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Tailoring Australian carbon farming can realise greater co-benefits

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Land managers face growing societal and policy expectations to produce more food, conserve biodiversity, enhance carbon sequestration, maintain economic viability and reduce greenhouse gas emissions, yet practices affording these outcomes may not be congruent. Using a transdisciplinary participatory approach with Australian sheep producers, we co-design interventions intended to reduce greenhouse gas emissions while simultaneously improving biodiversity, productivity and profitability. Planting native trees yields the greatest abatement potential, followed by antimethanogenic feed supplements. Nature-based solutions and emissions-removal practices are generally more profitable than emissions-reduction measures, particularly antimethanogenic feed additives. Nonetheless, carbon sequestration in soils and vegetation diminishes longitudinally and remains reversible, whereas emissions reductions, such as avoided enteric methane, are continual and permanent. We conclude that (1) greater benefits arise when interventions target contextualised economic, environmental, psychological and institutional constraints, and (2) stacking complementary innovations yields more favourable outcomes than isolated practice changes, particularly when interventions target underperforming indicators.

In response to climate change, population growth and biodiversity habitat destruction, prioritisation of land use has become increasingly important[1–3]. Farmers are under mounting pressure from markets, legislation, nascent regulation and consumer preferences to adopt innovations that sustainably reduce greenhouse gas (GHG) emissions[4,5]. At the same time, farm production must be profitable, lest farmers will be unable to endure[6]. As land use change is the primary driver of biodiversity loss, there is also a need to develop farm practices that preserve existing biodiversity habitat[7–9].

While pathways for reducing GHG emissions from the agricultural sector have long existed[10–15], little attention has been given to coincident implications for profit, productivity and biodiversity[16]. Such implications are important, because economic, environmental, social and/or psychological co-benefits and trade-offs associated with

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purported innovations ultimately catalyse or inhibit behavioural change[17]. Indeed, some scholars suggest that progress towards sustainable agriculture is hampered by lack of interdisciplinary dialogue and siloed scientific discourse[18].

In the absence of land-use change, enteric methane is the dominant form of livestock farm GHG emissions[16,19]. As a corollary, novel antimethanogenic feed supplements have gained popularity[20–23]. For example, when used as a feed supplement under controlled conditions, the red seaweed *Asparagopsis taxiformis* can inhibit enteric methane production by up to 98%[24]. Despite such mitigation potency, systems-level assessments indicate that enteric methane mitigation associated with feed supplements in commercial conditions is typically far lower due to enterprise-scale constraints—such as the need to maintain self-replacing herds—as well as variable diet quality, inconsistent additive intake, and other in situ limitations[5,25,26].

Pasture composition can also influence enteric methane emissions. Some species directly inhibit methanogenesis, whereas others reduce methane intensity indirectly by increasing liveweight gain and shortening the period animals remain in the production system[27,28]. For example, integrating pigeon pea into tropical C_4 grass systems has been shown to reduce enteric methane emissions by up to 70% relative to grass-only pastures[29]. Similarly, incorporating the perennial legume *Leucaena leucocephala* into grass pastures can reduce beef cattle emissions intensity by 23% through improved growth rates and lower enteric methane, while also increasing enterprise profitability[28,30]. Nonetheless, adoption of pasture species explicitly for methane mitigation may be constrained by reduced biomass yields, lower digestibility, or poor compatibility with existing pasture systems[27]. In semi-arid regions, large property sizes (often >500,000 ha), harsh biophysical conditions, and legislative barriers further limit opportunities for pasture renovation.

Carbon dioxide removal (CDR) through enhanced farm biomass can be achieved via silvopasture, agroforestry, shelterbelts, plantations, and restoration of remnant vegetation. Tree-dominated systems can also provide habitat[31], support ecosystem services[32] and improve agricultural productivity through mechanisms such as enhanced infiltration and reduced runoff[33]. Despite these potential co-benefits, perspectives on tree protection or establishment remain polarized. Some authors argue that trees reduce pasture production[34] or risk ecological degradation when planted in historically grass-dominated biomes[35]. To avoid maladaptation, whole-systems scenario analyses provide a critical framework for evaluating trade-offs among CDR strategies, emissions reductions, climate adaptation, revenue generation and biodiversity restoration, enabling assessment of complex interactions across biophysical, economic and policy constraints[35,36].

While much research has focused on perturbations caused by singular interventions, few studies have explored how simultaneous interventions impact coincident and ensuing interdisciplinary co-benefits and trade-offs[37]. Balmford, et al.[38] opine that multiple externalities alongside yields must be considered if environmental benefits from farm interventions are to persist and perpetuate. Herrero, et al. [19] suggest that the economic potential of managing interventions to livestock farms is less than 10% once trade-offs are accounted for, emphasising the need for research and investment that increase adoption while minimising risks to livelihoods, national economies and the environment.

Here, our purpose is to co-design GHG mitigation practices that simultaneously enhance production, profit and biodiversity. We work with farms across southern Australia and employ a transdisciplinary participatory action research framework, iteratively refining model inputs with producers to ensure robust simulation of historical production, profit, spatially explicit carbon stocks and biodiversity. Through a people-centred design process, we co-develop interventions that target carbon sequestration, enteric methane mitigation and avoidance, production efficiency and environmental stewardship, treating emissions abatement, carbon accrual and biodiversity enhancement as monetised outcomes. We then quantify changes borne by interventions relative to farm-specific historical baselines.

We find that planting native trees yields the greatest abatement potential, followed by antimethanogenic feed supplements, although emissions reductions from tree establishment and the use of antimethanogenic legumes generally invoke lower cost than other mitigation options. Carbon sequestration however decreases over time as tree biomass plateaus, whereas emissions reductions from avoided methane are immediate, permanent and cumulative. Although many interventions deliver unidimensional benefits—such as improvements to profit or GHG abatement alone—few simultaneously reduce net GHG emissions and enhance profitability and biodiversity. Antimethanogenic pasture species emerge as among the most favourable options, providing modest mitigation alongside economic gains.

We contend that the benefits of any farming system intervention must be evaluated using a broad suite of interdisciplinary indicators, because improvements in one domain can be offset by unintended losses in another. Our analysis also demonstrates that interventions are most appropriately assessed against each farm's own historical trajectory, rather than compared across farms, due to the particularised ecological, economic and management conditions that shape enterprise performance.

Results

Baseline production and greenhouse gas emissions

Farm S1 (Tasmania; TAS) had the highest biodiversity, whereas farm S7 (South Australia; SA) recorded the greatest protein sold per hectare of grazing land. Farm S4 (New South Wales; NSW) achieved the highest gross margin (GM) per unit protein mass and the lowest emissions intensities (Table 1). Protein sold per ha varied substantially among farms, reflecting differences in production systems, stocking strategies, and agroecological conditions. Farm S7 operated at the highest stocking rate −30 dry sheep equivalents (DSE) ha^{-1} – making it the most intensive protein-producing enterprise (Table 1). By contrast, variation in protein production per unit DSE was less pronounced than variation per ha of grazing area, indicating that spatial extent and stocking density were primary drivers of the observed differences (Fig. 1a).

Baseline protein produced per unit grazing area spanned a wide range, from 153 kg ha^{-1} for S7 (SA) to 12 kg ha^{-1} for S5 (Western Australia; WA) (Fig. 1a). This variation corresponded closely with differences in stocking rate: farm S2 operated at 4.7 DSE ha^{-1}, whereas farm S6 reached 24.6 DSE ha^{-1}. These patterns suggested that farm S6 produced less protein per DSE than farm S2, likely due to increased competition for feed resources at higher stocking densities. More broadly, protein production per ha was lower in low-rainfall zones, although differences in stocking rate among farms within comparable rainfall regions indicated that management decisions interacted strongly with biophysical constraints.

Baseline carbon dioxide reductions and removals

Gross emissions were closely related to total protein produced per farm, reflecting the strong coupling between production output and GHG emissions. Net farm emissions were additionally influenced by the extent of farm vegetation; several farms had historical vegetation that contributed to either carbon emissions or removals. Historical carbon sequestration in vegetation ranged from −950 to +71 t CO_2eq $annum^{-1}$ for S1 (TAS) and C3 (Victoria; VIC), respectively. Variability in net emissions per unit protein sold was relatively low across farms (36–56 kg CO_2eq kg $protein^{-1}$; Table 1). Farms S3 (VIC) and S4 (NSW) had the lowest values (36 kg CO_2eq kg $protein^{-1}$), whereas S1 (TAS) and S6 (VIC) showed higher emissions intensities (53–56 kg CO_2eq kg $protein^{-1}$; Fig. 1b). Net GHG emissions per unit grazed area ranged from 0.5 to 6.5 t CO_2eq ha^{-1}, with the highest values observed for S6 (VIC) and the lowest for S5 (WA) (Fig. 1b).

Table 1 | Baseline farm characteristics arranged from left to right following an average annual rainfall gradient (low to high)

Description	S5 (WA)	S2 (SA)	S1 (TAS)	S3 (VIC)	S7 (SA)	S6 (VIC)	S4 (NSW)
Avg. annual rainfall (mm)[1]	320	465	480	600	625	720	800
Farm area (ha)	5,850	890	7,777	690	2,000	495	250
Grazing area (ha)	3484	865	3170	600	1880	440	160
Pasture production (kg DM/ha/year)	5291	5480	6915	8242	12,296	12,374	12,465
Stocking rate per ha of farm area (DSE/ha)	1.5	4.6	3.2	14.2	27.9	21.9	3.8
Stocking rate per ha of grazed area (DSE/ha)	2.5	4.7	7.9	16.4	29.7	24.6	5.9
Annual meat sold (kg)	173,719	130,972	285,444	190,097	1,122,333	117,308	14,799
Annual clean fleece wool sold (kg)	10,379	6,837	78,026	23,063	85,918	30,488	2,097
Annual protein (meat + wool) sold (kg)	41,648	30,412	129,406	57,280	287,938	51,604	4761
Annual protein (meat + wool) sold per ha of grazed area (kg ha^{-1})	12.0	35.2	40.8	95.5	153.2	117.3	29.80
Tree carbon stocks on the farm in 2020 (t CO_2eq)	9208	7716	1,300,655	4795	407	7530	19,872
Effective habitat area in 2020 (ha)	130	38	4876	43	10	17	94
Area under high-quality habitat condition in 2020 (ha)	73	28	4629	18	0	7	71
Threatened species habitat 2020 (species.ha)	459	194	56,207	226	11	148	1367
Benefit for plant species persistence in 2020 (number of species)	0.001	0.0001	0.0007	0.0008	0.0005	0.0002	0.0485
Gross total farm GHG emissions (t CO_2eq year^{-1})	1593	1315	5935	2159	11,226	2601	226
Carbon sequestration/loss by trees on farm (t CO_2eq year^{-1})[2]	28	19	-950	71	4	-267	56
Net farm GHG emissions (t CO_2eq per year)	1565	1296	6885	2087	11,222	2867	170
Emissions intensity of meat (including sequestration) (kg CO_2eq kg liveweight^{-1})	6.8	7.7	9.6	6.6	7.0	10.0	6.4
Emissions intensity of wool (including sequestration) (kg CO_2eq kg clean fleece wool^{-1})	37.6	42.6	53.2	36.4	39.0	55.6	35.7
Gross margin per annum (profit) (AUD)	251,623	145,361	980,908	448,991	1,802,517	656,231	65,350
Gross margin per unit grazed area (AUD ha^{-1})	72	168	309	748	959	1491	408
Gross margin per unit protein (profit) (AUD kg^{-1})	6.0	4.8	7.6	7.8	6.3	12.7	13.7

[1] Long-term average mm rainfall, including irrigation (determined using climate for each farm location between 1992 and 2022).

