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Regenerative agriculture improves productivity and profitability while reducing greenhouse gas emissions on Australian sheep farms

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Regenerative agriculture can be deconstructed into several constituent practices, including adaptive multi-paddock (AMP) grazing, improved biodiversity, silvopasture, and minimizing cultivation and synthetic fertilizer inputs. Here, using farms across a rainfall gradient, we examined how three constituents—pasture species composition, antecedent soil organic carbon (SOC) and AMP grazing—influenced SOC accrual, greenhouse gas (GHG) emissions, production and profitability. Whole-farm stocking rate and rainfall exerted a stronger influence on pasture production, SOC, GHG emissions and profit than pasture diversity or grazing management. Production was more strongly associated with individual pasture species, rather than species diversity per se. Notwithstanding carbon removals through increased SOC stocks, enteric methane remained the dominant source of farm GHG emissions. Low-intensity grazing with short rest periods was generally more profitable, whereas AMP grazing promoted greater pasture growth, SOC accrual and emissions abatement; AMP also performed more favourably when emissions, profit and productivity were considered together. Persistent trade-offs between economic and environmental outcomes indicate that grazing regimes delivering the greatest SOC accrual and GHG mitigation are not necessarily the most profitable, reinforcing the need to rationalize objectives when designing resilient, practical and low-emissions farming systems.

In the absence of land-use change, livestock production systems typically exhibit higher greenhouse gas (GHG) emissions than most other agricultural sectors[1–3]. As a result, substantial effort has focused on identifying management interventions capable of delivering emissions reductions and removals within existing production landscapes. Regenerative agriculture has emerged prominently in this context, promoted both for its mitigation potential[4] and broader ecosystem services, including improved soil health, soil organic carbon (SOC), nutrient cycling, water infiltration and biodiversity[5,6]. Despite widespread adoption, regenerative agriculture remains loosely defined and is often evaluated as a bundled system, complicating attribution of observed outcomes to specific practices.

Regenerative agriculture is generally conceptualized as a constellation of practices intended to restore ecological function while sustaining or enhancing productivity. These practices include adaptive multi-paddock (AMP) grazing with short grazing durations and

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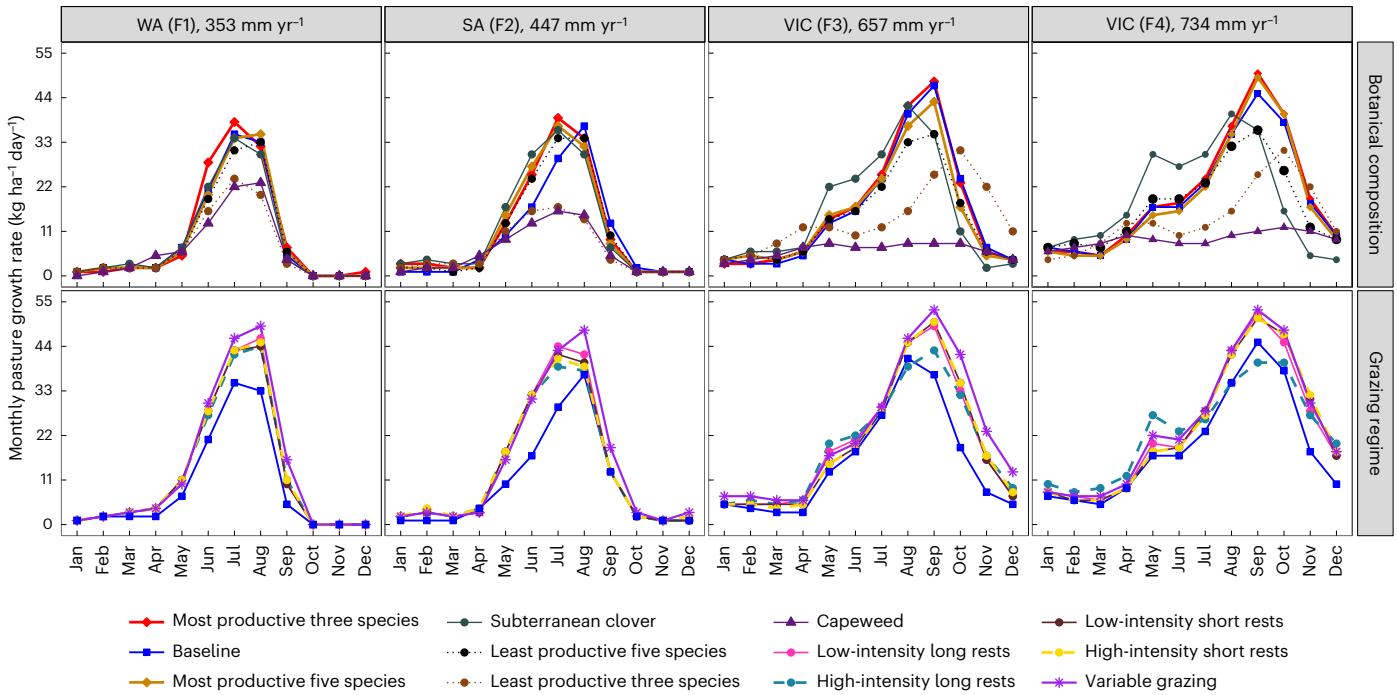


Fig. 1 | Monthly pasture growth rates in four regions across several botanical compositions and grazing regimes. Column titles depict farm abbreviation (F1–4), long-term average annual rainfall (mm yr^{-1}) and location (SA, South Australia; VIC, Victoria; WA, Western Australia). The top row shows pasture growth rate of several botanical compositions, and the bottom row shows pasture growth rate associated with several grazing treatments. The most and least productive three species represent the most and least productive swards, each comprising three pasture species, while the most and least productive five species indicate the highest and lowest productivity swards, each comprising five pasture species. Subterranean clover and capeweed represent swards comprising only that species. Baseline represents set stocking and is compared with five grazing treatments of varying stocking rate, duration and rest period (low-intensity long rests, high-intensity long rests, low-intensity short rests, high-intensity short rests and variable grazing with duration adjusted dynamically in response to seasonal conditions; see Extended Data Table 4 and the Methods for details).

extended recovery periods; increased pasture species and functional diversity; reduced reliance on synthetic fertilizers and pesticides; avoidance of cultivation; application of organic amendments; cover cropping; perennial pasture systems; and integration of trees, forage and livestock (for example, silvopasture)[7–9]. Collectively, these interventions aim to emulate natural disturbance–recovery dynamics and enhance ecosystem resilience.

When implemented in combination, regenerative practices have been purported to reduce net GHG emissions through enhanced pasture productivity and increased SOC sequestration[10,11]. However, outcomes are highly context dependent, varying with climate, soil type, historical management and extant SOC stocks. Several studies indicate additive or synergistic effects among regenerative components. For example, combining improved grazing management with diverse pasture composition can enhance SOC accrual relative to conventional grazing alone[12], and high-intensity grazing coupled with diverse swards has been associated with lower GHG emissions than low-intensity, low-diversity systems[13]. Yet, pasture productivity and species performance are themselves constrained by rainfall and edaphic conditions[5,11,14], and the interactive effects of grazing management and botanical composition across rainfall gradients remain poorly resolved. This knowledge gap is particularly important given that a large proportion of global livestock production occurs in rainfed environments, often under high prevailing aridity[15].

The effectiveness of management interventions is also contingent on baseline (antecedent) SOC. Organic carbon accrual potential is greatest where antecedent stocks are low[16]; as SOC stocks approach a biophysical ceiling determined by climate, carbon inputs, soil properties and management, further sequestration becomes increasingly constrained and can even reverse towards long-term equilibria[16,17]. These dynamics may explain divergent findings in meta-analyses of grazing effects on SOC[17], particularly where episodic drought offsets multiple years of accumulation[11,16]. Explicit consideration of antecedent SOC and long-term climatic variability is therefore essential when assessing regenerative agriculture outcomes.

Here, we quantified the relative influence of three core regenerative constituents—pasture species composition, antecedent SOC and AMP grazing—on SOC dynamics, GHG emissions, livestock production and profitability across a rainfall gradient in southern Australia. Using four commercial sheep farms representing dominant production regions and enterprise scales, we established 'Baseline' systems against which alternative management scenarios were evaluated using an integrated biophysical–economic modelling framework.

Recognizing that economic viability underpins long-term adoption, we assessed profitability by integrating livestock revenue, supplementary feed costs and carbon pricing. Carbon credits were applied where net farm emissions declined relative to Baseline, while notional carbon liabilities were assigned where SOC-driven CO_2 removals were overcompensated by increases in other GHGs, particularly enteric methane associated with higher stocking rates[18]. By initializing simulations across multiple SOC stock levels, antecedent SOC was treated explicitly as an experimental factor, allowing SOC accrual to be evaluated as a response variable rather than an assumed outcome.

