitigation of enteric methane of >5% to get a substantial economic benefit (Fig. 3 and 4). This highlight economic challenges in initiating and enabling adoption of new GHG emissions mitigation options (Harrison, Christie, Rawnsley, & Eckard, 2014; Meier, Thorburn, Bell, Harrison, & Biggs, 2020; Taylor et al., 2016) as well as the extent to which carbon prices would need to increase should biochar supplementation become a viable prospect. According to Wrobel-Tobiszewska, Boersma, Sargison, Adams, and Jarick (2015), improvement in the efficiency with which woody residues are collected, use of larger pyrolysis machines and a greater market share could potentially reduce biochar cost to less than 0.4 AUD kg^{-1}. This price would make incorporation of biochar in beef cattle system (e.g. via backgrounding and finishing) more viable (Fig. 3 and 4). Bundling of biochar within innovation bundles could yield complementary productivity co-benefits that may reduce GHG emissions in a profitable way (e.g., improved feed conversion efficiency, deep-rooted pastures species, etc.) (Bilotto et al., 2023b; Harrison et al. 2021).

4.2. Enablers and barriers to adoption of biochar as a feed supplement

We showed that potential peak of adoption of biochar as a feed supplement depends on potential economic and environmental benefits (Fig. 5, S1 and S2). Our results suggest that the modest profit advantage together with minor emissions reduction (CH_4 reduction and SOC sequestration) may be responsible for the relatively low adoption rates shown here (10-69% over 5-7 years). The feedstock and main components of feed-grade biochar have a direct impact on the quantities required and consumed by animals, thus influencing profitability or potential losses. While the modelling and participatory discussions indicate that the mitigation benefit was small, there could be multiple other co-benefits that would further add to the viability of biochar. Some of these include (1) soil health, (2) SOC accrual and (3) mitigation of nitrous oxide emissions, which can be high for intensive livestock systems (Christie et al., 2014; Bilotto et al., 2021). Biochar can be produced from waste crops or forestry products (e.g. waste forestry wood in Tasmania), suggesting potential fit with the circular economy and displacement of fossil fuel use (Box 1, Hedley et al., 2021). Partial life cycle analysis suggests that the gross impact for biochar production in Tasmania was 220 kg CO_2e (Norgate et al., 2011), which could potentially negate the reduction of GHG emissions at the farm level. However, production of biochar could also displace energy via electricity generation from coal and eucalyptus oil. These results clearly suggest that there would be merit in future assessments of life-cycle analysis of different types and uses of biochar.

Our work suggests that biochar feed supplementation is easily trialable. One approach to delivery of biochar was suggested in a farm workshop in north-western Tasmania, which was the integration of biochar into silage to guarantee consumption by livestock. The labor and farm operations required to implement this feeding mechanism are similar to other feed additives (Farney, Allen, & Muniz, 2023; Slozhenkina, Gorlov, Pristupa, Kolosov, & Fedorov, 2020) and could be argued to be very low given the silage would be fed regardless of whether or not biochar supplementation would take place. Indeed, many livestock production systems use feed supplementation for at least part of the year, particularly in pasture-based systems (Phelan et al., 2015; Langworthy et al., 2018). Additionally, biochar supplementation is arguably similar to other forms of feed supplementation (Box 1), which implies that most farmers would not require additional skills and knowledge if they already supplement livestock. We note that our participatory discussions with farmers and industry – where results from research were discussed and refined as part of farm workshops – improved the awareness of biochar as a feed supplement, but also allowed us to gauge industry perception of biochar as a mitigation intervention.

4.3. Unlocking biochar production potential: Implications for livestock farming

The International Panel on Climate Change (IPCC) 2019 called for deeper insight into biochar production, use (composting, animal feed, soil amendment) and potential sources (IPCC, 2019) to include in national inventories. Tasmania has a substantial potential for large-scale biochar production, driven by its sustainable supply of forest biomass, estimated at 3 Tg yr^{-1} (Wrobel-Tobiszewska et al., 2015), with State-based forestry plantations spanning more than 100,000 hectares. Assuming that (1) 15% of fresh harvested woody residues enters the biochar market for agricultural use (Wrobel-Tobiszewska et al., 2015), (2) 60% yield in air-dried wood (suitable for either burning on-site or kiln combustion) and (3) 25% conversion into biochar (Hedley et al., 2021), Tasmania could produce 67.5 gigagrams (Gg) of biochar *inter alia*. At 0.5-1% DMI, this quantum would be enough to feed 1.4-2.8M weaners (heifers and steers) until slaughter weight. We suggest that more data from trials and standardised methodologies are required to measure the impact of biochar on GHG emissions (CH_4, N_2O and CO_2) and confine uncertainties before more precise biochar emissions factors could be defined for the Australian National Inventory (DCCEEW, 2023).

5. Conclusions

We did not find evidence to suggest that biochar feed supplementation enriches organic carbon in manure, and thus we suggest that our trial would have had little influence on soil organic carbon. We note however that biochar fed over longer durations may have more influence on soil organic carbon than that observed here, particularly given that consumption increased with liveweight. At current carbon prices ($25-75 Mg^{-1} CO_2e) and biochar costs, liveweight gains of juvenile animals would need to be at least 5% greater than unsupplemented controls. We showed that profit per animal was generally more sensitive to liveweight gains rather than to enteric methane mitigation, suggesting that biochar eliciting a productivity co-benefit may yield greater economic returns than biochar which causes greater relative mitigation of enteric methane. While current carbon prices and liveweight gains suggest that use of biochar as a feed supplement was not economical, carbon prices of $75 Mg^{-1} CO_2e coupled with enteric methane mitigation of 10% or more were profitable, suggesting that biochar feed supplementation could become an attractive proposition if carbon and/or livestock prices increase in future. We showed that peak industry adoption of biochar would vary between 10-69% over 5-7 years, depending on perceived environmental benefits of biochar. Our social research further revealed multiple strengths (e.g. animal health co-benefits and recalcitrant properties of biochar in the soil), weaknesses (cost, difficulty in feeding, new knowledge required), opportunities (carbon markets, use in feedlots) and threats (potential antagonism with other feed additives, industry regulation) associated with biochar as a feed supplement. Overall, we contend that use of biochar feed supplementation comprises another pillar towards reducing agri-food GHG emissions in a sustainable way, and we recommend further research of how results vary with alternative types of biochar.

Author contributions

F.B., K.M.C-W., N.B., M.T.H. conceiving and/or designing the research output. F.B., K.M.C-W., N.B., M.T.H. 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.H. contributing knowledge, where justified, including indigenous knowledge. F.B., K.M.C-W., N.B., M.T.H. analysing and/or interpreting databases. F.B., K.M.C-

W., N.B., M.T.H. drafting significant parts of research output/s or critically revising output/s to contribute to interpretation.

Declaration of competing interest

The authors declare no competing interests.

Data availability

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

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Supplementary Material for

Operationalising net-zero with biochar: black gold or red herring?

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This file includes:

Table S1. Questionnaire and inputs (responses) to run ADOPT model (https://adopt.csiro.au/) informed through discussions with the regional reference group.

Table S2. Partial budgeting for use of feed-grade biochar as a feed supplement with a price of 500 AUD Mg^{-1}. Net profit plus carbon offset (AUD hd^{-1}) is shown as a function of the price of carbon removals (CCP: 25, 75 and 125 AUD Mg CO_2e), change liveweight gain (0, 5, 10 and 15%) and methane reduction (0, 5, 10 and 15%).

Table S3. Partial budgeting for use of feed-grade biochar as a feed supplement with a price of 1,000 AUD Mg^{-1}. Net profit plus carbon offset (AUD hd^{-1}) is shown as a function of the price of carbon removals (CCP: 25, 75 and 125 AUD Mg CO_2e), change liveweight gain (0, 5, 10 and 15%) and methane reduction (0, 5, 10 and 15%).

Table S4. Partial budgeting for use of feed-grade biochar as a feed supplement with a price of 1,500 AUD Mg^{-1}. Net profit plus carbon offset (AUD hd^{-1}) is shown as a function of the price of carbon removals (CCP: 25, 75 and 125 AUD Mg CO_2e), change liveweight gain (0, 5, 10 and 15%) and methane reduction (0, 5, 10 and 15%).

Table S5. Partial budgeting for use of feed-grade biochar as a feed supplement with a price of 2,000 AUD Mg^{-1}. Net profit plus carbon offset (AUD hd^{-1}) is shown as a function of the price of carbon removals (CCP: 25, 75 and 125 AUD Mg CO_2e), change liveweight gain (0, 5, 10 and 15%) and methane reduction (0, 5, 10 and 15%).

Fig. S6. Sensitivity analysis for peak adoption level associated with use of feed-grade biochar. Based on the data entered, the ADOPT model suggests what response (Table S1) would have the biggest effect on adoption rates.

Fig. S2. Sensitivity analysis for time to peak adoption level associated with use of feed-grade biochar. Based on the data entered, the ADOPT model suggests what response (Table S1) would have the biggest influence on time to peak of adoption.

Table S1. Questionnaire and inputs (responses) to run ADOPT model (https://adopt.csiro.au/) informed through discussions with the regional reference group

Questions/Practice	**Feeding Feed-Grade Biochar**
RELATIVE ADVANTAGE FOR THE POPULATION	
Profit orientation	
1. What proportion of the target population has maximising profit as a strong motivation?	Almost all have maximising profit as a strong motivation
Environmental orientation	
2. What proportion of the target population has protecting the natural environment as a strong motivation?	Almost all have protection of the environment as a strong motivation
Risk orientation	
3. What proportion of the target population has risk minimisation as a strong motivation?	A minority have risk minimisation as a strong motivation
Enterprise scale	
4. On what proportion of the target farms is there a major enterprise that could benefit from the innovation?	Almost all of the target farms have a major enterprise that could benefit
Management horizon	
5. What proportion of the target population has a long-term (greater than 10 years) management horizon for their farm?	Almost all have a long-term management horizon
Short term constraints	
6. What proportion of the target population is under conditions of severe short-term financial constraints?	Almost none currently have a severe short-term financial constraint
LEARNABILITY CHARACTERISTICS OF THE INNOVATION	

Trialable

7. How easily can the innovation (or significant components of it) be trialled on a limited basis before a decision is made to adopt it on a larger scale?	Easily trialable

Innovation complexity

8. Does the complexity of the innovation allow the effects of its use to be easily evaluated when it is used?	Slightly difficult to evaluate effects of use due to complexity

Observability

9. To what extent would the innovation be observable to farmers who are yet to adopt it when it is used in their district?	Easily observable

LEARNABILITY OF POPULATION

Advisory support

10. What proportion of the target population uses paid advisors capable of providing advice relevant to the project?	A majority use a relevant advisor

Group involvement

11. What proportion of the target population participates in farmer-based groups that discuss farming?	Almost all are involved with a group that discusses farming

Relevant existing skills & knowledge

12. What proportion of the target population will need to develop substantial new skills and knowledge to use the innovation?	A minority will need new skills and knowledge

Innovation awareness

13. What proportion of the target population would be aware of the use or trialing of the innovation in their district?	Almost all are aware that it has been used or trialed in their district