[2] Negative values reflect a loss in tree vegetation carbon sequestration between 2004 and 2020.

Baseline gross margins

For all farms except S4, mean GM tended to follow a rainfall gradient, with higher annual rainfall associated with greater production (Table 1) and higher GM per unit area (Fig. 1c). Farm S5, which had the lowest rainfall, also had lower stocking rates and lower GM per ha. In contrast, farm S6, with higher rainfall, produced more pasture and consequently supported higher stocking densities (22 DSE ha^{-1}; Table 1). Farm S4 produced the finest wool (lowest micron), resulting in the highest income per unit sale weight and the highest GM per unit protein mass. Farms with the highest GM per ha (S7, S3, S6, and S4) were located in higher rainfall regions (500–800 mm). Conversely, the three farms receiving <500 mm annual rainfall (S5, S2 and S1) had the lowest GM per ha (Fig. 1c). Average GM per unit protein mass was highest for farms S6 (VIC) and S4 (NSW), driven by greater pasture production in high rainfall zones and dilution of fixed costs (e.g., fertiliser, fuel, electricity) across larger volumes of protein produced.

Co-benefits and trade-offs between GHG emissions, production, biodiversity and profits caused by intervention

Across interventions, no single practice simultaneously reduced GHG emissions while improving profit, production and biodiversity. When applied universally, interventions reduced GHG emissions by <−1% to −120%, whereas farm-specific scenarios evoked −16% to +19% change in net GHG emissions (Fig. 2). Common interventions generally had minimal effect on GM, whereas farm-specific interventions often increased GM, indicating that farmers prioritised profit over livestock production or GHG reduction (Fig. 2). Impacts on meat and wool sold were similar for three of the common interventions, but production decreased by 1–12% under the tree planting and 50% liveweight gain scenarios. The 50% liveweight gain scenario reduced wool sales in some cases, as weaners were sold prior to shearing.

Planting native trees increased carbon sequestration and provided biodiversity habitat, although benefits varied across zones (Supplementary Fig. S1). The smallest reduction in GHG occurred for S7 (15%) and the largest for S5 (120%), reflecting differences in baseline net emissions, grazed area, and stocking density. For example, S5, with baseline net emissions of 1565 t CO_2eq annum^{-1} and an extensive grazed area of 3,484 ha, became a GHG sink of −317 t CO_2eq, demonstrating that farms with large grazing areas and low stocking rates derive more benefit from tree planting. In contrast, S7 (SA), with the highest stocking density (55,800 DSE) and baseline GHG emissions of 11,226 t CO_2eq annum^{-1}, achieved only a 15% offset through tree carbon sequestration.

Interventions effective in suppressing GHG emissions often came with drawbacks. Even accounting for profit from biodiversity and GHG reductions, tree planting was costly due to fencing, maintenance, and lost production, reducing GM by 9–32% under low carbon and livestock prices (Supplementary Tables S2 and S3). Under high carbon prices, however, five farms realised higher GM regardless of livestock sale prices. In these scenarios, GM increased by 2% (S6) to 14% (S5), whereas S3 and S7 experienced declines even under high sheep prices.

Antimethanogenic feed supplements caused substantial reductions in GHG emissions. When *Asparagopsis* was used as an antimethanogenic feed additive, farm S2 (SA) achieved the lowest reduction (19%), while S4 (NSW) achieved the highest (32%). High costs associated with *Asparagopsis* decreased GM by 63-115% under low carbon and livestock prices (Figs. 2 and 3). Under high carbon and livestock prices, reductions in GM were smaller (46-83%), as income from avoided enteric CH_4 partially offset input costs. These interventions also increased variability in GM per ha between farms (Fig. 4). Enteric CH_4 mitigation via 3-Nitrooxypropanol (3-NOP) supplementation followed similar trends to those of *Asparagopsis* supplementation (Fig. 2).

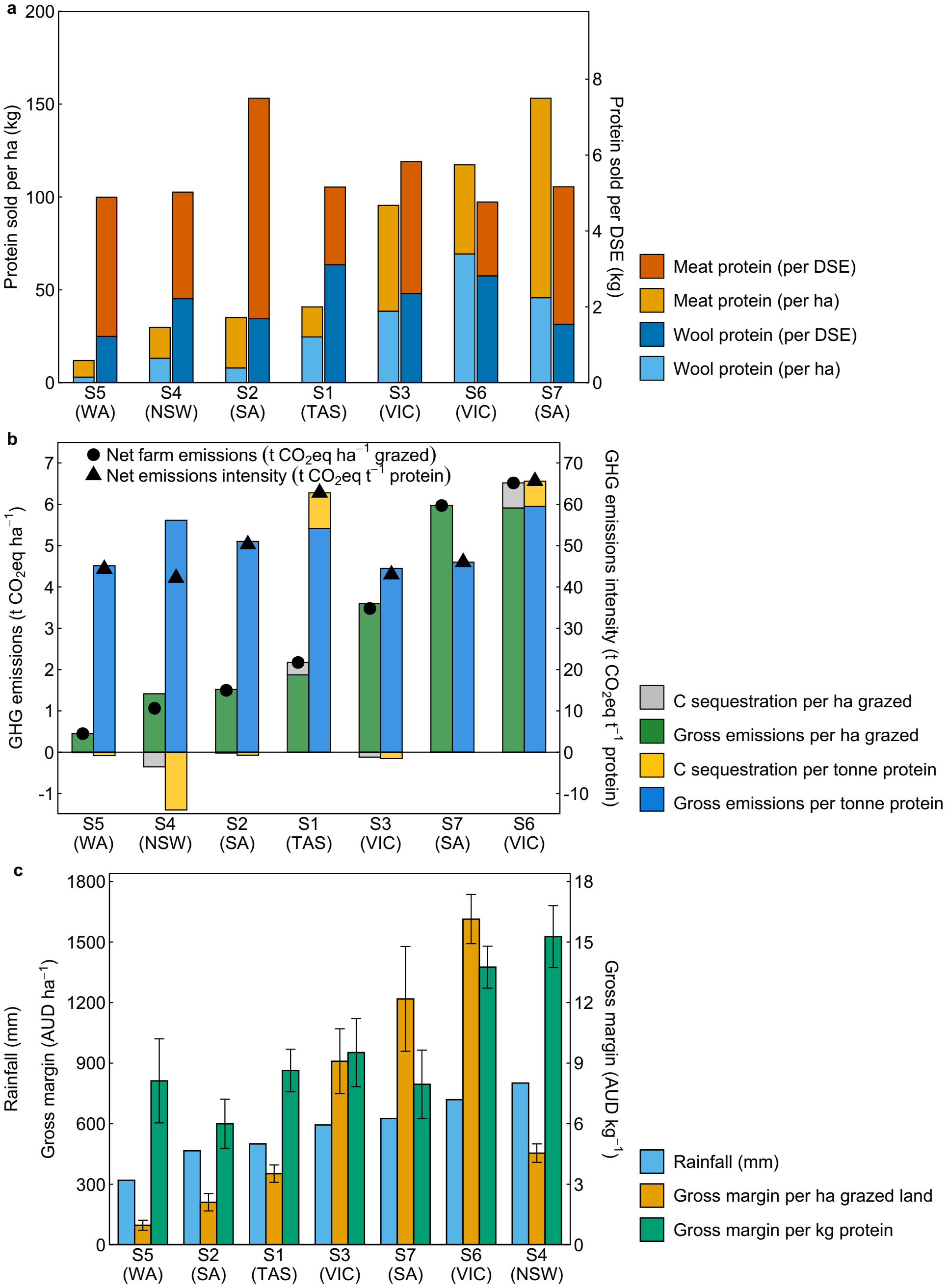


Fig. 1 | Average baseline production, GHG emissions and gross margins of sheep farms across seven agroecological zones. a Baseline wool and meat production per hectare (ha) of grazing area and per dry sheep equivalent (DSE). Results shown in ascending order of meat plus wool protein sold per hectare from left to right (*n* = 30); **b** Gross and baseline GHG emissions per hectare grazed area and per tonne of protein sold. Baseline emissions include gains/losses in carbon in CO_2eq due to changes in vegetation carbon sequestration between 2004 and 2020, with column segments below zero reflecting carbon sequestration, and with bars above zero reflecting carbon losses (*n* = 16); **c** Baseline gross margin per unit grazed area and per kilogram of protein. Farms are arranged from left to right in ascending annual rainfall gradient. Error bars show change in mean baseline gross margin at low and high carbon and sheep prices (*n* = 3). AUD Australian dollars, DSE dry sheep equivalents, S1-6 case study sheep farm 1-6, NSW New South Wales, SA South Australia, TAS Tasmania, VIC Victoria, WA Western Australia.

Renovating pastures with antimethanogenic species produced moderate reductions in net GHG and modest gains in profit. Net farm emissions decreased by 14-25%, with GM increasing by 2–5% under low carbon and livestock prices, and 5–9% under high prices (Figs. 2 and 3). Scenarios targeting enteric CH_4 mitigation through grazing management yielded similar but smaller effects compared with adopting antimethanogenic legumes.

Increasing liveweight gain of juvenile animals by 50%—achieved through grazing management, genetic improvement, and/or supplementary feeding—was, in most cases, detrimental. For example, wool production at S4 (NSW) declined by 28% due to the early sale of young sheep before shearing. Net farm GHG mitigation was generally <9%, while GM declined by 1–36% (Fig. 2). Improvements in grazing management alone resulted in marginal reductions in emissions (< 3%) and negligible gains in GM (< 1%). These counter-intuitive outcomes highlight the value of using systems-level assessments to quantify interactions among biophysical, production and management processes.