Results

Pasture species identity, not diversity, governs productivity and SOC accrual

Across farms, sward productivity was driven primarily by pasture species identity rather than species richness (Fig. 1 and Supplementary Table 1). The most productive swards comprised three high-yielding

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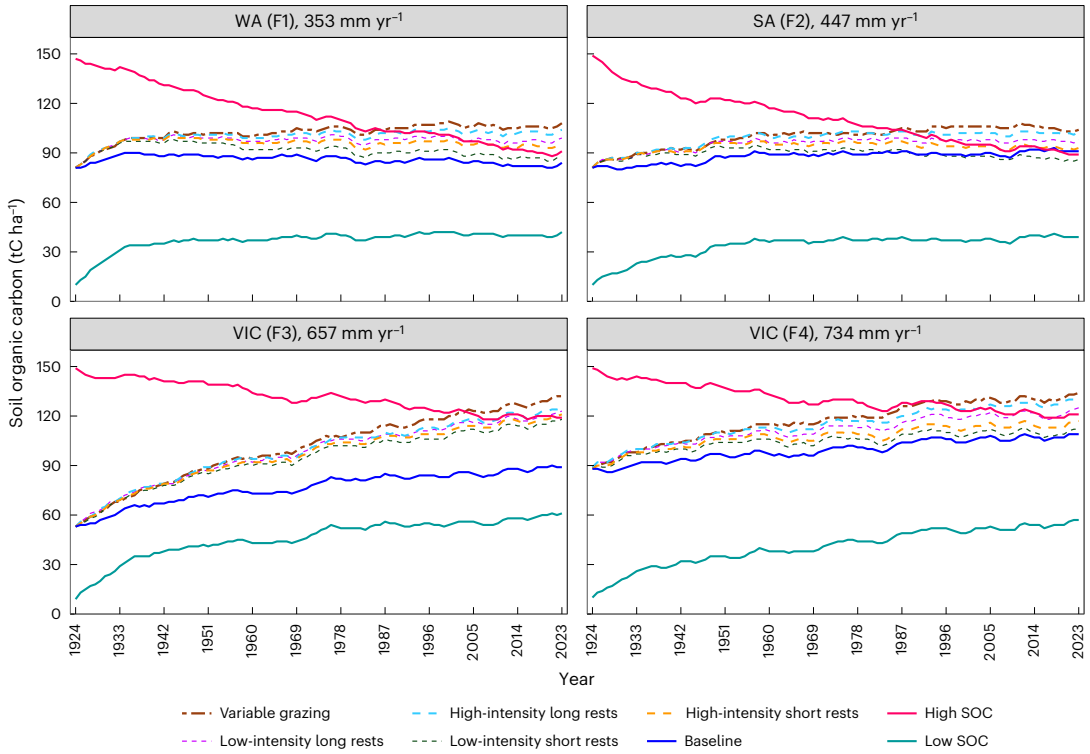


Fig. 2 | Long-term SOC in the surface layer (0–30 cm) for multiple grazing regimes, with simulations initialized at low (0.3%) and high (6%) antecedent SOC levels. Data shown for four regions positioned along a rainfall gradient in Western Australia (WA), South Australia (SA) and Victoria (VIC). Panel titles depict farm abbreviation (F1–4) and long-term average annual rainfall (mm yr^{-1}). Baseline represents set stocking and is compared with five grazing treatments of varying stocking rate, duration and rest period (low-intensity long rests, high-intensity long rests, low-intensity short rests, high-intensity short rests and variable grazing with duration adjusted dynamically in response to seasonal conditions; see Extended Data Table 4 for details).

species, whereas increasing species number consistently reduced productivity. Over the long term, high-performing swards increased mean annual pasture production by 7% relative to Baseline systems, while the least productive swards produced 39% lower seasonal yields (Fig. 1 and Supplementary Table 1). Reduced pasture production translated directly into higher supplementary feed requirements in low-performing swards across rainfall zones (Supplementary Table 1).

Differences in pasture productivity propagated to SOC dynamics. High-yielding swards increased SOC stocks over 100 years, with absolute gains ranging from 7 to 41 tC ha^{-1} (Fig. 2, Extended Data Fig. 1 and Supplementary Table 1). By contrast, low-productivity swards resulted in net SOC losses across sites (Extended Data Fig. 1). Increased SOC accrual reduced net GHG emissions and emissions intensity by approximately 6%, whereas low-productivity swards increased both net emissions and emissions intensity by ~13% (Figs. 2 and 3 and Extended Data Table 1).

Absolute GHG emissions scaled strongly with rainfall and stocking rate, ranging from >5.7 t CO_2 equivalents (CO_2e) ha^{-1} yr^{-1} in high-rainfall systems (F4) to 0.4–0.6 tCO_2e ha^{-1} yr^{-1} in low-rainfall systems (farm (F)1; Fig. 3, Extended Data Table 1 and Supplementary Table 1). These patterns demonstrate that agroecological context exerts dominant control over emissions, independent of pasture diversity.

Antecedent SOC exerts greater influence on SOC accrual than management practices

Antecedent SOC strongly constrained subsequent SOC trajectories across farms. Low antecedent SOC (0.3%) elevated SOC accrual in surface soils (0–30 cm), whereas high antecedent SOC (6%) resulted in substantial long-term SOC losses over 100 years (Fig. 2, Extended Data Table 1 and Supplementary Tables 1 and 2).

Low antecedent SOC reduced net GHG emissions and emissions intensity across the rainfall gradient, whereas high SOC increased emissions from 0.7 to 6.3 tCO_2e ha^{-1} yr^{-1} (Fig. 3 and Extended Data Table 2). Averaged across farms, low SOC reduced emissions intensity by 13%, while high SOC increased emissions intensity by 27%, highlighting the disproportionate influence of SOC flux on whole-farm GHG balances (Fig. 3). Increased emissions under high SOC were driven primarily by CO_2 losses associated with SOC decline, with secondary contributions from methane (Extended Data Table 2). Supplementary feed requirements were largely insensitive to antecedent SOC (Supplementary Table 2).

Emissions reductions associated with SOC accrual were proportionally greater in low-rainfall systems, indicating that extensified systems benefit most from SOC gains when starting from depleted carbon stocks (Fig. 3 and Extended Data Table 2).

AMP grazing is more conducive to SOC accrual than set stocking

AMP grazing based on pasture biomass ('variable grazing') achieved the greatest SOC accrual in surface soils across all sites, whereas low-intensity grazing with short rest periods produced smaller gains (Fig. 2, Extended Data Table 3 and Supplementary Table 3). SOC responses were strongest in high-rainfall, clay-rich soils (VIC F3) and constrained in low-rainfall, sandy soils (SA F2).

Variable grazing also maximized pasture growth across the rainfall gradient (Fig. 1 and Supplementary Table 3). Relative to Baseline systems, supplementary feed intake increased under variable grazing in low-rainfall regions but declined under high-productivity swards in higher-rainfall environments (Supplementary Table 3). High SOC accrual under variable grazing reduced emissions intensity (Fig. 3 and Extended Data Table 3), whereas high-intensity grazing with short rest periods increased net GHG emissions due to elevated methane, despite similar or lower emissions intensity than Baseline systems.

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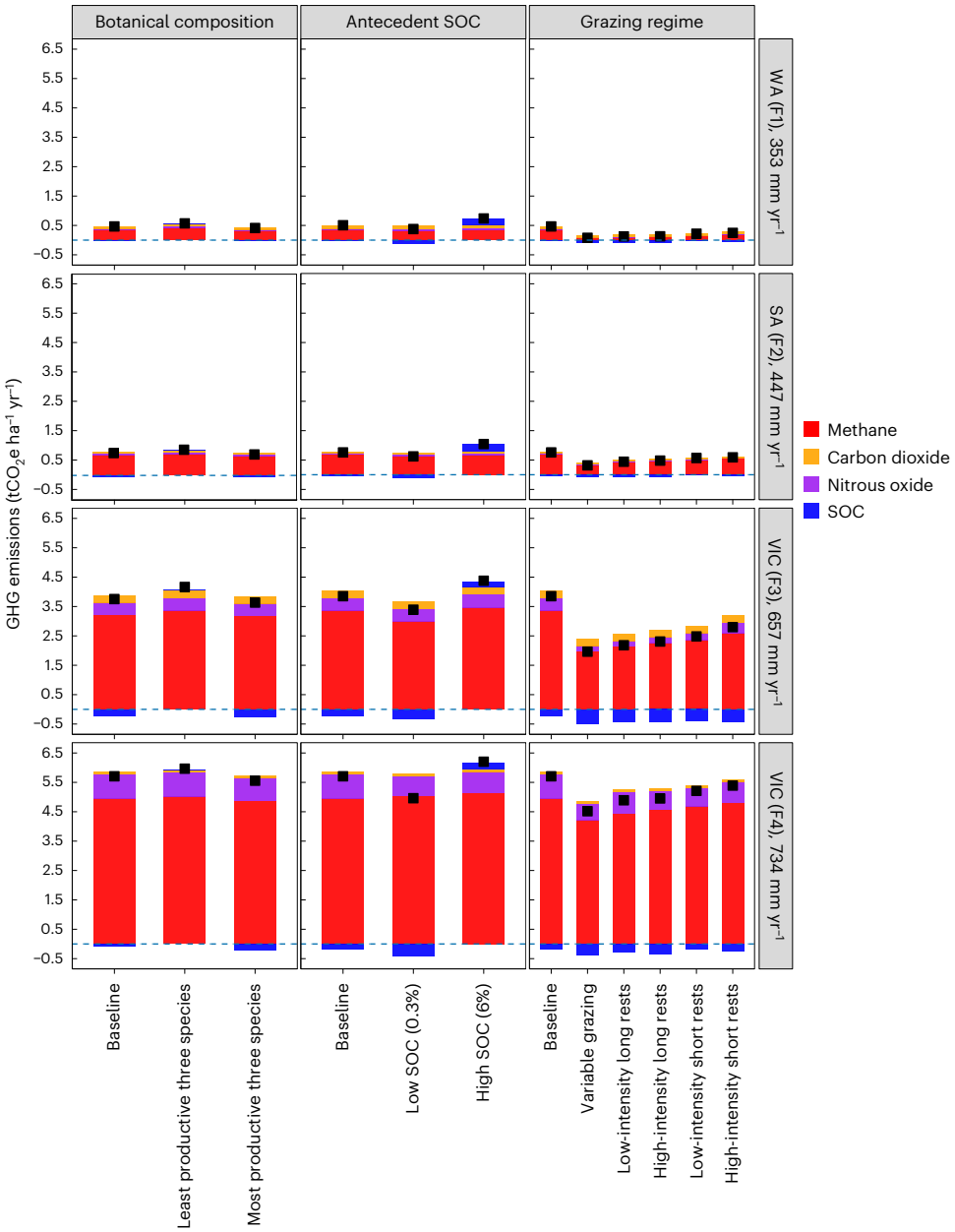