RELATIVE ADVANTAGE OF THE INNOVATION

Relative upfront cost of the innovation

14. What is the size of the up-front cost of the investment relative to the potential annual benefit from using the innovation?	Moderate initial investment
Reversibility of the innovation	
15. To what extent is the adoption of the innovation able to be reversed?	Easily reversed
Profit benefit in years that it is used	
16. To what extent is the use of the innovation likely to affect the profitability of the farm business in the years that it is used?	Small profit advantage in years that it is used
Future profit benefit	
17. To what extent is the use of the innovation likely to have additional effects on the future profitability of the farm business?	Small profit advantage in the future
Time until any future profit benefits are likely to be realised	
18. How long after the innovation is first adopted would it take for effects on future profitability to be realised?	1 - 2 years
Environmental costs & benefits	
19. To what extent would the use of the innovation have net environmental benefits or costs?	Small environmental advantage
Time to environmental benefit	
20. How long after the innovation is first adopted would it take for the expected environmental benefits or costs to be realised?	1 - 2 years
Risk exposure	
21. To what extent would the use of the innovation affect the net exposure of the farm business to risk?	No increase in risk
Ease and convenience	
22. To what extent would the use of the innovation affect the ease and convenience of the management of the farm in the years that it is used?	Small decrease in ease and convenience

Table S2. Partial budgeting for use of feed-grade biochar as a feed supplement with a price of 500 AUD Mg^{-1}. Net profit plus carbon offset (AUD hd^{-1}) is shown as a function of the price of carbon removals (CCP: 25, 75 and 125 AUD Mg CO_2e), change liveweight gain (0, 5, 10 and 15%) and methane reduction (0, 5, 10 and 15%)

		Change in liveweight gain (%)															
		0%				5%				10%				15%			
CCP (AUD Mg^{-1} CO_2e)	Methane reduction (%)	0%	5%	10%	15%	0%	5%	10%	15%	0%	5%	10%	15%	0%	5%	10%	15%
25	Amount fed per day (g biochar hd^{-1} d^{-1})	40.0	40.0	40.0	40.0	41.3	41.3	41.3	41.3	42.5	42.5	42.5	42.5	43.8	43.8	43.8	43.8
	Feeding period (days)	580				580				580				580			
	Total amount of biochar fed for lifetime (kg biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Cost of biochar (AUD kg-1 biochar)	0.5				0.5				0.5				0.5			
	Cost of biochar fed for lifetime (AUD kg^{-1} biochar hd^{-1})	11.6	11.6	11.6	11.6	12.0	12.0	12.0	12.0	12.3	12.3	12.3	12.3	12.7	12.7	12.7	12.7
	Additional livestock production (extra kg LW hd^{-1})	0	0	0	0	18.2	18.2	18.2	18.2	36.2	36.2	36.2	36.2	54.3	54.3	54.3	54.3
	Meat price (AUD kg^{-1} meat)	2.75				2.75				2.75				2.75			
	Additional income from extra livestock production (AUD hd^{-1})	0	0	0	0	50.1	50.1	50.1	50.1	99.7	99.7	99.7	99.7	149.3	149.3	149.3	149.3
	GHG emissions (Mg CO_2e hd^{-1})	4.07	3.92	3.62	3.17	4.15	4.00	3.69	3.23	4.23	4.07	3.76	3.29	4.31	4.15	3.83	3.35
	GHG emissions reduction with feed-grade biochar (Mg CO_2e hd^{-1})	0.00	0.15	0.30	0.45	0.00	0.15	0.31	0.46	0.00	0.16	0.31	0.47	0.00	0.16	0.32	0.48
	Additional SOC sequestration for lifetime (Mg CO_2e hd^{-1})	0.054	0.054	0.054	0.054	0.056	0.056	0.056	0.056	0.058	0.058	0.058	0.058	0.059	0.059	0.059	0.059
	Additional income derived from CH_4 reduction and SOC change (AUD hd^{-1})	1.4	5.1	8.9	12.6	1.4	5.2	9.1	12.9	1.4	5.4	9.3	13.2	1.5	5.5	9.5	13.5
	Net profit plus carbon offsets, CH_4 reduction and SOC sequestration (AUD hd^{-1})	-10.2	-6.5	-2.7	1.0	39.5	43.3	47.2	51.0	88.8	92.7	96.6	100.6	138.1	142.1	146.1	150.1
75	Amount fed per day (g biochar hd^{-1} d^{-1})	40.0	40.0	40.0	40.0	41.3	41.3	41.3	41.3	42.5	42.5	42.5	42.5	43.8	43.8	43.8	43.8
	Feeding period (days)	580				580				580				580			
	Total amount of biochar fed for lifetime (kg biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Cost of biochar (AUD kg^{-1} biochar)	0.5				0.5				0.5				0.5			
	Cost of biochar fed for lifetime (AUD kg^{-1} biochar hd^{-1})	11.6	11.6	11.6	11.6	12.0	12.0	12.0	12.0	12.3	12.3	12.3	12.3	12.7	12.7	12.7	12.7
	Additional livestock production (extra kg LW hd^{-1})	0	0	0	0	18.2	18.2	18.2	18.2	36.2	36.2	36.2	36.2	54.3	54.3	54.3	54.3
	Meat price (AUD kg^{-1} meat)	2.75				2.75				2.75				2.75			
	Additional income from extra livestock production (AUD hd^{-1})	0	0	0	0	50.1	50.1	50.1	50.1	99.7	99.7	99.7	99.7	149.3	149.3	149.3	149.3
	GHG emissions (Mg CO_2e hd^{-1})	4.07	3.92	3.62	3.17	4.15	4.00	3.69	3.23	4.23	4.07	3.76	3.29	4.31	4.15	3.83	3.35
	GHG emissions reduction with feed-grade biochar (Mg CO2e hd^{-1})	0.00	0.15	0.30	0.45	0.00	0.15	0.31	0.46	0.00	0.16	0.31	0.47	0.00	0.16	0.32	0.48
	Additional SOC sequestration for lifetime (Mg CO_2e hd^{-1})	0.054	0.054	0.054	0.054	0.056	0.056	0.056	0.056	0.058	0.058	0.058	0.058	0.059	0.059	0.059	0.059
	Additional income derived from CH_4 reduction and SOC change (AUD hd^{-1})	4.1	15.3	26.6	37.9	4.2	15.7	27.2	38.8	4.3	16.1	27.9	39.7	4.4	16.5	28.5	40.5
	Net profit plus carbon offsets, CH_4 reduction and SOC sequestration (AUD hd^{-1})	-7.5	3.7	15.0	26.3	42.3	53.8	65.4	76.9	91.7	103.4	115.2	127.0	141.0	153.1	165.1	177.1

125	Amount fed per day (g biochar hd^{-1} d^{-1})	40.0	40.0	40.0	40.0	41.3	41.3	41.3	41.3	42.5	42.5	42.5	42.5	43.8	43.8	43.8	43.8
	Feeding period (days)	580				580				580				580			
	Total amount of biochar fed for lifetime (kg biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Cost of biochar (AUD kg^{-1} biochar)	0.5				0.5				0.5				0.5			
	Cost of biochar fed for lifetime (AUD kg^{-1} biochar hd^{-1})	11.6	11.6	11.6	11.6	12.0	12.0	12.0	12.0	12.3	12.3	12.3	12.3	12.7	12.7	12.7	12.7
	Additional livestock production (extra kg LW hd^{-1})	0	0	0	0	18.2	18.2	18.2	18.2	36.2	36.2	36.2	36.2	54.3	54.3	54.3	54.3
	Meat price (AUD kg^{-1} meat)	2.75				2.75				2.75				2.75			
	Additional income from extra livestock production (AUD hd^{-1})	0	0	0	0	50.1	50.1	50.1	50.1	99.7	99.7	99.7	99.7	149.3	149.3	149.3	149.3
	GHG emissions (Mg CO_2e hd^{-1})	4.07	3.92	3.62	3.17	4.15	4.00	3.69	3.23	4.23	4.07	3.76	3.29	4.31	4.15	3.83	3.35
	GHG emissions reduction with feed-grade biochar (Mg CO_2e hd^{-1})	0.00	0.15	0.30	0.45	0.00	0.15	0.31	0.46	0.00	0.16	0.31	0.47	0.00	0.16	0.32	0.48
	Additional SOC sequestration for lifetime (Mg CO_2e hd^{-1})	0.054	0.054	0.054	0.054	0.056	0.056	0.056	0.056	0.058	0.058	0.058	0.058	0.059	0.059	0.059	0.059
	Additional income derived from CH_4 reduction and SOC change (AUD hd^{-1})	6.8	25.6	44.4	63.2	7.0	26.2	45.4	64.6	7.2	26.8	46.5	66.1	7.4	27.5	47.5	67.6
	Net profit plus carbon offsets, CH_4 reduction and SOC sequestration (AUD hd^{-1})	-4.8	14.0	32.8	51.6	45.1	64.3	83.5	102.7	94.5	114.2	133.8	153.4	144.0	164.0	184.1	204.1

Table S3. Partial budgeting for use of feed-grade biochar as a feed supplement with a price of 1,000 AUD Mg^{-1}. Net profit plus carbon offset (AUD hd^{-1}) is shown as a function of the price of carbon removals (CCP: 25, 75 and 125 AUD Mg CO_2e), change liveweight gain (0, 5, 10 and 15%) and methane reduction (0, 5, 10 and 15%)

		Change in liveweight gain (%)															
		0%				5%				10%				15%			
CCP (AUD Mg^{-1} CO_2e)	Methane reduction (%)	0%	5%	10%	15%	0%	5%	10%	15%	0%	5%	10%	15%	0%	5%	10%	15%
25	Amount fed per day (g biochar hd^{-1} d^{-1})	40.0	40.0	40.0	40.0	41.3	41.3	41.3	41.3	42.5	42.5	42.5	42.5	43.8	43.8	43.8	43.8
	Feeding period (days)	580				580				580				580			
	Total amount of biochar fed for lifetime (kg biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Cost of biochar (AUD kg-1 biochar)	1.0				1.0				1.0				1.0			
	Cost of biochar fed for lifetime (AUD kg^{-1} biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Additional livestock production (extra kg LW hd^{-1})	0	0	0	0	18.2	18.2	18.2	18.2	36.2	36.2	36.2	36.2	54.3	54.3	54.3	54.3
	Meat price (AUD kg^{-1} meat)	2.75				2.75				2.75				2.75			
	Additional income from extra livestock production (AUD hd^{-1})	0	0	0	0	50.1	50.1	50.1	50.1	99.7	99.7	99.7	99.7	149.3	149.3	149.3	149.3
	GHG emissions (Mg CO_2e hd^{-1})	4.07	3.92	3.62	3.17	4.15	4.00	3.69	3.23	4.23	4.07	3.76	3.29	4.31	4.15	3.83	3.35
	GHG emissions reduction with feed-grade biochar (Mg CO_2e hd^{-1})	0.00	0.15	0.30	0.45	0.00	0.15	0.31	0.46	0.00	0.16	0.31	0.47	0.00	0.16	0.32	0.48
	Additional SOC sequestration for lifetime (Mg CO_2e hd^{-1})	0.054	0.054	0.054	0.054	0.056	0.056	0.056	0.056	0.058	0.058	0.058	0.058	0.059	0.059	0.059	0.059
	Additional income derived from CH_4 reduction and SOC change (AUD hd^{-1})	1.4	5.1	8.9	12.6	1.4	5.2	9.1	12.9	1.4	5.4	9.3	13.2	1.5	5.5	9.5	13.5