Half of the farm-specific, demand-driven scenarios increased net emissions (up to 20%). Seven scenarios increased productivity by

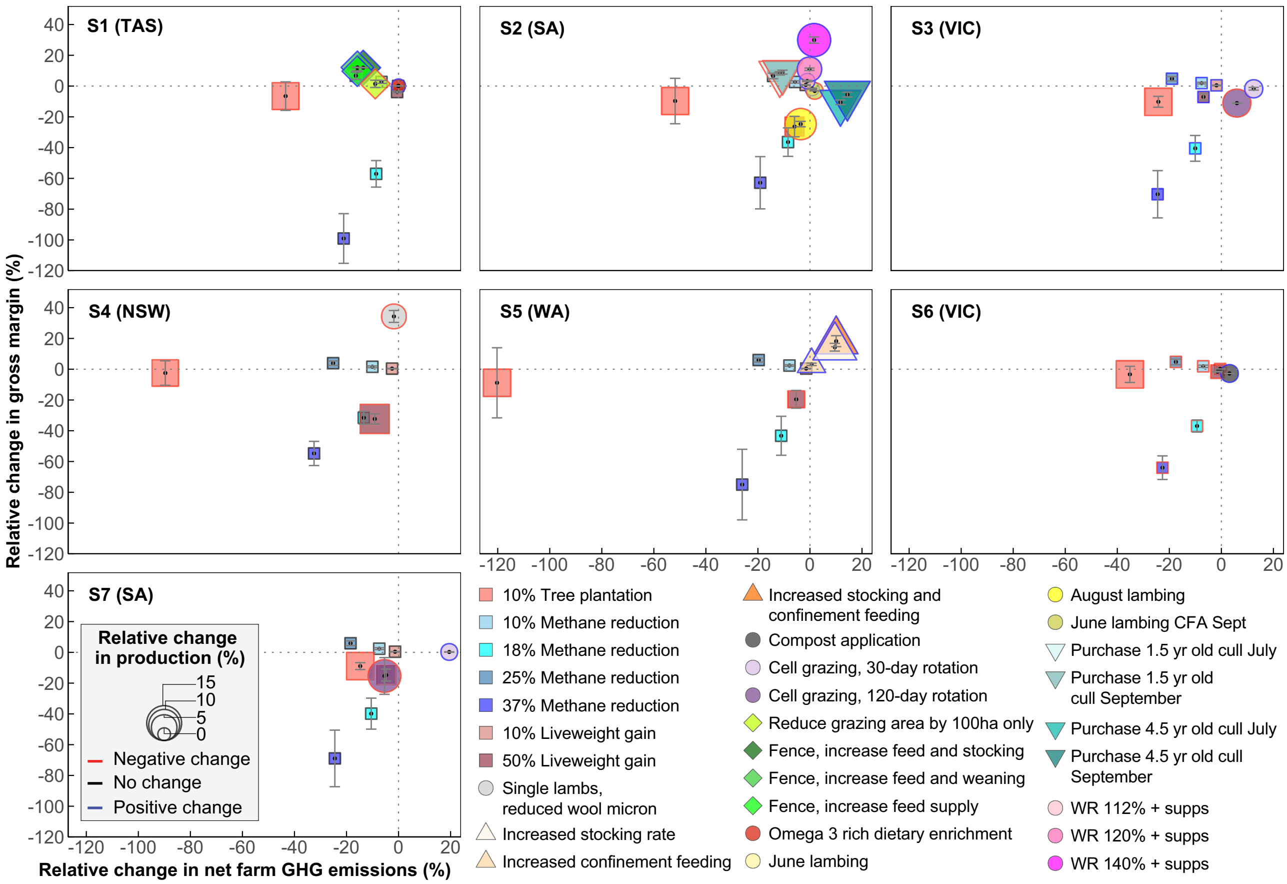


Fig. 2 | Average change in enterprise gross margin, net GHG and production relative to each baseline for common and/or demand-driven interventions across multiple agroecological zones. Relative change (points) computed as the mean of $n = 30$ climate-years. Error bars show range in gross margins at low and high carbon and sheep prices. Bubble size represents relative change in annual protein production. Blue, red, and black bubble margins indicate positive, negative, or zero change in livestock production relative to baseline conditions. Abbreviations S1-7 reflect farms. CFA cast for age, DSE dry sheep equivalents, NSW New South Wales, SA South Australia, TAS Tasmania, VIC Victoria, WA Western Australia, WR weaning rates, '+ve' positive, '-ve' negative.

5–14%, whereas 15 scenarios did not reduce production. Fourteen scenarios increased GM (up to 38%), while nine reduced GM (1–27% loss; Fig. 2). Purchasing ewes at a later age (4.5 years) and shifting culling from mid-August to early September increased both GHG emissions and protein by 14%. Increasing the number of older ewes cast for age (CFA) similarly increased protein sales but also raised net emissions. Extending the duration of confinement feeding and/or increasing stocking rate at S5 (WA) increased protein sold by up to 12%, net farm emissions by up to 10%, and GM by up to 22% under low livestock prices (Fig. 2).

Reducing ewe fecundity to produce more single lambs rather than twins or triplets, combined with lower wool micron, was one of the most promising demand-driven interventions. At S4 (NSW), fewer lambs reduced net farm GHG by 2% and protein production by 4% (Fig. 2), while GM increased by 30–38%, predominantly due to higher income from finer wool (baseline 14.2 µm at AUD 34 kg CFW^{-1} vs. intervention 11.0 µm at AUD 49 kg CFW^{-1}).

Fencing off 100 hectares of riparian area and creating additional pasture adjacent to native vegetation, coupled with increased weaning rates or stocking rate, was the most effective intervention for S1. Scenarios stacked with this intervention, except for the initial 100 ha reduction, reduced emissions by 14–16% (primarily through enhanced pasture production and greater soil organic carbon accumulation), increased protein production by 4–7%, and improved GM by 9–12% (Fig. 2). Biodiversity also increased when livestock were excluded from riparian zones by fencing, allowing simultaneous gains in emissions reduction, production, profit, and habitat provision.

Cell grazing on a 30-day rotation with high stocking rates in S3 and S7 increased net GHG by 12% and 19% (0.4 and 1.1 t CO$_2$eq ha^{-1}), resulting in a small GM reduction at S3 (AUD 24 ha^{-1}), while S7 experienced a nominal GM gain (Figs. 2, 4a). These farms also showed the largest increases in emissions intensity per kg protein, rising by 11% and 19% (4.2 and 7.4 kg CO$_2$eq kg^{-1} protein; Figs. 3, 4b).

Substituting inorganic fertiliser (mono-ammonium phosphate; MAP) with organic compost at S6 (VIC) negatively affected emissions abatement, production, and GM (Fig. 2). Assuming a 3% increase in the GrassGro fertility scalar, livestock production increased by 1% but GHG emissions rose by 3%, partly because compost has a higher emission profile than MAP and higher costs (Tables S10, S11).

To standardise perturbation across interventions, we conducted a sensitivity analysis examining the change in net farm GHG emissions associated with a 50% reduction in each intervention (Supplementary Fig. S5). For example, tree planting was reduced from 10% to 5% of grazing area, allowing livestock access to an additional 5% of land. Similar reductions were applied to antimethanogenic feed additives (3-NOP: 9% CH$_4$ reduction; *Asparagopsis*: 19% CH$_4$ reduction). This analysis indicated that tree planting was the most sensitive intervention, followed by antimethanogenic feed additives. These results reflect that tree planting influenced carbon sequestration and enteric methane (via reduced animal numbers), while antimethanogenic feed additives target enteric CH$_4$, which often dominates farm GHG emissions.

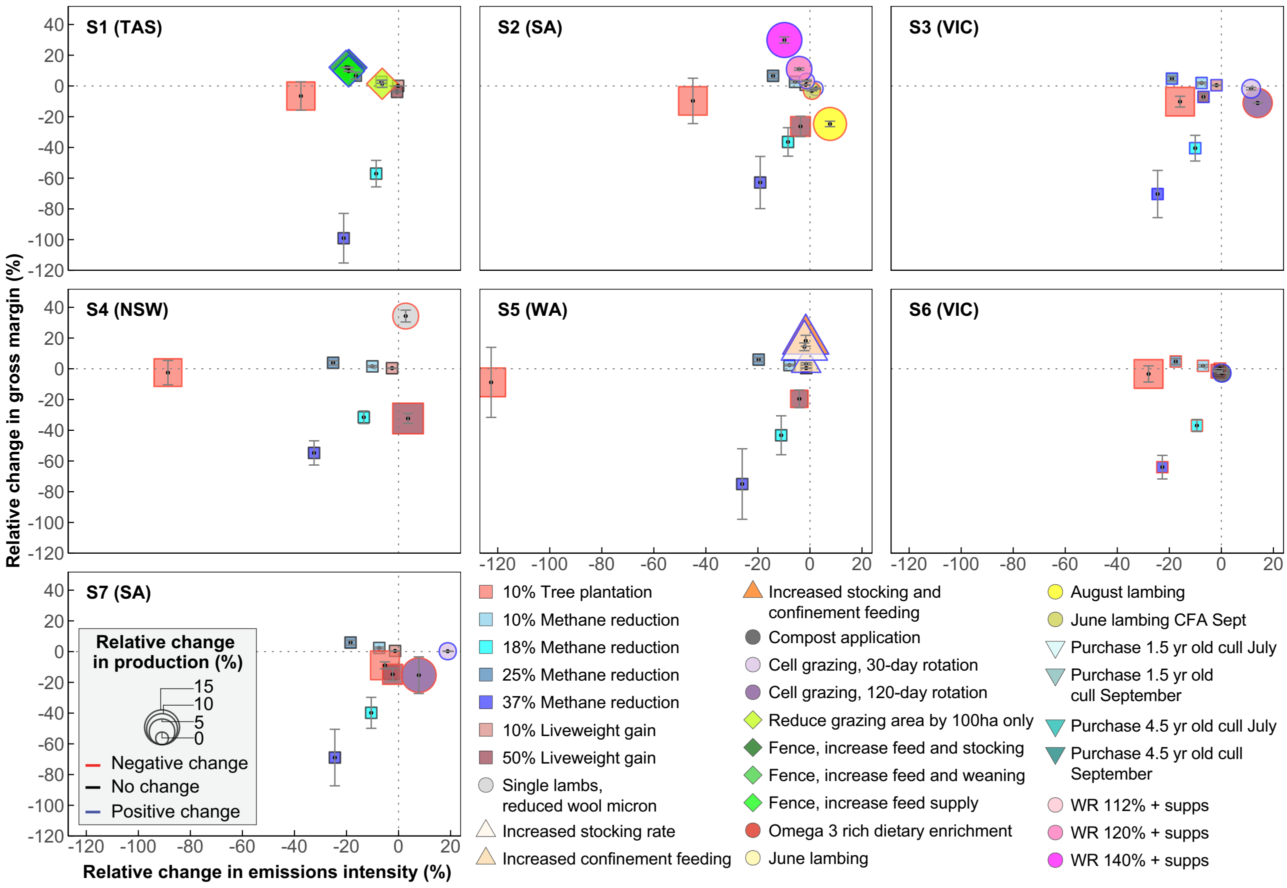


Fig. 3 | Average change in enterprise gross margins, emissions intensity and production relative to the baseline for common and/or demand-driven interventions across multiple agroecological zones. Relative change (points) computed as the mean of $n = 30$ climate-years. Error bars show range in gross margins at low and high carbon and sheep prices. Bubble size represents the relative change in annual protein production. Blue, red, and black bubble margins indicate positive, negative, or zero change in livestock production relative to each baseline. Abbreviations S1-7 reflect farms. CFA cast for age, DSE dry sheep equivalents, NSW New South Wales, SA South Australia, TAS Tasmania, VIC Victoria, WA Western Australia, WR weaning rates, '+ve' positive, '-ve' negative.

Interventions that increase production more conducive to reducing emissions intensity

When production increased following an intervention, emissions intensity generally decreased, and vice versa, except for tree planting (Fig. 3). Purchasing 4.5-year-old ewes and culling in September at S2 increased both production and GHG emissions by similar proportions, resulting in negligible change in emissions intensity. At S7 (SA), cell grazing with a long rotation increased emissions intensity by 8% due to a 12% decline in protein production. Tree planting resulted in smaller deviations in emissions intensity compared with net GHG due to production losses relative to additional carbon sequestration. These results suggest that farm-specific interventions that increase production generally achieve greater reductions in emissions intensity than interventions that primarily reduce net emissions.

