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Defining potential pathways for improving the resilience and sustainable development of rangeland grazing systems: Insights from northern Australia

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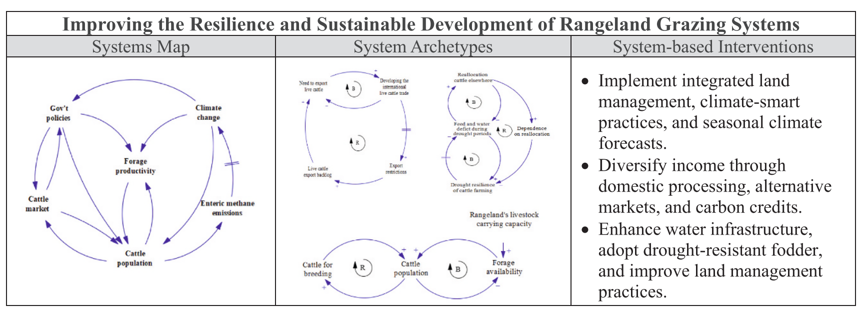
HIGHLIGHTS

- Rangeland grazing industry operates as a complex adaptive system
- Systems thinking enables identify strategies to improve resilience and sustainability
- Climate-smart practices and land management boost adaptive capacity
- Collaborative governance drives meaningful change for sustainable grazing

GRAPHICAL ABSTRACT



ARTICLE INFO

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1. Introduction

Rangelands, commonly defined as *"uncultivated land that provides the necessities of life for grazing and browsing animals"* (Briske, 2017, p. 5), encompass over 40 % of the Earth's land surface area (Sugita et al., 2007) and account for 77 % (around 51 million square kilometres) of the world's agricultural land (Neilly et al., 2018). A considerable portion of livestock grazing takes place on rangelands, which cover almost half of the globe's tropical savanna ecosystems (9.48 million square kilometres) (Runting et al., 2024). This rangeland-based grazing industry (RGI) is an important contributor to global food security, supplying approximately 18 % of the world's food energy intake and 37 % of global food protein (Greenwood, 2021). It also plays a vital role in providing employment to over 1.3 billion people worldwide (Runting et al., 2024), supporting the livelihoods of approximately 600 million small-scale farmers in developing countries (Herrero et al., 2009). Additionally, the industry, with good management, has potential to contribute a diverse range of ecosystem services (Godde et al., 2020; Barry, 2021).

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However, the RGI currently faces numerous sustainability challenges. It both contributes to and faces the consequences of a range of environmental issues including climate change (Baumber et al., 2020; Malerba et al., 2022; Xiong et al., 2022; McDonald et al., 2023; Raynor et al., 2024), biodiversity loss (Alkemade et al., 2013; Waters et al., 2017; Augustine et al., 2021; Barzan et al., 2021), and land degradation (Scoones, 1992; Mligo, 2015). Globally, the RGI accounts for 14.5 % of greenhouse gas emissions, with cattle contributing 62 % of this (Cheng et al., 2022). A major and pressing concern of climate change impacting the RGI is the resulting increase in climate variability, characterised by rising temperatures, increased rainfall variability, and more frequent and severe extreme weather events (Bowen and Chudleigh, 2021; Cobon et al., 2021; Godde et al., 2021). These factors contribute to adverse conditions such as heat waves, drought and flooding, which impact pasture productivity, animal health, and livestock production (Askarimarnani et al., 2020; Espeland et al., 2020; Raynor et al., 2020; Bowen et al., 2020; Godde et al., 2021).

Rangelands in many regions across the globe also exhibit signs of deterioration (Cobon et al., 2020a; Daba and Mammo, 2024), driven by factors such as overgrazing (Gaitán et al., 2018; Chawicha and Tussie, 2023; Fang and Wu, 2022), invasive species (Aryal et al., 2022; Chawicha and Tussie, 2023; Daba and Mammo, 2024), and unsustainable land management practices (Daba and Mammo, 2024). These issues can impact the extent to which essential rangeland ecosystem services associated with vegetative cover, soil and water functions, habitat provision and biodiversity are able to be maintained (Eldridge and Delgado-Baquerizo, 2017; Eldridge et al., 2016) – impacts that are often exacerbated at higher levels of grazing intensity (Eldridge and Delgado-Baquerizo, 2017) and aridity (Eldridge et al., 2016). Modelling indicates that climate change (at RCP8.5) will likely drive a decline in overall carbon storage and annual herbaceous net primary productivity (NPP) across Australia's rangelands by 2050, and ultimately a decline in overall livestock numbers (Boone et al., 2018). Such impacts may be mitigated with appropriate adaptation and management.

Climate variability and change not only impact on-farm productivity but also significantly disrupt the broader livestock food supply chain, including processing, storage, transportation, retail, and consumption of livestock products (McAvoy, 2015; Godde et al., 2021). In parallel, fluctuation of cattle prices, rising farm input costs (Godfrey et al., 2018; ABARES, 2024a), and trade disruptions (MLA, 2024a) further create uncertainty for producers. These factors directly reduce profitability, erode investment confidence, and compromise long-term financial resilience of livestock enterprises (Thornton, 2010). For northern Australian graziers, who often operate under high exposure to export markets and thin profit margins, such volatility poses a serious threat to economic stability of graziers (Morales et al., 2017; Bonny et al., 2018; Dong et al., 2018; Espeland et al., 2020).

The RGI also faces significant challenges stemming from inconsistent and unstable government policies. Such policy uncertainty may discourage landholders from investing in resilient and sustainable rangeland management (Abab et al., 2023; Chawicha and Tussie, 2023). Further, the global RGI involves diverse stakeholders, including Indigenous communities, landowners, and sectors such as mining, gas, and tourism, as well as conservationists and policymakers. Each has distinct agendas and management objectives, which may lead to unforeseen conflicts, potentially hindering the sustainable management of the RGI (Foran et al., 2019; Nielsen et al., 2020; Daba and Mammo, 2024).

The constraints and challenges confronting the RGI are complex and interconnected, extending beyond the capacity of any single entity or profession. As such, they cannot be addressed in isolation or within a single dimension (Foran et al., 2019). Effective management of the RGI requires a collaborative and holistic approach to understanding the industry, its constituent components, and how these dynamically interact to shape both current and future behaviour. This approach falls within the domain of systems thinking, a method used to understand the feedback mechanisms that drive system behaviour over time.

Systems thinking is commonly defined as a set of synergistic analytical tools used to describe complex interactions among factors that drive outcomes, predict system behaviour, and formulate intervention strategies to achieve desired results (Berry et al., 2018). The application of this holistic approach is typically an iterative process that involves five complementary phases: (i) problem articulation, (ii) formulation of dynamic hypotheses, (iii) development of a simulation model, (iv) model testing, and (v) policy design and evaluation (Sterman, 2000). The first two phases focus on qualitative modelling, with the goal of developing a conceptual model that captures the dynamics underlying interactions among system components. The remaining three steps emphasize quantitative modelling, aiming to build a computer-based model that simulates the dynamic relationships between these components.