Fig. 3 | Average annual net GHG emissions (points) and gross GHG emissions (bars) derived from SOC, carbon dioxide (CO_2), enteric methane (CH_4) and nitrous oxide (N_2O) for several botanical compositions (first column), antecedent SOC levels (second column) and grazing regimes (third column). Row titles depict farm abbreviation (F1–4) and long-term average annual rainfall (mm yr^{-1}) across regions, with Western Australia (WA), South Australia (SA) and Victoria (VIC). Least and most productive three species represent swards containing the least and most productive three pasture species averaged over the simulation. Low SOC (0.3%) and high SOC (6%) represent SOC concentrations used for model initialization. Baseline represents set stocking and is compared with five grazing treatments of varying stocking rate, duration and rest period (low-intensity long rests, high-intensity long rests, low-intensity short rests, high-intensity short rests and variable grazing with duration adjusted dynamically in response to seasonal conditions; see Extended Data Table 4 and the Methods for details).

Under drought, variable grazing mitigated SOC losses relative to high-SOC Baseline soils, whereas low-productivity swards exhibited the lowest SOC accrual and highest supplementary feed requirements (Supplementary Figs. 1–6).

Sward productivity has greater bearing on farm profit than carbon prices

High-productivity swards increased farm gross margins relative to Baseline systems, with rainfall exerting a stronger influence than livestock prices or carbon prices (Fig. 4a and Supplementary Tables 4–6). Carbon credits increased revenue in high-rainfall zones; however, carbon liabilities associated with higher emissions frequently offset these gains (Fig. 4b and Supplementary Fig. 8). Low-productivity swards were consistently least profitable, particularly in high-rainfall environments, due to higher carbon liabilities (Fig. 4a and Supplementary Figs. 7 and 8).

Preventing soil carbon loss is conducive to improved farm profitability

High antecedent SOC reduced long-term profitability through SOC losses, whereas low SOC increased gross margins via carbon credits, particularly under high carbon prices and low meat prices (Fig. 2, Supplementary Fig. 12 and Supplementary Tables 6 and 7). Low-intensity grazing with short rest periods generated the highest profitability through reduced supplementary feed costs (Figs. 5 and 6

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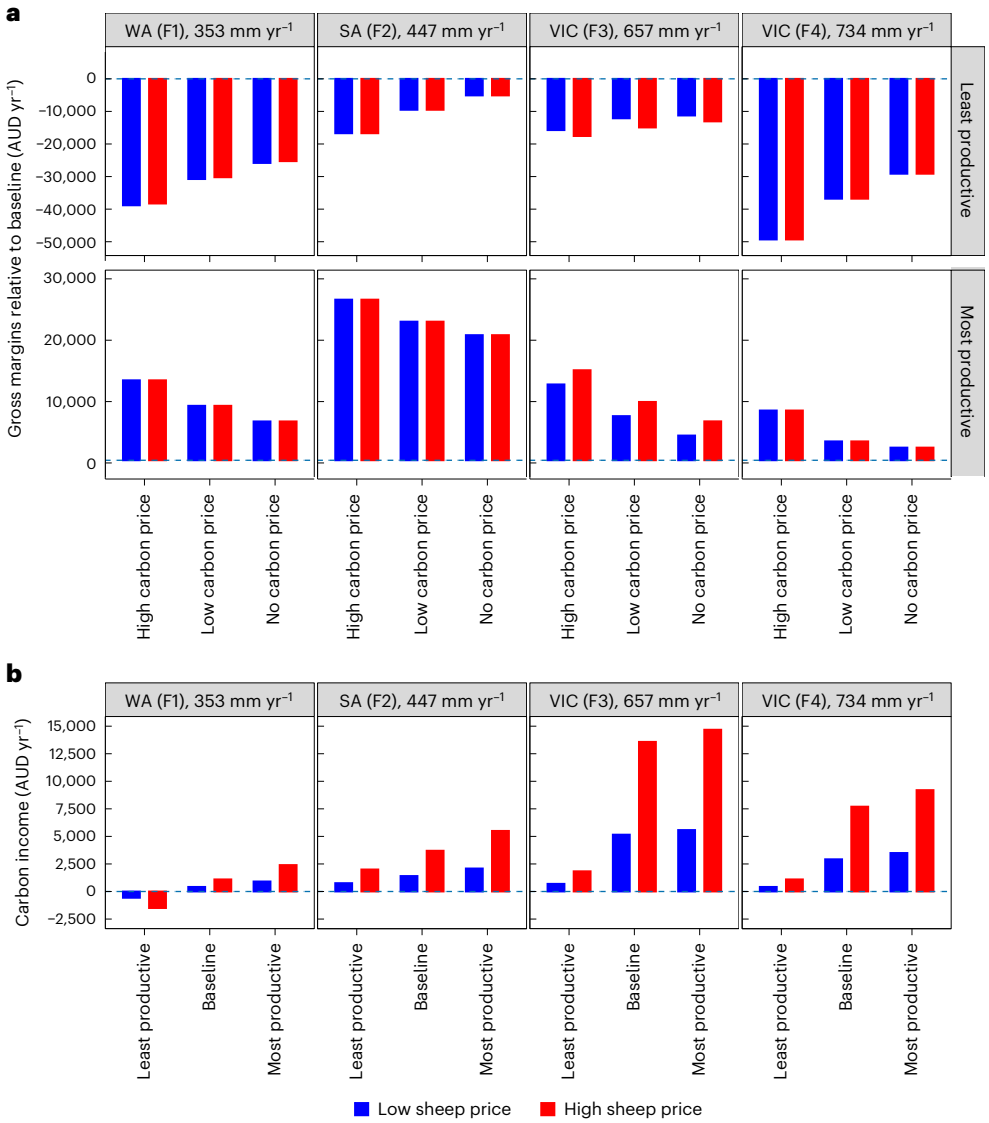


Fig. 4 | a,b, Effect of botanical composition, carbon price and sheep price on gross margins. Data are shown relative to Baseline gross margins (**a**) and in terms of income from carbon credits (received when GHG emissions were less than the Baseline) or loss from carbon taxes (applied when GHG emissions were greater than the Baseline; **b**). Panel titles depict farm abbreviation (F1–4), long-term average annual rainfall (mm yr^{-1}) and region, with Western Australia (WA), South Australia (SA) and Victoria (VIC). Panel rows in **a** and individual bars in **b** represent the least and most productive botanical compositions, each comprising three pasture species and averaged over the simulation. Baseline represents set stocking and existing pasture species (see Extended Data Table 4 and the Methods for details).

and Supplementary Tables 5, 6 and 8–10), while high-intensity grazing with long rest periods produced the lowest margins.

Gross margins per grazed area were more sensitive to rainfall, total livestock numbers and sheep prices than to carbon price or grazing regime (Fig. 5 and Supplementary Tables 8–10). High-rainfall farms with greater stocking rates achieved higher margins per unit area despite incurring larger carbon taxes (Fig. 5 and Supplementary Tables 6 and 8–10). Although variable grazing generated higher carbon credits and lower carbon taxes, increased supplementary feed costs reduced margins per DSE and per hectare relative to low-intensity grazing with short rest periods, particularly under high-rainfall environments (Fig. 5 and Supplementary Tables 5, 6 and 8–10). Over the long term, high-intensity grazing with long rest periods was the least profitable due to persistently higher feed costs (Supplementary Tables 5 and 8–10). Overall, the most profitable systems were characterized by faster rotations, short rest periods and lower stocking rates, which improved pasture utilization and reduced supplementary feed demand.

Normalized multidimensional impact analysis

Normalized multidimensional analysis showed that variable grazing delivered the highest integrated benefit across productivity, profitability, and GHG mitigation, although dominant drivers differed regionally (Fig. 7). In VIC (F4), benefits were driven primarily by increased production and profitability, whereas in F1–F3, GHG mitigation dominated the positive response. Low-productivity pastures performed poorly across all dimensions, underscoring the combined agronomic, environmental and economic advantages of maintaining productive, palatable swards under AMP grazing.