Improved biodiversity following planting native tree species

Tree planting improved effective habitat at S4 (NSW), S5 (WA), and S7 (SA), while gains in threatened species habitat were greatest at S3 (VIC) and S6 (VIC). Farm S4 (NSW) had the largest relative change in effective habitat (37%), gaining 5.9 ha from 16 ha planted, though high-quality habitat was minimally affected (Fig. 5a, b). High-quality habitat gains were greatest at S1 (TAS) and S2 (SA), likely due to (1) revegetation in riparian zones, (2) connection with existing vegetation creating wildlife corridors, and (3) sparse pre-existing vegetation that allowed complementary benefits (Fig. 5b).

Threatened species habitat increased by 43–353% over 30 years following tree planting. The highest relative gain in species persistence occurred at S7 (SA, 9%), while the change in threatened species habitat in other farms was *de minimus* (0–3%).

Impacts varied depending on whether absolute or relative measures were considered. For instance, S4 (NSW) had the lowest absolute increase in effective habitat area but the highest relative change, whereas S1 (TAS) had the lowest relative change in threatened species habitat but the highest absolute gain in hectares. In absolute and relative terms, changes in plant species persistence were lowest at S4 (NSW) and highest at S7 (SA).

Discussion

No two farms are identical, their current state reflecting the culmination of hitherto interactions between economic, environmental, social, and cultural factors leading up to the present. Depending on historical circumstances and future priorities, farm management decisions should account for not only current status but also those indicators in which farm managers perceive as most valuable (profit, production, environmental stewardship, social licence and/or market access, intergenerational sustainability or other), as prioritisation of one indicator can be at the expense of another.

A key conclusion from the present study is that the greatest gains in GHG mitigation, profit, biodiversity, and productivity are likely achieved when underlying deficits are addressed. Those deficits may be environmental, economic or management-related. Our study indicates that the notion that a single intervention could be applied generically and result in widespread benefit is implausible. Scalable and durable outcomes are more likely when interventions are tailored to

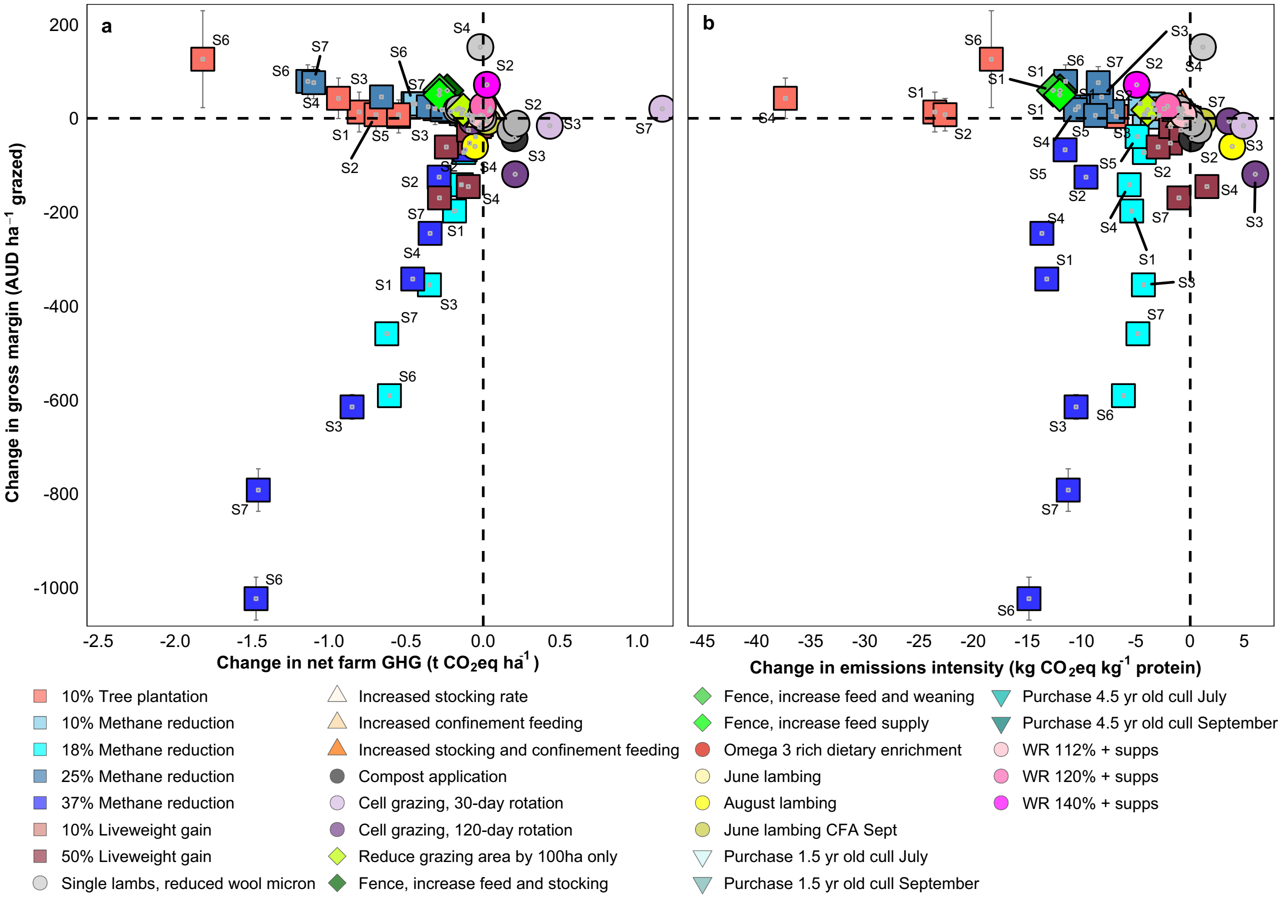


Fig. 4 | Absolute change in enterprise gross margins, net emissions and emissions intensity relative to the baseline system for common and/or demand-driven interventions across multiple agroecological zones. Absolute change in gross margin and net GHG emissions (a) and emissions intensity (b) for several interventions. Absolute change (points) computed as the mean of $n = 30$ climate-years. Error bars show range in gross margins at low and high carbon and sheep prices. Abbreviations S1-7 reflect farms. AUD Australian dollars, CFA cast for age, DSE dry sheep equivalents, NSW New South Wales, SA South Australia, supps supplementary feeding, TAS Tasmania, VIC Victoria, WA Western Australia, WR weaning rates.

the historical climate, management practices, and specific context of each farm system, enabling targeted diagnosis and remediation of underperformance.

Substantial variation in ecological conditions, economic performance and emission profiles across farms helps explain why some interventions produce marked effects, whereas others cause little perturbation. This heterogeneity is evident in the wide range of emissions intensities in our case studies. Baseline emissions intensity varies between 26 and 35kg CO$_2$eq kg greasy wool^{-1} (Fig.1b), exceeding the 20-25kg CO$_2$eq kg greasy wool^{-1} range reported by Wiedemann et al.[39]. Several factors underpin this difference: (1) Wiedemann et al.[39]. applied earlier global warming potentials (GWP$_{100}$ = 25), whereas we adopted a more contemporary value following the Australian National Greenhouse Gas Inventory (GWP$_{100}$ = 28); (2) variation in wool production per animal spans a broader range in our dataset (4-15 kg greasy wool per breeder) compared with that in Wiedemann et al.[39]. (8–10 kg greasy wool per breeder) and (3), the proportion of total farm emissions allocated to wool relative to meat is higher in our study. Collectively, these factors highlight intrinsic variability in management practices and environmental conditions across the production systems examined.

Approaches for diagnosing site-specific deficiencies could be operationalised by comparing indicators from low and high performing farms within a given agroecological region using the farm typologies framework[40,41]. This approach enables quantification of the gap between realised and potential performance, analogous to yield-gap analyses in cropping systems[40,41], but extended to economic and environmental dimensions by comparing performance clusters within regional and enterprise contexts. Farms with superior performance are also more likely to possess information on the practices, skills, and technologies that have underpinned their historical development trajectory and current performance levels[42]. Such farms can therefore act as exemplars, providing insight into strategies that may facilitate improvement over time among lower-performing counterparts.

Planting native trees on 10% of grazing land reduced net GHG emissions by up to 120% and improved threatened species habitat by as much as 300%. For conservatism, we assumed that tree areas planted on pastureland resulted in commensurate reductions in livestock carrying capacity. Under this assumption, the combined effects of reduced pasture production and the costs of vegetation establishment reduced profit under low carbon and biodiversity prices (Fig. 4). However, the economics associated with planting trees under higher carbon and biodiversity prices were more favourable. Empirical and experimental evidence indicate that shade and shelter can evoke productivity co-benefits[25], potentially increasing liveweight gain and reducing livestock exposure to climatic extremes. Some of the farmers we engaged suggested that livestock productivity may even improve with strategic tree plantings, for example shelter belts that reduce lamb mortality, or trees that reduce animal heat stress. We therefore suggest that productivity co-benefits of planting trees on farm—which depend on existing conditions, tree configuration, agroecological context and livestock management—deserve further attention; under

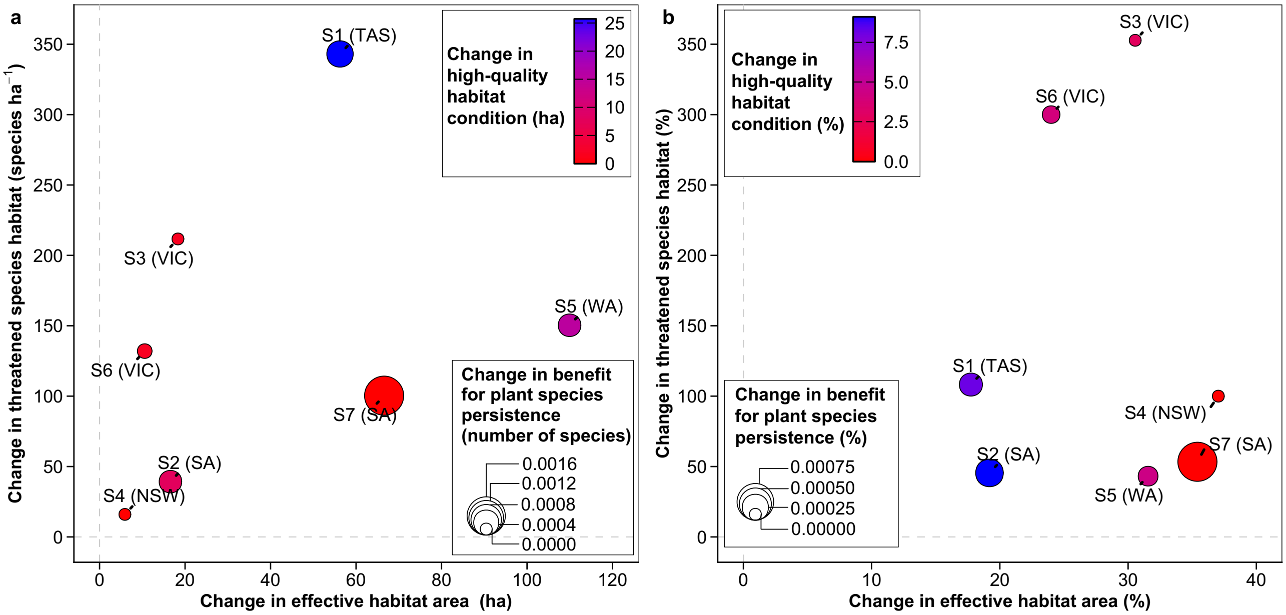


Fig. 5 | Effect of planting 10% of pasture area with native tree species. Mean change in absolute (**a**) and percentage (**b**) effective habitat area, high quality habitat condition, threatened species habitat and benefit for plant species persistence between 2020 to 2050 (n = 30 climate years). S1-7 = case study sheep farm 1-7, NSW New South Wales, SA South Australia, TAS Tasmania, VIC Victoria, WA Western Australia. Effective habitat area reflects the total habitat area available for biodiversity, accounting for habitat condition in each location (grid cell) and farm area. A larger value indicates a greater contribution of the farm in supporting biodiversity. High-quality habitat areas are those where the habitat condition is greater than 75%. Threatened species habitat combines spatial information on the distribution of all 1466 terrestrial nationally listed threatened species and the habitat condition data in Australia[86]. Threatened species habitat was estimated by multiplying the number of threatened species that may occur in a location by the habitat condition in that location when habitat condition was above 50%. Aggregated values for each location provide the number of 'threatened species hectares'. Higher values indicate a greater contribution of the area in providing habitat for threatened species[86]. The benefit of habitat for plant species persistence enumerates the benefit of farm habitat in contributing to long-term persistence of all Australian plant species, calculated by combining habitat condition with spatial biodiversity patterns for plant species assemblages[87].

some circumstances, trees may even improve pasture production[43]. Our assumption of reduced pasture growth—adopted for consistency and conservatism—may therefore not hold universally and warrants further investigation, including targeted sensitivity analyses.

