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LETTER

Balancing livestock production and environmental outcomes in northern Australia's tropical savanna under global change

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Abstract

Livestock production is an integral part of the global food system and the livelihoods of local people, but it also raises questions of environmental sustainability due to issues such as greenhouse gas (GHG) emissions, biodiversity decline, land degradation, and water use. Further challenges to extensive livestock systems may arise from changes in climate and the global economy (particularly variation in prices for livestock and carbon). However, significant potential exists for both mitigating these impacts and adapting to change via altering stocking rates, managing fire, and supplementing cattle diets to reduce methane emissions. We developed an integrated, spatio-temporal modelling approach to assess the effectiveness of these options for land management in northern Australia's tropical savanna under different global change scenarios. Performance was measured against a range of sustainability indicators, including environmental (GHG emissions, biodiversity, water intake, and land condition) and agricultural (profit, beef production) outcomes. Our model shows that maintaining historical stocking rates is not environmentally sustainable due to the accelerated land degradation exacerbated by a changing climate. However, planned early dry season burning substantially reduced emissions, and in our simulations was profitable under all global change scenarios that included a carbon price. Overall, the balance between production and environmental outcomes could be improved by stocking below modelled carrying capacity and implementing fire management. This management scenario was the most profitable (more than double the profit from maintaining historical stocking rates), prevented land degradation, and reduced GHG emissions by 23%. By integrating the cumulative impacts of climate change, external economic drivers, and management actions across a range of sustainability indicators, we show that the future of rangelands in Australia's savannas has the potential to balance livestock production and environmental outcomes.

1. Introduction

Livestock production, particularly beef cattle, is an important source of human nutrition and employs over 1.3 billion people worldwide (Herrero *et al* 2009), but grazing has a range of environmental impacts including biodiversity decline (Alkemade *et al* 2013), land degradation, and contributions to climate change. Globally, livestock emits 12% of anthropogenic greenhouse gas (GHG) emissions, with cattle comprising 62% of these emissions (FAO 2022). Extensive grazing systems cover almost half of the world's tropical savanna ecosystems (9.48 M km^2) (Asner *et al* 2004), and cattle in these rangeland ecosystems have a particularly high methane intensity due to poor quality pasture (Tomkins and Charmley 2015). Future environmental and socio-economic changes are likely to affect livestock production and livelihoods and exacerbate environmental pressures. However, changes in land management have the potential to reduce these impacts and contribute to several UN Sustainable Development Goals (e.g. SDGs '1 No Poverty', '2 Zero Hunger', '13 Climate Action', and '15 Life on Land') as small changes over such large areas can amount to large aggregate impacts (Steinfeld *et al* 2006, Thornton 2010, Witt *et al* 2011, Holechek 2013). Therefore, management interventions are urgently required to promote the sustainability of rangeland systems under rapid but highly uncertain socio-economic and environmental change.

In extensive grazing systems, management interventions for improving sustainability include conservative stocking rates, dietary supplementation, and fire management, amongst others (O'Reagain *et al* 2014, Walton *et al* 2014). Stocking at, or just below, the carrying capacity of the land not only has environmental benefits (i.e. climate change, biodiversity, and land condition), but can also be profitable for the landholder in the long run (O'Reagain *et al* 2011). This is because stocking rates that exceed carrying capacity can cause environmental degradation, especially during low rainfall years, resulting in animals in poor condition (O'Reagain and Scanlan 2013) and reduced capacity of rangeland vegetation to respond to rainfall. Modifying pastures through the introduction of non-native forage species can increase the rate of liveweight gain (Hunt *et al* 2013), but can damage ecosystems with profound impacts on native species (Rhodes *et al* 2021). Supplementation to reduce enteric methane production shows promise (Kinley *et al* 2020), but is likely to come with a high economic cost (Callaghan *et al* 2014) especially in extensive grazing systems. Prescribed burning of tropical savanna ecosystems early in the dry season can also help to mitigate climate change and benefit biodiversity by reducing intense late dry season wildfire (Lipsett-Moore *et al* 2018) which can provide biodiversity benefits. While these management actions appear promising, their future performance under global change has not been evaluated.

Climate change will challenge the future economic and environmental sustainability of rangeland systems and the effectiveness of management interventions. Increasing temperatures and changes in rainfall will have direct effects and also influence fire regimes, potentially leading to more intense and more frequent fires (Boer *et al* 2016, Jones *et al* 2022). Climate change affects biodiversity and ecosystem services both directly (e.g. by shifting habitat suitability) and via interactions with other drivers (Williams *et al* 2022). These changes will also have complex implications for cattle grazing, primarily via their effects on pasture production (McKeon *et al* 2009), which can influence productivity, profitability, and the potential for land degradation.

Changing global economic conditions add further uncertainties surrounding the viability of management actions. Changes in the livestock sale prices and the cost of farm inputs alter the profitability of livestock production (Thornton 2010). Growing global demand for beef is likely to increase livestock sale prices; however, production costs are also likely to increase (Hatfield-Dodds *et al* 2015a). These changes may create opportunities for emissions reduction (if livestock production becomes less profitable relative to payments for emissions abatement), or alternatively intensify the trade-off (if livestock production increases to meet global demand). At the same time, a higher carbon price is likely to make emissions abatement efforts more profitable, but has complex interactions with other economic and environmental drivers. As profitability is likely to strongly influence the level of uptake of management interventions, their impact on production and environmental outcomes will ultimately depend on the future trajectories of multiple socio-economic and environmental drivers.

This paper is a significant advance on previous studies in tropical savanna that have looked at the relationship between livestock production and GHG emissions (e.g. McDonald *et al* 2023 and

Castonguay *et al* 2023), as we have considered the combined effects of global climate and economic change and multiple sustainability indicators. Such work is urgently needed as savannas are globally important for both biodiversity and people, but are being degraded faster than most other ecosystems (Williams *et al* 2022). In particular, Australia's tropical savanna has been repeatedly proposed as a location to intensify agricultural production to supply Australia and Asia (Ash and Watson 2018), yet a strong focus on production risks the degradation of other ecosystem services and loss of globally unique species.

Here we developed an integrated spatio-temporal model of Australia's savanna rangelands to assess the impact of management actions on socio-economic and environmental sustainability under global change. The model links economic and biophysical sub-models to estimate each outcome for each year from 2023 to 2050. We ran the model under four future global outlooks which combine different internally consistent assumptions for climate, global emissions abatement, population, livestock demand, and GDP. We developed five broad management scenarios, which included plausible combinations of stocking rate changes, supplementation, prescribed burning, and modified pastures. We explored how these management scenarios performed in terms of key SDG indicators including livestock production, GHG emissions, livelihoods, water use, land degradation, and biodiversity under different scenarios of climate change and global economic drivers.