In this paper, we employed the first two phases of the systems thinking approach (problem articulation, and formulation of dynamic hypotheses) to develop a dynamic hypothesis that captures the underlying structure of the RGI. This systems model will serve to identify leverage points for systems-based intervention strategies aimed at enhancing the industry's resilience and sustainability. Focusing on the RGI in northern Australia as a case study, the study seeks to improve understand the dynamics of the industry's dynamics and inform policy and investment decisions to support more effective adaptation strategies. The findings are also intended to foster knowledge-sharing and learning across regions, both within Australia and globally, that face similar challenges.

2. Overview of rangeland grazing industry in northern Australia

Northern Australia's RGI extends across large areas of tropical and sub-tropical savannas and semi-arid shrublands (Cobon et al., 2021). Here grazing predominantly occurs on native grassland vegetation, followed by modified pastures, while irrigated pastures are rare in the region (Fig. 1). These pasturelands support nearly 60 % of Australia's national cattle herd, which totals 24.7 million head (Cobon et al., 2021). The region experiences highly seasonal rainfall, with approximately 80 % occurring between November and April (Sharmila and Hendon, 2020), followed by a prolonged and variable dry season lasting 6–8 months (Cobon et al., 2021). This seasonal variability greatly influences grazing patterns and significantly challenges sustainable and profitable management of livestock production systems (Godde et al., 2019; Cobon et al., 2020b; Bowen and Chudleigh, 2021). Increasing climate variability, driven by changes in global atmospheric dynamics (Wang et al., 2021; Heidemann et al., 2023), exacerbates these challenges. For instance, global analysis indicates that increasing evapotranspiration due to human induced climate change is driving intensification of the dry season (i.e., drier dry seasons) in extratropical latitudes including much of northern Australia (Padrón et al., 2020).

Cattle from northern Australia supply both domestic and international markets, with 70 % of the northern Australian herd being raised specifically for live cattle export (MLA, 2024b). Notably, there are significant live cattle exports from northern Australia into southeast Asian markets (Chilcott et al., 2020). In the financial year 2020–21, the live cattle export trade contributed up to $AUD1.4 billion to Australia's GDP and supported more than 6500 full-time jobs, with northern Australia accounting for 82 % of direct employment (MLA, 2024a). This region also contributes 74 % of the $AUD1 billion farm gate value of the live cattle export trade, with just three regions (Katherine, Barkly, and Kimberley) accounting for over 50 % of the value (ACIL Allen, 2022).

The livestock grazing industry in northern Australia faces challenges from fluctuating cattle and commodity prices, as well as pressures on long-term financial performance and sustainability (ABARES, 2019). For example, a recent decline in livestock prices has been influenced by several key factors, including a sudden shift to drier seasonal conditions following consecutive La Niña years from 2019 to 20 to 2022–23, combined with an increased supply of animals in saleyards and

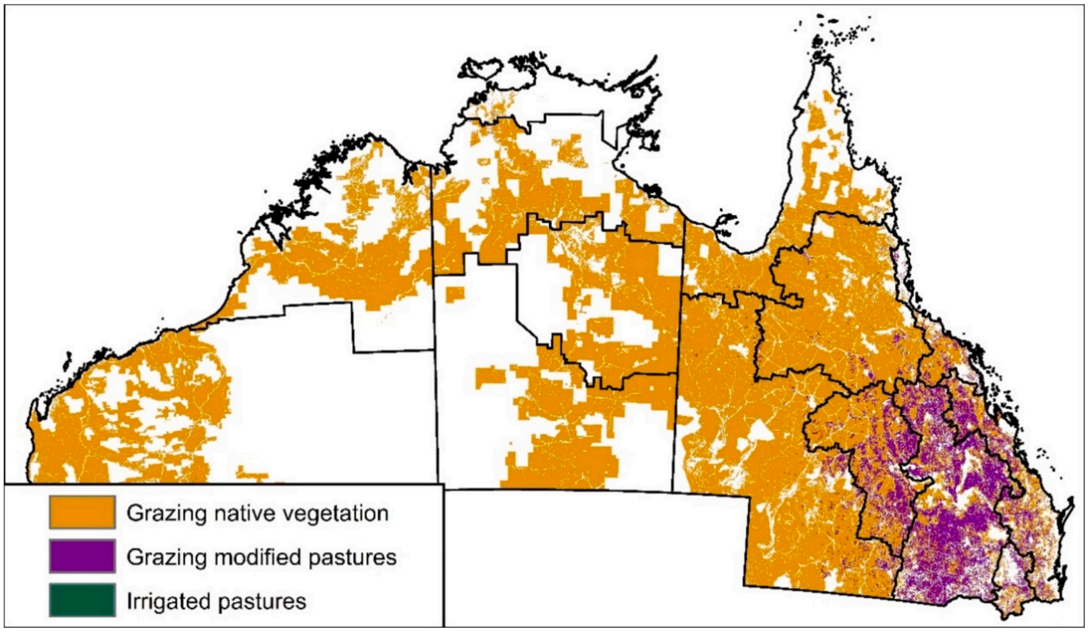

Fig. 1. The distribution of rangeland grazing systems in northern Australia.

decreased demand as producers destock in response to drier conditions and reduced pasture availability. At the same time, lags in meat processing capacity limit the industry's ability to readily absorb this additional supply (ABARES, 2024b). A decrease in global meat prices, particularly for sheep meat, due to higher global meat supply, has further exacerbated the situation (ABARES, 2024a). Previously, three consecutive La Niña events led to strong pasture growth across Australia, improving feed availability and encouraging producers to expand their herds and flocks. Consequently, the national cattle herd and sheep flock grew by approximately 10 % and 14 %, respectively, between 2019 and 20 and 2022–23. Interestingly, the COVID-19 pandemic, which saw international and intra-national restrictions on the movement of people, appears to have had little impact on overall cattle trade (Aboah et al., 2024). However, current government policy may see the close of live export of sheep by sea by 2028, requiring significant economic and social adjustment within the sheep supply chain (DAFF, 2024), and concern has been expressed that, should live cattle exports cease forthwith, the beef cattle industry could face a loss of $AUD8.1 billion over the next 20 years. Estimates are that the national cattle price would drop by 2–4 % and the value of Northern Territory grazing land decline by an estimated 34 % (MLA, 2024a).

The complexity of making decisions under the dynamic environmental and policy conditions facing the northern Australian cattle industry lends itself to exploration using the system dynamics approach. Our aim is to better understand the dynamics of the northern Australian rangeland grazing system to support industry and policy decision-making that avoids maladaptive outcomes and ensures the resilience of the system–its landscapes and communities–to external shocks.