As with any farming-system intervention, tree planting can generate co-benefits and adverse outcomes. Although trees show strong mitigation potential and positive economic returns under favourable market conditions, they can also increase fuel loads that contribute to bushfire risk—an issue of growing concern in southern Australia under climate change[44]. Bushfires affect native taxa and ecosystem structure[35], while inappropriate tree establishment can have additional ecological costs. Veldman et al.[36]. distinguish afforestation from reforestation and caution that afforestation of historically non-forested ecosystems—such as grasslands, savannas and open-canopy woodlands—can alter hydrology, light regimes and nutrient cycles, compromising biodiversity and natural capital. Although regions examined here supported woodland vegetation prior to European settlement[45,46], we are not advocating widespread planting of trees on farmland *en masse*. Rather, targeted tree establishment in low-productivity areas, along fence lines, or in locations that enhance landscape connectivity is likely to enhance ecological benefits while minimising trade-offs. Connecting remnant vegetation can improve habitat continuity and facilitate species movement across fragmented landscapes[47,48]. Regardless of whether or not trees are planted, judicious management of detrimental species—such as invasive plants and feral animals—remains essential to prevent land degradation and competition with native species[44].

Introducing antimethanogenic legumes increased profitability while reducing GHG emissions, making this one of the most favourable interventions assessed (Figs. 2–4). In contrast to antimethanogenic feed additives—whose intake can vary depending on delivery method—legumes are consumed as part of routine grazing. Although their antimethanogenic potency per unit mass is typically lower than that of feed additives, the larger quantities consumed via pasture intake can yield substantial emissions reductions. Pasture renovation is already a common management practice in intensive production systems across Australia, suggesting that adoption of antimethanogenic legume species is operationally feasible[26]. Because the compounds responsible for suppressing enteric CH_4—such as tannins, saponins and other polyphenolics—have multiple physiological effects, antimethanogenic pastures merit further investigation. For example, condensed tannins can reduce protein digestibility and inhibit livestock productivity[49], yet reduced protein digestion also reduces urinary N excretion and associated nitrous oxide emissions[49]. Further, condensed tannins can reduce gut parasites and improve milk and wool production, immune functioning and reproductive performance[50,51].

The antimethanogenic feed additives examined here (*Asparagopsis taxiformis* and 3-NOP) have been much-lauded for their abatement potency[24,26]. Across production systems, carbon and livestock prices, we revealed that antimethanogenic feed supplements reduced net GHG emissions by 19–32%. The ceiling of this range was amongst the highest mitigation of all measures examined and, in contrast with tree carbon sequestration which diminished over time, yielded consistent temporal avoidance of enteric methane, presuming feed supplements were always available and consumed. As such, mitigation of enteric methane offers permanence (methane avoided cannot be returned to the atmosphere) and continual accumulation, assuming other aspects of the farm remain ceteris paribus. In contrast, carbon sequestration in trees and soils slows over time[52,53], making the quest to offset farm GHG using carbon sequestration increasingly difficult as trees approach maturity. As well, sequestered carbon in vegetation and soils will eventually return to the atmosphere, particularly where regions are prone to wildfire, drought, or land-use change[54,55].

A primary barrier to the adoption of antimethanogenic feed additives is their cost. Our modelling indicates that adoption of *Asparagopsis* or 3-NOP can reduce gross margin by at least 45%, even when accounting for potential future increases in carbon prices. Further, in situ efficacy may be lower than commonly reported: a review of *Asparagopsis* supplementation trials found mitigation efficacy ranging from 9% to 100%, with most studies conducted under controlled conditions[56]. We found that gross margins were reduced primarily due to the high cost per unit mass of these supplements and the requirement for daily animal intake. Although emerging evidence suggests minimal bromoform residues in meat from animals consuming *Asparagopsis*[57], other factors—including high product cost, limited accessibility, regulatory uncertainty[56] and incomplete understanding of animal health impacts—may further constrain uptake[58].

Individual interventions often generate both co-benefits and trade-offs; combining multiple interventions can magnify benefits or mitigate negative effects if they address underlying system constraints[25]. For example, re-establishing riparian vegetation on farm S1 reduced production and profit when implemented in isolation, even after accounting for income from carbon credits and biodiversity benefits. However, when coupled with complementary measures—such as boundary fencing and increased weaning rates—both production and profit improved, while GHG emissions declined further. Stacking interventions can therefore reduce trade-offs associated with single practices, but only when the sum of co-benefits exceeds the sum of associated costs[59]. Where trade-offs outweigh benefits, continuation of current practices may be more advantageous, although evolving market access or environmental credential requirements could shift economic incentives toward adoption[4,59,60].

The magnitude of intervention benefits is strongly dependent on baseline conditions. For instance, in the absence of wildlife grazing on farm S1, boundary-fencing trade-offs would likely have outweighed co-benefits. Bewsell et al.[61] reported that dairy farmers generally support fencing water bodies to comply with legislation or societal expectations, even when perceived environmental gains are modest. This suggests that economic incentives—such as productivity gains or payments for ecosystem services—are critical for interventions targeting environmental stewardship[62].

Flock-management strategies, such as purchasing replacement ewes at a younger age (1.5 versus 5 years), were economically and environmentally favourable on several farms (e.g. S2), despite a decline in total meat output due to fewer older cast-for-age ewes. These findings align with Alcock, et al. [63]., who showed that earlier mating and sale of ewes can increase profitability. Emissions reductions resulted mainly from decreased ewe purchases and lower associated Scope 3 emissions. Given their relative simplicity and reversibility, flock-management interventions represent accessible, low-cost mitigation options.

Producers also demonstrated substantial capacity for innovation. Adjusting purchase and sale timings on farm S2 reduced net farm GHG emissions by 12%, one of the largest reductions observed among demand-driven strategies. This aligns with Browne, et al. [64]., who found that higher productivity systems, such as dairy relative to beef or sheep, tend to exhibit lower emissions intensity despite higher absolute emissions per unit area. Other studies show that enhancing production efficiency through improved pasture management, optimised stocking rates, and increased genetic fecundity can reduce emissions intensity without compromising profitability[16,64,65]. Interventions targeting production efficiency, including animal health and liveweight gain, therefore provide a robust pathway to reduce emissions intensity and net emissions while maintaining or increasing profit.

Through co-design and iterative engagement, we observed that farmers prioritise interventions that enhance profitability and long-term sustainability, reflecting the dual need to support livelihoods and maintain natural, human, and social capital. This contrasts with generalisations that farmers prioritise short-term gains at the expense of environmental outcomes, which often arise from studies in intensively managed cropping systems characterised by irrigation, mechanisation, or pesticide use[66]. Globally, agricultural expansion–related ecosystem losses are concentrated in a few hotspots, such as the Amazon and Afrotropics[67].

Farmers in our study placed relatively low priority on increasing production, highlighting tension between producer motivations—centred on livelihood security and sustainability—and societal goals for food security, GHG mitigation, and biodiversity conservation[68,69]. Achieving substantial carbon storage or biodiversity gains on farms may therefore require market prices for these ecosystem services that are comparable to or exceed those for conventional agrifood commodities[69].

A wide range of modelling approaches exists for analysing farming systems, including artificial intelligence, biophysical, bioeconomic, statistical, and agent-based methods[5,18,60,70,71]. Among these, farm typologies—statistical classification of heterogeneous systems using principal component analysis or hierarchical clustering—have become popular[72]. While typologies can group farms by lifestyle, production system, agroecological context, income, technology, or food security, their construction should be informed by contextualised biophysical and socio-economic factors[73]. Moreover, typologies are generally unsuitable for model calibration or validation because real farm data are not directly incorporated. To address this, we used a case-study modelling approach, iteratively refining inputs in consultation with end-users until outputs closely represented biophysical, economic, and environmental baselines[25]. Given our focus on changes relative to historical conditions, grounding simulations in real farm data was essential.

Methods

Case study farms

To examine implications associated with interventions on baseline farm systems, we invoke data from seven real enterprises as case studies (Fig. 6). As climate and soil type influence plant growth, livestock carrying capacity, enterprise and often farm size, real farms were strategically chosen across Australia following advertisement of the study in national industry newsletters in January 2022 (Meat & Livestock Weekly, South Australia Livestock Research Council and Western Australia Livestock Research Council). Of 115 expressions of interest, seven farms were chosen based on (1) their location within key sheep production zones of Australia[74], (2) agroecological region, from cool temperate in southern Victoria to semi-arid in Western Australia, (3) enterprise mix and livestock numbers, and (4) willingness to engage and likelihood of persisting with the study over four years. Farms chosen practise enterprises typical of Australian sheep production systems, focussing on meat and/or wool production (Supplementary Information section 1 and Table S1). Climate, soil, pasture and production system parameters of these farms were used to initialise models before which several interventions, and several scenarios within interventions, were examined in silico. As most of the Australian sheep flock is located in southern Australia (MLA, 2022), case studies were selected from Western Australia (WA), South Australia (SA), Victoria (VIC), New South Wales (NSW), and Tasmania (TAS), acknowledging that seven farms cannot encompass the full diversity of the industry. Farm sizes ranged from 250 ha to 7,777 ha, with 41-97% of area subject to livestock grazing, supporting 950-56,000 dry sheep equivalents (DSE; Fig. 6). Following convention, we assume that one DSE represents a two-year-old 45 kg Merino wether consuming 7.6 MJ per day[75]. Baseline data were collated from each farm to calibrate a range of biophysical, economic, and ecological models (see below).