2. Methods

2.1. Study area

Northern Australia has a largely semi-arid tropical climate and highly seasonal rainfall, with 85% falling between November and April (Watson *et al* 2021) (figure 1(c)). These conditions support large tracts of savanna grasslands and open woodlands, covering ~2 million km^2, forming one of the largest areas of mostly intact ecosystems in the world (Woinarski *et al* 2007, Beyer *et al* 2020). Species richness generally increases with rainfall (Mokany *et al* 2022) and there is a steady rate of discovery of new species (Tingley *et al* 2019). Since colonisation, fire regimes have shifted from diverse fine-scale patterns of burning (a result of traditional fire management by Aboriginal peoples) to a regime dominated by large wildfires in the late dry season, with many areas experiencing fires every 1–2 years on average (Edwards *et al* 2021). Beef production from rainfed native pastures is the dominant agricultural land use in the region, occupying ~60% of the land area (figure 1) with some individual grazing enterprises exceeding 1 million ha. Grazing has been implicated in the widespread declines of many birds, mammals, and reptiles across northern Australia, through alterations of the vegetation composition, ground cover and grass seed availability (Kutt *et al* 2012, Neilly *et al* 2021). Given the large land areas and low productivity, management strategies must be relatively low cost and easy to implement. Landholders' ability to impose management solutions can be constrained by land tenure arrangements. With the exception of small areas of freehold in the south-east, most of the study area is pastoral leasehold land (the land is owned by the Crown) and certain conditions of the lease need to be met (such as grazing livestock). The study area includes three Australian jurisdictions (Western Australia, the Northern Territory, Queensland) and lease conditions differ in each jurisdiction.

2.2. Integrated model

We developed an integrated, spatio-temporal model of land managed for cattle grazing across northern Australia's savannas (figure 2). Simulation modelling offers a useful approach to assess the impact of global change, allowing the integration of economic and biophysical models. We used a combination of scenario analysis and sensitivity analysis to incorporate uncertainties in global change and local management strategies from 2023 to 2050 at annual time steps.

Global change scenarios. We included 4 'global outlooks' from the Australian National Outlook (Hatfield-Dodds *et al* 2015a) which are linked to representative concentration pathways (RCP) from the IPCC CMIP5 (van Vuuren *et al* 2011). These provide quantitative, internally consistent, projections of key economic parameters influencing livestock systems, including demand for livestock, and prices for oil and carbon (Bryan *et al* 2016) (table 1). For each global outlook, projections of climate change parameters were derived from 3 different General Circulation Models (GCMs) to encompass the range of plausible climate outcomes (Hatfield-Dodds *et al* 2015a, 2015b). Specifically, the GCMs used were: the Canadian Earth System Model (CanESM) (Chylek *et al* 2011); Max Planck Institute—Earth System Model—Low Resolution (MPI-ESM-LR) (Giorgetta *et al* 2013); and the Model for Interdisciplinary Research on Climate version 5 (MIROC5) (Watanabe *et al* 2010). For each GCM, changes in temperature and rainfall were calculated for each year and interpolated to 0.01 decimal degrees (see SI section 2.3). The combination of 4 global outlooks and 3 GCMs created 12 global change scenarios.

Management scenarios were developed by grouping key management actions (changes in stocking rates, fire management, dietary supplementation, and modifying pasture) to represent the diverse array of potential management trajectories for northern Australia. These management scenarios included: 'Baseline'—a continuation of historical practices, 'Production'—focusing on livestock

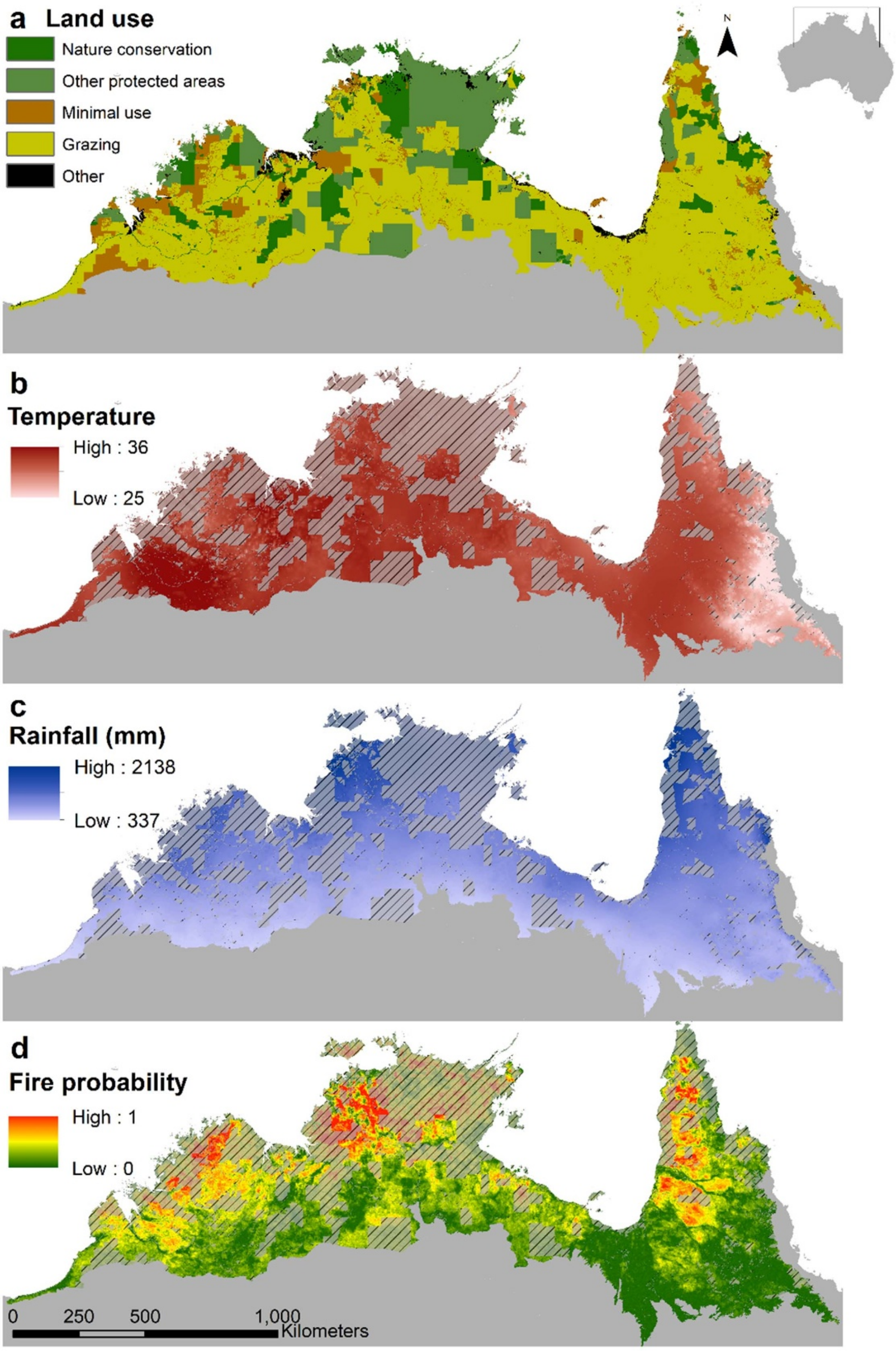

Figure 1. The northern Australian study region. The area depicted was defined by the Interim Biogeographic Regionalisation for Australia (IBRA) (Australian Government 2012) at 0.01 decimal degrees ($\sim$1 km^2) to match the resolution of our model. Panel (a) shows the dominant land uses of the region (ABARES 2016), (b) and (c) show the mean daily maximum temperature (°C) and mean annual rainfall (respectively) from 1987–2010, and (d) shows the probability of fire in a given year from 1988–2014, as described in the supplementary information. This study focuses on land managed for grazing (non-hatched areas in (b)–(d)), which comprised 689 562 pixels. In panel (a) 'other' includes water, forestry, and intensive uses; 'minimal use' includes defence land (natural areas), stock routes, and residual native cover; and 'other protected areas' includes Indigenous Protected Areas and managed resource protected areas (IUCN category VI).

production, 'Conservation'—destocking and managing fire, and 'Balanced'—integrating 'safe' stocking rates with fire management (and dietary supplementation for 'Balanced +') (table 2). These management scenarios were compared for each global outlook in terms of their performance against each sustainability outcome (unweighted) over time. Further context is provided by presenting these outcomes spatially and illustrating the percentage change from historical conditions.