CCP	Item																
	Net profit plus carbon offsets, CH_4 reduction and SOC sequestration (AUD hd^{-1})	-21.8	-18.1	-14.3	-10.6	27.5	31.4	35.2	39.1	76.5	80.4	84.3	88.2	125.4	129.4	133.4	137.4
75	Amount fed per day (g biochar hd^{-1} d^{-1})	40.0	40.0	40.0	40.0	41.3	41.3	41.3	41.3	42.5	42.5	42.5	42.5	43.8	43.8	43.8	43.8
	Feeding period (days)	580				580				580				580			
	Total amount of biochar fed for lifetime (kg biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Cost of biochar (AUD kg^{-1} biochar)	1.0				1.0				1.0				1.0			
	Cost of biochar fed for lifetime (AUD kg^{-1} biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Additional livestock production (extra kg LW hd^{-1})	0	0	0	0	18.2	18.2	18.2	18.2	36.2	36.2	36.2	36.2	54.3	54.3	54.3	54.3
	Meat price (AUD kg^{-1} meat)	2.75				2.75				2.75				2.75			
	Additional income from extra livestock production (AUD hd^{-1})	0	0	0	0	50.1	50.1	50.1	50.1	99.7	99.7	99.7	99.7	149.3	149.3	149.3	149.3
	GHG emissions (Mg CO_2e hd^{-1})	4.07	3.92	3.62	3.17	4.15	4.00	3.69	3.23	4.23	4.07	3.76	3.29	4.31	4.15	3.83	3.35
	GHG emissions reduction with feed-grade biochar (Mg CO2e hd^{-1})	0.00	0.15	0.30	0.45	0.00	0.15	0.31	0.46	0.00	0.16	0.31	0.47	0.00	0.16	0.32	0.48
	Additional SOC sequestration for lifetime (Mg CO_2e hd^{-1})	0.054	0.054	0.054	0.054	0.056	0.056	0.056	0.056	0.058	0.058	0.058	0.058	0.059	0.059	0.059	0.059
	Additional income derived from CH_4 reduction and SOC change (AUD hd^{-1})	4.1	15.3	26.6	37.9	4.2	15.7	27.2	38.8	4.3	16.1	27.9	39.7	4.4	16.5	28.5	40.5
	Net profit plus carbon offsets, CH_4 reduction and SOC sequestration (AUD hd^{-1})	-19.1	-7.9	3.4	14.7	30.3	41.9	53.4	64.9	79.3	91.1	102.9	114.7	128.3	140.4	152.4	164.4
125	Amount fed per day (g biochar hd^{-1} d^{-1})	40.0	40.0	40.0	40.0	41.3	41.3	41.3	41.3	42.5	42.5	42.5	42.5	43.8	43.8	43.8	43.8
	Feeding period (days)	580				580				580				580			
	Total amount of biochar fed for lifetime (kg biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Cost of biochar (AUD kg^{-1} biochar)	1.0				1.0				1.0				1.0			
	Cost of biochar fed for lifetime (AUD kg^{-1} biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Additional livestock production (extra kg LW hd^{-1})	0	0	0	0	18.2	18.2	18.2	18.2	36.2	36.2	36.2	36.2	54.3	54.3	54.3	54.3
	Meat price (AUD kg^{-1} meat)	2.75				2.75				2.75				2.75			
	Additional income from extra livestock production (AUD hd^{-1})	0	0	0	0	50.1	50.1	50.1	50.1	99.7	99.7	99.7	99.7	149.3	149.3	149.3	149.3
	GHG emissions (Mg CO_2e hd^{-1})	4.07	3.92	3.62	3.17	4.15	4.00	3.69	3.23	4.23	4.07	3.76	3.29	4.31	4.15	3.83	3.35
	GHG emissions reduction with feed-grade biochar (Mg CO_2e hd^{-1})	0.00	0.15	0.30	0.45	0.00	0.15	0.31	0.46	0.00	0.16	0.31	0.47	0.00	0.16	0.32	0.48
	Additional SOC sequestration for lifetime (Mg CO_2e hd^{-1})	0.054	0.054	0.054	0.054	0.056	0.056	0.056	0.056	0.058	0.058	0.058	0.058	0.059	0.059	0.059	0.059
	Additional income derived from CH_4 reduction and SOC change (AUD hd^{-1})	6.8	25.6	44.4	63.2	7.0	26.2	45.4	64.6	7.2	26.8	46.5	66.1	7.4	27.5	47.5	67.6
	Net profit plus carbon offsets, CH_4 reduction and SOC sequestration (AUD hd^{-1})	-16.4	2.4	21.2	40.0	33.1	52.3	71.6	90.8	82.2	101.9	121.5	141.1	131.3	151.4	171.4	191.4

Table S4. Partial budgeting for use of feed-grade biochar as a feed supplement with a price of 1,500 AUD Mg^{-1}. Net profit plus carbon offset (AUD hd^{-1}) is shown as a function of the price of carbon removals (CCP: 25, 75 and 125 AUD Mg CO_2e), change liveweight gain (0, 5, 10 and 15%) and methane reduction (0, 5, 10 and 15%)

	Change in liveweight gain (%)			
	0%	5%	10%	15%

CCP (AUD Mg^{-1} CO_2e)	Methane reduction (%)	0%	5%	10%	15%	0%	5%	10%	15%	0%	5%	10%	15%	0%	5%	10%	15%
25	Amount fed per day (g biochar hd^{-1} d^{-1})	40.0	40.0	40.0	40.0	41.3	41.3	41.3	41.3	42.5	42.5	42.5	42.5	43.8	43.8	43.8	43.8
	Feeding period (days)	580				580				580				580			
	Total amount of biochar fed for lifetime (kg biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Cost of biochar (AUD kg-1 biochar)	1.5				1.5				1.5				1.5			
	Cost of biochar fed for lifetime (AUD kg^{-1} biochar hd^{-1})	34.8	34.8	34.8	34.8	35.9	35.9	35.9	35.9	37.0	37.0	37.0	37.0	38.1	38.1	38.1	38.1
	Additional livestock production (extra kg LW hd^{-1})	0	0	0	0	18.2	18.2	18.2	18.2	36.2	36.2	36.2	36.2	54.3	54.3	54.3	54.3
	Meat price (AUD kg^{-1} meat)	2.75				2.75				2.75				2.75			
	Additional income from extra livestock production (AUD hd^{-1})	0	0	0	0	50.1	50.1	50.1	50.1	99.7	99.7	99.7	99.7	149.3	149.3	149.3	149.3
	GHG emissions (Mg CO_2e hd^{-1})	4.07	3.92	3.62	3.17	4.15	4.00	3.69	3.23	4.23	4.07	3.76	3.29	4.31	4.15	3.83	3.35
	GHG emissions reduction with feed-grade biochar (Mg CO_2e hd^{-1})	0.00	0.15	0.30	0.45	0.00	0.15	0.31	0.46	0.00	0.16	0.31	0.47	0.00	0.16	0.32	0.48
	Additional SOC sequestration for lifetime (Mg CO_2e hd^{-1})	0.054	0.054	0.054	0.054	0.056	0.056	0.056	0.056	0.058	0.058	0.058	0.058	0.059	0.059	0.059	0.059
	Additional income derived from CH_4 reduction and SOC change (AUD hd^{-1})	1.4	5.1	8.9	12.6	1.4	5.2	9.1	12.9	1.4	5.4	9.3	13.2	1.5	5.5	9.5	13.5
	Net profit plus carbon offsets, CH_4 reduction and SOC sequestration (AUD hd^{-1})	-33.4	-29.7	-25.9	-22.2	15.6	19.4	23.3	27.1	64.1	68.1	72.0	75.9	112.7	116.7	120.7	124.7
75	Amount fed per day (g biochar hd^{-1} d^{-1})	40.0	40.0	40.0	40.0	41.3	41.3	41.3	41.3	42.5	42.5	42.5	42.5	43.8	43.8	43.8	43.8
	Feeding period (days)	580				580				580				580			
	Total amount of biochar fed for lifetime (kg biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Cost of biochar (AUD kg^{-1} biochar)	1.5				1.5				1.5				1.5			
	Cost of biochar fed for lifetime (AUD kg^{-1} biochar hd^{-1})	34.8	34.8	34.8	34.8	35.9	35.9	35.9	35.9	37.0	37.0	37.0	37.0	38.1	38.1	38.1	38.1
	Additional livestock production (extra kg LW hd^{-1})	0	0	0	0	18.2	18.2	18.2	18.2	36.2	36.2	36.2	36.2	54.3	54.3	54.3	54.3
	Meat price (AUD kg^{-1} meat)	2.75				2.75				2.75				2.75			
	Additional income from extra livestock production (AUD hd^{-1})	0	0	0	0	50.1	50.1	50.1	50.1	99.7	99.7	99.7	99.7	149.3	149.3	149.3	149.3
	GHG emissions (Mg CO_2e hd^{-1})	4.07	3.92	3.62	3.17	4.15	4.00	3.69	3.23	4.23	4.07	3.76	3.29	4.31	4.15	3.83	3.35
	GHG emissions reduction with feed-grade biochar (Mg CO2e hd^{-1})	0.00	0.15	0.30	0.45	0.00	0.15	0.31	0.46	0.00	0.16	0.31	0.47	0.00	0.16	0.32	0.48
	Additional SOC sequestration for lifetime (Mg CO_2e hd^{-1})	0.054	0.054	0.054	0.054	0.056	0.056	0.056	0.056	0.058	0.058	0.058	0.058	0.059	0.059	0.059	0.059
	Additional income derived from CH_4 reduction and SOC change (AUD hd^{-1})	4.1	15.3	26.6	37.9	4.2	15.7	27.2	38.8	4.3	16.1	27.9	39.7	4.4	16.5	28.5	40.5
	Net profit plus carbon offsets, CH_4 reduction and SOC sequestration (AUD hd^{-1})	-30.7	-19.5	-8.2	3.1	18.4	29.9	41.4	53.0	67.0	78.8	90.6	102.4	115.7	127.7	139.7	151.7
125	Amount fed per day (g biochar hd^{-1} d^{-1})	40.0	40.0	40.0	40.0	41.3	41.3	41.3	41.3	42.5	42.5	42.5	42.5	43.8	43.8	43.8	43.8
	Feeding period (days)	580				580				580				580			
	Total amount of biochar fed for lifetime (kg biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Cost of biochar (AUD kg^{-1} biochar)	1.5				1.5				1.5				1.5			
	Cost of biochar fed for lifetime (AUD kg^{-1} biochar hd^{-1})	34.8	34.8	34.8	34.8	35.9	35.9	35.9	35.9	37.0	37.0	37.0	37.0	38.1	38.1	38.1	38.1
	Additional livestock production (extra kg LW hd^{-1})	0	0	0	0	18.2	18.2	18.2	18.2	36.2	36.2	36.2	36.2	54.3	54.3	54.3	54.3
	Meat price (AUD kg^{-1} meat)	2.75				2.75				2.75`				2.75			