Using a participatory co-design process, each farmer worked with the research team to co-refine model inputs so that simulated baselines aligned with observed performance. This process required

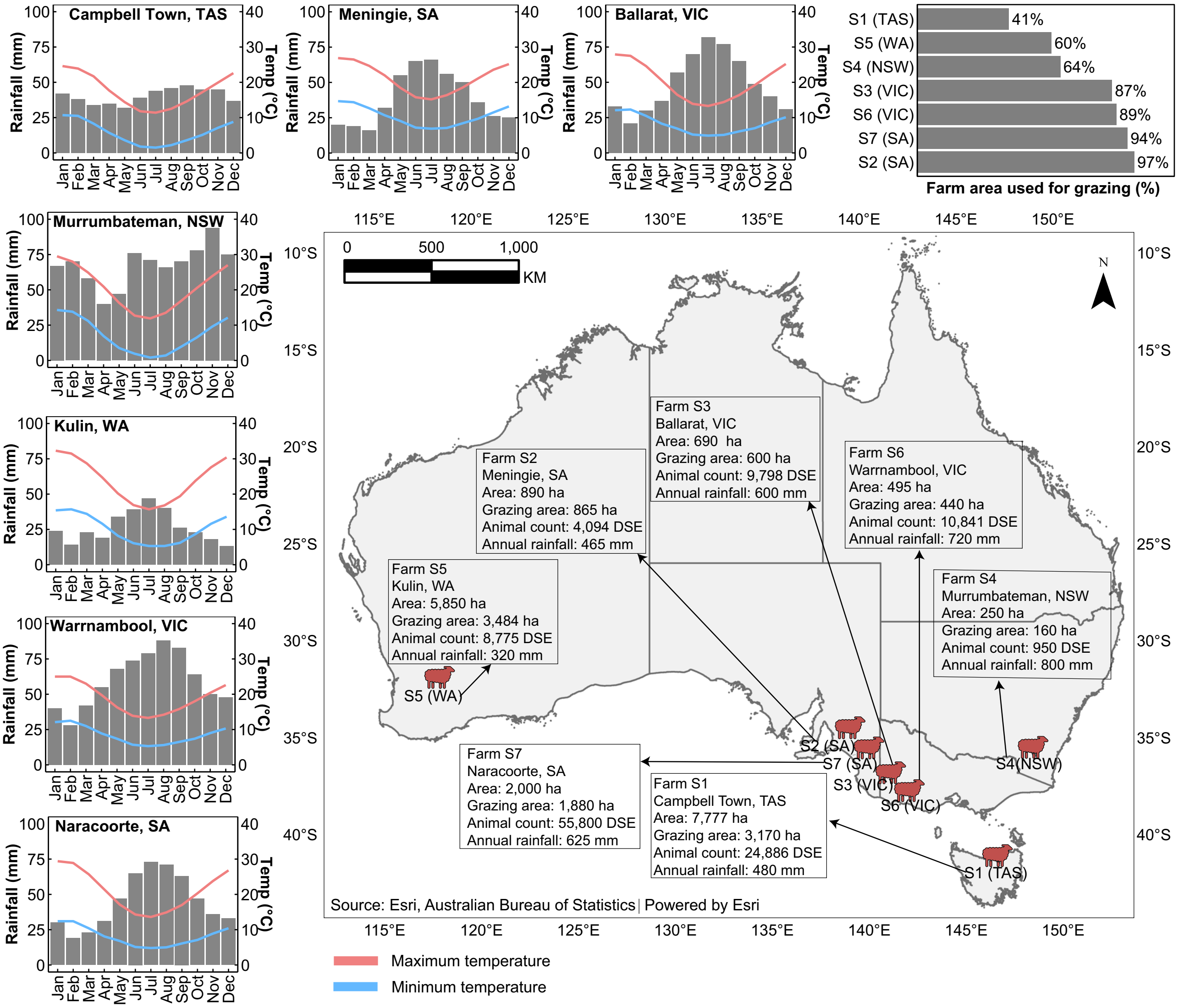


Fig. 6 | Climate and management characteristics of farms selected for case-study. Charts display the long-term average monthly climate (rainfall, minimum and maximum temperatures) over the simulation duration (July 1992 to June 2022) and the percentage of farm area subjected to grazing ($n = 30$ for charts showing rainfall and temperature). DSE dry sheep equivalents, S1-7 case study sheep farm 1-7, SA South Australia, TAS Tasmania, VIC Victoria, WA Western Australia.

several iterations between researchers and each case study farmer until consensus was reached on key outputs. Modelled baseline variables included livestock numbers and classes (ewes, lambs, weaners), liveweights, wool and meat production, seasonal pasture dynamics, supplementary feeding, farm area under vegetation, timing of historical tree planting, costs and financial income. Baseline data for model initialisation were derived from farm management records, livestock inventories, sale records, and input use (fuel, fertiliser, irrigation, electricity) between 2021 and 2024. Baseline biodiversity, habitat, and woodland carbon stocks are detailed in the 'Baseline woodland carbon sequestration' and 'Baseline woodland biodiversity' sections.

Because biophysical simulations extended beyond the period of available empirical data ('Biophysical livestock production systems simulation' section), initial model parameters were iteratively refined with each farmer to ensure fidelity to farm-specific biophysical constraints and management practices following the participatory process articulated in Bilotto, et al.[25]. For example, breeder flock size was adjusted until simulated maiden ewe and wether turn-off matched the farmer's experience. This process strengthened the rigour of simulated variables and enhanced trust, credibility, and legitimacy of the modelling framework. Consensus baseline information is presented in Table 1, with full inputs provided in Tables S1–S5.

Once baselines were agreed, two categories of interventions were co-designed: demand-driven interventions specified by farmers, and generic interventions devised by the research team and applied consistently across all farms. Only variables directly associated with each intervention were modified; all other parameters remained at baseline values. Model inputs for farmer-driven interventions (e.g., spatial placement of tree planting) were specified by the case study farmers, whereas inputs for generic interventions (e.g., magnitude of enteric methane reduction with *Asparagopsis* supplementation) were derived from peer-reviewed literature. Assumptions for all interventions are provided in Tables 2 and 3, the "Farming systems interventions" section, and the Supplementary Information.

While transdisciplinary people-centric assessments are more difficult to operationalise cf. reductionist studies due coordination and co-learning required between parties, they are arguably more amendable to impact, because they elucidate enablers and inhibitors of behavioural change[16,25]. Use of people-centric design in this way meant engaging end-users to develop fit-for-purpose interventions

Table 2 | Thematic and demand-driven interventions applied to baseline farm systems

Intervention	Abbreviation (scenario number)	Detail
Planting 10% of grazing land with native species endemic to each farm's location (All farms)	10% tree plantation (1)	Planting trees on 10% of farm grazing land with subsequent reduction of grazing area, and key inputs such as fertiliser, electricity, fuel, animal husbandry, etc by 10%.
Feeding generic enteric methane inhibitor to all weaned sheep to achieve 18% or 37% methane reduction (All farms)	1. 18% feed additive methane reduction (2) 2. 37% feed additive methane reduction (3)	Intervention applied to all weaned stock and implemented year-round. To account for variability associated with enteric methane inhibition, we examine low (18%) and high (37%) abatement. The 18% reduction in enteric methane assumed achieved through supply of 3-Nitrooxypropanol (3-NOP)[20], the 37% reduction in enteric methane assumed achieved through feed supplementation with *Asparagopsis taxiformis*[88]. Stock were fed grain as a feed supplement carrier.
Grazing antimethanogenic pastures for enteric methane reduction (All farms)	1. 10% pasture methane reduction (4) 2. 25% pasture methane reduction (5)	To account for variability associated with enteric methane inhibition, we examine low and high abatement, adopting 10% and 25% reduction in enteric methane as a result of grazing antimethanogenic pastures[89] including *Desmanthus*, *Leucaena*, *Lotus* and *Stylo*. This intervention was applied to all weaned stock and implemented year-round to replicate grazing of antimethanogenic pastures.
Improved liveweight gain at 10% and 50% level for non-replacement animals (All farms)	1. 10% liveweight gain (6) 2. 50% liveweight gain (7)	To account for variability associated with liveweight gain, we examine low and high growth rates via 10% or 50% liveweight gain relative to baseline daily liveweight gain from birth to sale. All non-replacement animals sold at the same liveweight as per the baseline farm system. The 10% improvement in LWG was achieved through improved grazing management and animal genetic improvement (i.e. improved feed efficiency) with no economics implication[59]. The 50% improvement in LWG was a stretch target assumed to occur via grazing management (no cost) as well as supplementary feeding (economic cost) through additional metabolisable energy required to gain additional LW per day (Supplementary Tables S12, S13). We assumed all young stock were sold at the new sale date, which in some cases resulted in lower wool production if lambs were sold prior to shearing.
Cell grazing (high stocking rate short duration grazing) (Farms S3 and S7)	1. Cell grazing, 30-day rotation (8) 2. Cell grazing, 120-day rotation (9)	To examine likely variation caused by cell grazing, two realistic scenarios were modelled (1) 30 paddocks grazed on a short rotation, 1 paddock per day, rest 29 days; (2) 30 paddocks grazed on a long rotation, 1 paddock per 4 days, rest 116 days.
Improve Omega-3 intake to increase wether lambs relative to ewe lambs (Farm S1)	Omega-3 dietary enrichment (10)	This intervention examined the effect of a feed additive to alter the wether-to-ewe lamb ratio. Re-distribute supplementary feed to enrich the diet of the breeding ewes for 59 days pre- and post-conception following[99]. Increase ratio of wether to ewe lambs conceived from 50:50 to 55:45 by adjusting the number of non-replacement wether and ewe lambs in the meat flock.

S1 Campbell Town, Tasmania; S2 Meningie, South Australia; S3 Ballarat, Victoria; S4 Murrumbateman, New South Wales; S5 Kulin, Western Australia; S6 Warrnambool, Victoria; S7 Naracoorte, South Australia. See methods and supplementary information for more detailed information.

aimed at GHG emissions reduction or removal, but also (ideally) improvements in livestock production, profit, and biodiversity habitat.

Livestock production systems modelling

Biophysical modelling of pasture and livestock productivity was undertaken using GrassGro version 3.4.3 (https://grazplan.csiro.au/grassgro/)[76,77]. GrassGro simulates daily dynamics in pasture growth and senescence, soil water balance, ground cover, livestock growth, feed intake, animal movement between paddocks, purchases and sales, and supplementary feeding. The model integrates ruminant nutrition and intake functions[78] with mechanistic representations of pasture growth and soil–water processes, driven by historical climate data, to simulate whole-farm biophysical performance at daily resolution[77]. Multiple paddocks can be represented, with livestock movement governed by grazing rules, biomass thresholds, and animal condition.

Model inputs allow explicit separation of livestock classes (e.g., mature vs. young stock), and supplementary feeding can be specified either to maintain condition score/liveweight within defined thresholds or achieve target liveweights under paddock or feedlot conditions. Simulated monthly pasture growth, stocking rates, and liveweight production were validated with each case study farmer following the participatory process described earlier. Maximum root depth was adjusted to ensure that simulated seasonal pasture growth aligned with that required to support liveweight gain and annual production at baseline stocking rates (Table S1). Except for root depth, other biophysical parameters were not calibrated, consistent with extensive evidence demonstrating the capacity of GrassGro to accurately reproduce pasture growth and livestock dynamics across Australian grazing systems[59,79,80].