3. Research methods

3.1. Systems thinking iceberg model

The iceberg model is a framework used in systems thinking (ST) to illustrate different levels of abstraction to reality, known as the ‘Four Levels of Thinking’ (Fig. 2). This ST iceberg model enables us to gain a deeper understanding by shifting our viewpoint to see the bigger picture. The top level, the visible part of the iceberg above the waterline,

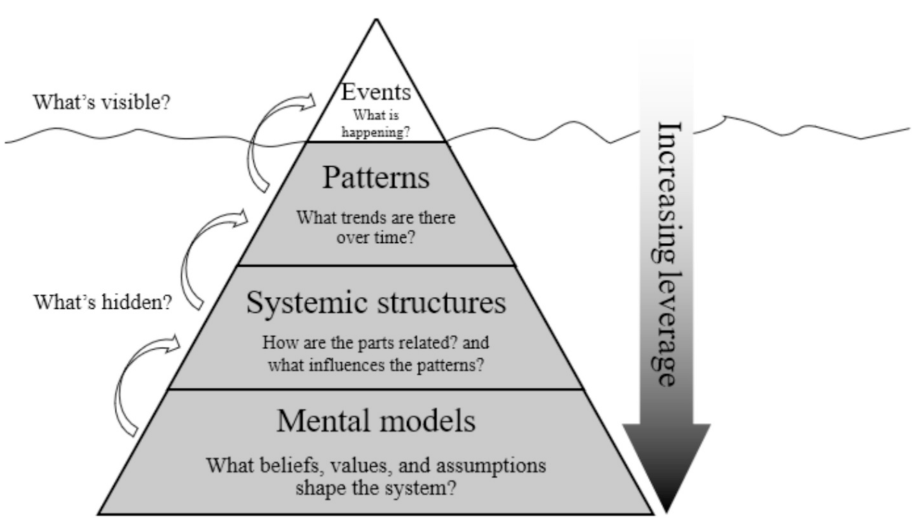

Fig. 2. Four levels of thinking (Adapted from Maani and Cavana, 2007).

represents events or the symptoms of a problem. Events are generated from the underlying patterns level, which represents the trends of events over time. These patterns are the result of deeper systemic structures, which determine how the system is organised. There is yet another deeper and more influential level that rarely comes to the surface. This level refers to the mental models that reflect the beliefs, values, and assumptions of individuals and organizations, which shape the system. Mental models have a significant impact on the formulation and perpetuation of the emergent systemic structures.

As a society, most of our decisions and interventions are made at the uppermost levels. This is because events and patterns that occur at these levels are the most visible parts and often require attention (Bosch et al., 2013; Nguyen and Bosch, 2013). However, greater impact (i.e., leverage) from interventions occurs when decisions are based on deeper systemic understanding and transformation of our mental models (i.e., at the Systemic structures and Mental models levels of the iceberg depicted in Fig. 2) (Meadows, 1999). By shifting decisions and interventions from events to these deeper levels, the ST iceberg model serves as a systemic framework for better understanding and dealing with complex problems. Specifically, understanding events allows for an apparently suitable response; recognizing patterns or trends enables us to anticipate future events; but comprehending the structure of a system provides an opportunity to change those things that influence both patterns and events, potentially resolving the problem. Identifying leverage points within the system can allow us to design a better system structure that enhances the resilience and sustainability of the system.

3.2. Application of the ST iceberg framework to address the sustainability challenges of northern Australia's RGI

3.2.1. Identify key issues and events

The key sustainability issues and challenges confronting the RGI in northern Australia are identified by answering questions such as "what is happening?" and "why it is happening?". In this study, this involved conducting a comprehensive literature review spanning diverse sources, including journal articles, governmental and industry reports, and media outlets. These findings were subsequently refined through consultations with knowledgeable experts in the RGI and familiar with northern Australia.

3.2.2. Create behaviour over time (BOT)

The pattern of events, referred to as Behaviour Over Time (BOT), is a graphical representation that shows overall trends and variations of events over an extended period (Maani and Cavana, 2007). Typically, BOT graphs are roughly drawn without precise numerical values, where the vertical axis represents the performance measures of variables of interest, while the horizontal axis denotes time. In this research, BOT graphs of several variables that reflect the performance of the RGI in northern Australia were sketched based on the literature review and consultation with expert panels. These variables were derived from the three pillars of sustainability (Boussemart et al., 2020), which comprise the environment (e.g., atmospheric greenhouse gas concentrations, biodiversity, land condition), economy (e.g., profit, beef production), and social factors (e.g., animal welfare).

3.2.3. Develop systemic structures

Developing systemic structures, known as systems models, involves mapping the system and primarily identifying the feedback loops embedded in the system that explain the system's behaviour over time (Mai and Smith, 2015). There are several tools available for mapping a system (e.g., subsystem diagrams, causal loop diagrams, and stock and flow diagrams). In this study, we used a causal loop diagram (CLD) as it allows for the simple visualization of feedback loops that govern system behaviour over time and is thus relatively easy for stakeholders to review. Overall, CLDs consist of variables (words or phrases) and arrows that represent causal links between pairs of variables; links are assigned either a positive (+) or negative (−) polarity, where a '+' polarity indicates a positive relationship, and a '-' polarity represents a negative relationship between two variables. All CLDs consist of underlying interacting networks of feedback loops, either reinforcing (R) or balancing (B), where an R loop represents a positive feedback mechanism that results in growing or declining trajectories and a B loop maintains the system's equilibrium.

The construction of the CLD for this study involved three main steps. Initially, we developed a 'straw' CLD based on our prior understanding of northern Australia's RGI (see Appendix A). This preliminary CLD was then further refined and informed by the existing literature, resulting in a working CLD (see Appendix B). Subsequently, the working CLD was refined through stakeholder surveys conducted using a Direct Impact Matrix (DIM) (see Appendix C). Stakeholders were identified through a purposive sampling strategy, guided by insights from our literature review and consultations with regional experts. They were asked, "Does variable A have a direct impact on variable B? If so, how does this impact manifest?" with the possible results being: no impact = 0, small = 1, medium = 2, strong = 3. The relationship between a pair of variables was indicated as follows: positive impact = '+', negative impact = '-'. This process resulted in a total of 961 questions (31 × 31 variables). The working CLD was further validated through consultations with knowledgeable experts to produce the final CLD of northern Australia's RGI.

3.3. Identify leverage points and systems-based interventions

Leverage points are commonly defined as specific places within a complex system where small shifts can lead to significant impacts on the entire system (Meadows, 1999). These critical points exist in all complex systems but can be difficult to identify as they are typically hidden beneath the surface of the system's visible components (Senge, 1990). However, system archetypes (SAs) – recognisable patterns–provide a guide to identifying such power points within the system of interest (Nguyen and Bosch, 2013; McLean et al., 2019). SAs are generic system models or templates that describe recurring patterns of system behaviour over time (Braun, 2002).

Using our systems model for northern Australia's RGI, we holistically examined groups of feedback loops that align with the structures of common SAs. These identified SAs were then used to explain the potential consequences of rangeland grazing policies currently being implemented in the region. Finally, we applied the management principles associated with these SAs to propose improvements to existing rangeland grazing management practices (Mai et al., 2024). For example, the *'Limits to Growth'* SA suggests that if growth is the desired outcome, the factors that inhibit growth should be eliminated or relaxed; conversely, if constraint is the objective, those limiting factors should be reinforced (Senge, 1990).

4. Results

4.1. Key sustainability issues of the RGI in northern Australia

The key identified sustainability issues and challenges facing the RGI in northern Australia are summarised in Table 1. They are categorized into five key themes: climate, economic and market dynamics, rangeland and environment, livestock production, and government policy.

Climate extremes are identified as key factors that have a profound impact on the industry (Cobon et al., 2021). High temperatures and rainfall variability contribute to prolonged drought and water scarcity in the region, with a significant impact on feed availability and beef production (Nguyen et al., 2020); hence, the productivity of pasture is a major concern in many locations across northern Australia (Cobon et al., 2020a; Nielsen et al., 2020). Additionally, livestock production is impacted by extreme temperature conditions that affect animal health (e.g., heat and chill stress), as well as disease and pest infestations (Cowan et al., 2024).