	Additional income from extra livestock production (AUD hd^{-1})	0	0	0	0	50.1	50.1	50.1	50.1	99.7	99.7	99.7	99.7	149.3	149.3	149.3	149.3
	GHG emissions (Mg CO_2e hd^{-1})	4.07	3.92	3.62	3.17	4.15	4.00	3.69	3.23	4.23	4.07	3.76	3.29	4.31	4.15	3.83	3.35
	GHG emissions reduction with feed-grade biochar (Mg CO_2e hd^{-1})	0.00	0.15	0.30	0.45	0.00	0.15	0.31	0.46	0.00	0.16	0.31	0.47	0.00	0.16	0.32	0.48
	Additional SOC sequestration for lifetime (Mg CO_2e hd^{-1})	0.054	0.054	0.054	0.054	0.056	0.056	0.056	0.056	0.058	0.058	0.058	0.058	0.059	0.059	0.059	0.059
	Additional income derived from CH_4 reduction and SOC change (AUD hd^{-1})	6.8	25.6	44.4	63.2	7.0	26.2	45.4	64.6	7.2	26.8	46.5	66.1	7.4	27.5	47.5	67.6
	Net profit plus carbon offsets, CH_4 reduction and SOC sequestration (AUD hd^{-1})	-28.0	-9.2	9.6	28.4	21.2	40.4	59.6	78.8	69.9	89.5	109.2	128.8	118.6	138.7	158.7	178.8

Table S5. Partial budgeting for use of feed-grade biochar as a feed supplement with a price of 2,000 AUD Mg^{-1}. Net profit plus carbon offset (AUD hd^{-1}) is shown as a function of the price of carbon removals (CCP: 25, 75 and 125 AUD Mg CO_2e), change liveweight gain (0, 5, 10 and 15%) and methane reduction (0, 5, 10 and 15%)

		Change in liveweight gain (%)															
		0%				5%				10%				15%			
CCP (AUD Mg^{-1} CO_2e)	Methane reduction (%)	0%	5%	10%	15%	0%	5%	10%	15%	0%	5%	10%	15%	0%	5%	10%	15%
25	Amount fed per day (g biochar hd^{-1} d^{-1})	40.0	40.0	40.0	40.0	41.3	41.3	41.3	41.3	42.5	42.5	42.5	42.5	43.8	43.8	43.8	43.8
	Feeding period (days)	580				580				580				580			
	Total amount of biochar fed for lifetime (kg biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Cost of biochar (AUD kg-1 biochar)	2.0				2.0				2.0				2.0			
	Cost of biochar fed for lifetime (AUD kg^{-1} biochar hd^{-1})	46.4	46.4	46.4	46.4	47.9	47.9	47.9	47.9	49.3	49.3	49.3	49.3	50.8	50.8	50.8	50.8
	Additional livestock production (extra kg LW hd^{-1})	0	0	0	0	18.2	18.2	18.2	18.2	36.2	36.2	36.2	36.2	54.3	54.3	54.3	54.3
	Meat price (AUD kg^{-1} meat)	2.75				2.75				2.75				2.75			
	Additional income from extra livestock production (AUD hd^{-1})	0	0	0	0	50.1	50.1	50.1	50.1	99.7	99.7	99.7	99.7	149.3	149.3	149.3	149.3
	GHG emissions (Mg CO_2e hd^{-1})	4.07	3.92	3.62	3.17	4.15	4.00	3.69	3.23	4.23	4.07	3.76	3.29	4.31	4.15	3.83	3.35
	GHG emissions reduction with feed-grade biochar (Mg CO_2e hd^{-1})	0.00	0.15	0.30	0.45	0.00	0.15	0.31	0.46	0.00	0.16	0.31	0.47	0.00	0.16	0.32	0.48
	Additional SOC sequestration for lifetime (Mg CO_2e hd^{-1})	0.054	0.054	0.054	0.054	0.056	0.056	0.056	0.056	0.058	0.058	0.058	0.058	0.059	0.059	0.059	0.059
	Additional income derived from CH_4 reduction and SOC change (AUD hd^{-1})	1.4	5.1	8.9	12.6	1.4	5.2	9.1	12.9	1.4	5.4	9.3	13.2	1.5	5.5	9.5	13.5
	Net profit plus carbon offsets, CH_4 reduction and SOC sequestration (AUD hd^{-1})	-45.0	-41.3	-37.5	-33.8	3.6	7.5	11.3	15.1	51.8	55.7	59.7	63.6	100.0	104.0	108.0	112.0
75	Amount fed per day (g biochar hd^{-1} d^{-1})	40.0	40.0	40.0	40.0	41.3	41.3	41.3	41.3	42.5	42.5	42.5	42.5	43.8	43.8	43.8	43.8
	Feeding period (days)	580				580				580				580			
	Total amount of biochar fed for lifetime (kg biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Cost of biochar (AUD kg^{-1} biochar)	2.0				2.0				2.0				2.0			
	Cost of biochar fed for lifetime (AUD kg^{-1} biochar hd^{-1})	46.4	46.4	46.4	46.4	47.9	47.9	47.9	47.9	49.3	49.3	49.3	49.3	50.8	50.8	50.8	50.8
	Additional livestock production (extra kg LW hd^{-1})	0	0	0	0	18.2	18.2	18.2	18.2	36.2	36.2	36.2	36.2	54.3	54.3	54.3	54.3

	Meat price (AUD kg^{-1} meat)	2.75				2.75				2.75				2.75			
	Additional income from extra livestock production (AUD hd^{-1})	0	0	0	0	50.1	50.1	50.1	50.1	99.7	99.7	99.7	99.7	149.3	149.3	149.3	149.3
	GHG emissions (Mg CO_2e hd^{-1})	4.07	3.92	3.62	3.17	4.15	4.00	3.69	3.23	4.23	4.07	3.76	3.29	4.31	4.15	3.83	3.35
	GHG emissions reduction with feed-grade biochar (Mg CO2e hd^{-1})	0.00	0.15	0.30	0.45	0.00	0.15	0.31	0.46	0.00	0.16	0.31	0.47	0.00	0.16	0.32	0.48
	Additional SOC sequestration for lifetime (Mg CO_2e hd^{-1})	0.054	0.054	0.054	0.054	0.056	0.056	0.056	0.056	0.058	0.058	0.058	0.058	0.059	0.059	0.059	0.059
	Additional income derived from CH_4 reduction and SOC change (AUD hd^{-1})	4.1	15.3	26.6	37.9	4.2	15.7	27.2	38.8	4.3	16.1	27.9	39.7	4.4	16.5	28.5	40.5
	Net profit plus carbon offsets, CH_4 reduction and SOC sequestration (AUD hd^{-1})	-42.3	-31.1	-19.8	-8.5	6.4	17.9	29.5	41.0	54.7	66.5	78.2	90.0	103.0	115.0	127.0	139.1
	Amount fed per day (g biochar hd^{-1} d^{-1})	40.0	40.0	40.0	40.0	41.3	41.3	41.3	41.3	42.5	42.5	42.5	42.5	43.8	43.8	43.8	43.8
	Feeding period (days)	580				580				580				580			
	Total amount of biochar fed for lifetime (kg biochar hd^{-1})	23.2	23.2	23.2	23.2	23.9	23.9	23.9	23.9	24.7	24.7	24.7	24.7	25.4	25.4	25.4	25.4
	Cost of biochar (AUD kg^{-1} biochar)	2.0				2.0				2.0				2.0			
	Cost of biochar fed for lifetime (AUD kg^{-1} biochar hd^{-1})	46.4	46.4	46.4	46.4	47.9	47.9	47.9	47.9	49.3	49.3	49.3	49.3	50.8	50.8	50.8	50.8
	Additional livestock production (extra kg LW hd^{-1})	0	0	0	0	18.2	18.2	18.2	18.2	36.2	36.2	36.2	36.2	54.3	54.3	54.3	54.3
	Meat price (AUD kg^{-1} meat)	2.75				2.75				2.75				2.75			
125	Additional income from extra livestock production (AUD hd^{-1})	0	0	0	0	50.1	50.1	50.1	50.1	99.7	99.7	99.7	99.7	149.3	149.3	149.3	149.3
	GHG emissions (Mg CO_2e hd^{-1})	4.07	3.92	3.62	3.17	4.15	4.00	3.69	3.23	4.23	4.07	3.76	3.29	4.31	4.15	3.83	3.35
	GHG emissions reduction with feed-grade biochar (Mg CO_2e hd^{-1})	0.00	0.15	0.30	0.45	0.00	0.15	0.31	0.46	0.00	0.16	0.31	0.47	0.00	0.16	0.32	0.48
	Additional SOC sequestration for lifetime (Mg CO_2e hd^{-1})	0.054	0.054	0.054	0.054	0.056	0.056	0.056	0.056	0.058	0.058	0.058	0.058	0.059	0.059	0.059	0.059
	Additional income derived from CH_4 reduction and SOC change (AUD hd^{-1})	6.8	25.6	44.4	63.2	7.0	26.2	45.4	64.6	7.2	26.8	46.5	66.1	7.4	27.5	47.5	67.6
	Net profit plus carbon offsets, CH_4 reduction and SOC sequestration (AUD hd^{-1})	-39.6	-20.8	-2.0	16.8	9.2	28.4	47.6	66.8	57.6	77.2	96.8	116.5	105.9	126.0	146.0	166.1