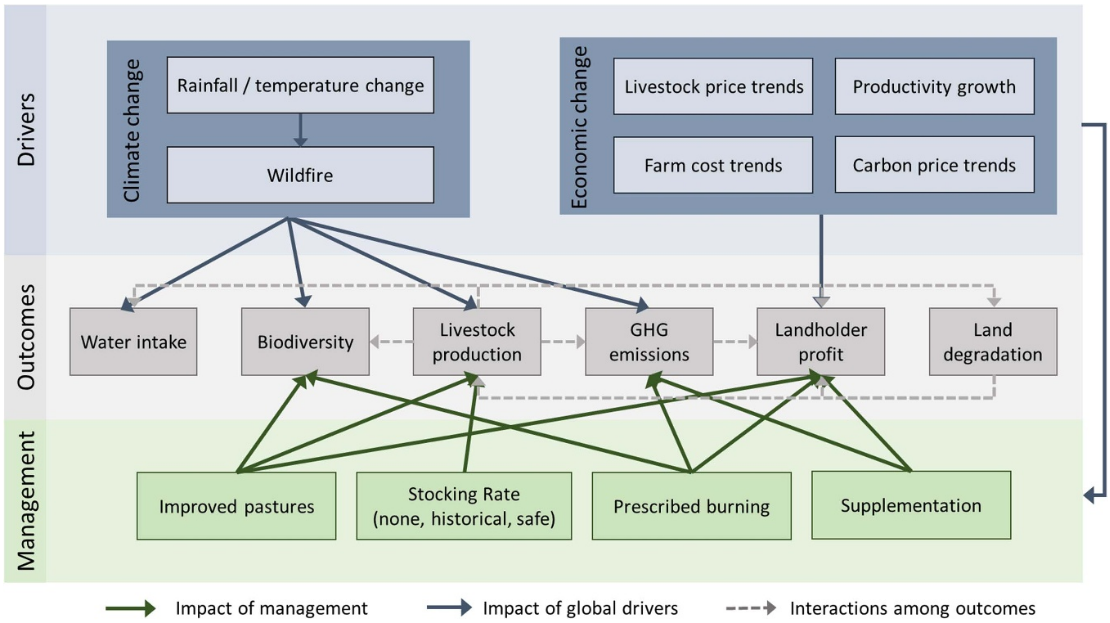

Figure 2. A simplified conceptual model of the integrated assessment of sustainable management for grazing land under global change in northern Australia.

Table 1. Illustrative overview of the key components of the global change scenarios used in this study: L1 (low population, strong abatement), M3 (high population, strong abatement), M2 (medium population, moderate abatement, high global agricultural productivity), and H3 (high population, no abatement action) (Bryan *et al* 2014, Hatfield-Dodds *et al* 2015a).

		Global outlook			
Parameter	Units	L1	M3	M2	H3
Representative concentration pathway		2.6	4.5	4.5	8.5
Global temperature increase in 2100	°C	1.3–1.9	2.0–3.0	2.0–3.0	4.0–6.1
Global population	Billion people	8.1	10.6	9.3	10.6
Global emissions abatement effort		Very strong	Strong	Moderate	None
Carbon price (in 2050)	A$ tCO_2^{-1}	199.74	118.73	59.31	0
Livestock price	% change 2007–2050	147	112	22	61
Oil price	% change 2007–2050	42	44	45	43

Table 2. Different management scenarios, formed by combinations of stocking, dietary supplementation, prescribed burning, and pasture. 'Safe' stocking rates refer to the number of livestock that could be supported by the amount of pasture growth in each year without adversely impacting land condition over the long term.

Management scenario	Stock	Supplementation	Prescribed burning	Pasture
Baseline	Historical	Urea	—	Native
Conservation	—	—	Yes	Native
Balanced	Safe	Urea	Yes	Native
Balanced +	Safe	+ Macroalgae	Yes	Native
Production	Safe	Urea	—	Modified

2.3. Overview of sub-models

To determine the combined impacts of management scenarios and global change scenarios on sustainability outcomes, the following sub-models were built and combined to form the integrated systems model (figure 2). Full details for each sub-model are provided in the Supplementary information (SI).

Livestock production. A regression model was developed to predict pasture growth, with annual rainfall and average maximum daily temperature as the explanatory variables and was used to project pasture growth to 2050 under the 12 global change scenarios (SI section 2). We then calculated the number of cattle (adult equivalents, AE) that could be supported by the amount of simulated pasture growth in each year without adversely impacting land condition (i.e. the modelled *'safe' stocking rate* (Scanlan *et al* 1994)) by combining pasture growth, safe utilisation rates for different pasture types, and animal intake. We then reduced these maximum stocking rates by 15% to represent a risk-adverse approach (SI section 3.1). *Modifying pastures* could increase the safe stocking level and revenue while also reducing the methane produced per head (due to faster liveweight gain from higher quality feed), so we simulated a management action of aerial sowing of legumes (e.g. stylo (*Stylosanthes spp.*)) by helicopter or light aircraft (SI section 3.6). To simulate a continuation of the *baseline stocking level*, we also included a spatial approximation of historical stocking rates by updating livestock density maps from Navarro *et al* (2016) (SI section 3.2).

Land condition. When modelling a continuation of historical stocking rates ('Baseline' scenario), the stocking rate could result in depletion of biomass that can harm vegetation recovery (i.e. overgrazing), thus leading to land degradation when repeated over multiple years. This was modelled using a threshold function with different forms (linear, concave, convex) where the level of stocking exceeds the carrying capacity of the pasture (SI section 5). In addition, we also accounted for the impacts of overgrazing on liveweight gain and profits using a (thresholded) linear function (figure S23).

Landholder profit. We calculated the profitability (measured as profit at full equity) of the baseline and simulated safe stocking rates from historical time series data for each Australian broadacre region in our study area (ABARES 2015, Navarro *et al* 2016). We then calculated the change in profit under each global outlook by varying livestock price trends, oil price trends, and future efficiency gains from technological innovation in line with global outlook assumptions (table 1).

GHG emissions. Quantifying emissions involved two sub-models: one accounted for fire risk reduction from prescribed burning (SI section 1), and the second accounted for methane emission reductions (from reduced stocking rates and/or supplementation with macroalgae) (SI section 3).