Table 1
The key sustainability issues of northern Australia's RGI.

Theme	Key issues	Reference
Climate	Increased variability and shift in rainfall pattern	Bowen et al., 2020; Bowen and Chudleigh, 2021; Cobon et al., 2021
	Increased frequency, duration, and severity of drought and wet seasons	Bowen and Chudleigh, 2021; Bowen et al., 2021
	Increased climate extremes (heatwaves, sudden cold, flash drought, flooding)	Nguyen et al., 2020; Cowan et al., 2022; Cowan et al., 2024
Economic and market dynamics	Cattle market price fluctuations	Dong at el. Godfrey et al., 2018; Godfrey et al. Godfrey et al., 2018; Harper et al., 2019; Almadani et al., 2021
	High input costs	Bowen and Chudleigh, 2020; Greenwood, 2021
	Exchange rates variations	Greenwood et al. Godfrey et al., 2018
	Decline in profitability	Bowen et al., 2020; Bowen and Chudleigh, 2021; Bowen et al., 2021
	Threats to live export	Harper et al., 2019; Fleming et al., 2020; Hing et al., 2021; Duval et al., 2024
	Limited market options	Greenwood et al., 2018; Xiong et al., 2023
Rangeland and Environment	Decline in pasture conditions	McKeon et al., 2009; Ash et al., 2011; O'Reagain and Scanlan, 2013; Scanlan et al., 2014; Mccollum et al., 2017
	Soil degradation	Yates et al., 2000; Ash et al., 2011; Waters et al., 2017; Abdalla et al., 2018
	Invasive species	Pandey et al., 2019; Weeds of National Significance https://weeds.org.au/lists/established/
	Overgrazing	O'Reagain et al., 2011; O'Reagain and Scanlan, 2013; Scanlan et al., 2014; O'Reagain et al., 2014; Bowen et al., 2020
	GHG emissions	Bray et al., 2016; Harper et al., 2019; McDonald et al., 2023
Livestock production	Threats to biosecurity	Thompson, 2018; Harper et al., 2019; Paquette et al., 2020; Schneider et al., 2020; Jori et al., 2021; Evans et al., 2024
	Decreased cattle herd size	Foran et al., 2019
	Consistent herd size since 1980s	Fordyce et al., 2021
	Increased mortality	Bowen et al., 2020
	Reduced mortality since 1980s	Fordyce et al., 2021
	Diseases and pest infestations	Stanger and Bowden, 2022; Mackereth et al., 2024; Animal Health Australia (2024)
	Animal welfare	Harper et al., 2019; Cowan et al., 2022, 2024; Animal Health Australia, 2024
	Increased productivity	Fordyce et al., 2021
Government policy	Policy and regulatory changes	McAvoy, 2015; Foran et al., 2019
	Land tenures and land use	Foran et al., 2019
	Drought grants and assistance	Drought grants and assistance Drought grants and assistance | Business Queensland
	Sustainability loan	Sustainability Loan Sustainability Loan | Queensland Rural and Industry (qrida.qld.gov.au)
	Carbon abatement/GHG emission reduction schemes	Suybeng et al., 2019; Cobon et al., 2020a, 2020b; Baumber et al., 2020; McDonald et al., 2023

The resilience and sustainability of northern Australian's RGI are also significantly impacted by volatility in the commodity and cattle market. During periods of decreased cattle prices, graziers may struggle to generate sufficient income, a challenge further compounded by the increasingly high costs of cattle production (Almadani et al., 2021). The impacts of price and cost fluctuations on the grazing industry are well illustrated by a case study of merino sheep enterprises in southern New South Wales (Godfrey et al., Godfrey et al., 2018). Such instability makes it difficult for graziers to maintain stable income levels, leaving them vulnerable to production and financial risks, particularly under conditions of increasing climate variability (McCartney, 2017; Cobon et al., 2021). The combined effect of price fluctuations and rising operational costs places considerable strain on livestock producers, threatening the long-term economic stability of the regional industry (Bowen and Chudleigh, 2020).

Inconsistencies and instability in government policies have also significantly impacted the RGI in the region. Abrupt policy shifts, such as the temporary ban on live cattle exports to Indonesia in 2011, have caused severe market disruptions, raised animal welfare concerns, and undermined producer confidence (Windsor, 2021). In Queensland state, the major policy reform has been phasing out of the Drought Relief Assistance Scheme (DRAS), replaced by a more strategic approach centred on self-reliance, proactive risk management, and targeted support during prolonged droughts. In addition, several significant policy changes over recent decades have reshaped the state's land and water governance, including restrictions on tree clearing, reforms in water licensing and allocation, and capping of the Great Artesian Basin. While these reforms are designed to enhance long-term resilience and sustainability of the RGI, they can also introduce transitional pressures on graziers. Furthermore, ongoing land use conflict between sectors, such as mining, gas, agriculture, and urban development (Paton et al., 2021; Witt et al., 2021), along with changes in policy and regulatory regimes related to environmental conservation, climate change mitigation, and animal welfare (Morton and Whittaker, 2022; Boronyak and Jacobs, 2023), continue to create operational constraints and financial burdens for producers in the region.

On the other hand, government initiatives to incentivise practices that result in improved environmental outcomes, such as biodiversity conservation, carbon sequestration and reduced greenhouse gas (GHG) emissions, present opportunities for rangeland beef producers and land managers to diversify their income through payments for environmental services (Eberhard et al., 2021; Yates et al., 2023; Milne et al., 2024; Runting et al., 2024). For example, the extensive grazing lands and substantial livestock industry of the northern Australian RGI contribute significantly to the country's reportable GHG emissions (McDonald et al., 2023), accounting for 8–10 % of national emissions through sources such as enteric methane, savanna burning, vegetation clearing, and land degradation (Bray et al., 2016). Since 2012, Australia has implemented a national carbon market designed to cost-effectively generate a reduction in GHG emissions through a variety of environmental accounting methodologies (e.g., savanna burning; avoided deforestation; environmental plantings (Edwards et al., 2021; CER, 2024)); increasingly, such market based instruments are viewed as having potential to deliver not only financial benefits, but also a range of ecological, socio-economic and cultural co-benefits to regional areas, including the rangelands (Milne et al., 2024).