Discussion

Sustainable livestock carrying capacity must be calibrated on production during climatic adversities

Regenerative agriculture encompasses multiple practices, including increased biodiversity, adaptive grazing, minimal cultivation and reduced synthetic inputs. When implemented together, isolating the

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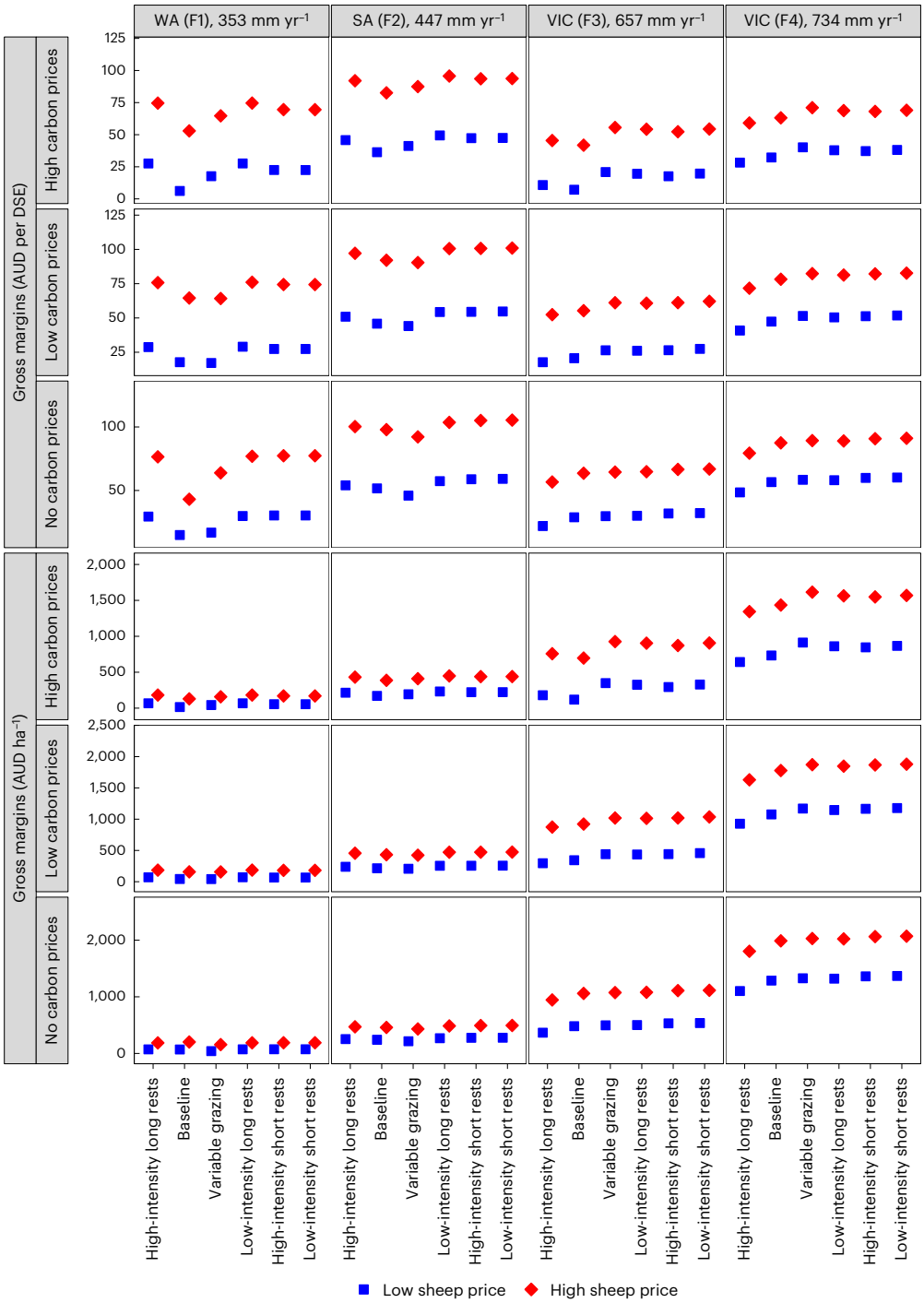


Fig. 5 | AMP grazing gross margin per DSE and per grazed area for six grazing regimes at low and high sheep prices and with nil, low or high carbon prices. Column titles depict farm abbreviation (F1–4), long-term average annual rainfall (mm yr^{-1}) and region, with Western Australia (WA), South Australia (SA) and Victoria (VIC). Rows represent gross margin per DSE or per hectare at high, low and nil carbon prices. Baseline represents set stocking and is compared with five grazing treatments of varying stocking rate, duration and spelling period (low-intensity long rests, high-intensity long rests, low-intensity short rests, high-intensity short rests and variable grazing with duration adjusted dynamically in response to seasonal conditions; see Extended Data Table 4 and the Methods for details).

contribution of individual components is challenging due to complex interactions and feedbacks within agroecosystems. Here, we disentangled the effects of pasture species diversity, antecedent SOC and AMP grazing on pasture productivity, GHG emissions and farm profitability across contrasting environments.

Through interdisciplinary assessment, we showed that AMP grazing exerted a stronger influence than pasture species diversity on pasture production, SOC accrual and GHG mitigation (Fig. 1 and Extended Data Table 3). Under high carbon prices, these gains translated into higher gross margins per DSE and per unit area (Fig. 5, Supplementary Figs. 7 and 8 and Supplementary Tables 8–10) and substantially lower emissions intensity, with variable grazing averaging 54% lower emissions intensity than Baseline systems (Extended Data Table 3). Although variable grazing optimized productivity and emissions abatement through enhanced SOC sequestration (Figs. 1 and 2 and Supplementary Table 3), higher supplementary

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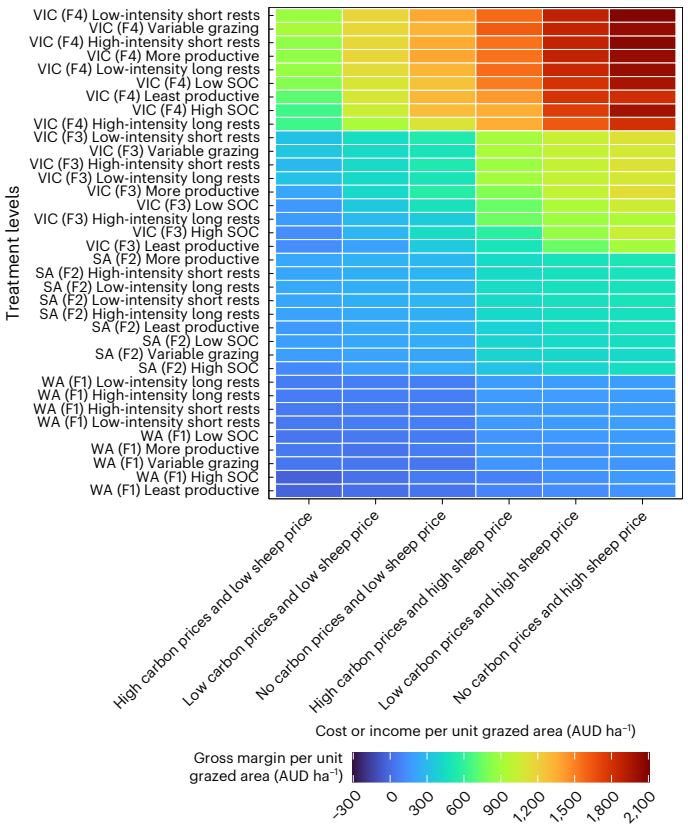


Fig. 6 | Gross margin per grazed area as a function of costs associated with supplementary feeding and carbon taxes for high and low sheep prices. Interventions comprised pasture species diversity, antecedent SOC and AMP grazing assessed across four agroecological environments. Rows depict farm abbreviation (F1–4), region (Western Australia, WA; South Australia, SA; Victoria, VIC) and grazing treatment. Baseline represents set stocking and is compared with five grazing treatments of varying stocking rate, duration and spelling period, including low-intensity long rests, high-intensity long rests, low-intensity short rests, high-intensity short rests and variable grazing with duration adjusted dynamically in response to seasonal conditions; low and high SOC represent SOC concentrations used for model initialization (0.3% and 6%, respectively); least and most productive species represent swards containing three pasture species with the lowest or highest average annual production, respectively. Columns depict factorial combinations of carbon price and sheep price, while colours show gross margin per grazed area.

feed requirements occasionally offset economic returns (Figs. 5 and 6). By contrast, low-intensity grazing with short rest periods required less supplementary feed and frequently maximized gross margins per area on intensively stocked farms in wetter regions and profit per DSE in arid, lightly stocked systems (Figs. 5 and 6).

These findings indicate that, while specific grazing regimes can deliver substantial SOC accrual and GHG abatement[19,20], downside economic risk persists when pasture supply is constrained[21,22]. Sustainable stocking rates must therefore respond to both short-term climatic variability and long-term carrying capacity, governed by regional climate and soil water holding capacity. Carrying capacity should be calibrated to the most severe seasonal conditions or sequences of climatic adversity, which vary spatially and are projected to intensify under climate change[23–25]. Importantly, this principle extends beyond regenerative practices to all rainfed pastoral systems.

Long-term simulations that integrate grazing management, herd or flock dynamics, and pasture production during minimum forage availability provide a robust basis for estimating sustainable carrying capacity. Such approaches can incorporate farmer risk preferences, including decisions around supplementary feeding, agistment or enterprise restructuring. Maintaining livestock numbers within thresholds imposed by drought ensures adequate pasture per animal, reduces labour requirements, limits erosion, maintains ground cover, facilitates pasture recovery and prevents SOC loss[26–28]. AMP grazing operationalizes these principles through paddock subdivision and grazing duration adapted according to available biomass, with some AMP practitioners adjusting paddock size to inherent soil productivity to maintain consistent grazing pressure across heterogeneous landscapes.