- Future fire frequency and severity was modelled using stochastic simulations, determined by the instantaneous hazard for each year (calculated using recurrent-event regression analysis with shared frailty (Munda *et al* 2012) from historical burn scar data and future climatic conditions). Fuel load was increased where previously grazed land was destocked (and vice versa). GHG emissions from wildfire, and the emissions abated via prescribed burning, were calculated using methods adapted from the Australian Government GHG accounting methodology (DEE 2015) using plausible ranges for emission reductions for prescribed burning (Russell-Smith *et al* 2009b, 2013, Heckbert *et al* 2010).
- GHG emissions per head of cattle were calculated for each broadacre region (adjusting for herd structure) (Navarro *et al* 2016). Supplementation (with macroalgae) has the potential to reduce biogenic emissions from cattle without impacting livestock production) (Kinley *et al* 2016, 2020), but this comes with additional costs and uncertain outcomes in extensive grazing systems (Callaghan *et al* 2021). We therefore included a large range in potential methane reduction (and costs) from macroalgae supplementation via lick blocks.

Biodiversity under climate change was modelled using a combination of existing species distribution models for 609 vertebrates (43 amphibians, 286 birds, 93 mammals and 187 reptiles (table S12)) (Graham *et al* 2019) in conjunction with taxa-specific dispersal kernels and expert elicitation of management impacts for each functional group (Alvarez-Romero *et al* 2021). This gives a 'biodiversity index' based on probability-adjusted species richness for each pixel in each year.

Water intake by cattle will increase with the higher temperatures that come with climate change. We modified the equation linking water intake and temperature for *Bos indicus* cattle (Watts *et al* 1994) to simulate water intake over the study region under climate change and for different stocking levels.

2.4. Sensitivity analysis

We conducted a global sensitivity analysis using elementary effects parameter sampling for 24 parameters (table 3) (Gao and Bryan 2016). A triangular distribution for each parameter was produced based on the lower, mid, and upper values for each parameter (table 3). In the cases where the input parameters were spatial, different values were used for each pixel. The elementary effects parameter sampling produced 250 parameter combinations (with 0–1 for each parameter) which were used to return the corresponding value from the triangular distribution. This analysis allowed us to determine the uncertainty for each management scenario and outcome, along with the model parameter sensitivity.

3. Results

Continuing with the historical level of grazing, which was already exceeding carrying capacity in some areas (figure 5), in the absence of any emissions abatement actions ('Baseline' management scenario) performs poorly across all outcomes by 2050 (figure 3). When historical stocking rates were left unchanged ('Baseline'), climate change accelerated land degradation, which ultimately tempered profits from the increasing livestock prices that occurred under all global outlooks (figure 4, table 1). Further, GHG emissions continued to rise to 9.1 million Mg CO_2e yr^{-1} in 2050 (M3, MPI, unless otherwise stated), varying from 8.66 to 9.67 million Mg CO_2e yr^{-1} over the different GCM's and outlooks. The total water intake of cattle increased by 18.6 ML d^{-1} in 2050 (ranging from 9.83 to 27.83 ML d^{-1}) (figure 4), which represented a moderate increase (13%, table 4).

Table 3. Parameters varied in the global sensitivity analysis. This does not include global outlooks or GCMs. Code corresponds to the *X*-axis in figure S26.

Parameter (code)	Units	Lower	Mid	Upper	Detail
Historical rainfall baseline (RainBase)	Percentile	10	50	90	Baseline for historical rainfall. Percentiles calculated over the range of years used to generate the historical climate (1987–2010).
Historical temperature baseline (TempBase)	Percentile	10	50	90	Baseline for historical temperature. Percentiles calculated over the range of years used to generate the historical climate (1987–2010).
Wildfire frequency and severity (Fire)	Spatial simulations	Lowest 20%	Mean	Highest 20%	Lower: mean of lowest 20% of fire simulations for each pixel. Mid: mean of all fire simulations for each pixel. Upper: mean of highest 20% of fire simulations for each pixel.
Safe pasture utilisation rate (Utilise)	Proportion (spatial)	Low	Mid	Upper	Safe pasture utilisation rates for each pasture community (from table S7). The range varied per community.
Dry matter intake (IntakeAE)	kg day^{-1}	8	9	10	Cattle dry matter intake per AE per day.
Cattle increase from modified pastures (AEincrImprov)	Percentage (spatial)	Low	Mid	Upper	Increase in adult equivalents from modified pastures. The values (and range) varied by broadacre region (table S9)
Land condition functional form (DegFunction)	z value	−2.5	0	2.5	Land condition function z value (0 gives a linear function) (Supplementary Information). Negative or positive values give convex and concave functional forms. All functions have a threshold at the safe utilisation rate (table S7).
Prescribed burning emissions reductions (ERBurn)	Proportion	0.25	0.34	0.48	Emissions reduction from wildfire by undertaking prescribed burning. This was set at 0.34 for the main analysis (Russell-Smith *et al* 2009b, Russell-Smith *et al* 2013) and varied between 0.25 (a conservative estimate of management effectiveness (Heckbert *et al* 2010)) and 0.48 (the upper potential of management (Russell-Smith *et al* 2009a)).
Change in fuel load (FuelChange)	Percentage	0.077	0.11	0.143	The percent (0.11%) increase in biomass each year following stock removal, or decrease if grazing ungrazed land. Upper and lower ±30%
Macroalgae supplementation cost (SeaweedCost)	$ per Adult Equivalent (AE) year^{-1}	62.05	93.08	124.1	The additional cost of using macroalgae lick blocks. Low, mid and upper = 1, 1.5, and 2 times cost of molasses nitrate supplementation respectively.
Macroalgae supplementation emissions reduction (SeaweedGHG)	Percent reduction per AE	0	18.14	36.28	The GHG emissions reduction (per animal) of using macroalgae lick blocks. Informed by Callaghan *et al* (2021) and Roque *et al* (2021).
Cattle revenue (AERevenue)	$ per AE per year	−1SD	Mean	+1SD	Baseline revenue per AE (without pasture improvement). Used the mean and standard deviation of time series farm survey data (1997–2013) for each broadacre region (Navarro *et al* 2016) (table S10).

(Continued.)

Table 3. (Continued.)

Parameter (code)	Units	Lower	Mid	Upper	Detail
Cattle costs (AECost)	\$ per AE per year	−1SD	Mean	+1SD	Baseline costs per AE (without pasture improvement) calculated as per cattle revenue.
Cattle GHG emissions (AECO2e)	Mg CO_2e per AE per year	−1SD	Mean	+1SD	Biogenic GHG emissions per AE (without pasture improvement), using the mean and standard deviation for the historical baseline (Navarro *et al* 2016). Modified according to the total head and herd structure per broadacre region (table S10).
Gross margin increase from modified pastures (ImpAERev)	% gross margin increase	Lower	Mid	Upper	Increase in gross margin per AE from modified pastures. The main value and range varied by broadacre region (table S9).
GHG emissions reductions from modified pastures (ImpAECO2e)	% decrease in CO2e per AE	Lower	Mid	Upper	The reduction in biogenic GHG emissions per AE from modified pastures. The main value and range varied by broadacre region (table S9).
Modified pasture cost (ImpAEcost)	\$ per km^2	150	270	720	Cost per km^2 for modified pastures. The main value and range varied by broadacre region (table S9).
Prescribed burning cost (BurnCost)	\$ per km^2	32.795	46.85	60.905	Cost per km^2 for prescribed burning. Upper and lower = ± 30%.
TFP increase (TFP)	TFP increase per year	0%	1%	2%	Future annual increases in total factor productivity (TFP).
Fire impact on biodiversity (FireThreat)	Percentile /best guess	5th	Best	95th	'Best guess', 5th and 95th percentiles from the expert elicitation of fire impact on biodiversity.
Grazing impact on biodiversity (Grazthreat)	Percentile /best guess	5th	Best	95th	'Best guess', 5th and 95th percentiles from the expert elicitation for grazing impact on biodiversity.
Modified pastures impact on biodiversity (ShrubThreat)	Percentile /best guess	5th	Best	95th	'Best guess', 5th and 95th percentiles from the expert elicitation for introduced species impact on biodiversity.
Overgrazing impact (LWGImpact)	x	0.85	1	1.15	Overgrazing impact x value (see supplementary information for function). This would lessen (lower) or increase (upper) the impact of overgrazing on liveweight gain and profit.
'Safe' stocking percentage (SafeStock)	Percentage	75%	85%	95%	The stocking rate used in safe stocking management scenarios as a percentage of the maximum carrying capacity.