4.2. Behaviour over time (BOT)

The key sustainability indicators for northern Australia's RGI depicted in Fig. 3 represent conceptual trends rather than specific numerical values. They include cattle population or production, greenhouse gas emissions, rangeland condition, and animal welfare, and are used to represent the industry's performance over time. Key trends portrayed are the nominal growth in the cattle population in northern Australia in recent decades (MLA, 2024b), where it has made a significant

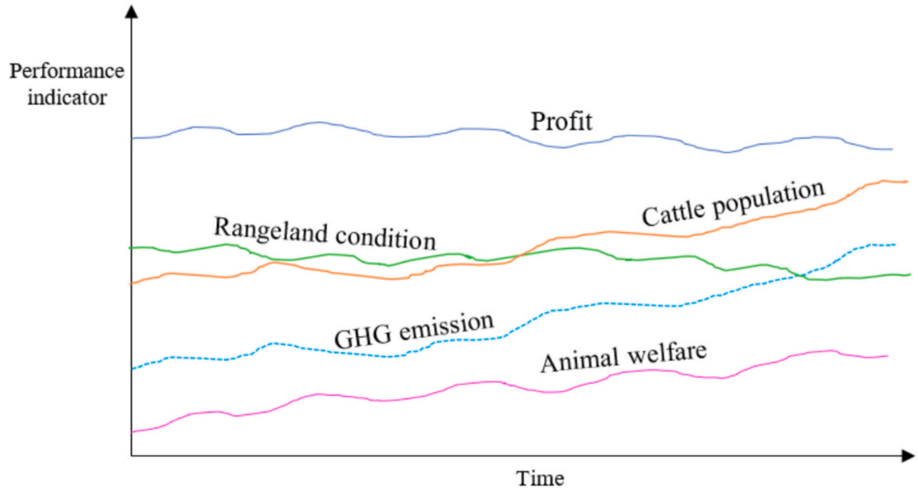

Fig. 3. BOT of key variables of northern Australia's RGI.

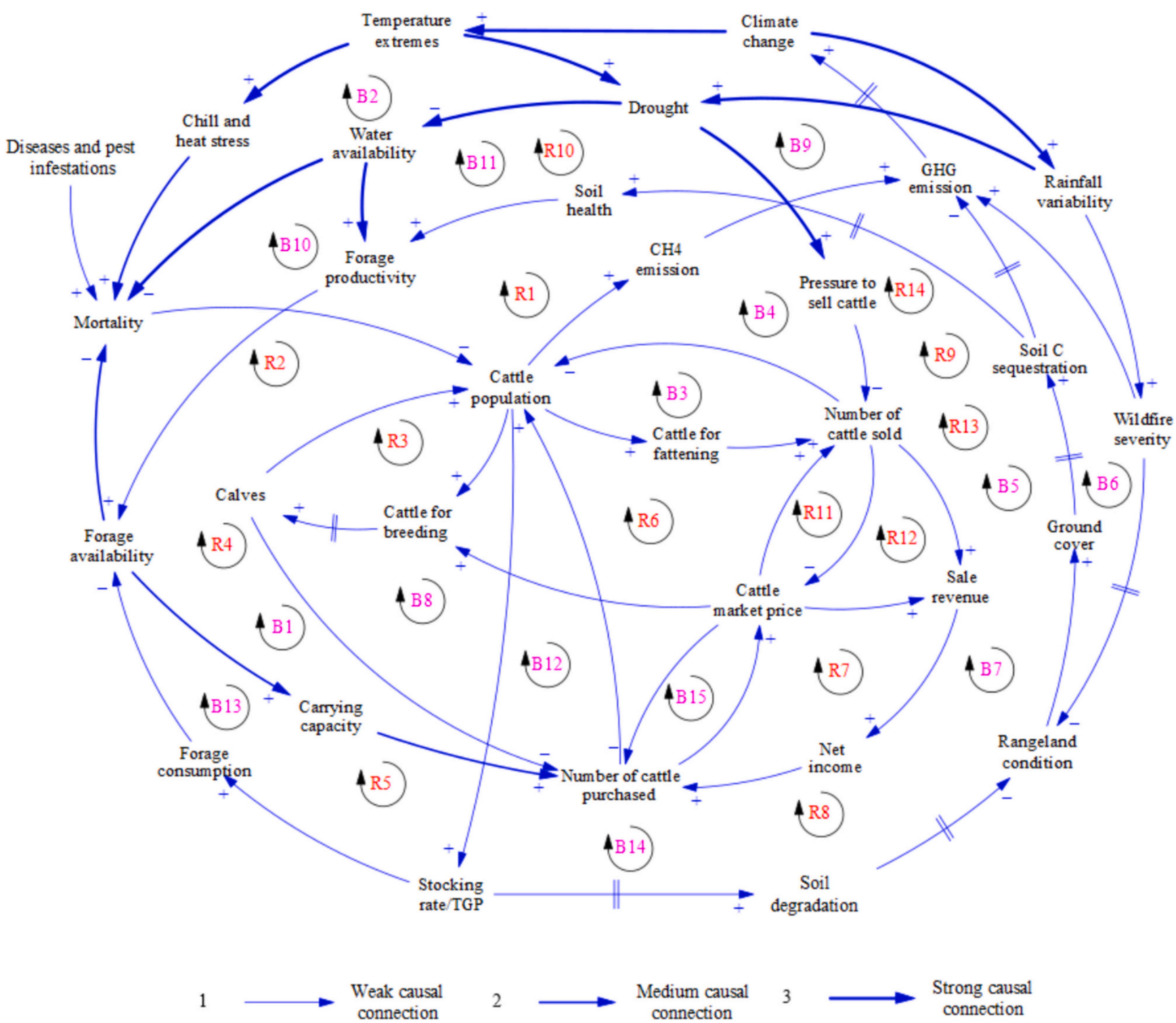

Fig. 4. CLD for northern Australia's RGI. A positive (+) polarity implies that two variables change in the same direction, while a negative (−) polarity indicates that they move in opposite directions. Loop identifiers R and B represent reinforcing and balancing loops, respectively: reinforcing loops (R) are positive feedback loops that amplify changes, whereas balancing loops (B) are negative feedback loops that promote stability. A double bar (||) signifies a time delay or lag between a pair of variables.

contribution to the regional economy (Russell-Smith and Sangha, 2018; McLean and Holmes, 2019); rising GHG emissions (Lean and Moate, 2021; Black et al., 2021); and indications of declining rangeland condition (Nielsen et al., 2020) in the region. Furthermore, the increased frequency and severity of climate extremes have raised concerns about animal welfare (Cowan et al., 2022, 2024). The degradation of the environment and concerns about animal welfare suggest that the RGI in northern Australia may not be sustainable without suitable adaptation practices and technologies.

4.3. Dynamic hypothesis of northern Australia's RGI

A causal loop diagram (CLD) representing a dynamic hypothesis for RGI in northern Australia is presented in Fig. 4. This conceptual systems model consists of various interconnected components, including biophysical, ecological, and socio-economic elements. The relationships among these components are often non-linear and involve feedback loops. There are twenty-nine feedback loops embedded in the model including fourteen reinforcing (R1 to R14) and fifteen balancing feedback loops (B1 to B15). The specific variables within each feedback loop are detailed in Appendix D. For conciseness, not all feedback loops are discussed in this paper. Instead, a group of feedback loops that reflect the structures of common SAs are analysed to identify leverage points, where intervention strategies can be formulated to improve the resilience of the RGI in the region. These details are outlined in the following section.

4.4. System archetypes

4.4.1. Limits to growth

The *limits to growth* archetype describes situations where improvement in a system's performance or growth is limited and cannot continue indefinitely (Senge, 1990). In the context of the RGI in northern Australia, the limits to growth archetype is associated with forage availability in the region. As the cattle population increases, more animals become available for breeding, leading to the birth of additional calves. These calves expand the overall herd size, providing even more cattle for future breeding, which results in continuous and potentially rapid cattle population growth. Additionally, government development policies, such as investments in water management, transportation, and rangeland productivity enhancements, can further accelerate this cycle, contributing to sustained and potentially rapid cattle population growth in northern Australia (represented by the R loop in Fig. 5).