Pasture identity, not diversity, drives productivity, SOC accrual and carbon dioxide removals

Inclusion of high-yielding pasture species enhanced both productivity and GHG mitigation (Extended Data Table 1). Swards containing subterranean clover, phalaris and lucerne increased annual pasture production by 7% and liveweight by 2% relative to Baseline species, whereas low-productivity swards reduced output by 39% and increased net emissions and emissions intensity. These effects were driven primarily by differences in peak spring growth (Fig. 1) and are consistent with empirical evidence of summer–autumn production gains from species with superior production[29–31]. Aligning whole flock feed demand with seasonal pasture supply through tactical lambing and destocking can further reduce emissions intensity and improve profitability[32–34].

Together, these findings suggest that functional traits and seasonal growth patterns of dominant species, rather than botanical diversity per se, determine both production and SOC inputs. Diversity may still confer resilience or ecological benefits not captured here, but productivity and SOC outcomes in temperate grazing systems appear to be governed primarily by the performance of key species.

Antecedent SOC exerts stronger control over SOC accrual than climate or practice change

Antecedent SOC exerted a stronger control on subsequent SOC dynamics than either management or climate[35–37]. Our 100-year simulations showed long-term SOC additionality ranging from −0.7 to 0.5 t SOC ha^{-1} yr^{-1} in the top 30 cm, depending on initial SOC (Fig. 2), far lower than short-term gains reported in some carbon projects[38]. Such discrepancies probably reflect anomalously high seasonal rainfall affecting carbon flux portioning and potential contamination of organic carbon measurements with inorganic carbonates[39], underscoring the need for biophysically plausible SOC flux ceilings to maintain carbon market legitimacy[38].

Low antecedent SOC stocks exhibited greater sequestration potential, consistent with previous studies[16] and delivered disproportionate reductions in farm-level GHG emissions (Figs. 3 and 7). However, antecedent SOC had minimal influence on pasture productivity or supplementary feed demand, indicating that soil organic matter (SOM) status exerted weaker control over forage production than grazing management. These results emphasize the importance of multimetric evaluation and highlight opportunities to target degraded soils for SOC restoration, nutrient cycling, biodiversity restoration and natural capital accumulation[14].

Variable grazing durations outperform conventional set stocking, yet trade-offs abound

Variable grazing increased SOC stocks relative to set stocking, whereas low-intensity short-rest grazing produced the lowest SOC accrual (Extended Data Table 3). Variable grazing also enhanced herbage productivity, particularly in high rainfall zones, delivering up to 35% higher annual production, compared with 16% under high-intensity long-rest grazing. Supplementary feed requirements increased under variable grazing in arid systems, while long-rest grazing raised supplementary feed demand in wetter, heavily stocked environments (Supplementary Table 3).

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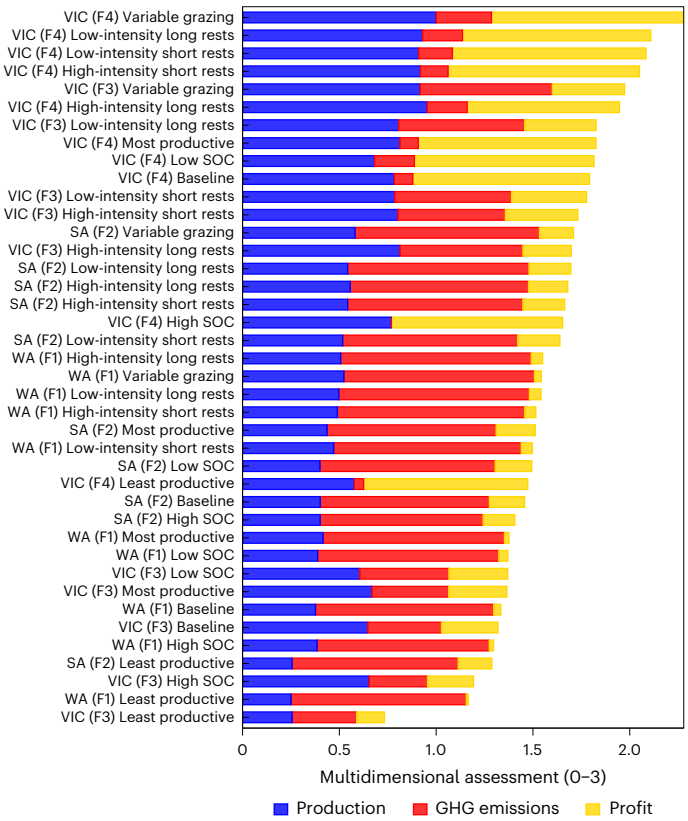


Fig. 7 | Normalized multidimensional integration of productivity, profitability and GHG emissions. Interventions comprised pasture species diversity, antecedent SOC and AMP grazing assessed across four agroecological environments. Bars show normalized multidimensional impact scores integrating pasture production, GHG emissions and profit. Higher integrated assessment scores indicate more desirable outcomes (Methods). Rows depict farm abbreviation (F1–4), region (Western Australia, WA; South Australia, SA; Victoria, VIC) and grazing treatment. Baseline represents set stocking and is compared with five grazing treatments of varying stocking rate, duration and spelling period, including low-intensity long rests, high-intensity long rests, low-intensity short rests, high-intensity short rests and variable grazing with duration adjusted dynamically in response to seasonal conditions; low and high SOC represent SOC concentrations used for model initialization (0.3% and 6%, respectively); the least and most productive species represent swards containing three pasture species with the lowest or highest average annual production, respectively.

AMP grazing influenced profitability more strongly than pasture diversity (Figs. 5 and 6). While variable grazing enhanced productivity and SOC sequestration, higher feed costs sometimes reduced net margins. Conversely, low-intensity short-rest grazing minimized feed costs, offset carbon taxes and maximized profit. These outcomes reflect inherent trade-offs: productive pastures reduce feed dependence, whereas extended rest periods enhance recovery and SOC but can increase reliance on imported feed, with secondary nutrient inputs potentially benefitting fertility in nutrient-limited systems[40–42].

Context-dependent management outcomes and policy relevance

The relative performance of grazing systems was context dependent and influenced by the weighting attributed to sustainability objectives. In low-rainfall regions, low-intensity short-rest grazing was most profitable under high livestock prices and in the absence of carbon pricing, whereas set stocking and variable grazing performed poorly under low livestock prices and high carbon costs. In high-rainfall systems, variable grazing delivered superior SOC accrual and GHG mitigation, although short-rest grazing remained most profitable under high livestock prices without carbon pricing. Carbon pricing was more influential in productive, high-emissions systems, while grazing management remained the dominant determinant of profitability across environments.

When profitability was prioritized, low-intensity short-rest grazing was optimal; when productivity, profitability and mitigation were weighted equally, variable grazing provided the most balanced outcome (Fig. 7). These results highlight the potential for regionally differentiated carbon incentives that better align emissions mitigation with production and stewardship objectives.

SOC responses to grazing management were governed primarily by antecedent SOC and environmental constraints, with species performance outweighing diversity effects. AMP grazing, combined with appropriate species selection and stocking rate calibration, enhanced SOC accrual and reduced GHG emissions but did not universally maximize profitability. Short-rest grazing maximized profit, whereas longer rests maximized SOC sequestration. Persistent trade-offs among productivity, profitability and mitigation outcomes underscore the need for context-specific, multimetric assessment. Aligning stocking rates with pasture growth, feed demand and climatic expectations can reduce supplementary feed reliance and moderate carbon exposure. Ultimately, practices that maximize SOC accrual and emissions mitigation are not always the most profitable, reinforcing the need to balance economic and environmental objectives when designing resilient, low-emissions pastoral systems.

Methods

Climate and soil characteristics

Historical daily climate data including maximum and minimum temperature, rainfall and solar radiation spanning 1 January 1924 to 31 December 2023 were obtained as SILO[43] patch-point data[43] (Supplementary Table 11). The most representative soil types for each farm were selected using the Digital Atlas of Australian Soils[44]. To account for variability in antecedent SOC stocks, simulations were initialized with contrasting SOC stocks in upper (0–30 cm) and lower (30–50 cm) soil profiles.

Case study farming systems

Because climate and soil type influence pasture growth, SOC dynamics, livestock carrying capacity and often farm scale, commercial farms were strategically selected across Australian sheep production zones[45] following a national call for participation (January 2022; MLA Weekly, SALRC, NABRC and WALRC). From 115 expressions of interest, 4 farms were chosen to represent distinct agroecological regions, spanning cool temperate Victoria to semi-arid Western Australia (Supplementary Table 11), based on their position within key livestock production zones of Australia[45] and agroecological region, ranging from cool temperate in southern Victoria to semi-arid in Western Australia. Enterprises typified Australian meat and/or wool production systems. Site-specific climate, soil, pasture and management data were used to initialize simulations before testing alternative interventions—and scenarios within interventions—in silico.

