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Towards resilient, inclusive, sustainable livestock farming systems

Franco Bilotto [a,b], Matthew T. Harrison [a,*], Ronaldo Vibart [b], Alec Mackay [b], Karen M. Christie-Whitehead [c], Carla S.S. Ferreira [d], Richard S. Cottrell [e,f,g], Daniel Forster [h], Jinfeng Chang [i]

[a] Tasmanian Institute of Agriculture, University of Tasmania, Newnham Drive, Launceston, TAS, 7248, Australia
[b] AgResearch, Grasslands Research Centre, Tennent Drive, Private Bag 11008, Palmerston North, 4442, New Zealand
[c] Tasmanian Institute of Agriculture, University of Tasmania, 16-20 Mooreville Rd, Burnie, TAS, 7320, Australia
[d] Polytechnic Institute of Coimbra, Applied Research Institute, Rua da Misericórdia, Lagar dos Corticos, S. Martinho do Bispo, 3045-093, Coimbra, Portugal
[e] Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Australia
[f] Centre for Marine Socioecology, University of Tasmania, Hobart, Australia
[g] Centre for Biodiversity and Conservation Science, School of Earth and Environmental Sciences, The University of Queensland, Brisbane, Australia
[h] Grasslands and Sustainable Farming, Production Systems, Natural Resources Institute Finland (Luke), Halolantie 31 A, 71750, Maaninka, Finland
[i] College of Environmental and Resource Sciences, Zhejiang University, 310058, Hangzhou, China

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ABSTRACT

Background: While livestock products comprise the cornerstone of food security, livestock managers face the dual challenge of adapting to a climate crisis and sustainably reducing greenhouse gas emissions. Climatic variability and extreme weather events impact the agri-food chain, hindering global agricultural productivity and threatening safe, nutritious, and affordable livestock products.

Scope and approach: This review delves into five key aspects: (1) the cultural, socio-economic, and food security importance of livestock, (2) the impact of climatic, economic, and geopolitical shocks on the global livestock sector, (3) the livestock sector's role in climate change, (4) opportunities for transitioning to inclusive, sustainable livestock farming systems, and (5) prerequisites and transformative initiatives for the livestock sector.

Key findings and conclusions: Climatic, economic, and geopolitical shocks have increased, particularly affecting the poultry, dairy, and small ruminant sectors in the last three decades. These shocks have amplified risks of contravening tipping points. Low adaptive capacity and high vulnerability to the climate emergency demand place-based adaptation. Interventions reducing food waste and restoring tropical forests offer the greatest mitigation potential, while agrivoltaics and on-shore wind production appear most promising economically. Trade-offs between production, conservation, prosperity, and mitigation demand contextualization and co-design of innovations for credibility, legitimacy, and adoptability.

1. Introduction

Climatic variability and increasingly frequent extreme weather events impact agri-food chain supply, slowing global agricultural productivity growth and threatening provision of safe, nutritious and affordable livestock products (Godde, Mason-D'Croz, Mayberry, Thornton, & Herrero, 2021). While the climate crisis undermines consistent and sustainable food supply on the one hand, a burgeoning global population, an increasingly affluent middle class have evoked unprecedented demand for livestock products and natural resources on the other hand (Godde, Garnett, Thornton, Ash, & Herrero, 2018). As such, adaptation to the climate emergency and mitigation of greenhouse gas (GHG) emissions are increasingly recognized by governments and international agencies as one of the grandest challenges faced by humanity in the 21st century (Harrison et al., 2021).

Most of global mitigation potential (60–70%) associated with livestock supply chains is thought to lay in ruminant productions systems with low productivity, such as Latin America, the Caribbean and East/Southeast Asia (Gerber et al., 2013; Twine, 2021). Livestock systems in these regions tend to have larger GHG emissions (>40% GHG emissions) than those from other regions (Opio et al., 2013), and are projected to have the greatest global growth in livestock production over the coming

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* Corresponding author.
E-mail address: matthew.harrison@utas.edu.au (M.T. Harrison).

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decades (Harrison et al., 2021). At the same time, these socio-economically vulnerable regions are expected to bear the brunt of the changing climate due to low resilience and adaptive capacity (IPCC, 2021). Nevertheless, natural disasters and shocks to agri-food systems have and continue to occur in developed countries including the United States, New Zealand and Australia (Cottrell et al., 2019; FAO, 2021). The global livestock industry thus faces the challenge of reconfiguring food systems to deliver inclusive, healthy, sustainable and equitable diets to feed future generations (Herrero et al., 2021).