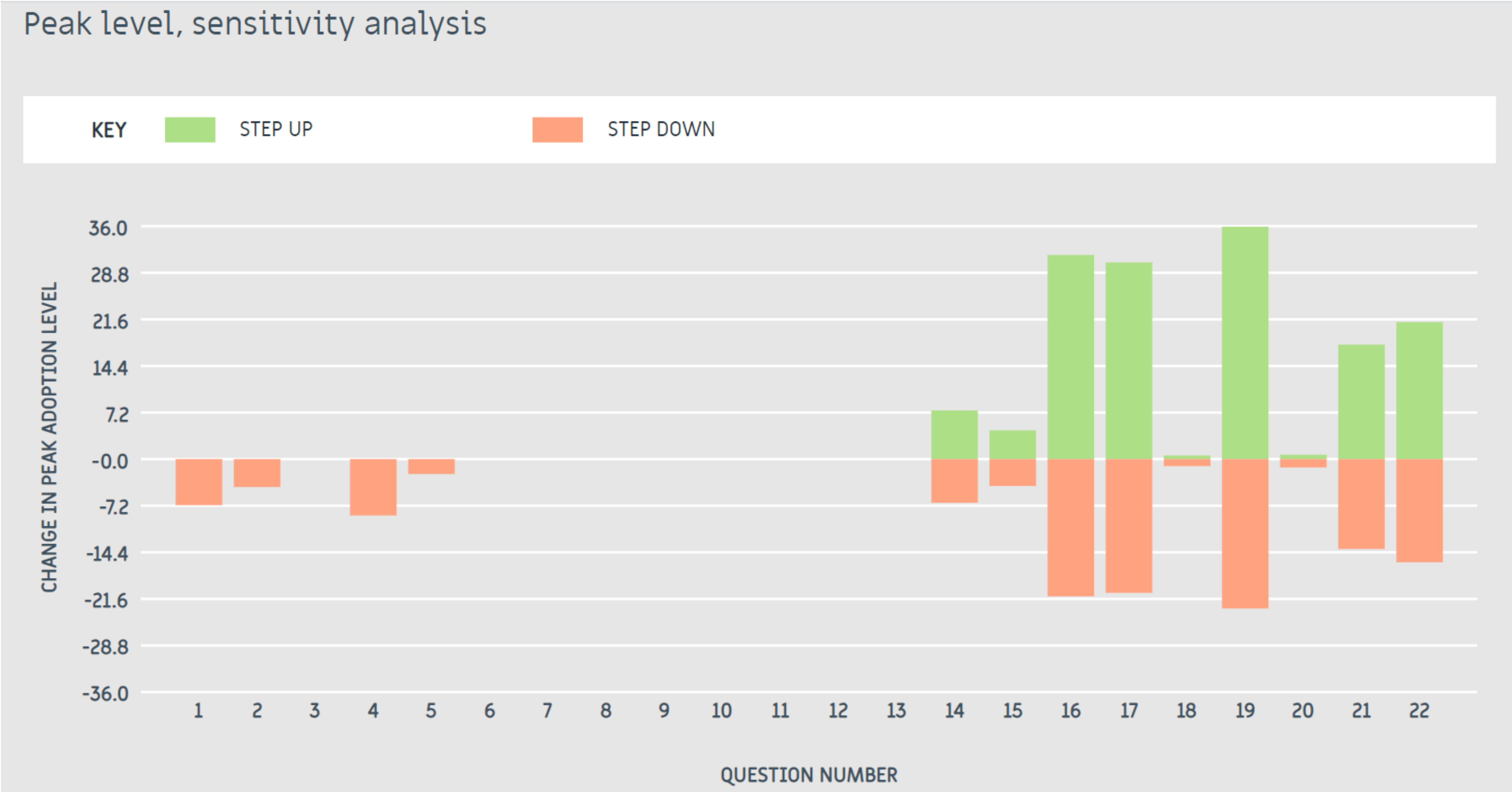

Fig. S7. Sensitivity analysis for peak adoption level associated with use of feed-grade biochar. Based on the data entered, the ADOPT model suggests what response (Table S1) would have the biggest effect on adoption rates.

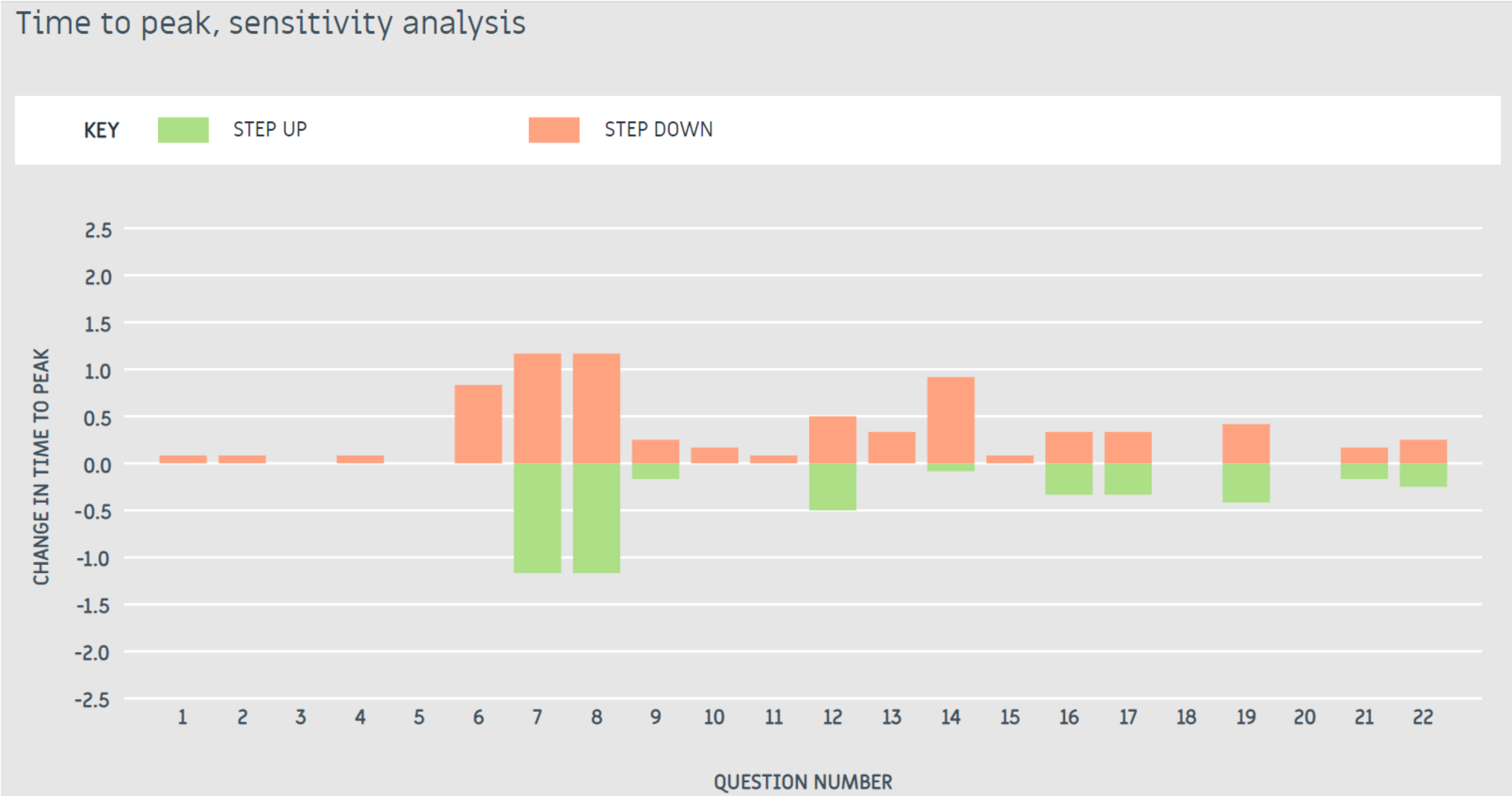

Fig. S2. Sensitivity analysis for time to peak adoption level associated with use of feed-grade biochar. Based on the data entered, the ADOPT model suggests what response (Table S1) would have the biggest influence on time to peak of adoption.

8.3 Responding to societal change: understanding consumer and producer perceptions of red meat

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Declaration of Interest

None

Abstract

Background

Social, political, climatic and economic issues and events have recently had a significant impact on the red meat industry. Multiple contextual and nuanced understandings are vital for exploring appropriate responses to support the red meat sector. Consumer public opinion gives producers the social license and responsibility to operate in particular ways. However, producers are faced with multiple challenges, the complexity of which is often not understood outside the sector. Meeting consumer demands is one such challenge.

Scope and Approach

This paper draws on two surveys that provide an understanding of the relationship between red meat consumers and producers by exploring the concerns of those at the two ends of the food chain within a Tasmanian context.

Key findings and Conclusions

We found that across both surveys, producer and consumer concerns around prioritising environmental stewardship and land care, minimising the carbon footprint of production, and prioritising animal health and welfare were generally aligned. However, consumer and producer reasoning for decisions around these common understandings were sometimes different. Where these concerns meet provides a space on which to build a responsive red meat industry as the consumer survey showed that 82% of Tasmanians consume red meat.

Key Words

Beef cattle, sheep, social license, climate change adaptation, greenhouse gas mitigation, food supply chains.

Introduction

With a change of the Australian Federal government in May 2022, and societies increasing recognition of climate change's anthropogenic origins, the politically influenced climate change debate shifted radically from a focus on 'climate change denial' to 'how do we deal with it?' In the wake of this shift, international events and issues have impacted the globe, including catastrophic climate events (Harrison, 2021; Wong, Read, Van-Lane & Xia, 2022), COVID-19 (Snow et al., 2021), and Russia's invasion of the Ukraine (Hellegers, 2022). China/Australia trade disruptions and ongoing tensions in the Pacific, the spread of foot and mouth and lumpy skin diseases (Kane, 2022) and the pressures reported in the media of the skyrocketing cost of living and food prices (National Farmer's Federation, 2023), have created concerns for the Australian red meat industry. Issues around food access and food security come with these types of events, resulting in significant impacts for consumers and food producers alike. The combination of these natural, health, political and social events seem to have amplified the spotlight on consumer concerns about red meat access (Denver, Jensen, Olsen & Christensen, 2019; Pawlak & Kolodziejczak, 2020), source (Henchion, De Backer, Hudders & O'Reilly, 2022; Stampa, Schipmann-Schwarse & Hamm, 2020), quality (de Araújo, Araújo, Patarata & Fraqueza, 2022; Webb & O'Neill, 2008), and the ethical and sustainable production of food (Johnston, Weiler & Baumann, 2022; Pawlak & Kolodziejczak, 2020; Read, Rollan, Creed & Fell, 2023). In turn, these consumer concerns have impacted the responses of red meat producer organisations, such as Australia's peak red meat marketing, research and development corporation, Meat & Livestock Australia (MLA). MLA have instigated a proactive stance in response to climate change with 2030 targets to be met by producers and, despite assurances to the contrary, have entered political debate concerning taxing those who do not (see for example Murphy & Remeikis, 2022).

These broad ranging issues in the red meat industry cannot simply be addressed by a one-size-fits-all blanket strategy as is typically expected by many policies ascribed by governments and organisations (Henry, Dalal, Harrison & Keating, 2022; Read, Rollan, Creed & Fell, 2023; Sloan et al., 2019). We know that, despite all the cutting edge science, extension activity for food production and educational outreach, strategies must be contextualised to have impact. Australia has environmental diversity and protecting this diversity is seen to be vital for sustainable approaches in agriculture (Read, Rollan, Creed & Fell, 2023). However, despite these claims, the ruminant production industry, including beef, sheep, goats and buffalo, must engage on some level with those who chose to consume (or not) red meat products. Consumers actively engage in very real ways with the products they access, either directly or at various points down a complex food chain. Consumer opinions, beliefs, values, food choices/practices all impact on their food consumption and therefore also impact on what is possible on farm. Likewise, producer opinions, beliefs, values, product choices and farming practices impact what is available for the consumer, giving rise to strong interactions between food supply and demand (Beacham & Evans, 2023). Public opinion and dialogue give red meat producers the social license and responsibility to operate in particular ways. The simplistic bottom line is that if society turns against livestock farming in sufficient quantities, the industry may cease to exist due to a lack of consumers. However, there are far more nuanced understandings that are required to explicate the social space that surrounds red meat production and the range of ethical positions, physical conditions, 'mis-information', economic possibilities and social/political understandings that can play a large part in this. This is where contextualised understandings are vital as every context will differ. An understanding of the osmotic social relationship between red meat consumers and producers, and the impact of this relationship in economic terms on livestock supply and demand, requires deeper exploration.

In the current environmental, political and social climate, red meat has probably produced the most debate of all the agricultural sectors in recent years (Bonnet, Bouamra-Mechemache, Réquillart & Treich, 2020). Consumer concerns have played largely in this debate with consumer 'sovereignty' making heavy demands on producers to drive a specifically 'ethical meatscape' (Baumann, Johnston & Oleschuk, 2023). Significant transformations in agri-food relations have therefore become essential (Beacham & Evans, 2023). Globally, meat consumption patterns reflect this debate. While there has been a 58% increase in the consumption of meat over the last 20 years, which is expected to continue to rise, this has generally been white meat (Whitnall & Pitts, 2023). In Australia, meat requirements are generally met by domestic sources whereas other countries must import their meat sources, e.g., China and Indonesia, the effect of which has driven the global increase in white meat consumption, coupled with a decline in red meat consumption (Whitnall & Pitts, 2023).