Regenerative farm F1, Kulin, Western Australia. Large flocks under rotational grazing. Rams were purchased; wethers were sold in late summer (February–April) or mid-winter (August). Approximately 80% of wether lambs were marketed at 130 days and 20% at 210 days. Ewes were culled at 5–8 years. Soils were sandy loams and medium clays (Supplementary Table 11).

Conventional management farm F2, Meningie, South Australia. Paddock rotations occurred at 7–21-day intervals depending on pasture availability. Breeding ewes were purchased at 5 years; no replacements were retained. Around 1,040 ewe lambs were sold from

October at 60 kg (7.5 months). Approximately 1,040 wether lambs were sold from mid-August at 46 kg (≤6 months). Breeding ewes were culled at 7–8 years (Supplementary Table 11).

Conventional management farm F3, Casterton, Victoria. Wool and meat production with 2,200 ewes plus 480 replacements per age cohort. Meat flock ewes were set stocked during lambing (July–September); Merino ewes rotationally grazed (August–October). Lambing occurred in mid-July (meat) and mid-August (wool), with weaning in November. Wether lambs were sold from mid-July at 45 kg or by mid-November. A total of 2,300 lambs were sold from December at 38 kg or by February. Ewes were culled at 5–6 years (Supplementary Table 11).

Regenerative farm F4, Winslow, Victoria. Case Merino wool enterprise with 2,532 ewes and 884 replacements per age group. Rotational grazing operated across 440 ha arable pasture. Lambing occurred in early September and weaning in late November. Lambs (1,340 head) were sold May–November at 27 kg liveweight. Ewes were culled at 5–6 years (Supplementary Table 11).

Biophysical modelling

Farming systems were simulated using the SGS model (v5.4.3)[46,47], which has been extensively calibrated and validated alongside sister model DairyMod. The model operates at daily time steps and simulates soil water balance, SOC and nutrient dynamics, botanical composition, ground cover, livestock growth and production (wool, meat, milk), pasture growth and senescence, animal transactions, and pasture and supplementary feed utilization[46].

SOC is partitioned into fast (particulate), slow (humus) and inert pools derived from litter, manure and roots. The inert pool does not decay in the absence of fire and is not simulated. SOC turnover depends on temperature, soil moisture, substrate inputs and pool-specific decay rates. Soil nutrient processes include mineralization, immobilization, leaching, adsorption and gaseous losses[46].

Livestock movement among paddocks followed rule-based management reflecting each farm system. Supplementary feeding to maintain target liveweights included lupins (24 MJ metabolisable energy (ME) kg^{-1} dry matter (DM)), barley straw (11 MJ), barley grain (14 MJ), faba beans (12.8 MJ), grass silage (12 MJ) and hay (7.6 MJ).

Simulations ran continuously from 1 January 1924 to 31 December 2023. Atmospheric CO_2 concentration was fixed at 380 ppm to approximate mid-simulation atmospheric conditions[48]. Stocking intensity was standardized using dry sheep equivalents (DSEs), where 1 DSE equals a 45-kg Merino wether consuming 7.6 MJ ME per day. To examine rainfall extremes, we analysed consecutive 2-year high (>20% above mean) and low (>20% below mean) rainfall periods for F1 (2019–2020 wet; 1992–1993 dry) and F4 (1989–90 wet; 2014–15 dry). SOC fluxes were normalized to initial SOC stocks (Supplementary Figs. 8–13).

GHG accounting

Model outputs for livestock numbers, feed intake, production and SOC were entered into the Sheep & Beef Greenhouse Gas Accounting Framework (SB-GAF)[49] to quantify average annual GHG emissions over 100 years. SOC sequestration was converted into CO_2e using a factor of 3.67, and 100-year global warming potentials of 28 for CH_4 and 265 for N_2O were applied[50]. Net farm emissions were calculated as gross emissions plus soil respiration minus SOC sequestration. Emissions were allocated to meat and wool in proportion to protein output to derive product-level intensities ($kgCO_2e\ kg^{-1}$ liveweight or clean wool)[49].

Economic analyses

Gross margins (Australian dollars (AUD) ha^{-1} and AUD per DSE) were calculated from SGS and SB-GAF outputs combined with literature-derived prices. Scenarios reducing net emissions relative to the Baseline generated carbon credit income, whereas increased net emissions incurred carbon tax liabilities. Carbon prices of AUD $38 and $100 per tonne of CO_2e were examined. Other costs were held constant (Supplementary Table 12).

Farming systems interventions

Using codesign with case study farmers, we simulated three farming systems interventions to deconstruct constituent principles underpinning the broader 'regenerative agriculture' philosophy: AMP, antecedent SOC and pasture species diversity. The pasture species intervention was designed to examine effects of ecotype diversity compared with Baseline botanical compositions (Supplementary Table 13), with appropriate pasture species being informed by case study farmers. Within each intervention, we examined multiple scenarios. For example, several botanical compositions were simulated, first including swards with individual pasture species, then by combining the most and least productive botanical compositions (Supplementary Table 13). For AMP, we contrasted short, intense grazing with conventional long-duration, lower stocking rates including six grazing regimes with scenarios configured relative to Baseline farming systems (Extended Data Table 4). One AMP scenario, 'variable grazing', was explored by initiating and terminating grazing duration as a function of seasonal conditions based on pasture biomass availability (Extended Data Table 4). To examine effects of historical (antecedent) SOC stocks, two SOM levels were used to initialize SGS. These were designed to represent low or high SOC (0.5% SOM/0.3% SOC and 10% SOM/6% SOC, respectively) in the 0–30 cm and 30–50 cm soil layers on the first day of the simulation (1 January 1924). The ensuing simulated SOC (including slow, fast, and inert pools) was compared across interventions and farm locations.

Normalized multidimensional impact assessments

To integrate productivity, profitability and mitigation, annual pasture production (kg DM ha^{-1}), profit (AUD ha^{-1}) and net GHG emissions ($tCO_2e\ ha^{-1}$) were normalized against scenario maxima[40] (Fig. 7). Emissions were inverted, such that higher values indicated better mitigation. Equal weighting produced an integrated score ranging from 0 (least favourable) to 3 (most favourable).

Reporting summary

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

Data availability

Model files and datasets are available via Zenodo at https://doi.org/10.5281/zenodo.18400404 (ref. 51).

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Author contributions

M.T.H.: conceptualization, methodology, software, formal analysis, investigation, funding acquisition, resources, supervision and writing—original draft, review draft. A.M.: formal analysis, software, investigation, and writing—original draft. K.M.C.-W.: methodology, formal analysis, software, investigation, supervision and writing—original draft, review draft. M.C.: investigation, supervision and writing—review draft. K.L.: formal analysis, investigation, data curation, supervision and writing—review draft. P.J.B.: formal analysis and writing—review draft. C.W.: formal analysis and writing—review draft. G.P.: formal analysis writing—review draft. All authors discussed interpretation of the results and significance of the conclusions.

Competing interests

The authors declare no competing interests.

Additional information

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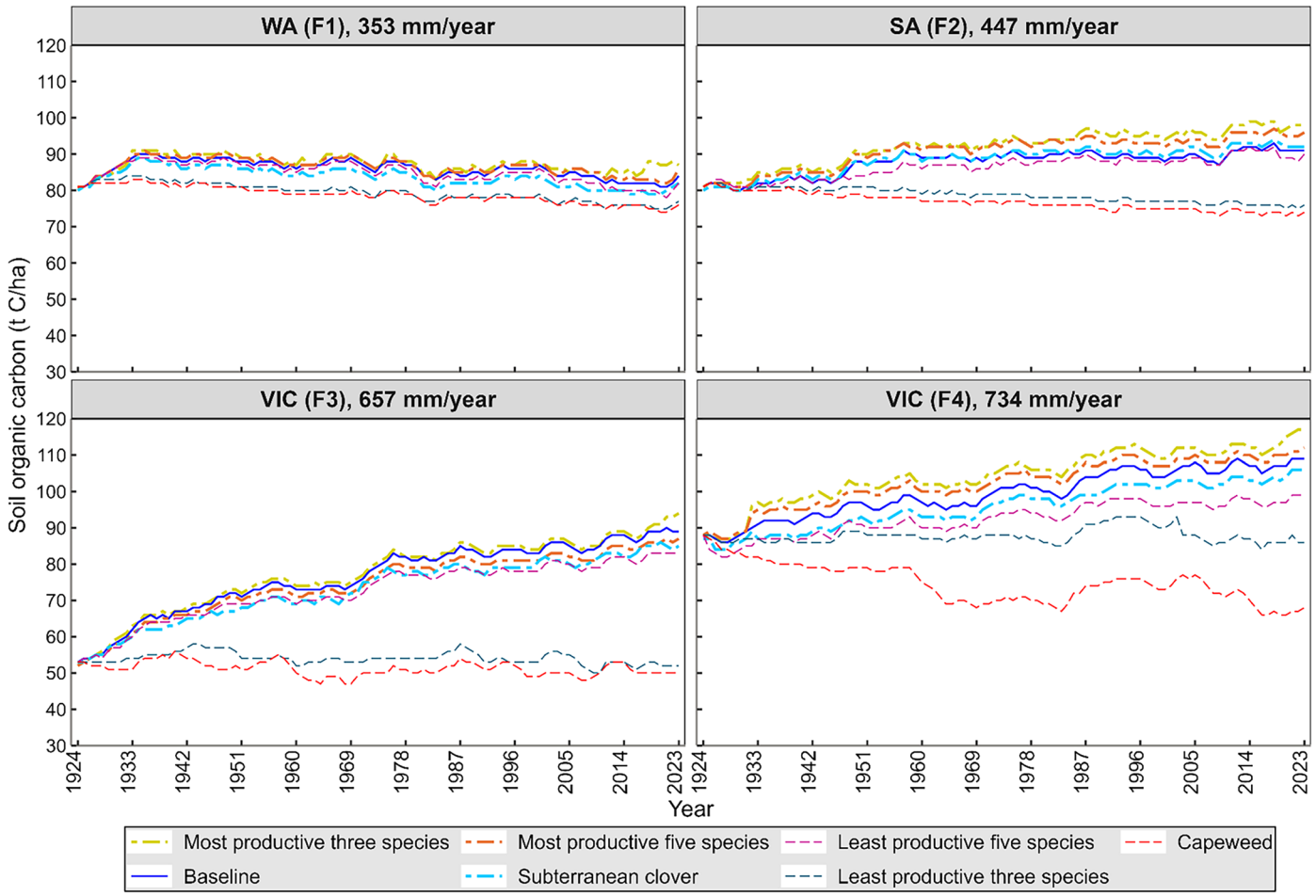
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Extended Data Fig. 1 | Long-term soil organic carbon (SOC) in the surface layer (0-30 cm) for the most and least productive botanical compositions. The most and least productive three-species swards represent the highest and lowest productivity compositions containing three species, while the most and least productive five-species swards indicate the highest and lowest productivity compositions containing five species. Baseline represents existing species, while subterranean clover and capeweed represent swards containing only that species. Panel titles indicate State (SA, South Australia; VIC, Victoria; WA, Western Australia), farm number (F1–F4), and average annual rainfall. F, farm; SOC, soil organic carbon; SA, South Australia; VIC, Victoria; WA, Western Australia.