There is growing evidence that effects of climate change on livestock production systems will vary by agroecological region, animal species and production system (Harrison, Christie, Rawnsley, & Eckard, 2014; Phelan, Harrison, Kemmerer, & Parsons, 2015). Climate change can impact livestock directly, through animal physiology, behaviour, production and welfare and indirectly, through feed availability, composition and quality (Henry, Eckard, & Beauchemin, 2018). Contemporary science has investigated new plant or animal genotypes for climate change adaptation, focusing on drought or heat tolerance (Langworthy et al., 2018; Meier, Thorburn, Bell, Harrison, & Biggs, 2020). For instance, adopting deep-rooted pastures can enhance pasture production and soil organic carbon (SOC) in drier conditions, leading to increased profitability and reduced net farm greenhouse gas (GHG) emissions, to the extent that net GHG of livestock and cropping systems are similar (Meier et al., 2020). While many studies have examined climate change adaptations and mitigations in isolation, research exploring simultaneous application of multiple interventions within whole systems is scarce (Harrison et al., 2021). It is clear from past work that there are no panaceas for solving the climate emergency, much less singular GHG emissions reduction or removal option (Rogelj, Geden, Cowie, & Reisinger, 2021) available that could be scaled across production systems and regions (Herrero et al., 2016; Zhu, Kros, Lesschen, Staritsky, & de Vries, 2016). While some authors imply significant potential to improve net emissions and emissions intensities (emissions per unit product) from the livestock sector through greater research translation, many questions remain.

The purpose of this review was to: 1) outline the roles of livestock production systems in society beyond their valid environmental criticisms, 2) assess the effects of climatic, economic, and geopolitical shocks on the global livestock sector, quantifying production losses over the last decades and highlighting the need for improved resilience through forecasting, preparation, local adaptation, and infrastructure, 3) examine the contributions of the livestock sector to climate change, identifying the primary drivers and temporal dynamics of GHG emissions, 4) advocate for analytical frameworks to assess opportunities for transitioning towards more inclusive and sustainable livestock farming systems by exploring cross-sectoral and cross-scale adaptation options, and 5) discuss prerequisites for transformational initiatives, emphasizing that adoption relies on the readiness, cost, complexity, and end-user engagement of new technologies, alongside built adaptive capacity in communities and robust government support.

2. Cultural, socio-economic and food security importance of livestock systems

Livestock production systems exist for many cultural, socioeconomic, and food security reasons; these reasons vary by location. The Food and Agriculture Organization of the United Nations (FAO) suggest that livestock contribute 40% of global agricultural output value, supporting the livelihoods and food security of 1.3 billion people (Bonilla-Cedrez et al., 2023). Livestock production systems include pastoral/grassland, covering extensive areas with low human densities; mixed crop-livestock, mixed production regions suitable for both agriculture and livestock; and intensive systems, typically found in peri-urban or urban areas (Herrero et al., 2013). While livestock production is essential for food security (particularly in developing nations), the sector receives regular criticism for detrimentally impacting the environment, having high water use, contributing to GHG emissions and catalysing climate change. Livestock systems contribute significantly to global food security, producing 90% of the world's milk supply and 80% of meat and nearly 50% of cereal output (Herrero et al., 2013; Thornton & Herrero, 2014). Livestock systems indirectly enhance crop production through recycling via manure and animal traction. Discarded biomass, plant residue and by-products from mixed-crop livestock systems compete less for natural resources than do cropping systems and represent an important feed resource for livestock production that is often unsuitable for human consumption (Gatto, Kuiper, van Middelaar, & van Meijl, 2024). Embracing these low-opportunity-cost feeds, regenerative agendas and local resources as part of livestock production may mitigate feed-food competition, reducing environmental impacts as part of circular food systems (Shahpari, Allison, Harrison, & Stanley, 2021).