Several iterative exchanges between researchers and farmers ensured that simulated outputs appropriately reflected baseline production and management. Simulations were initialised using contemporary farm practices provided by each producer, including livestock genotype, class structure, and liveweights, mating and weaning dates, wool production and fibre diameter, pasture species composition, grazing management (e.g., stocking rates, rest triggers based on biomass or liveweight gain), irrigation, shearing time, and sale dates (Supplementary Table S1). Soil types were selected using the Digital Atlas of Australian Soils[81], accessible within the GrassGro interface.

GrassGro was run from 1 July 1982 to 30 June 2022 with a 10-year equilibration period (discarded from analyses) followed by a 30-year analytical phase (1 July 1992 to 30 June 2022). Atmospheric carbon dioxide (CO_2) concentration was set to 350 ppm to reflect average CO_2 concentrations during the simulation period[82]. Daily meteorological inputs (solar radiation, precipitation, maximum and minimum temperature) were sourced from SILO climate archives (http://www.

Table 3 | Demand-driven interventions and scenarios within interventions

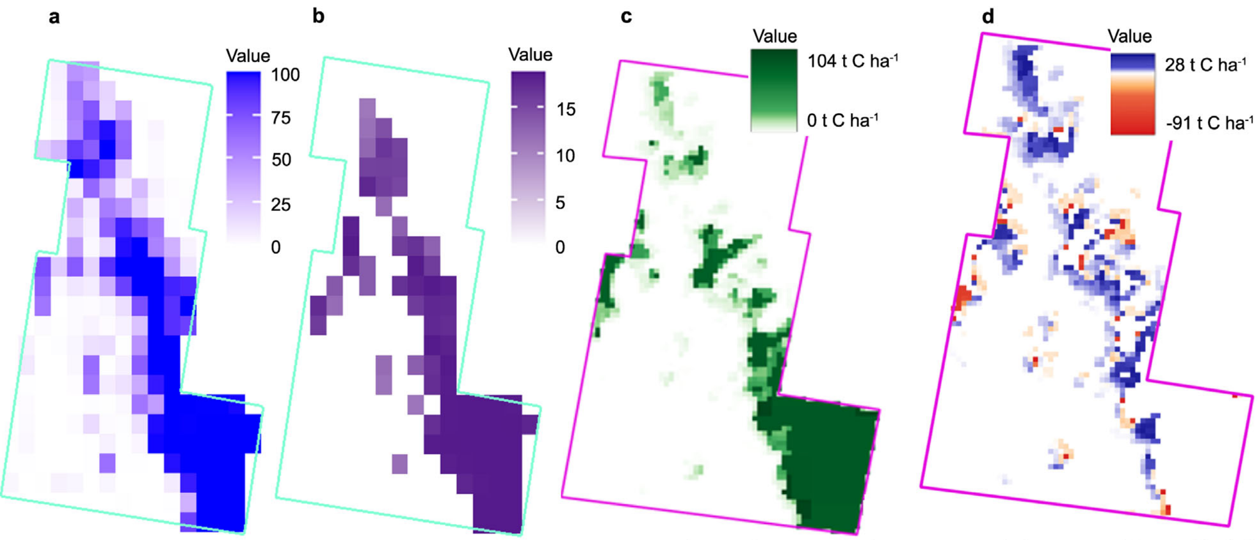
Intervention	Abbreviation (scenario number)	Detail
Fencing off wetlands and boundary areas to restrict excessive native wildlife grazing (Farm S1)	1. Reduce grazing area by 100 ha (11) 2. Fence, increased feed supply (12) 3. Fence, increase feed supply and weaning (13) 4. Fence, increase feed and stocking rate (14)	To account for variability in land allocation, improvements in pasture growth, improvements in weaning rate or impacts on stocking rates, four scenarios are simulated: i. Fence off 100 ha of poorer productive land adjacent to the two rivers flowing through the property; ii. In addition to i., fence off an additional 9 km of boundary fence adjacent to native tree vegetation to increase pasture production in the adjacent paddocks increasing feed supply by approx. 125 ha of feed across the whole farm[100]; iii. In addition to i. and ii., increased weaning rate due to increased feed supply; iv. In addition to ii., increased stocking rate due to increased feed supply. See supplementary information for changes in weaning and stocking rates
Change in lambing date (Farm S2)	1. June lambing (15) 2. August lambing (16) 3. June lambing CFA Sept (17)	To account for variation in lambing time, three lambing/ purchased ewe date combinations were examined (in each case with shearing dates altered in a commensurate manner; baseline was lamb in late March and cast for age (CFA) in mid- August)): i. Lambing begins 1 June and ewes cast for age (CFA) mid-October ii. Lambing begins 1 August and ewes CFA mid-December iii. Lambing begins 1 June and ewes CFA mid-September
Ewe purchase and sale age (Farm S2)	1. Purchase 1.5 yr old Cull July (18) 2. Purchase 1.5 yr old Cull Sep (19) 3. Purchase 4.5 yr old Cull Jul (20) 4. Purchase 4.5 yr old Cull Sep (21)	To examine implications associated with ewe culling age and month of year, four scenarios were assessed. The baseline purchases ewes at 5 years of age and sells in mid-August at 7-8 years of age. The intervention involves changing the purchase and sale age and period, where ewes are purchased at 1.5 or 4.5 years of age and sold at 6-7 years of age at either the end of July or early September.
Feeding supplements for earlier weaning and higher weaning rates (WR) (Farm S2)	1. WR 112% + supp feeding (22) 2. WR 120% + supp feeding (23) 3. WR 140% + supp feeding (24)	To examine variability associated with lamb weaning rates, three scenarios were assessed. The baseline farm system does not include any supplementary feed to reach production targets. This was altered with the feeding of lupins to the breeding ewes in the paddock for a week on either side of mating to improve conception. We modelled three conception rates, to stimulate targeted weaning rates of 112% (baseline), 120% and 140%
Single lambing and reduced wool micron (Farm S4)	Single lambs, reduced wool micron (25)	To examine the plan for the farmer to target low micron wool production, lambing rates were reduced to single lambs per ewe (baseline had a proportion of twin-bearing ewes) and decreased wool micron from 14 with the baseline down to 11 in line with farmer targets
Change in confinement feeding and stocking rate (Farm S5)	1. Increased stocking rate (26) 2. Increased confinement feeding (27) 3. Increased stocking and confinement feeding (28)	To examine trade-offs between ground cover conservation and supplementary feed use when animals were in confinement pens, three scenarios were examined: i. stocking rate was increased by 10%, keeping the timeframe of confinement feeding the same as the baseline, ii. commenced confinement feeding one month earlier than baseline while maintaining baseline stocking rate, and iii. The stocking rate increased, combined with the commencement of confinement feeding sooner.
Replacement of inorganic fertiliser with compost (Farm S6)	Compost application (29)	The purpose of this intervention was to substitute synthetic inorganic fertiliser (mono-ammonium phosphate) with organic compost, increasing pasture production[101]. Costs and GHG emissions are provided in Supplementary Tables S10 and S11.

S1 Campbell Town, Tasmania; S2 Meningie, South Australia; S3 Ballarat, Victoria; S4 Murrumbateman, New South Wales; S5 Kulin, Western Australia; S6 Warrnambool, Victoria; S7 Naracoorte, South Australia. See methods and supplementary information for more detailed information. CFA cast for age, supp supplementary feeding.

longpaddock.qld.au/silo). Additional initialisation and simulation details are provided in Supplementary Table S1.

Greenhouse gas emissions quantification

Scope 1, 2 and 3 GHG emissions were quantified for each baseline and intervention scenario. Scope 1 emissions comprised all direct farm emissions; Scope 2 captured emissions associated with electricity consumption; Scope 3 encompassed indirect emissions embodied in upstream production of farm inputs (e.g., supplementary feed and fertiliser). Gross and net emissions for Scopes 1–3 were estimated using the Sheep & Beef GHG Accounting Framework (hereafter referred to as SB-GAF, V2.2, https://piccc.org.au/resources/Tools[83]), consistent with methods applied in the Australian National Greenhouse Gas Inventory. Net emissions were calculated as total GHG emissions minus annual carbon sequestration (Section 2.4). Long-term average livestock numbers, liveweight gain, diet quality, supplementary feed requirements, and meat and wool production simulated by GrassGro were entered into SB-GAF, together with electricity, fuel, and fertiliser inputs and wool yield parameters. Where supplementary feed was sourced from farm and external suppliers, the proportional contribution of each source was retained when estimating Scope 1 emissions. For farms with multiple flocks (e.g., S1 TAS), enterprises were modelled separately, and emissions from fuel, electricity, fertilisers, and tree carbon sequestration were apportioned according to each flock's share of total livestock emissions. Scope 3 emissions from purchased supplementary feed were allocated using feed requirements derived from GrassGro. Net emissions were then partitioned according to the mass of protein in meat and wool[39] and divided by clean wool yield and liveweight to determine wool (kg CO_2eq kg clean wool weight^{-1}) or meat (kg CO_2eq kg liveweight^{-1}) emissions intensity. For one intervention at S6 (VIC), replacing synthetic mono-ammonium phosphate with green-waste organic compost increased emissions by 30.6 t CO_2eq annum^{-1} (Supplementary Table S11).



Sources: Data.gov.au; environment.gov.au; industry.gov.au | Powered by Esri

Fig. 7 | Spatially-explicit quantification of biodiversity and carbon stocks for farm S4 (New South Wales, Australia). **a** Effective habitat area for biodiversity in 2020; **b** Habitat provision for terrestrial threatened species in 2020 in units of species.hectares; **c** Total vegetation carbon in 2020 including above-ground, below-ground and dead organic matter; **d** Net woodland carbon flux from 2004 to 2020 ($n = 16$ climate years). Negative values indicate a carbon source; positive values indicate carbon sinks. Effective habitat area reflects total habitat area available for biodiversity, accounting for habitat condition in each location (grid cell) and farm area. A larger value indicates greater contribution of the farm in supporting biodiversity. High quality habitat areas are those where habitat condition is greater than 75%. Threatened species habitat combines spatial information on the distribution of all 1466 terrestrial nationally listed threatened species and the habitat condition data in Australia[86]. Threatened species habitat was estimated by multiplying the number of threatened species that may occur in a location by the habitat condition in that location when habitat condition was above 50%. Aggregated values for each location provide the number of 'threatened species hectares'. Higher values indicate a greater contribution of the area in providing habitat for threatened species[86].

Baseline woodland carbon sequestration

Spatially explicit woodland carbon stocks were simulated at 25 m^2 resolution using FLINTpro (https://flintpro.com/), which employs algorithms aligned with the Australian National Greenhouse Gas Inventory (Fig. 7). Carbon stocks included aboveground biomass (AGB), belowground biomass (BGB) and dead organic matter (DOM). 'Woodlands' were defined according to the National Forest and Sparse Woody Vegetation Data (Version 6.0, 2021) as areas with ≥20% canopy cover and ≥2.0 m vegetation height recorded at least three times during the simulation period, consistent with the Australian Government Department of Agriculture, Fisheries and Forestry [DAFF][84]. Areas not satisfying this criterion were classified as non-woodland. Transitions from woodland to non-woodland were treated as vegetation loss events that shifted carbon from living biomass to DOM pools; transitions from non-woodland to woodland were modelled as carbon accumulation determined by vegetation type and site conditions. This approach ensured that woodland carbon dynamics reflected changes in extent rather than assumptions about initial biomass. Simulations spanned 1989–2021, with 1989–2005 discarded as a model equilibration phase. Woodland present in 1989 was initialised at 80% of potential carbon stock; scenario testing showed that higher initialisation thresholds generated unrealistically low mature biomass relative to the National Forest and Sparse Woody Vegetation Data. Annual carbon sequestration was calculated as the net change in carbon stocks between 2005 and 2021 divided by 16 years and used directly in SB-GAF.