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Extended Data Table 1 | SOC sequestration, annual GHG emissions, and emissions intensity for pastures under Baseline, low or high productivity swards

Pasture type	WA (F1), 353 mm yr^{-1}	SA (F2), 447 mm yr^{-1}	VIC (F3), 657 mm yr^{-1}	VIC (F4), 734 mm yr^{-1}
SOC sequestration (t CO_2e ha^{-1} yr^{-1})				
Most productive	0.02	0.06	0.25	0.21
Least productive	-0.02	-0.02	-0.03	-0.03
Baseline	0.01	0.04	0.23	0.10
Net farm GHG emissions (t CO_2e ha^{-1} yr^{-1})				
Most productive	0.4	0.7	3.6	5.6
Least productive	0.6	0.9	4.2	6.0
Baseline	0.5	0.8	3.8	5.7
CH_4 emissions (t CO_2e ha^{-1} yr^{-1})				
Most productive	0.3	0.7	3.2	4.9
Least productive	0.4	0.7	3.4	5.0
Baseline	0.3	0.7	3.2	5.0
N_2O emissions (t CO_2e ha^{-1} yr^{-1})				
Most productive	0.04	0.04	0.41	0.79
Least productive	0.05	0.04	0.43	0.82
Baseline	0.04	0.05	0.42	0.80
CO_2 emissions (t CO_2e ha^{-1} yr^{-1})				
Most productive	0.09	0.06	0.26	0.09
Least productive	0.09	0.06	0.26	0.09
Baseline	0.09	0.06	0.26	0.09
Emissions intensity of wool including sequestration (kg CO_2e kg clean fleece $weight^{-1}$)				
Most productive	19.5	25.3	24.8	29.6
Least productive	26.3	31.0	30.2	31.7
Baseline	22.1	27.4	25.7	30.4
Emissions intensity of sheep meat including sequestration (kg CO_2e kg $liveweight^{-1}$)				
Most productive	5.3	4.5	4.5	5.3
Least productive	7.3	5.6	5.4	5.7
Baseline	5.9	4.9	4.6	5.5

SOC sequestration, annual GHG emissions, and emissions intensity of wool and sheep meat for the highest- and lowest-productivity three-species pasture swards across four regions with differing average annual rainfall. Negative SOC sequestration indicates SOC loss and increased net GHG emissions, while positive SOC sequestration indicates SOC accrual and reduced net GHG emissions. SOC is reported for the surface layer (0–30 cm). Net GHG emissions include methane, nitrous oxide, and carbon dioxide from soil and livestock. Column headings indicate State (WA = Western Australia; SA = South Australia; VIC = Victoria), farm number (F1–F4), and average annual rainfall (mm $year^{-1}$). Abbreviations: CH_4, methane; CO_2, carbon dioxide; F, farm; GHG, greenhouse gas; N_2O, nitrous oxide; SA, South Australia; SOC, soil organic carbon; VIC, Victoria; WA, Western Australia.

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Extended Data Table 2 | SOC sequestration, annual GHG emissions and emissions intensity for Baseline farm systems, low (0.3%) and high (6%) antecedent SOC levels across four Australian sheep farms

Antecedent SOC levels	WA (F1), 353 mm yr^{-1}	SA (F2), 447 mm yr^{-1}	VIC (F3), 657 mm yr^{-1}	VIC (F4), 734 mm yr^{-1}
SOC sequestration (t CO_2e ha^{-1} yr^{-1})				
Baseline	0.01	0.04	0.23	0.18
Low SOC (0.3%)	0.12	0.13	0.32	0.41
High SOC (6%)	-0.21	-0.25	-0.18	-0.23
Net farm GHG emissions (t CO_2e ha^{-1} yr^{-1})				
Baseline	0.5	0.8	3.9	5.7
Low SOC (0.3%)	0.4	0.6	3.4	5.0
High SOC (6%)	0.7	1.0	4.4	6.3
CH_4 emissions (t CO_2e ha^{-1} yr^{-1})				
Baseline	0.3	0.7	3.4	5.0
Low SOC (0.3%)	0.3	0.6	3.0	5.0
High SOC (6%)	0.4	0.7	3.5	5.1
N_2O emissions (t CO_2e ha^{-1} yr^{-1})				
Baseline	0.04	0.05	0.43	0.80
Low SOC (0.3%)	0.04	0.04	0.43	0.66
High SOC (6%)	0.04	0.05	0.44	0.72
CO_2 emissions (t CO_2e ha^{-1} yr^{-1})				
Baseline	0.13	0.06	0.26	0.09
Low SOC (0.3%)	0.13	0.06	0.26	0.09
High SOC (6%)	0.13	0.06	0.26	0.09
Emissions intensity of wool including sequestration (kg CO_2e kg clean fleece $weight^{-1}$)				
Baseline	24.0	36.3	26.5	30.4
Low SOC (0.3%)	17.9	29.9	25.5	28.9
High SOC (6%)	34.9	50.0	30.4	33.1
Emissions intensity of sheep meat including sequestration (kg CO_2e kg $liveweight^{-1}$)				
Baseline	6.4	6.5	4.8	5.5
Low SOC (0.3%)	4.8	5.4	4.6	5.2
High SOC (6%)	9.4	9.0	5.5	6.0

Antecedent SOC represents the SOC concentration used for model initialization. Negative SOC sequestration represents SOC loss and increased net GHG emissions, while positive SOC sequestration represents SOC accrual and reduced net GHG emissions. SOC values are reported for the surface layer (0–30 cm). Column titles indicate State (SA, South Australia; VIC, Victoria; WA, Western Australia), farm number (F1–F4), and average annual rainfall. CH_4, methane; CO_2, carbon dioxide; N_2O, nitrous oxide; F, farm; GHG, greenhouse gas; SOC, soil organic carbon.

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Extended Data Table 3 | SOC sequestration, annual GHG emissions and emissions intensity under adaptive multi-paddock (AMP) grazing regimes across four agroecological regions