Removing cattle and managing the land through prescribed burning ('Conservation' management scenario) delivered the best outcomes for the environment of all the potential management scenarios (figure 3). GHG emissions were reduced to 2.69 (2.23–2.93) million Mg CO_2e yr^{-1} in 2050 (figure 4), which were solely comprised of GHG emissions from fire. Additionally, there was no land degradation nor water intake from cattle, and biodiversity outcomes were improved (figures 3 and 4). This came at the expense of beef production outcomes. Although the only profit to the landholder was via carbon payments, this delivered robust profits, and became more profitable than the 'Production' scenario in global outlooks L1 and M2 (figures 4 and S25). In contrast, in H3 (the global outlook without a carbon price) landholders faced a loss, which suggests a conflict between environmental and economic objectives (figures 5 and 6(a)).

Our 'Balanced' scenario evaluated a range of management options to achieve a balance between competing production and environmental outcomes. Here, stocking rates were set in accordance with simulated pasture growth and therefore eliminated land

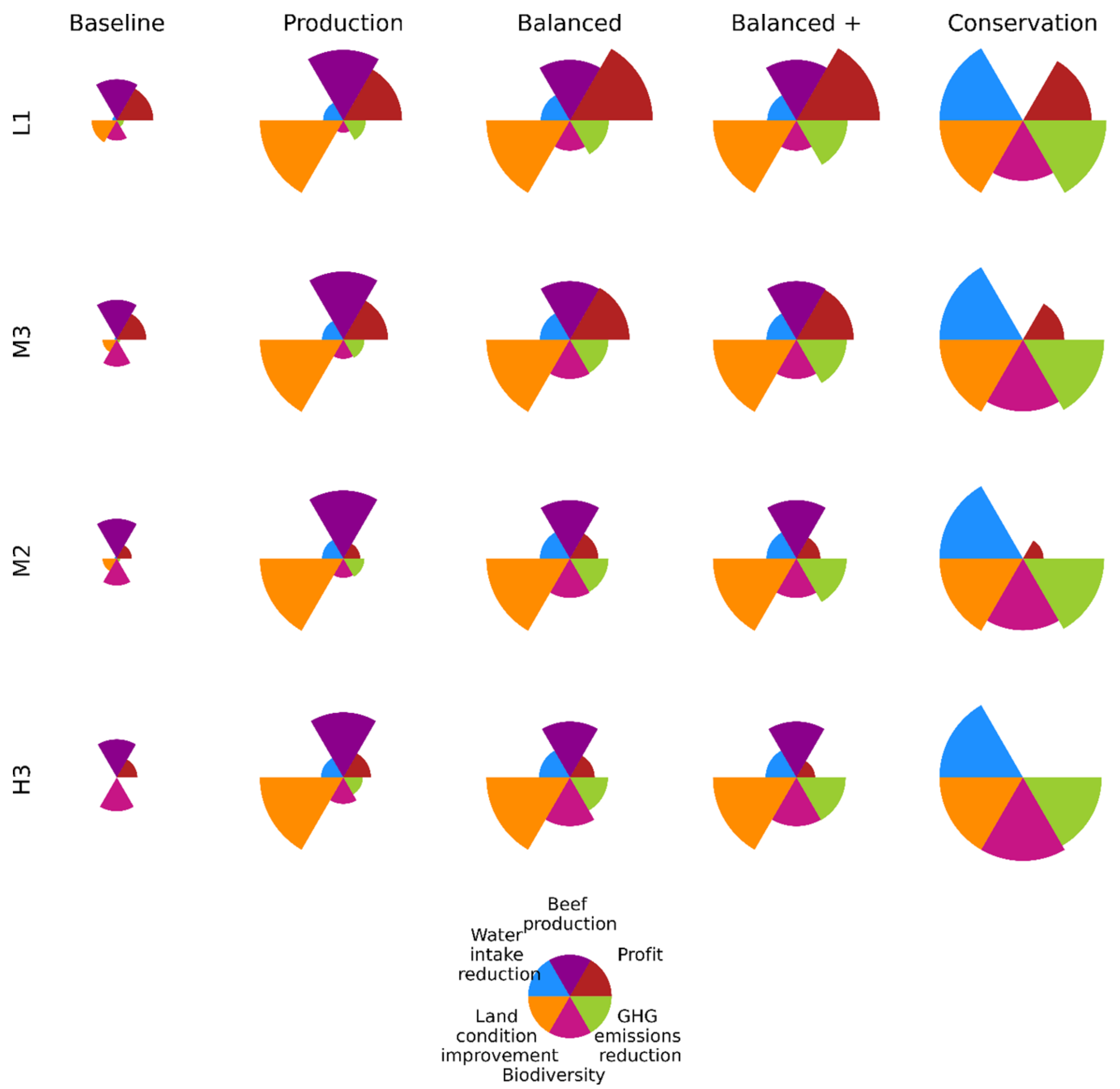

Figure 3. Sustainability of different future management scenarios for northern Australia in 2050 under different global outlooks from L1 (strong global emissions abatement) to H3 (global business as usual), based on the means across the three GCMs used. Each outcome (beef production, landholder profit, GHG emissions reduction, biodiversity, land condition improvement and water intake reduction) is range-normalised on a scale of 0–1 (0 at the centre, 1 on the edge). Therefore, 0 refers to the minimum value across all scenarios (rather than the complete absence of that outcome).

degradation but reduced food production by 30% relative to the historical stocking level (table 4). This scenario reduced GHG emissions to 6.19 (6.14–6.24) million Mg CO_2e yr^{-1} (figure 4), was the most profitable (except in H3), and had the second-best outcome for biodiversity (though substantially lower than the 'Conservation' scenario) (figure 3). The 'Balanced +' scenario, which included the additional emissions abatement action of dietary supplementation, reduced GHG emissions even further (to 5.23 (5.11–5.33) million Mg CO_2e yr^{-1}), but supplementation on its own never became profitable, even with a high carbon price (figure S25).