Baseline woodland biodiversity

Woodland biodiversity was assessed using the Landscape Options and Opportunities Calculator for Biodiversity (LOOC-B, https://looc-b.farm/), which estimates annual habitat condition at 1 ha resolution (2004–2020; Fig. 7). Habitat condition represents each pixel's capacity to support native species present in 1750, prior to European settlement[85]. These habitat condition layers were integrated with spatial biodiversity models to estimate species persistence and habitat provision for nationally declared threatened species. Analyses were undertaken using spatial files delineating farm boundaries.

Four biodiversity indicators were calculated for the final assessment year and for the change over the full assessment period:

1. Effective habitat area quantified the amount of habitat available for biodiversity, weighted by habitat condition and scaled to the farm area
2. High-quality habitat area was defined as the area where habitat condition exceeded 75%
3. Threatened species habitat was estimated by combining habitat condition with the spatial distributions of all 1466 terrestrial nationally listed threatened species[86]. For each pixel, the number of threatened species potentially occurring was multiplied by habitat condition when that condition exceeded 50%, generating values expressed as 'threatened species hectares'. Higher values reflect greater contribution to habitat provision for threatened species, and
4. Benefit of habitat for plant species persistence quantified the contribution of farm habitat to long-term persistence of Australian plant species. This was calculated by integrating habitat condition with spatial patterns of plant species assemblages[87]. Higher values indicate a greater contribution to national-scale plant diversity.

Across metrics, higher values indicate stronger biodiversity support and greater ecological contribution at the farm scale.

Farming systems interventions

Several interventions to the baseline farm systems were evaluated (Tables 2 and 3). Interventions fell into two categories: (i) demand-driven interventions, co-designed with individual case-study farmers and tailored to their agroecological and enterprise context, and (ii) thematic interventions, applied uniformly across all farms to enable systematic comparison of mitigation potential across regions. Demand-driven interventions were included because producers possess detailed knowledge of their soils, climate, finances, management constraints, and enterprise goals, and were therefore expected to propose practices most likely to deliver improvements within their systems. Thematic interventions—such as native tree planting or provision of low-emissions feed supplements—enabled assessment of how carbon sequestration or enteric CH_4 abatement influenced net GHG outcomes across contrasting agroecological regions and enterprises.

For each intervention, we examined multiple scenarios where relevant to quantify sensitivity of net farm GHG outcomes to the magnitude of change. Rationale and assumptions for interventions are provided in Tables 2 and 3. In brief, the thematic interventions applied to all farms comprised:

1. Planting native tree species on 10% of grazing land, reflecting the percentage farmers identified as a realistic target for sequestration-based mitigation;
2. Use of a low-emissions feed supplement for weaned sheep to achieve either low (18%) or high (37%) reductions in enteric CH_4, based on empirical observations in grazing contexts[20,88];
3. Pasture renovation with antimethanogenic ecotypes, targeting either low (10%) or high (25%) CH_4 inhibition, consistent with values reported in peer-reviewed studies[89];
4. Improved grazing management and/or livestock genetic improvement to realise either low 10%[63,65]; or high (50%) enhancement in liveweight gain from birth to sale for all non-replacement animals. The 50% scenario represented a stretch target intended to estimate the upper bound of enteric CH_4 avoidance via earlier sale of younger stock.

Demand-driven, farm-specific interventions co-designed with producers included the introduction of confinement feeding during dry periods to preserve ground cover, the substitution of synthetic inorganic nitrogen fertiliser with organic compost on grazed pastures, the adoption of cell grazing (high-intensity, short-duration grazing), and omega-3 supplementation during pregnancy to increase the ratio of wether to ewe lambs. For interventions that materially altered stock numbers or movement (e.g., reduced flock size or increased rotational grazing), key farm inputs such as fuel use were adjusted proportionally.

Tree-planting potential and associated carbon sequestration were evaluated using FLINTpro. This intervention was conceptualised as establishing mixed-species environmental plantings dominated by eucalypts with some acacia species[90]. Carbon abatement was quantified under assumptions consistent with the Environmental Plantings policy prescribed under the Australian Carbon Credit Unit (ACCU) Scheme administered by the Clean Energy Regulator, including the requirement for the absence of woodland for ≥7 years prior to planting. Eligible areas were identified using the National Forest and Sparse Woody Vegetation Data[91]. Long-term average carbon sequestration (t CO_2eq ha^{-1} yr^{-1}) was estimated by dividing total carbon abatement by eligible area and 25 years, and then multiplying by the total planted area to derive annual sequestration (t CO_2eq yr^{-1}), which was entered into SB-GAF.

Case-study farmers and researchers jointly identified the spatial configuration of plantings. Biodiversity outcomes from revegetation were modelled for 2020–2050. All case-study farms occur within regions where natural ecosystems are predominantly woodland or heathland, and the revegetation intervention was therefore modelled as establishment of diverse, mixed-species native plantings with full livestock exclusion.

Other interventions were simulated in GrassGro by modifying relevant model parameters (e.g., conception rates, supplementary feeding, rotational grazing intensity, soil fertility). GrassGro outputs were subsequently used as inputs to SB-GAF following the same procedures as for baseline simulations. Except for the tree-planting intervention, all interventions were processed entirely within SB-GAF for GHG accounting.

Economic analysis

Enterprise budgets were constructed using biophysical outputs simulated by GrassGro, including pasture growth and animal production. To evaluate economic sensitivity to market volatility, we applied the 25th and 75th percentiles of inflation-adjusted carcass-weight prices (47% dressing percentage; AWI and MLA, 2008) over 2012–2023 (www.mla.com.au/prices-markets/statistics/; Supplementary Table S2). Wool prices were estimated from historical relationships between micron and market indicators (www.awex.com.au/market-infomation/awex-wool-market-indicators/; Supplementary Table S3). Stock husbandry and selling costs for meat and wool were standardised across farms, whereas farm-specific costs (e.g., pasture renovation, repairs and maintenance) were informed directly by case-study farmers (Supplementary Information; Tables S4 and S5).

Where interventions altered livestock numbers or input use, associated changes in GHG emissions were valued using a contemporary price of AUD 38 per tonne CO_2eq[92] and a projected price of AUD 100 per tonne CO_2eq[93]. Farms were credited or taxed relative to baseline emissions. Income from carbon sequestration via tree planting incorporated a 5% risk buffer for potential reversal and a 20% permanency discount, consistent with 25-year carbon projects under Australian legislation (Supplementary Information Section 2.5). Antimethanogenic pasture interventions were assumed to incur no additional establishment cost because they were integrated into routine pasture renovation. Interventions involving additional activities—such as delivering 18% and 37% methane reductions via 3-NOP and *Asparagopsis* supplementation, respectively—were costed from published estimates (Supplementary Information Section 2.4).

Soil organic carbon

We coupled a simplified pasture growth model with debris-pool dynamics into the RothC 26.5 soil model[94] within FLINTpro. Initial soil organic carbon (SOC) stocks were derived from SCARP data (https://data.csiro.au/collection/csiro:5883), and climate inputs were sourced from national grids and TERN. FLINTpro simulations were run from 1990 to 2040 to establish empirical relationships between pasture production and SOC fluxes. Where an intervention produced >5% change in average annual pasture production (from GrassGro), we estimated the corresponding SOC response; production changes <5% were assumed to have de minimis effects on SOC. Where SOC perturbations were material, average annual carbon fluxes were incorporated into SB-GAF to determine net-farm GHG emissions (Supplementary Information Section 2.8; Table S9).

Planting 10% of grazing area with native tree species

The objective of this study was to design GHG mitigation interventions that could also generate co-benefits in biodiversity, profitability, and productivity. Biodiversity was economically quantified as a co-benefit associated with carbon sequestered by newly planted trees. Habitat condition, effective habitat area, and threatened species habitat attributable to tree planting were quantified as detailed in the "Baseline woodland biodiversity" section. Biodiversity associated with pre-existing woodlands was not included in economic calculations because no case study farmer derived revenue from existing woodland ecosystems.

Costs of tree planting were based on Summers, et al.[95]; Supplementary Information, section 2.5, Figs. S2–S4, Tables S6–S8), while revenue from carbon sequestration was discounted by 5% to account for the risk of reversal and 20% for the permanency requirement under the Australian Government ACCU Scheme[90]. As the economic value attributed to biodiversity is subjective and market prices are unclear

Summers, et al.[95,96]; Supplementary Information, section 2.5) while income from carbon sequestered was discounted by 5% for risk of reversal and 20% for the permanency period following the Australian Government ACCU Scheme[90]. As the economic value attributed to biodiversity is subjective and market prices are unclear Summers, et al.[95,96]; Supplementary Information, section 2.5) while income from carbon sequestered was discounted by 5% for risk of reversal and 20% for the permanency period following the Australian Government ACCU Scheme[90]. As the economic value attributed to biodiversity is subjective and market prices are unclear[96], biodiversity was credited as a co-benefit for carbon sequestered in trees following Carbon Neutral's Biodiverse Reforestation Carbon Offsets[97]. To account for uncertainty in valuation, biodiversity co-benefits were assigned low and high economic values of AUD 29 and 65 t CO_2eq sequestered^{-1}, respectively, reflecting a range derived from peer-reviewed literature, comparable projects, and prior methodologies for valuing ecosystem co-benefits[97]. This approach provides one of the most rigorous and relevant economic valuations available, recognising that biodiversity markets associated with native tree planting in Australia are nascent. Notably, the first project under the legislated Nature Repair Market was registered on 12 August 2025, CER[98]. Analyses of this type are both analytically defensible and highly topical for informing land-use policy and investment.

Additional interventions included the fencing of riparian areas on farm S1 (TAS), which allowed regeneration of native tree species across 100 ha previously subject to grazing. Carbon sequestration from this riparian fencing was estimated at 60% of that for the 10% tree planting intervention, based on comparative simulations in LOOC-C. Liveweight gain interventions were implemented as follows: the 10% improvement in juvenile liveweight gain was assumed achievable via genetic selection and/or optimized grazing management, whereas the 50% liveweight gain intervention was assumed to require supplemental metabolisable energy delivered through grain and hay from birth to sale (Supplementary Information, section 2.10).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Data generated in this study are deposited in Zenodo under accession code https://doi.org/10.5281/zenodo.17708034. Further information are provided in the Supplementary Information file.

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Author contributions

G.B., K.M.C.-W. and M.T.H. wrote the first draft; R.A., L.J.W., F.C.G., N.D.B., G.B. and K.M.C.-W. conducted farm systems simulations; K.M. and H.B. conducted biodiversity assessments; G.B,. A.D., C.C., C.M.R., L.J.W., K.M.C.-W., and M.J.K. economic analyses; M.T.H. and S.M. liaised with case study farmers; R.W. and G.R. conducted FlintPRO simulations; M.T.H. conceptualised the study; G.B., K.M.C.-W. and M.T.H. conceptualised the interventions; all authors revised the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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