Grazing regime	WA (F1), 353 mm yr^{-1}	SA (F2), 447 mm yr^{-1}	VIC (F3), 657 mm yr^{-1}	VIC (F4), 734 mm yr^{-1}
SOC sequestration (t CO_2e ha^{-1} yr^{-1})				
Variable grazing	0.10	0.10	0.48	0.38
High intensity long rests	0.08	0.09	0.44	0.35
Low intensity long rests	0.07	0.07	0.43	0.30
High intensity short rests	0.06	0.05	0.42	0.24
Low intensity short rests	0.03	0.02	0.40	0.20
Set stocked (*Baseline*)	0.01	0.04	0.23	0.18
Net farm GHG emissions (t CO_2e ha^{-1} yr^{-1})				
Variable grazing	0.08	0.32	1.96	4.52
High intensity long rests	0.13	0.48	2.31	4.95
Low intensity long rests	0.13	0.44	2.18	4.89
High intensity short rests	0.25	0.59	2.80	5.39
Low intensity short rests	0.22	0.57	2.48	5.21
Set stocked (*Baseline*)	0.47	0.76	3.85	5.71
CH_4 emissions (t CO_2e ha^{-1} yr^{-1})				
Variable grazing	0.07	0.31	1.97	4.21
High intensity long rests	0.10	0.46	2.25	4.57
Low intensity long rests	0.09	0.43	2.13	4.43
High intensity short rests	0.18	0.54	2.59	4.79
Low intensity short rests	0.13	0.49	2.36	4.68
Set stocked (*Baseline*)	0.35	0.68	3.36	4.96
N_2O emissions (t CO_2e ha^{-1} yr^{-1})				
Variable grazing	0.01	0.03	0.19	0.57
High intensity long rests	0.02	0.04	0.21	0.62
Low intensity long rests	0.02	0.04	0.19	0.73
High intensity short rests	0.03	0.03	0.34	0.73
Low intensity short rests	0.02	0.02	0.24	0.62
Set stocked (*Baseline*)	0.04	0.05	0.43	0.80
CO_2 emissions (t CO_2e ha^{-1} yr^{-1})				
Variable grazing	0.09	0.06	0.26	0.09
High intensity long rests	0.09	0.06	0.26	0.09
Low intensity long rests	0.09	0.06	0.26	0.09
High intensity short rests	0.09	0.06	0.26	0.09
Low intensity short rests	0.09	0.06	0.26	0.09
Set stocked (*Baseline*)	0.09	0.06	0.26	0.09
Emissions intensity of wool including sequestration (kg CO_2e kg clean fleece $weight^{-1}$)				
Variable grazing	3.7	15.2	12.2	24.1
High intensity long rests	6.2	23.0	14.8	26.4
Low intensity long rests	6.0	21.2	13.9	26.6
High intensity short rests	11.7	28.3	18.5	28.8
Low intensity short rests	10.3	27.2	16.1	27.8
Set stocked (*Baseline*)	22.1	36.3	26.5	30.4
Emissions intensity of sheep meat including sequestration (kg CO_2e kg $liveweight^{-1}$)				
Variable grazing	1.0	2.7	2.2	4.3
High intensity long rests	1.7	4.1	2.7	4.8
Low intensity long rests	1.6	3.8	2.5	4.8
High intensity short rests	3.1	5.1	3.3	5.2
Low intensity short rests	2.8	4.9	2.9	5.0
Set stocked (*Baseline*)	5.9	6.5	4.8	5.5

Negative SOC sequestration represents SOC loss and increased net GHG emissions; positive SOC sequestration represents SOC accrual and reduced net GHG. SOC values reported for the surface layer (0–30 cm). Baseline represents set stocking; variable grazing represents grazing duration dynamically adjusted according to seasonal conditions; intensity represents stocking rate; rest period represents time between grazing events. Column titles indicate State (SA, South Australia; VIC, Victoria; WA, Western Australia), farm number (F1–F4), and average annual rainfall. AMP, adaptive multi-paddock; CH_4, methane; CO_2, carbon dioxide; F, farm; GHG, greenhouse gas; N_2O, nitrous oxide; SOC, soil organic carbon.

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Extended Data Table 4 | Grazing management scenarios simulated for four agroecological regions

Grazing regime	Indicator	WA (F1), 353 mm yr^{-1}	SA (F2), 447 mm yr^{-1}	VIC (F3), 657 mm yr^{-1}	VIC (F4), 734 mm yr^{-1}
Scenario 1: Set stocked (*Baseline*)	N°. paddocks	1	1	1	1
	Paddock area (ha)	3,484	865	600	440
	Stocking rate (DSE ha^{-1})	2	5	17	25
	Days on paddock	120	120	120	120
	Rest period (days)	120	120	120	120
Scenario 2: low intensity grazing with long rest periods (12 paddocks 14-day rest)	N°. paddocks	12	12	12	12
	Paddock area (ha)	290	72	50	37
	Stocking rate (DSE ha^{-1})	29	56	200	273
	Days on paddock	14	14	14	14
	Rest period (days)	132	132	132	132
Scenario 3: high intensity grazing with long rest periods (30 paddocks 12-day rest)	N°. paddocks	30	30	30	30
	Paddock area (ha)	116	29	20	15
	Stocking rate (DSE ha^{-1})	73	141	500	682
	Days on paddock	12	12	12	12
	Rest period (days)	348	348	348	348
Scenario 4: low intensity grazing with short rest periods (12 paddocks 1-day rest)	N°. paddocks	12	12	12	12
	Paddock area (ha)	290	72	50	37
	Stocking rate (DSE ha^{-1})	29	56	200	295
	Days on paddock	1	1	1	1
	Rest period (days)	11	11	11	11
Scenario 5: high intensity grazing with short rest periods (30 paddocks 1-day rest)	N°. paddocks	30	30	30	30
	Paddock area (ha)	116	29	20	15
	Stocking rate (DSE ha^{-1})	73	141	500	682
	Days on a paddock	1	1	1	1
	Rest period (days)	29	29	29	29
Scenario 6: variable rotational grazing with duration dependent on pasture biomass ("variable grazing")	N°. paddocks	30	30	30	30
	Paddock area (ha)	116	29	20	15
	Stocking rate (DSE/ha)	73	141	500	682
	Pasture biomass required to end grazing (t DM ha^{-1})	1.0	1.0	1.0	1.0
	Pasture biomass required to initiate grazing (t DM ha^{-1})	2.5	2.5	2.5	2.5

Baseline represents set stocking; variable grazing represents grazing duration dynamically adjusted according to seasonal conditions; intensity represents stocking rate; rest period represents time between grazing events. Column titles indicate State (SA, South Australia; VIC, Victoria; WA, Western Australia), farm number (F1–F4), and average annual rainfall. DM, dry matter; DSE, dry sheep equivalent; F, farm; VIC, Victoria; WA, Western Australia.

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Reporting Summary

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For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed
☐	☒ The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐ A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐ The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐ A description of all covariates tested
☒	☐ A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒ A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐ For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐ Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used to collect data.
Data analysis	Biophysical production was conducted with the Sustainable Grazing Systems model (SGS version 5.4.3): Johnson IR. DairyMod and the SGS Pasture Model. A mathematical description of the 671 biophysical model structure.). IMJ Consultants (2016). Gross and net emissions for Scopes 1-3 were calculated using the Sheep & Beef GHG Accounting Framework (hereafter referred to as SB-GAF, V2.2, https://piccc.org.au/resources/Tools (Lopez et al., 2023), which encapsulates Australian National Greenhouse Inventory guidelines. Economic, financial and other analyses were computed in Microsoft Excel. Spreadsheets are available on request from the corresponding author.

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All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

All data underpinning the study have been uploaded to https://zenodo.org/records/18400404. This URL is referenced in the 'data availability' section of the paper.

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	NA
Reporting on race, ethnicity, or other socially relevant groupings	NA
Population characteristics	NA
Recruitment	Because climate and soil type influence pasture growth, SOC dynamics, livestock carrying capacity and often farm scale, commercial farms were strategically selected across Australian sheep production zones following a national call for participation (January 2022; MLA Weekly, SALRC, NABRC, WALRC). From 115 expressions of interest, four farms were chosen to represent distinct agroecological regions, spanning cool temperate Victoria to semi-arid Western Australia (Supplementary Table 11). based on their position within key livestock production zones of Australia and agroecological region, ranging from cool temperate in southern Victoria to semi-arid in Western Australia. Enterprises typified Australian meat and/or wool production systems. Site-specific climate, soil, pasture and management data were used to initialise simulations prior to testing alternative interventions—and scenarios within interventions—in silico.
Ethics oversight	The University of Tasmania Human Ethics Committee approved methods underpinning this study (review reference H0027905 (H-89952)).

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We conducted a transdisciplinary assessment of farms positioned across the southern seaboard of Australia. Of 115 applications, we selected farms shown in the paper based on their location relative to major production zones in Australia, farm size, their willingness to engage, annual rainfall and characteristics of their production system (self-replacing, breeder-finisher, purchase sell or mixed enterprises). Selected case study farmers completed questionnaires on their farm operations and participated in meetings to provide data and refine and validate the modelling. Baseline farm data were collected in Word documents first completed by the farmers, then refined online with researchers. Baseline information were then used to calibrate a range of modelling packages to reproduce status quo pasture and livestock production, carbon in vegetation and soils, biodiversity and profitability. To examine implications associated with interventions relative to status quo farming systems (hereafter, 'baseline systems'), we invoke data from four enterprises as case studies. Farms were selected across the four predominant livestock production zones in Australia (MLA, 2021). Farm area ranged between 495 ha and 5,850 ha, with annual rainfall ranging from 353 mm/year to 734 mm/year. Baseline data was collected from each farm to calibrate a range of biophysical, economic and ecological models. Using a participatory approach, farmers co-designed interventions and co-refined model inputs to validate modelled outputs for baseline systems, including seasonal pasture growth, supplementary feed use, total animal numbers, farm areas under vegetation, timing of historical tree planting, costs and financial income. This process required several iterations between researchers and each case study farmer until final model inputs were agreed. Because carbon sequestration, production and profit vary with rainfall, we study results across a rainfall gradient. Baseline information is detailed in the Supplementary Information of the paper (Table S11).
Research sample	Please see above.

Sampling strategy	Please see above.
Data collection	The corresponding author collected the data using questionnaires first sent to each case study farmer. These data were checked and refined in subsequent meetings with each farmer.
Timing and spatial scale	Data were collected between January 2021 and December 2024. Farm locations are shown in Table 1 (spread across all sheep production zones in Australia).
Data exclusions	NA
Reproducibility	NA
Randomization	NA
Blinding	NA

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks	NA
Novel plant genotypes	NA
Authentication	NA



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Regenerative agriculture improves productivity and profitability while reducing greenhouse gas emissions on Australian sheep farms

Muleke, Albert; Christie-Whitehead, Karen Michelle; Cain, Michelle; Liu, Ke; Burgess, Paul J. ...

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