Integrating exotic legumes into native pastures, evaluated in the 'Production' scenario, maintained the highest level of food production (though this was 18% less than the historical stocking level) and profit (the most profitable management without a carbon price, H3), and did not cause land degradation by pasture over-use (figure 4). Here, the GHG emissions per animal were lower than the baseline (due to faster liveweight gain and the higher quality feedbase) which led to lower overall emissions. However, the absence of additional abatement actions (such as prescribed burning or macroalgae supplementation) meant overall emissions were still high (7.72 [7.52–7.88] million Mg CO_2e yr^{-1}). Unfortunately, the introduction of exotic plants can be damaging to habitats in northern Australia, which also gives this management scenario the worst biodiversity outcomes (figures 3 and 4).

All outcomes and management scenarios showed substantial variation across northern Australia to 2050 (figures 5 and 6). Cattle production was generally higher in the east (in the state of Queensland), and particularly the south-east, due to better conditions for grazing. However, the decline in livestock production brought about by climate change

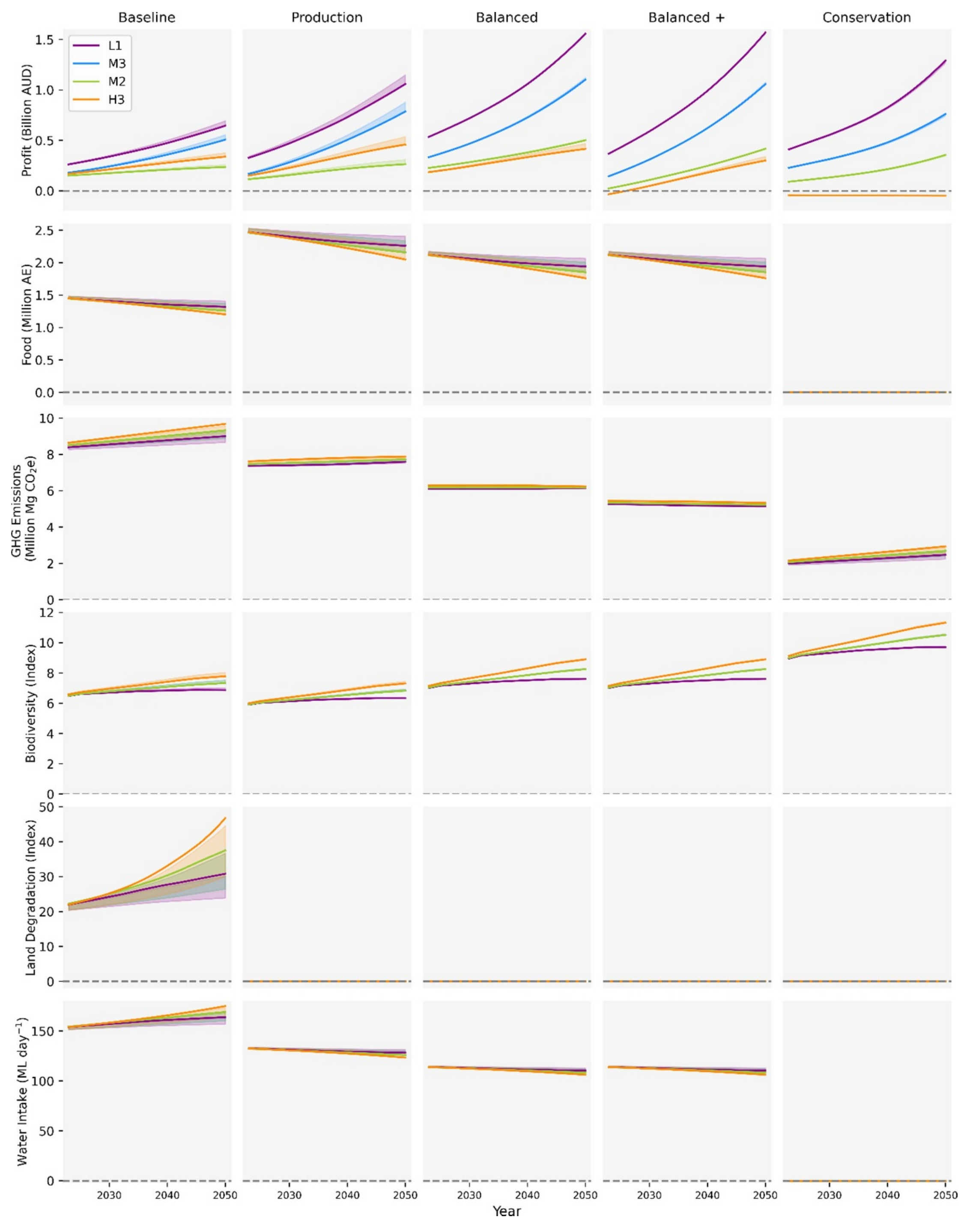

Figure 4. Change over time for each outcome under the different future management scenarios for northern Australia. Solid line shows GCM MPI, with the variation from GCMs CE2 and MR5 as shading.

was also larger in this area (figure 5). Species richness was generally higher in the East, and climate change brought increases in richness in the south, due to a slightly wetter (on average) climate (figure 5, column 4). Without fire management, GHG emissions are likely to increase in the north of the study area, although much of this can be abated with prescribed burning in the early dry season (which is a component of the Conservation, Balanced, and Balanced + management scenarios) (figure 5, column 3). These spatial patterns were similar under the different GCMs and global outlooks (figures S27–S37). Aside from the spatial patterns, there was also considerable uncertainty across all scenarios and objectives from variations in key parameters (table 3), but general trends were still identifiable (figure 6). The parameters that contributed the most to this variation were the frequency and severity of fire (for GHG emissions and biodiversity), the safe pasture utilisation rate (for beef production) and future increases in technological innovation (for profit) (figure S26).