However, an opposing balancing loop exists (represented by the B loop in Fig. 5) that counteracts the effect of the reinforcing loop. As the cattle population grows, feed consumption increases, reducing forage availability. Additionally, climate impacts in northern Australia may further diminish vegetation cover (McKeon et al., 2009). The combination of these factors leads to a shortage of forage for cattle. Without intervention to improve the rangeland's livestock carrying capacity in the region and/or on individual properties, the cattle population must eventually be compromised (Fig. 5(b)).

4.4.2. Fixes that fail

The *fixes that fail* archetype represents circumstances where managers (including policy makers) implement hasty solutions to tackle a problem, which may provide short-term benefit. However, such solutions may ultimately lead to unintended and harmful consequences that further exacerbate the issue. Consequently, the system may revert to its original condition or an even worse state after a system delay (Senge, 1990). In the context of the RGI in northern Australia, there is limited access to domestic cattle markets due to distance. With the expansion of the cattle population in the region, government and industry have implemented what might be viewed as a quick fix through developing international markets for live cattle export (represented by the B loop in Fig. 6), rather than onshore processing facilities for northern Australian

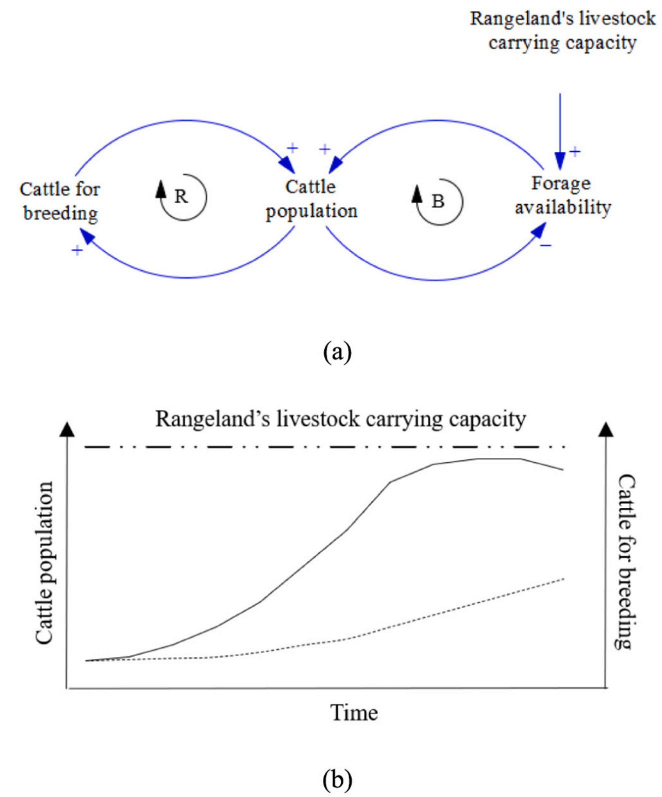

Fig. 5. (a) system structure and (b) behaviour of limit to growth archetype applied to forage availability.

cattle. However, recent experience has shown that this action may have unintended consequences. The halting of live exports resulting from animal welfare concerns in receiving countries, such as in Indonesia in 2011 (Blanchett and Zeller, 2012; Hastreiter, 2013), and import restrictions applied by receiving countries in the case of suspected Lumpy Skin Disease (LSD) in Australian cattle in 2023 (Mackereth et al., 2024) resulted in market failure. Northern Australian live export cattle producers were left with a backlog of saleable cattle, resulting in overstocking, with significant implications for pasture availability, land condition, animal welfare and ultimately enterprise viability (represented by the R loop in Fig. 6(a)).

Ongoing community concerns about the ethics of the international live cattle (and sheep) trade are also problematic for the northern Australian RGI. While the quick fix of developing the international live cattle trade in lieu of local domestic abattoirs and processing facilities accommodated the growing cattle population across northern Australia in the short term, the industry may ultimately face a more serious market problem than it originally had unless this situation is addressed (Fig. 6 (b)).

4.4.3. Shifting the burden

The *shifting the burden* archetype presents a scenario in which a quick-fix solution is implemented to tackle a problem, instead of a more sustainable longer-term solution. Regrettably, such short-term solutions may provide only temporary relief, but ultimately lead to a reliance on the quick fix while leaving the underlying issue unaddressed or even exacerbating it (Senge, 1990). In the case of the northern Australian RGI, the shifting the burden archetype is clearly evident in the mobility of cattle during drought periods, where cattle are relocated on short-term agistment to other less affected regions. The typical system structure and behaviour of these dynamics are depicted in Fig. 7 (a) and (b), respectively.

Northern Australia is known for its high rainfall variability and

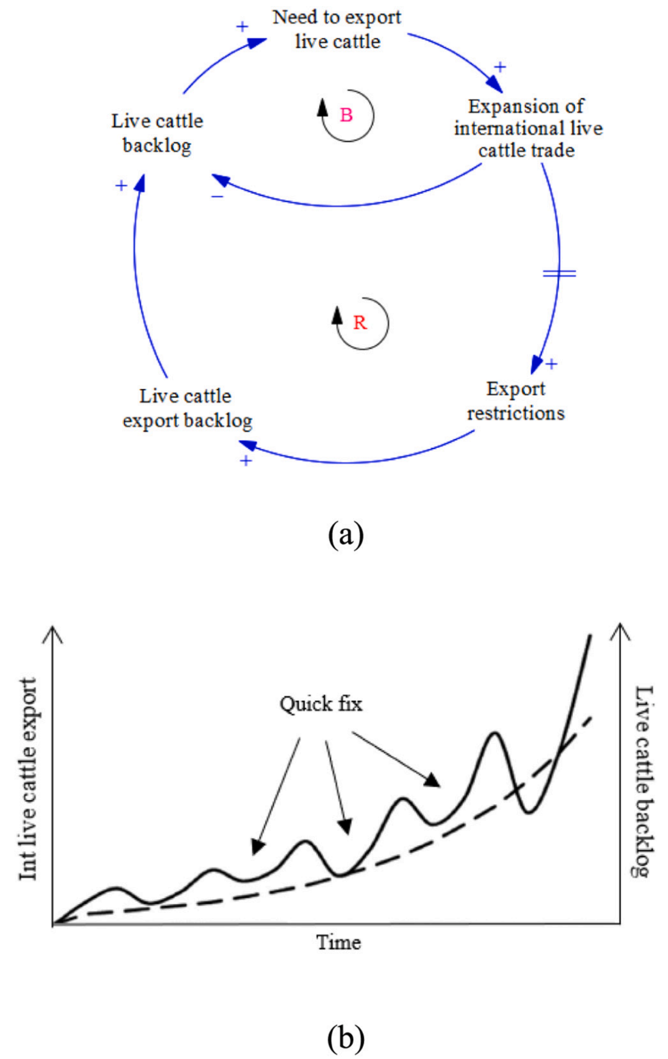

Fig. 6. (a) system structure and (b) behaviour of fixes that fail archetype applied to international live cattle market.