The issues that have impacted red meat consumption generally include, but are not limited to, debates around 'animal welfare' (Buddle, Bray & Ankeny, 2021), 'ethical farming practices' (Hübel & Schaltegger, 2022; Johnston, Weiler & Baumann, 2022; McCutecheon et al., 2015), and 'sustainable' food production systems, including impact on climate change (Pawlak & Kolodziejczak 2020; Reisinger & Clark 2018). While there are other debates, these three areas were central to our findings in the survey data, so we have focused on these in the literature.

Issues in debates about animal welfare

Consumer demand for meat sourced from producers concerned with animal welfare is strong and is often driven by public image and media misconceptions of what actually happens on farm and in the red meat industry. As Coleman, Hemsworth, Hemsworth, Munoz & Rice (2022) states, "red meat producers are concerned about the role of social media and the internet in spreading false information about livestock production in Australia" (p. 10). Producers are identifying the need for informed education about what they actually do on farm, in order to interrupt a diminishing social license related to misinformation about animal welfare. Education, Buddle, Bray & Ankeny (2021) argue, would encourage efforts by producers to engage more proactively with the community. However, despite this apprehension, "producers and the public share similar views regarding the importance of safeguarding sheep and beef cattle welfare" (Coleman, Hemsworth, Hemsworth, Munoz & Rice 2022, p. 10) and many producers have already changed and adopted new practices to support animal welfare concerns (Buddle, Bray & Ankeny, 2021; Coleman, Hemsworth, Hemsworth, Munoz & Rice, 2022). For example, small scale farmers in Canada "were passionately committed to the idea of raising animals in a way that felt intimate, humane, and sustainable" (Johnston, Weiler & Baumann, 2022, p.187).

Issues in debate around ethical and sustainable farming practices

Ethical and sustainable farming practice is also at the forefront of current debate. Read, Rollan, Creed & Fell (2023), in an ABARES report on international comparisons of environmental sustainability and agri-environmental indicators, suggest that Australia is achieving some of the most impressive results in sustainable agriculture. They have identified that Australian producers are in fact more sustainable in their agricultural practices than most other countries. Our agricultural land use has fallen, with land being converted for conservation purposes. This however has not impacted production, as improvements in productivity have been central to development. Australia also has "an exceptionally low stocking rate" (Read, Rollan, Creed & Fell, 2023, p. 10), which is argued to support biodiversity. While Australia's estimated emissions have reduced and are currently one of the lowest of those countries mentioned in the ABARES report (Read, Rollan, Creed & Fell, 2023, p. 23), agricultural methane remains a major greenhouse gas source.

Ederer and Leroy (2023) add to this more positive debate around sustainability, arguing that livestock systems *must* be built into future solutions for environmentally sustainability to be maintained. "[O]ne of the key necessary conditions for such a future will be large investments to build livestock food systems that are environmentally sustainable as well as nutritionally adequate" (Ederer and Leroy, 2023, p. 6). However other indicators of ethical practice and sustainability are not as positive. Termed 'happy' meat, the notion of grassfed beef and sheep (as opposed to grain fed) is a popular ethical farming system as is organic farming (Johnston, Weiler & Baumann 2022). These types of ethical systems are central to much of the red meat debate. McCutcheon et al. (2015) draws out the need for an understanding of the market to meet the needs of local food programs that have 'ethically' converted from grain to grassfed systems. Hübel & Schaltegger (2022) raise the ethical challenge of industrial scale meat production but claim that even when viable options are available, change does not necessarily follow. This is due to the influenced of both internal and external factors to farming systems that are often contradictory, making it hard for producers and industry to respond. However, Johnston, Weiler & Baumann (2022), showed that many small scale producers are passionately committed to ethical practice and fitting it to sustainable practices. They argue that reviews of eating meat show that although red meat production/consumption functions in a 'contested' space, red meat consumption/production is also 'cultural', and 'commonplace', and becomes even more culturally acceptable when sourced from 'ethical' farms.

Johnston, Weiler & Baumann (2022) assert that it is therefore perilous to ignore producer experiences when establishing new production systems that support the transformative approaches necessary on farm. They identify three significant understandings that are both drive and hinder the need for change. Firstly, they contend that the advent of ethical 'happy' meat practices doesn't necessarily make the process of mass-production meat disappear as this is predominantly cost driven and these processes do not necessarily need to be altered to be sustainable. The second issue addresses the trend for eating less, but better quality, red meat. The third understanding concerns the contested argument that meat is not central to human health and that sustainable food systems *should not* focus on meat. However they also identify that the contrasting argument highlights that animals could and should be part of the nutrient system of agriculture, adding nutrients to the soil and 'joy' to farm life (Johnston, Weiler & Baumann 2022).

Issues in debate around carbon accounting and footprints

One other issue within the sustainable/ethical farming debate relates to carbon accounting or carbon foot printing. Osei-Owusu, Thomsen, Jonathan, Nino & Dario (2020), in a Danish study , suggest that while producers are working on becoming more sustainable, modest changes in consumer lifestyle is also pivotal for climate mitigation. They contend that "[g]enerally, urban municipalities had higher emissions embodied in food consumption than remote and rural municipalities where food production was often the most dominant economic activity" (p. 13). We mention this only because it is the antithesis of producer choice as an avenue for addressing sustainability.

Most of the focus of research on the consumer/producer relationship is on the consumer and meeting consumer needs (Coleman, Hemsworth, Hemsworth, Munoz & Rice, 2022). Exploration of producer perspectives is limited and therefore provides constrained understanding. However, what this exploration has revealed is that there is an apparent lack of understanding of industry and thus, agricultural practices can frequently be judged by a less knowledgeable and educated public (Johnston, Weiler & Baumann, 2022). For example, Hübel and Schaltegger (2022, p. 137), when discussing meat slaughterhouses, argue that the lack of consumer knowledge "hamper[s] the consumer's image of the meat industry".

Ongoing work is required to connect consumer and producer understandings and practices in order to both address misinformation and maintain the social permissions required for red meat production and consumption in Tasmania. Tasmania has a reputation for clean, green, high quality produce. It is considered to be one of Australia's food bowls (Cica, 2010; Currey, 2013) and is lauded for its biosecure status (Bishop, 2021) compared to the rest of Australia and international standards due to its geographical 'island' isolation. Therefore our aim for this paper is to explore the synergies and disparities between consumer and producer perspectives of red meat production as it plays out in the context of Tasmania, Australia; arguing that identifying these will allow a point of consensus between producers and consumers from which future directions in the red meat industry might be built, regardless of the consumer and producer reasoning behind these synergies. This commentary is drawn from two surveys: *The Tasmania Project* concerning Tasmanian consumer perspectives and the Tasmanian Red Meat Producers Survey, targeting a range of producer concerns across Tasmania.

Tasmania Project consumer survey

Through the Institute for Social Change at the University of Tasmania (ISC), we surveyed over 3,500 people in the Australian state of Tasmania. The survey targeted key understandings in demographic consumption patterns and attitudes towards production, sourcing and consumption of dairy, red meat and seafood. A total of 1,176 people responded to the survey. Around two-thirds of respondents were female, the majority were 45+ years of age, and two-thirds of respondents were highly educated with a Bachelor's degree or higher. Approximately half of the respondents were residents in the Greater Hobart area (Tasmania's capital with ~ 45% of the state's population), with the proportion of respondents relatively equally split between three household income brackets (~40% had annual salaries < $60K/annum, 28% between $60K-$100K, and 32% had annual salaries > $100K/annum) (Lester, Kocar & Horton, 2021a).

The consumer survey found that approximately 98% of the respondents currently consume red meat, dairy and/or seafood (wild caught and farmed), with approximately two-thirds of all respondents consuming all three (Lester, Kocar & Horton, 2021b) (Fig. 1). Specifically related to red meat, around four in five respondents currently consume red meat (Fig. 1). Male respondents were more likely to eat red meat, with the older generations (65+ years) more likely to eat red meat than younger responders (Lester, Kocar & Horton, 2021a; Fig. 2). Red meat consumers also tended to have lower levels of education (i.e., high school), came from households located outside of the greater Hobart region, with either pre-school, school-aged or adult children still at home, and had a combined household income > $100,000/annum (Lester, Kocar & Horton, 2021a; Fig. 2).

[Insert Fig. 1 near here]

[Insert Fig. 2 near here]

When asked if "I eat less red meat now than 5 years ago", with the choice of five responses (Strongly agree, Agree, Neither agree or disagree, Disagree or Strongly disagree), six in ten respondents agreed or strongly agreed with this statement, while only two in ten respondents either disagreed or strongly disagreed (Lester, Kocar & Horton, 2021a). In contrast, only three in ten respondents are consuming less dairy now than 5 years ago, with similar results for wild-caught fish (Lester, Kocar & Horton, 2021b). Not surprisingly, due to the negative publicity around farmed fish in Tasmania, and in particular salmon (Condie, Vince & Alexander 2022), the number of respondents consuming less farmed fish now, compared to 5 years ago, was slightly higher at four in ten respondents (Lester, Kocar & Horton, 2021b). The results of this Tasmanian consumer survey would suggest that consumers are decreasing their consumption of red meat at a higher rate than other animal-based protein sources which is supported by other Australian research (Whitnall & Pitts, 2023).

Consumers were also asked questions pertaining to what is important to them in relation to sourcing red met, with the option to select either 'Very important', 'Important', 'Moderately important', 'Slightly important' or 'Not important'. The questions were:

- Meat sourced from farms that prioritise environmental stewardship and land care,
- Meat has been farmed using practices to minimise carbon footprint
- Meat sourced from farms that prioritise animal health and welfare,
- Meat sourced from farms that use the latest technology and automation,
- Meat source guarantees a fair price to farmers,
- Meat comes from Tasmanian farms,
- Meat is source from farms in your local area,
- Meat comes from family-owned and managed farm.

Tasmanian Red Meat Producers Survey

The Tasmanian Red Meat Producers Survey, targeted red meat producers and was developed by Tasmanian Institute of Agriculture (TIA) while conducted through the Redcap online survey portal (https://www.project-redcap.org/). The survey questions explored demographic and farm details, generational farming and succession planning, employment, employees and recruitment, and responding to climate change, including past practice implementation and future plans to implement practices on farm. Here we focus on the demographic data and responses to climate change questions. Respondents were located throughout Tasmania, with twenty males, thirteen females and one other, reflecting diversity of interviewees across farms. Respondents were between 20 and 80 years of age, although around 70% were over 40. Farm size ranged from < 50 ha up to 24,000 ha, with an average of ~ 2,300 ha. Their farms ran sheep, cattle, or a combination of both. While not asked specifically, using a dry sheep equivalent (DSE) conversion (https://www.evergraze.com.au/library-content/evergraze-tools-calculators/index.html), stock numbers varied between ~ 100 and 70,000 DSE, with a mean of ~ 8,450 DSE per farm.

One aspect explored through the survey was a gauge of producers' perspectives of climate change, as this would have a major bearing on the likelihood of implementation, or lack thereof, of adaptation and mitigation options to cope with a future warmer and drier environment while concomitantly implementing practices on farm to reduce greenhouse gas emissions. Producers were asked to select 'Which option best describes your perspective on the changing climate' from a drop-down list containing:

- 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, or
- None of the above.