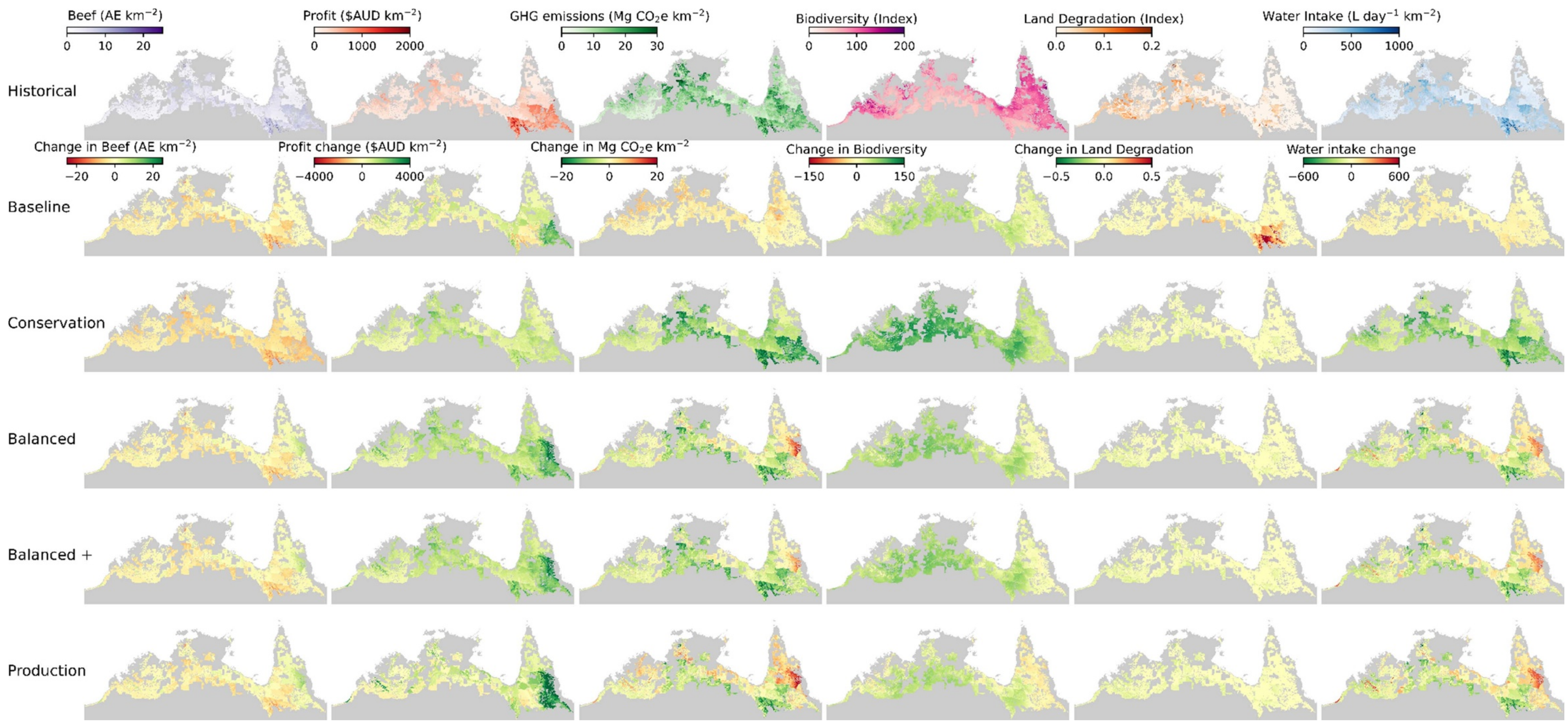

Figure 5. Spatial variation in sustainability outcomes for the different future management scenarios in northern Australia by 2050. Results are depicted for GCM MPI and global outlook M3 (spatial outcomes for the other GCMs and global outlooks are given in the supplementary information). 'Historical' represents stocking rates and climatic conditions representative of the period from 1987–2010. The remaining rows show the change from historical conditions to 2050 for each outcome under each management scenario.

Table 4. Percentage change in outcomes from historical conditions. Results are shown for the mean across GCMs for global outlook M3 in 2050. The values in parenthesis show the variation across all global outlooks and GCMs. If there are no values in parenthesis there was no variation. Shading represents changes in the sustainability indicators as improvements (green) or deterioration (blue).

Management scenario	Profit	Beef production	GHG emissions	Biodiversity index	Land degradation	Water intake
Baseline	130% (3–204)	−52% (−56 – −48)	14% (8–21)	34% (25–46)	187% (104–300)	13% (7–19)
Production	259% (16–588)	−18% (−52 – −12)	−4% (−36–12)	25% (15–38)	−100%	−13% (−25–11)
Balanced	386% (82–586)	−30% (−35 – −24)	−23% (−24 – −22)	50% (38–63)	−100%	−26% (−28 – −23)
Balanced +	366% (31–591)	−30% (−35 – −24)	−35% (−36 – −34)	50% (38–63)	−100%	−26% (−28 – −23)
Conservation	230% (−121–467)	−100%	−68% (−72 – −63)	91% (76–107)	−100%	−100%

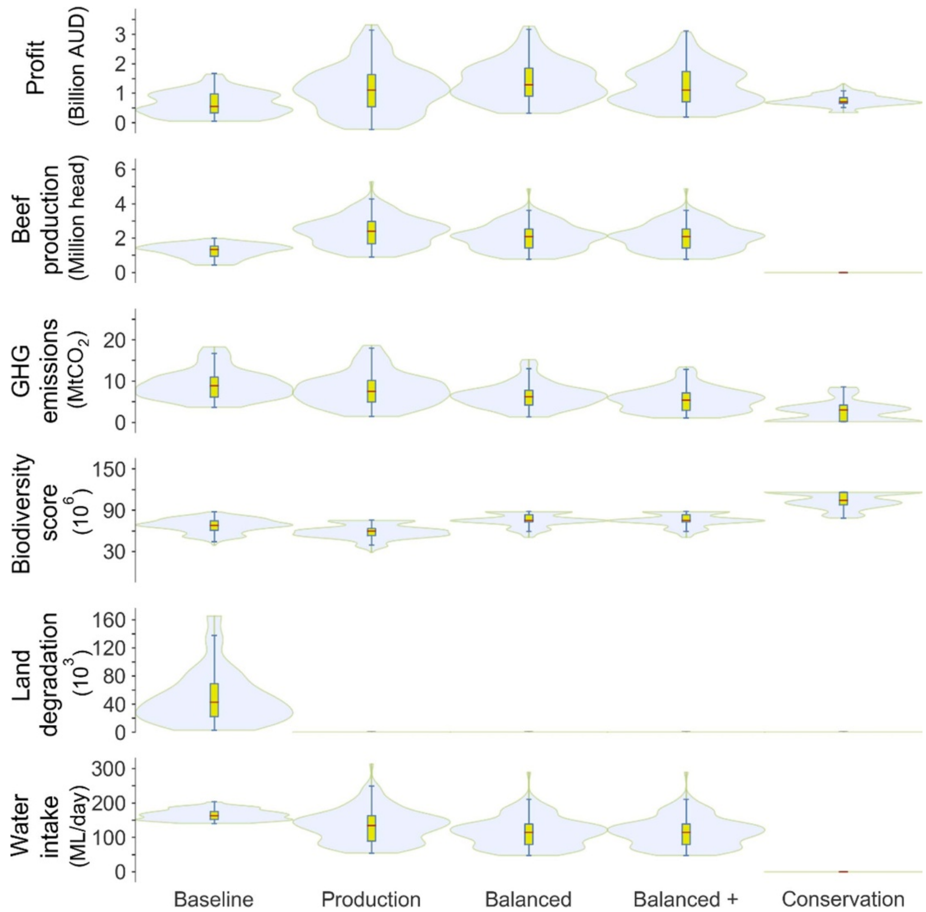

Figure 6. The variation in outcomes for each management scenario based on a global sensitivity analysis of all 23 parameters in table 4. All outcomes are for global outlook M3, GCM MPI, and year 2050.

4. Discussion

4.1. Cumulative impacts on sustainability indicators

Our model shows that continuing historical grazing management is not environmentally sustainable, but combinations of management actions can improve the balance between production and environmental outcomes, even under changing climatic and economic conditions. In the 'Balanced' management scenario, combining prescribed burning with stocking below the carrying capacity of pastures prevents land degradation, reduces GHG emissions by 23%, supports higher species richness (increases the biodiversity index by 50%), and more than doubles baseline profits (compared to the baseline in M3, table 4). In fact, this was the most profitable management scenario across all global outlooks that included a carbon price (L1, M3, M2). However, this still represents a significant compromise. Compared with the 'Conservation' scenario, the biodiversity index was 22% lower and emissions were 130% higher (figure 4). Overall, our findings are in line with other studies that have found significant emissions abatement potential from managed fire across the region (Heckbert *et al* 2012, Adams and Setterfield 2013), and these emissions reductions (and profits) could be further increased if the maximum (rather than average) potential for emissions reduction is achieved (Russell-Smith *et al* 2009a).