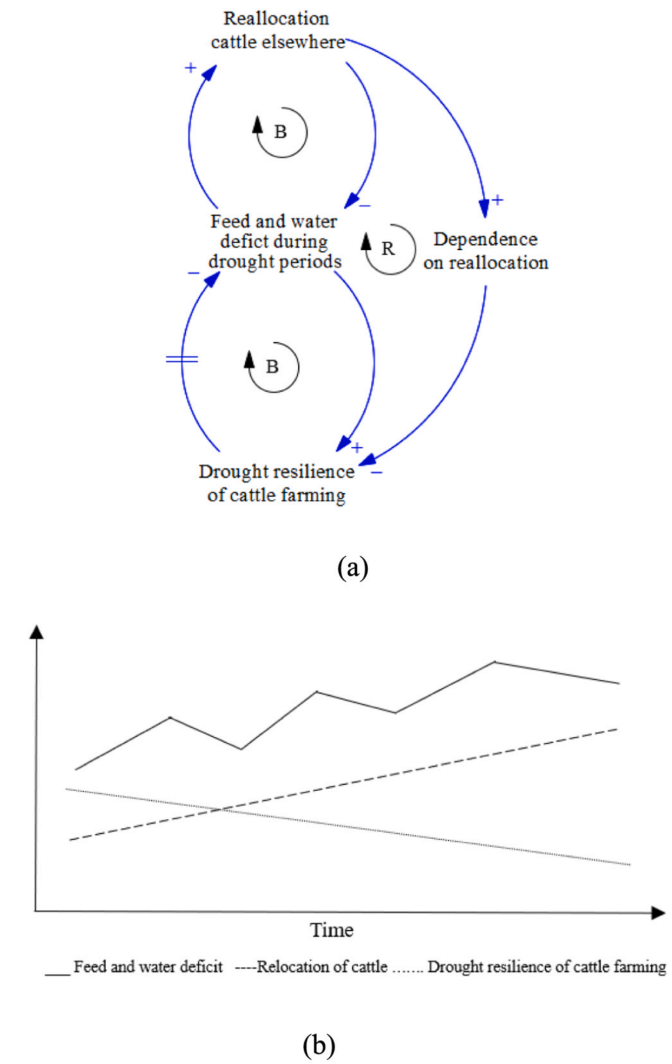

Fig. 7. (a) system structure and (b) behaviour of the shifting burden archetype applied to the mobility of cattle during drought periods.

extended (and often widespread) droughts, which pose significant challenges for graziers in the region, particularly with regard to the scarcity of feed and water for livestock (Bowen et al., 2021). During periods of drought, various risk management strategies have been adopted by graziers to mitigate drought impacts. One common approach is the relocation of cattle to areas with adequate resources (McAllister et al., 2006; Reeson et al., 2008) – a practice that is currently supported through government policy. This quick-fix solution provides immediate relief by ensuring access to essential feed and water. However, widespread drought means that there may be few options for the agistment of cattle (McAllister et al., 2006). Reliance on the relocation of cattle may also shift the burden away from developing robust, more durable, and long-lasting strategies that would otherwise enhance the resilience of in situ beef production.

5. Discussion

The rangeland-based grazing industry (RGI) is crucial to rural economies, food security, and livelihoods across northern Australia and many other regions globally, while often also contributing a range of ecosystem services (Foran et al., 2019; Godde et al., 2020; Barry, 2021). However, its future is increasingly uncertain due to the combined pressures of climate variability, market volatility, and inconsistent government policies (Broadfoot et al., 2017; Holechek et al., 2020). These pressures are not unique to northern Australia but also observed in RGIs in the western United States of America, Mongolia, and western New South Wales (Fernández-Giménez et al., 2019; Cowie et al., 2019; Holechek et al., 2020).

Our conceptual model highlights northern Australia's RGI as a complex adaptive system shaped by external drivers, feedback mechanisms, and dynamic interdependencies among its components. The model therefore serves as a shared framework that contributes to enhanced understanding, communication, collaboration, and coordination among stakeholders – key elements for fostering accountability and long term sustainability in northern Australia's RGI (McLeod and Hacker, 2020; Nielsen et al., 2020).

International studies emphasize similar resilient elements in the RGI, such as climate variability, economic vulnerability, and institutional dynamics, which are reflected in our conceptual model. However, our study advances this field by explicitly mapping the feedback structures that give rise to systemic issues. By identifying common system archetypes including *Limits to Growth*, *Fixes that Fail*, *Shifting the Burden*, our approach provides diagnosis and insights into the behavioural patterns of the RGI and highlights leverage points for systems-based interventions. Specifically, the *Limits to Growth* archetype (Fig. 5) underscores how constraints such as forage and water availability, worsened by climate variability and intensifying rangeland pressures in northern Australia, must be addressed through adaptive management to support sustainable industry growth.

In this region, climate variability and extremes directly impact forage availability, water resources, and livestock health (McKeon et al., 2009; Cobon et al., 2020a). Under severe drought conditions, these limitations can significantly erode the rangeland's carrying capacity (Skroblin et al., 2014), ultimately compromising herd productivity and the viability of grazing enterprises (Godde et al., 2019; Cobon et al., 2021). These challenges underlie the need to integrate seasonal climate forecasts and scenario analysis into grazing management strategies (Cobon et al., 2020b; Johnston et al., 2000; Cobon et al., 2021), enabling stakeholders to make informed decisions that build resilience and support the sustainable development of the industry (Cobon et al., 2020b; Johnston et al., 2000; Cobon et al., 2021).

Seasonal climate forecasts provide graziers with actionable insights into rainfall patterns and temperature extremes, supporting timely adjustments to stocking rates or supplementary feeding strategies (e.g., Cobon et al., 2020b, 2021). For instance, forecasts of low seasonal rainfall can guide timely destocking, often meaning producers can sell at higher market prices and protecting rangeland condition, while predictions of favourable conditions can inform restocking and pasture management decisions. By leveraging climate forecasts, graziers can better prepare for climate variability, reducing economic losses and maintaining ecosystem health.

Climate-smart agriculture (CSA) practices present another crucial and promising opportunity to projected higher temperatures, shifting rainfall patterns and increased frequency and severity of drought. Improved grazing management techniques, such as rotational grazing and wet season spelling, are central to CSA's effectiveness. Rotational grazing evenly distributes grazing pressure across rangelands, reducing soil compaction and promoting vegetation recovery (Schatz et al., 2020). This practice not only preserves soil health but also enhances its functionality, supporting better water infiltration and nutrient cycling (Teague and Kreuter, 2020; Williams et al., 2022). Similarly, wet season spelling plays a vital role in rangeland restoration by allowing pastures to recover during critical growth periods. This targeted recovery period improves forage quality and availability, ensuring a sustainable feed supply for livestock while maintaining the ecological integrity of the grazing system (O'Reagain et al., 2014). In some instances, pasture improvement can also be achieved by introducing more productive forage species. For example, incorporating productive drought-resistant forage species may provide a more sustainable feed source while contributing to soil carbon sequestration and improved water retention (Buck et al., 2019).

The Fixes that Fail archetype (Fig. 6) warns that short-term fixes (e.g., reliance on international live cattle exports) can lead to long-term economic vulnerabilities (e.g., market volatility, ethical concerns). For example, fluctuations in live cattle export prices, as occurred in the Kimberley during 2019, can also disrupt graziers' incomes, emphasizing the economic vulnerability of the industry. This volatility underscores the need for strategies to buffer producers from similar disruptions in the future. Diversifying income streams by developing domestic processing infrastructure could create opportunities for graziers to add value to their products locally, reducing reliance on fluctuating export markets and fostering regional economic growth. Furthermore, exploring alternative markets, such as premium beef exports to emerging economies, may offer significant potential for increasing profitability and greater market stability.