Producers were then asked if they had undertaken a range of climate change adaptation or greenhouse gas mitigation practices in the past 5-10 years, responding with either yes or no. Producers were also then asked if they were likely to undertake these same practices in the next 5-10 years, responding with either 'Very likely', 'Likely', 'Neutral', 'Unlikely' or 'Very unlikely'. The areas of adaptation and mitigation (past/future) were:

- Adjusted/adjusting seasonal stocking rate to better fit feed demand to the changed pattern of feed supply,
- Increased/increase the extent of deeper-rooted legumes in your perennial pastures,
- Actively improved/improving soil fertility through addition of PKS fertilisers,
- Planted/plant trees with the intention of reaping environmental benefits,
- Purchased/purchase an additional block of arable land,
- Purchased/purchase carbon offsets,
- Diversified/diversify by introducing a new enterprise to your farming system,
- Invested/invest in irrigation water and/or infrastructure, and
- Explored/explore dairy beef as a potential production pathway.

Other aspects of the survey relevant included whether producers currently irrigate pastures. If no, which factors are contributing to your decision to not increase irrigation capacity (i.e., limited or no access to water, cost of purchasing water and/or infrastructure). If yes, what factors are required to increase capacity (i.e., purchasing more water and/or infrastructure). The survey also asked if producers plan to maintain or increase livestock production, and if yes, was it through increasing lamb and/or beef, or decreasing one commodity while increasing the other.

Synergies and differences between consumer and producer surveys

There was no direct and targeted alignment between the consumer survey, with its focus on the importance of a range of issues with respect to sourcing red meat (Fig. 3), and the producer survey, giving a comparison of likelihood of having undertaken (past), or planning to undertake (future) adaptation and mitigation practices (Fig. 4). However, there were three clear theme areas across both surveys which facilitated the ability to explore the synergies and differences between consumers and producers. These three areas relate to prioritising environmental stewardship and land care, minimising their carbon footprint, and prioritising animal health and welfare. Just as importantly, nearly two-thirds of producers indicated that they believed the climate is changing, and they are already adapting to it in the ways that they manage their farming operation. Interestingly, only 6% of respondents (2 producers) indicated that, for them, the climate is not changing significantly. We cannot deduce from these responses whether these two producers are climate change 'deniers' or are farming in a location where the impact of climate change is less noticeable, thus not requiring a noticeable change of farming practice to adapt.

[Insert Fig. 3 near here]

Consumers prioritised animal welfare

After fair price to farmers and sourcing red meat from Tasmanian farmers, prioritising animal welfare was the third most important aspect considered by consumers, with 78% responding with either very important or important when considering where they source their red meat from (Fig. 3). Producer survey questions with a clear and positive outcome to improved animal welfare included altering stock rates to match feed supply, planting trees, and exploring dairy-origin beef as a potential production pathway.

Historically, 85% of the surveyed red meat producers have altered stocking rates to match pasture supply, with 76% of producers indicating they are either likely or very likely to continue undertake this practice into the future (Fig. 4). Avenues to undertake this include selling stock sooner or agisting core breeding stock off farm during periods of low pasture supply, or alternatively, during favourable seasons, retaining young stock longer to increase their liveweight prior to selling. For example, Glindemann et al. (2007) illustrated that, across six equally-spaced grazing intensities between 1.5 and 9.0 sheep/ha, increasing grazing intensity significantly reduced pasture herbage, resulting in a 2.5 times reduction in liveweight gain over a 14-week period between the two extremes of stocking rate. Altering animal stocking rates to match pasture supply can therefore also have environmental benefits, such as maintaining ground cover, pasture persistence, soil structure and soil carbon (McDonald et al., 2023).

[Insert Fig. 4 near here]

Around 60% of producers indicated that they had planted trees in the past, with nearly three-quarters of all respondents indicating they plan to include tree plantings on farm into the future (Fig. 4). Tree plantings can assist in reducing lamb mortality during winter/early spring (Young et al., 2014) while alternatively providing shade and shelter during summer. While there is clear evidence of the effect of lack of shelter and shade on dairy cattle animal welfare (Chang-Fung-Martel, Harrison, Rawnsley, Smith & Meinke, 2017), there is diverse evidence as to whether providing shade to beef cattle and sheep would necessarily lead to better animal welfare outcomes. For example, Knight et al. (2023) found that providing shade to sheep led to reduced respiration rates. However, this was not the case when comparing beef cattle grazing either an open pasture system or a silvopastoral systems in Brazil (Huertas, Bobadilla, Alcántara, Akkermans & van Eerdenburg, 2021) under similar climatic extremes. Neither study found any animal performance associated with providing shade, thus not jeopardising production and producer profit.

One animal welfare intervention that was a very low priority for producers was dairy beef. This is a relatively new consideration for Tasmanian red meat producers, with around one in five producers having raised dairy-origin beef in the past (Fig. 4). The likelihood of red meat producers considering raising dairy-origin beef into the future still remains low, with only 28% producers responding with either likely or very likely (Fig. 4). There may be a range of reasons that red meat producers may not be considering this as another form of farm income diversification, including perceived lower growth rates compared to their beef-origin counterparts, access to markets and additional rearing costs (Barber, Bauer & Sullivan, 2020). Outside of this study, the authors have found some anecdotal evidence that some red meat producers don't see it as 'their job to clean up' the dairy industry.

Producers prioritise environmental stewardship

The three highest ranking activities that producers considered undertaking into the future were increasing rooting depth of legumes in the pasture sward, altering stocking rates and planting trees, with the majority of producers indicating they were likely or very likely to undertake these activities into future (Fig. 4). This aligns well with the consumer survey, with two-thirds of consumers (69%) responding that environmental stewardship was either a very important or important when considering where to source their red meat from (Fig. 3).

Around 50% of producers have actively included deeper rooted legumes into the pasture sward in the past, with an increased likelihood of undertaking this practice into the future (Fig. 4). Deeper rooted legumes, such as lucerne (*Medicago sativa*), are able to access soil moisture and nutrients further down the soil profile, maintaining ground cover over a longer period of the year compared to annual legume species such as subterranean clover (*Trifolium subterraneum)* and extended growing seasons for pasture swards resulting in increased meat production per unit area (Hayes et al., 2019; McCaskill et al., 2016; McGrath et al., 2021).

In addition to altering stocking rates and planting trees, as discussed above, it is plausible that the introduction of a new enterprise may also assist in improving farm environmental stewardship, depending on the enterprise implemented. Around half of all producers indicated that they had diversified into other enterprises historically, with a similar number planning to do so into the future. What was not asked specifically, was whether enterprise change could include transitioning from wool-only production to wool and prime lamb production, as illustrated by the decline in wool production in concert with increases in lamb production in Tasmanian over recent years (MLA, 2023; Woods, 2021). There has also been a large expansion of irrigation capacity and capability within Tasmania, which has resulted in increased wealth in aspects of agricultural productivity, land values, direct and indirect employment, while reducing production and profitability volatility (Tasmanian Irrigation, 2019).

Divergence around minimising the carbon footprint of red meat production

Nearly three in five consumers indicated that they considered red meat being sourced from farms that implement practices to minimise the carbon footprint as being important or very important (Fig. 3). One clear pathway for producers to indicate that they prioritise supplying low carbon product into the marketplace is through the purchase of carbon credits. Historically, only one producer had participated in a carbon market, with the majority (55%) indicating they do not plan to purchase carbon credits in the future, with a further 34% still undecided (Fig. 4). At first glance, this appears to be a disconnect between producers and consumers. However, what may be more accurate is that producers would rather implement on-farm practices rather than purchase off-site carbon credits. A clear example of this is nearly three-quarters of all producers plan to plant trees on farm to reap the environmental benefits. Planting trees on farm is the one activity that has the potential to not only decrease their farm's carbon footprint but also improving their environmental stewardship of the land coupled with improved animal welfare outcomes.

In contrast, there are activities which producers plan to implement into the future which may not reduce the carbon footprint of red meat production. More than two-thirds of producers plan to increase overall meat production (data not shown) which may result in an increase in the carbon footprint of the farm operation. Bilotto, Christie-Whitehead, Malcolm & Harrison (2023) found that incorporating a range of intervention options into a single 'low hanging fruit' package, such as increased rooting depth of pastures and increasing soil fertility, two options with high likelihood of uptake into the future by consumers (Fig. 4), would increase the net carbon footprint of red meat production in Tasmania, although any additional production realised would dilute increased emissions. Understanding that the metrics being targeted can have major implications of the success or otherwise of on-farm practices is important.

Another aspect impacting sustainable practice being considered by producers into the future is to invest in irrigation water and/or infrastructure, especially if increased irrigation leads to increased livestock numbers and production, thus increasing the carbon footprint of the farm operation. Over 60% of producers have invested in irrigation water and infrastructure in the last 5-10 years, and while the percentage of producers likely or highly likely to continue investment in irrigation into the future was slightly lower, at 55%, the number of producers not considering irrigation into the future was substantially lower, at 24% compared to 39% historically (Fig. 4). While not presented here, the majority of those producers considering additional irrigation are typically the larger farms, seeking to increase red meat production. The reason some producers are not considering irrigation into the future vary between limited or no access to water, costs of purchasing water and/or infrastructure, or they are located in a region that has high and reliable rainfall already (e.g. north-western Tasmania). Interestingly, most consumers did not see importance in their meat being sourced from farms using the latest technology and automation, which is where irrigation infrastructure and technology has advanced in recent decades (Koech and Langat, 2018), highlighting that consumers do not always understand best practice on farm (Coleman, Hemsworth, Hemsworth, Munoz & Rice, 2022).

Conclusions

Through the exploration of two surveys, we have been able to understand and explore concerns between red meat consumers and producers, through a Tasmanian lens. Around 80% of consumers surveyed consume red meat, although around three in five are eating less than they did five years ago. We found that consumer and producer concerns in general were generally similar. These concerns intersected on climate change, sustainability, ethical practice and animal welfare. Within these responses, consumers were very supportive of producers and producers were willing to adjust their approaches to meet consumer demands. Consumer and producer reasoning for coming to these concerns, however, was sometimes different. Where these concerns meet in principle provides a space on which to build a responsive red meat industry.

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Ethics statement

The consumer survey was undertaken as per The Tasmania Project's approved ethics protocol (HREC Project ID 20587). The producer survey was undertaken by an UTAS approved ethics protocol (HREC Project ID 17705).