However, we found that climate change will likely reduce the capacity of northern Australia to support livestock, with the number of cattle that could be safely stocked declining over time, especially under more severe increases in temperature. This finding is supported by other studies, with a review by McKeon *et al* (2009) finding that safe stocking rates were strongly dependent on climate. Yet, profits increased under all scenarios due to rising livestock and carbon prices (table 1), with strong global emissions abatement (L1) delivering the highest profits (figure 4). Additional climatic factors not included here may reduce the modelled safe stocking rates and profitability. This includes extreme events such as droughts and floods (Harrison *et al* 2016, Murray-Tortarolo and Jaramillo 2019) and elevated atmospheric CO_2 which may lead to woody thickening and reduced pasture quality (Chilcott *et al* 2020, Raubenheimer *et al* 2022). Ultimately, fewer cattle resulted in lower total GHG emissions from livestock, and we found these emissions could be further reduced by supplementing cattle with macroalgae (i.e. the 'Balanced +' scenario). While this strategy is not yet proven for extensive grazing systems, and the cost may be prohibitive, it may become feasible in some markets, particularly if low carbon (or carbon neutral) beef can be sold at a premium (Kilders and Caputo 2023).

Livestock grazing has largely negative impacts on biodiversity in northern Australia by degrading habitat, altering ecological communities and facilitating the spread of invasive species (Garnett *et al* 2010, Woinarski *et al* 2011). Biodiversity outcomes are somewhat improved with lower stocking rates and are significantly improved with destocking and fire management (Lunt *et al* 2007, Legge *et al* 2011a, 2019). Our results also showed that species richness may increase over time in northern Australian rangelands under climate change. This corresponds with projected increases in annual precipitation within the savannas, particularly increases in bird species richness in southern part of the savanna (Reside *et al* 2012). However, the positive trend in total species richness is far from certain, and including climate extremes (rather than averages) in species distribution models may restrict future species ranges (Morán-Ordóñez *et al* 2018). Similarly, other threats (such as invasive species) show large impacts on the savanna species (especially small mammals), and these threats are likely to be exacerbated by climate change (Dunlop *et al* 2012).

4.2. Influencing land management change

Our results can inform future modelling of land-use change in the region under different global change scenarios, but these results need to be combined with realistic models of human behaviour (Rounsevell *et al* 2014). Although actions to mitigate GHG emissions become more profitable under most global outlooks, landholders have a wide range of risk aversion behaviours and attitudes towards adopting new practices (Rolfe and Gregg 2015). Land tenure may also constrain options for conservation land management, particularly pastoral leasehold which has a requirement to run cattle, although these conditions are not always enforced and diversification leases are emerging (DPLH 2023). Further, Indigenous lands cover large areas in northern Australia (ABARES 2016) and Indigenous peoples' attitudes towards different types of grazing land management have not yet been explored in the region. Accordingly, the potential increase in profitability of GHG emissions abatement actions is unlikely to directly translate into management change, so risk aversion and barriers to adoption should also be considered (Bryan *et al* 2016).

Additionally, it may not be possible to achieve these multiple objectives through financial incentives alone, and a more strategic planning approach may be required (Morán-Ordóñez *et al* 2016). For instance, having a diversity of time-since-burnt patches across the landscape (pyrodiversity) is hypothesised to be optimal for biodiversity (Martin and Sapsis 1992, Griffiths *et al* 2015, Perry *et al* 2016), but achieving this would require a more strategic design of prescribed fires across the landscape (Legge *et al* 2011b), including the involvement of, and benefits to, Indigenous people (Perry *et al* 2018). Strategic planning may also be needed to ensure the landscape is robust to uncertainty (Polasky *et al* 2011, Reside *et al* 2017, Runting *et al* 2018). By conducting a global sensitivity analysis, we illustrated substantial spatial and temporal variation in all sustainability outcomes to 2050. Ultimately, any spatial plan or policy needs to be robust to these uncertainties to ensure a sustainable future is not solely dependent on a particular set of parameters.

4.3. Future directions

Our model was necessarily general to encompass the broad scale of Australia's northern rangelands, so some details and dynamics were omitted that may be relevant at finer scales. Our estimates of safe stocking numbers were primarily determined by pasture growth and type (Scanlan *et al* 1994). Whilst this relationship is broadly representative, other factors can also influence the safe stocking rate at finer scales, particularly topography, location of water bodies, and the spatial distribution of grazing pressure within a property (Orr and O'Reagain 2011). Dynamic simulations that more closely resemble grazier actions exist at smaller spatial scales (Scanlan *et al* 2013, Ash *et al* 2015), but scaling this up to larger regions is an area for future research.

Although our study included multiple indicators (food production, landholder profit, GHG emissions, land degradation, water intake, and biodiversity), the management strategies could have further environmental impacts not considered here. While extensive livestock grazing has lower environmental impacts (per unit area) than other more intensive land use options, local and cumulative impacts can still be significant (Eldridge *et al* 2022, Halpern *et al* 2022). For example, grazing is likely to influence hydrological ecosystem services in the region, especially as grazing pressure tends to be concentrated around water points and water courses (O'Reagain and Scanlan 2013), leading to heterogenous impacts on vegetation, soils, and water, along with the potential for gully erosion (Wilkinson *et al* 2018). Management of stocking rates and fine-scale grazing pressure is particularly challenging in the region, due to low overall densities of cattle and relatively high costs of fencing or adding water points to alter grazing patterns (O'Reagain *et al* 2014). Stocking at safe levels can reduce, but not eliminate, hydrological impacts, and recovery from past grazing can take many years (Koci *et al* 2020). Ideally, future studies should consider the impacts of grazing land management on the full suite of ecosystem services.

4.4. Conclusions

Integrating multiple climate and economic drivers is often overlooked in assessments of ecosystem services, which can create misleading results and limit their utility for decision making (Runting *et al* 2017). Here we incorporated multiple drivers (i.e. temperature increase, rainfall change, fire, productivity growth, and price trajectories for livestock, farm inputs, and carbon) to assess multiple sustainability indicators to 2050. Although compromises are required under all scenarios, the balance between production and environmental outcomes could be improved by combining safe stocking rates and GHG emissions abatement action. Although our modelling is based on northern Australia, our findings are likely to be relevant to other tropical savanna rangelands, which all face a likely increase in temperatures and uncertain changes in rainfall with climate change (Williams *et al* 2022). Rising cattle prices, driven by a growing demand for beef, is also a global phenomenon that influences markets beyond northern Australia (Turk 2016). Constraining climate change to the less severe scenarios will require strong global action, producing substantial incentives for emissions abatement (Hatfield-Dodds *et al* 2015a). As the grazing lands in northern Australia and elsewhere become less suitable for livestock production, the opportunity to diversify income streams may prove vital in a changing climate (Russell-Smith and Sangha 2018).

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.26188/26241620 (Runting *et al* 2024).

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