In addition to traditional livestock markets, financial mechanisms like carbon credits or biodiversity credits could provide supplementary income while promoting environmental stewardship (Baumber et al., 2020; Nielsen et al., 2020). Investments in transport and processing infrastructure, supported by consistent policy measures, could also reduce dependence on southern meatworks and bolster regional resilience (Higgins et al., 2015, 2018). However, inconsistent government policies often hinder such transitions. For instance, sudden shifts in export regulations or inadequate support for domestic processing have exacerbated market volatility, underlining the need for stable, long-term policy frameworks developed in collaboration with stakeholders.

The Shifting the Burden archetype (Fig. 7) highlights the importance of prioritizing fundamental, long-term solutions, such as resilience-building strategies, rather than short-term, reactive measures like relocation of cattle during drought periods. In such reactive approaches, cattle are temporarily moved to less affected regions on short-term agistment. This approach allows graziers to conserve their livestock and maintain the breeding line while giving their grazing land a break, enabling pasture regeneration (Reeson et al., 2008). However, this method can involve significant transportation and access costs (McAllister et al., 2006; Reeson et al., 2008) and, as described above, shifts the burden to other regions. As the effects of climate change become apparent, new studies indicate potential for 'contagious' self-propagating drought events (e.g., Xie et al., 2024), increasing the spatial extent of the impacted area and increasing competition for and costs associated with accessing 'safe' agistment options.

Effective strategies to strengthen rangeland resilience include investing in improved water infrastructure, such as enhanced water storage and distribution systems to ensure a reliable water supply during drought. Similarly, developing and cultivating drought-resistant fodder and pasture species that thrive in arid conditions can provide a steady food source for cattle, improving both animal welfare and productivity. In addition to infrastructure and feed improvements, implementing effective in situ land management practices is essential for maintaining and enhancing rangeland health and drought resilience. These practices include wet season spelling, invasive weed control, fire risk reduction, landscape rehydration, and soil conservation (Bowen and Chudleigh, 2021; Rolfe et al., 2021).

As mentioned earlier, integrating seasonal climate forecasting tools enables rangeland managers to make informed and proactive decisions regarding stocking and destocking (Schantz et al., 2023). For instance, Cobon et al. (2020b, 2021) advocate for a regional adaptation program that combines predictive climate modelling with financial support for water storage infrastructure. This integrated approach could significantly reduce reliance on cattle relocation during droughts, offering a more sustainable and resilient solution to the challenges posed by climate variability.

Our findings align with resilience frameworks developed for grazing systems in regions with climate conditions similar to these in northern Australia. Notable examples include the Resilience Adaptation Pathways and Transformation Approach (RAPTA) applied to rangelands in western New South Wales (Cowie et al., 2019); the adaptive capacity-focused (ACF) framework implemented in US and Mongolian rangelands (Fernández-Giménez et al., 2019); and the synthesis by Holechek et al. (2020), which outlines practical strategies for climate-resilient grazing management in the western United States. While these frameworks emphasize the importance of ecological thresholds, climate variability, and socio-economic divers, our study builds on them by employing a systems thinking approach to uncover feedback relationships and identify the underlying causes—leverage points—for systems-based aimed at improving the industry' resilience and sustainability.

To optimise the resilience of the RGI in the northern Australia region and beyond, proposed interventions should be implemented within a holistic framework that integrates insights from all three archetypes. For instance, enhancing rangeland's carrying capacity *(Limits to Growth)* can alleviate overstocking pressures caused by market failures *(Fixes that Fail)*, while strengthening in situ resilience *(Shifting the Burden)* supports sustainability under climate variability. Effective implementation of these strategies depends heavily on institutional and governance structures that play a critical role in shaping the industry's adaptive capacity. However, government policies in northern Australia are often fragmentated and inadequately coordination, factors that hinder the development of long-term adaptation strategies (McLean and Holmes, 2019; Broadfoot et al., 2017).

In this context, effective stakeholder engagement is vital to ensuring that interventions are not only technically sounds but also socially and institutionally supported. Participatory approaches that bring together a diverse array of stakeholders, including policymakers, graziers, indigenous communities, conservationist, and industry representatives, can enhance the legitimacy of decision-making, align incentives, and help identify leverage points for systematic changes (McLeod and Hacker, 2020; Nielsen et al., 2020). Strengthening these institutional and participatory dimensions is therefore critical to improving the long-term resilience of RGS under increasing climate risks and economic pressures.

6. Conclusion and future research

This study applies a systems-thinking approach to diagnose the dynamically complex challenges faced by RGI. By developing a dynamic hypothesis using a causal loop diagram (CLD), we have identified key system archetypes that reflect critical feedback structures, such as *the Limits to Growth, Fixes that Fail, and Shifting the Burden*, which contribute to recurring patterns of overgrazing, economic vulnerability, and policy misalignment.

The pressing issues facing northern Australia's RGI are multifaced and interconnected. They include climate variability and extremes, forage and water limitation, cattle price volatility, overreliance on live cattle export markets, and inconsistence in government policies. Further challenges include structural constraints such as long supply chains, remote locations, inadequate infrastructure and competing land use priorities. Such issues align with global patterns observed in other semi-arid rangelands, underscoring the need for systemic approaches that address root causes rather than their symptoms.

Our analysis presents a holistic approach framework that not only enhances stakeholder understanding, but also identifies key leverage points for system-based interventions. These systemic interventions help avoid maladaptation and reduce compounding ecological and economic risk to rangeland systems, thereby improving the resilience and sustainable growth of the global RGI. The findings of this study not only provide valuable insights for reshaping adaptation policies in northern Australia but also establish a robust foundation for knowledge sharing and learning across rangeland grazing industries worldwide that face similar challenges.

While systems thinking offers valuable insights, it also has its limitations, such as potential biases in stakeholder selection, reliance on qualitative data, and difficulties in fully capturing dynamic system interactions. These can be mitigated by triangulating data sources and refining CLDs through expert input. Additionally, the feedback loops and system archetypes identified in this study remain hypothetical and require further validation through implementing the final three phases of Sterman's framework, which involve developing quantitative simulation models.

These computer-based simulation models will illustrate how different system components interact quantitatively, enabling the assessment of the resilience rebound of the RGI under various climate variability and change scenarios, and other sources of uncertainty (e.g., market and policy uncertainties), thereby providing deeper insights for informed decision-making. Notably, such models can be updated with new data, enhancing their relevance and reliability over time. The development of these models for northern Australia's RGI is the focus of our ongoing research.

CRediT authorship contribution statement

Thanh Mai: Methodology, Formal analysis, Conceptualization, Writing – review & editing, Writing – original draft. **Kathryn Reardon-Smith:** Validation, Investigation, Formal analysis, Data curation, Writing – review & editing. **David H. Cobon:** Funding acquisition, Writing – review & editing. **Thong Nguyen-Huy:** Visualization, Validation. **Shahbaz Mushtaq:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.179488.

Data availability

Data will be made available on request.

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