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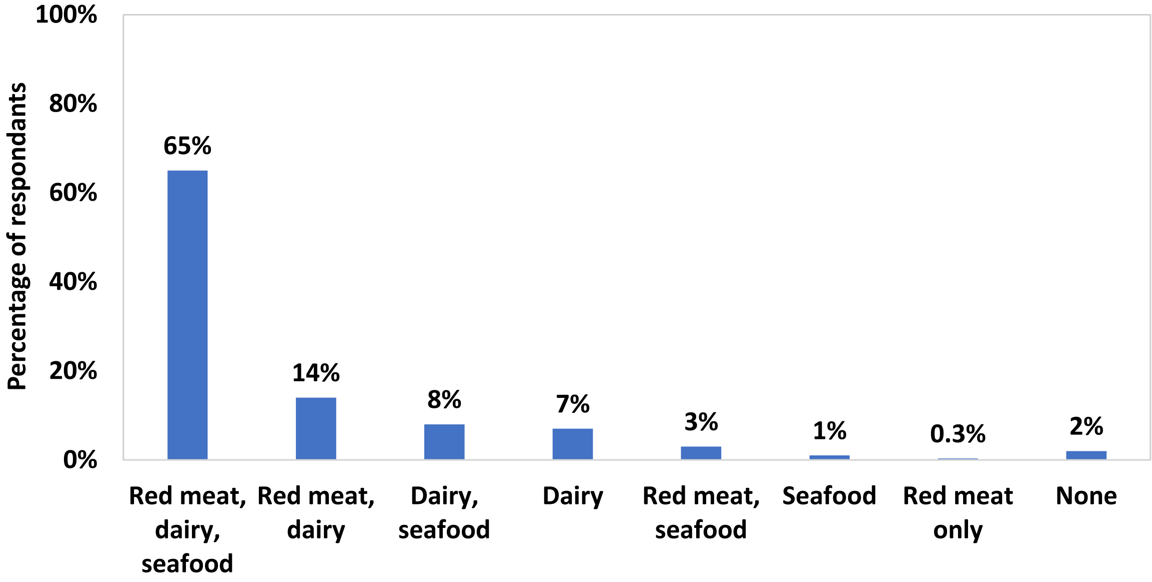

Fig. 1 Percentage of consumers consuming red meat, dairy and/or seafood (*n=1,176)*

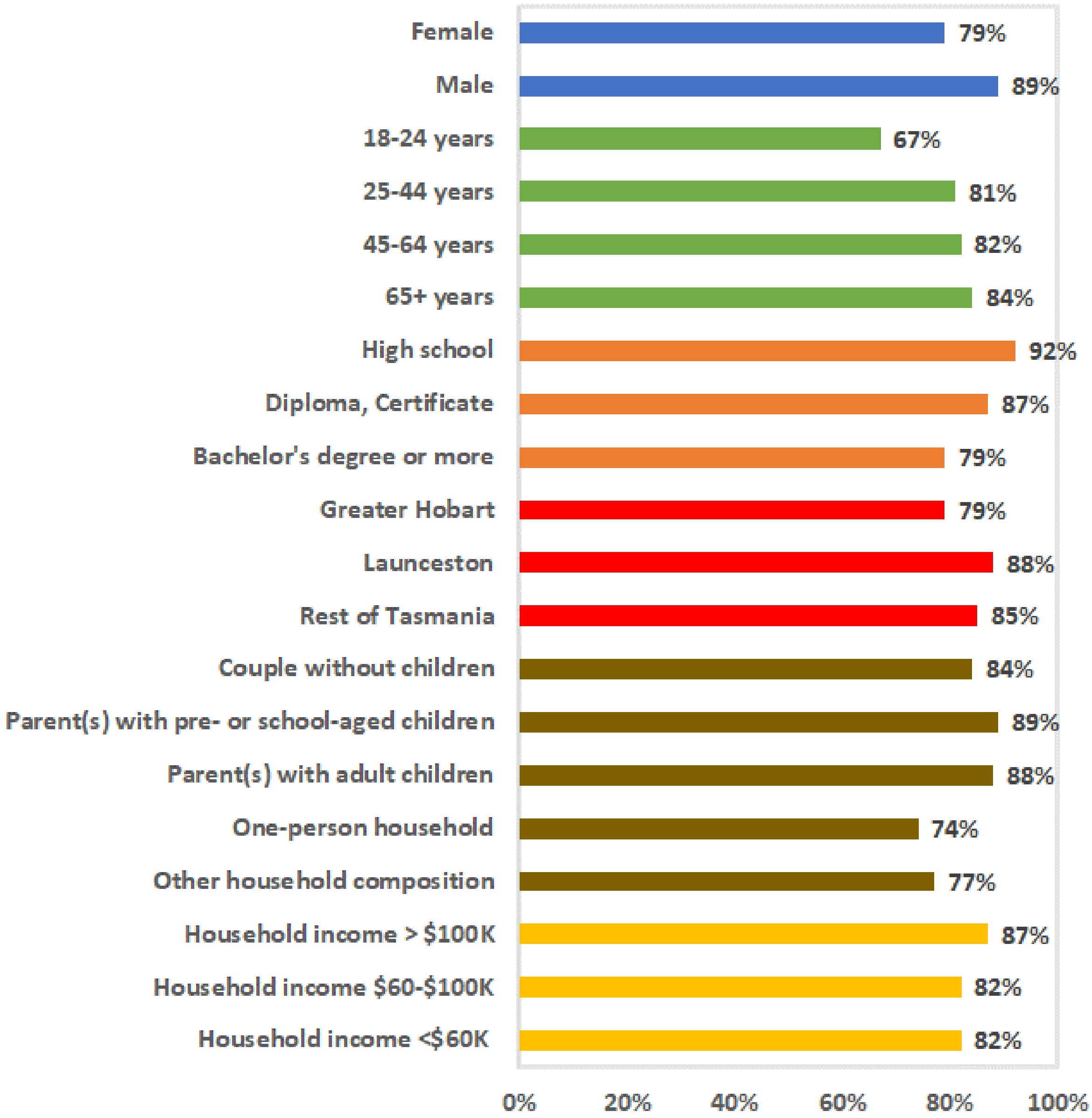

Fig. 2 Key red meat eating habits by sociodemographic variables.

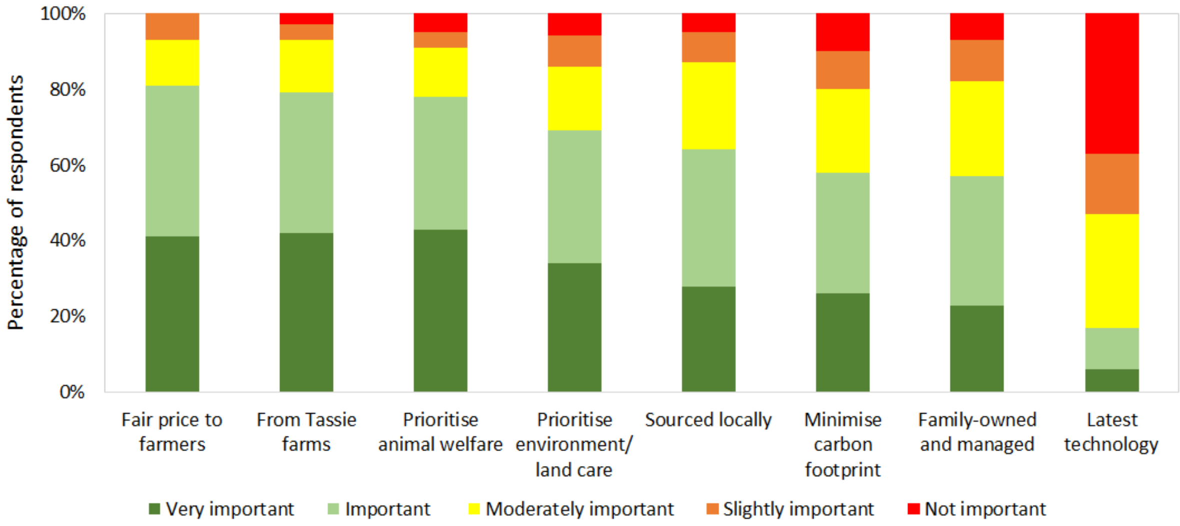

Fig. 3 Consumer response (*n=1,176*) to importance of a range of questions in relation to sourcing red meat.

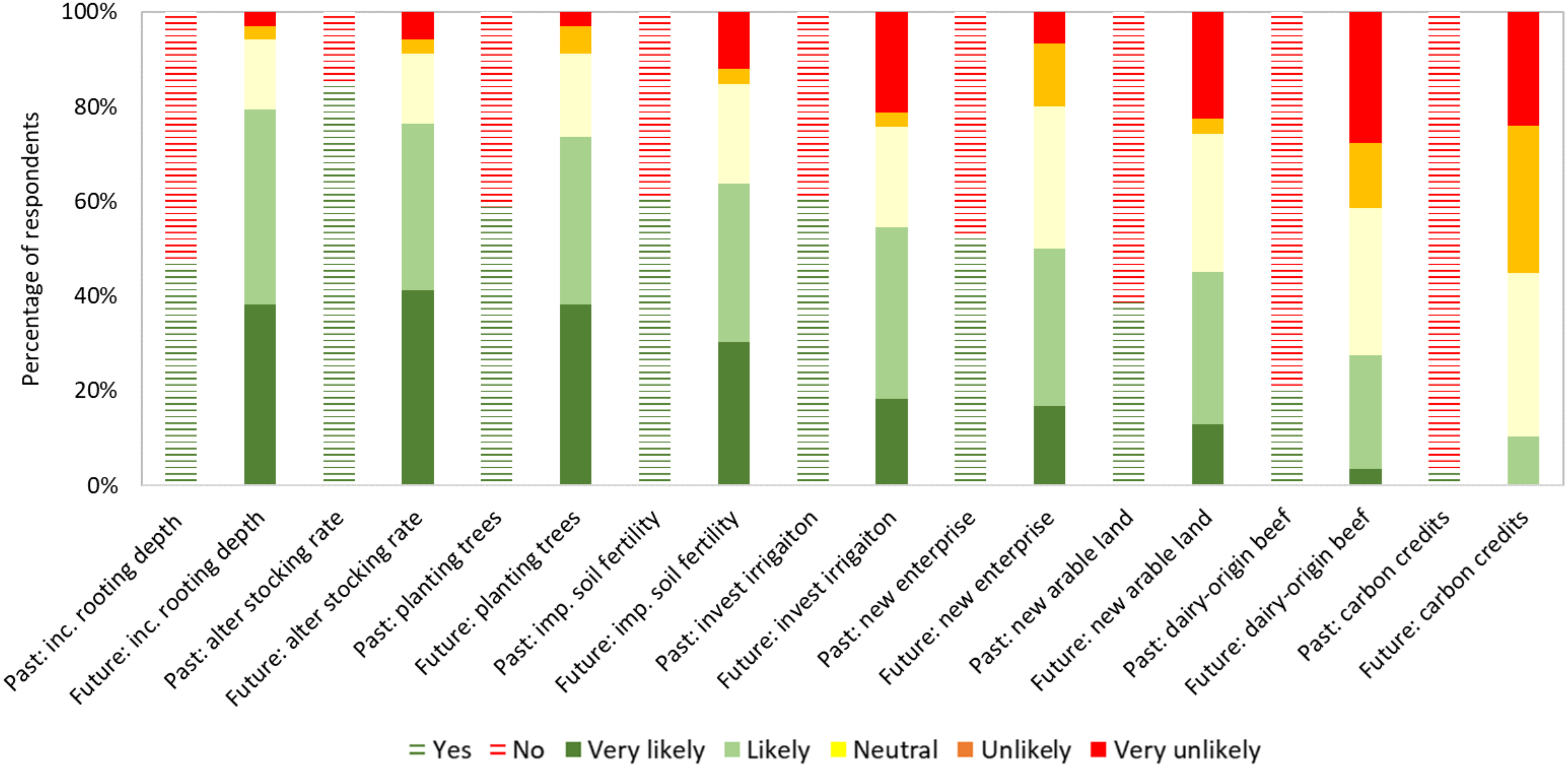

Fig. 4 Producer response (*n=34*) to whether they have undertaken an activity in the past 5-10 years (hashed columns; yes or no) or intend to undertake an activity in the future 5-10 years (solid columns; Very likely through to very unlikely) to adapt to climate change. Columns ranked according to likelihood to undertake a climate change adaptation activity in the future 5-10 years.