Livestock production significantly contributes to the economies of developing nations, particularly in providing essential commodities, such as milk and meat with high production values. Since the year 2000, beef production has grown by 3.7%, 2.3%, and 1.4% per year in Northern Africa, Central America, and Southeastern Asia, respectively (FAOSTAT, 2023). Livestock-related jobs, especially in trading and processing, are prevalent in the informal sectors of low- and middle-income countries (LMIC) (IsDB, 2020). LMICs have a significant local consumption of livestock products, with trade occurring within enhanced internal connectivity, transport networks, and improved value chains. Livestock also hold significant cultural value - even in developed countries - shaping distinctive landscapes and playing pivotal roles in local communities (Sirimarco, Villarino, Barral, Puricelli, & Laterra, 2023; Thornton, 2010). Local breeds are crucial in cultural networks, influencing income distribution (e.g., 'livestock ladder' from poultry to goats or sheep, to cattle/buffaloes), and symbolizing wealth (Pica-Ciamarra, Tasciotti, Otte, & Zezza, 2015). In developing countries, rural households maintain livestock as liquid assets and income sources, ensuring nutrition and access to credit, with cascading implications for their social status through education and health care.

Livestock improve gender equity, being more equitably distributed in developing countries compared to other assets like land or financial resources. Gender equity refers to achieving equivalent life outcomes for women and men by addressing their distinct needs, interests, balancing their access to resources and power (Galiè et al., 2019). Livestock ownership empowers women by providing income, improving access to resources (e.g. credit and veterinary services), and enhancing social status, leading to greater financial independence and participation in decision-making. This economic and social empowerment helps break the cycle of poverty, supports children's education, reduces labor burdens, and promotes long-term gender equity. In intensified Asian livestock systems, women typically manage over three-quarters of livestock-related tasks. Despite their pivotal role, women face lower access to technologies and inputs, reflecting gender disparities in extension services and information across the developing world (Medendorp et al., 2022). Women contribute significantly at various stages of livestock value chains as producers, traders and as consumers and they influence over decisions on the sale, consumption, and income management of family animal products which is crucial for household nutritional well-being (Grace, Roesel, Kang'ethe, Bonfoh, & Theis, 2015). Innovations, such as the introduction of Brachiaria in Kenya and Ethiopia or delivering livestock vaccines by drone in Ghana (CGIAR, 2023), aim to enhance participation of women in livestock systems and promote inclusive food systems.

In developed nations, health concerns related to animal-based diets are on the rise. Increasingly controversial media foreshadows greater risk of atherosclerosis, colorectal cancer, type II diabetes, and bone and kidney issues associated with excessive consumption of animal products (Carrero et al., 2020). In practice however, animal source foods, with their energy density and palatability, are vital sources of energy and high-quality protein (Day, Cakebread, & Loveday, 2022) when consumed in moderation. Animal foods are particularly important for marginalised and vulnerable groups such as infants, children, pregnant and nursing women, and individuals with heightened nutritional requirements (Visser, McLachlan, Maayan, & Garner, 2018. Animal source foods also provide essential micronutrients like vitamin A, vitamin B12, riboflavin, calcium, iron, zinc, and essential fatty acids (Adesogan, Havelaar, McKune, Eilittä, & Dahl, 2020), which can be challenging to obtain in sufficient quantities from plant-based foods.

Global food security requires a strategic approach to conserve, preserve and restore existing natural capital (Fleming et al., 2022). Sustainable management of livestock production should foster improved soil cover, mitigate land degradation and erosion, and promote increased soil organic carbon (SOC) accumulation (Teague & Kreuter, 2020). Integrating forages and ruminants into regenerative cropping systems enhances SOC, improves soil ecological function, and reduces production costs by avoiding annual tillage, inorganic fertilizers, biocides and synthetic fertilizers. Meeting the growing demand for livestock products is closely tied to external nutrient inputs (Barbieri, MacDonald, Bernard de Raymond, & Nesme, 2022). Regenerative land management also provides ecosystem services like enhanced water infiltration, SOC sequestration, nutrient cycling, biodiversity promotion, and wildlife habitat creation (Teague & Kreuter, 2020). Well-managed grasslands contribute to regulate global climate warming by acting as carbon sinks (Sándor et al., 2020). Sustainable practices are essential to preserve and enhance SOC storage in grasslands, contributing to the reduction of GHG emissions. These attributes collectively enhance ecosystem resilience, economic stability, and overall robustness in agricultural systems, crucial for withstanding short-term crises or shocks (Modernel et al., 2019).

3. Climatic, economic and geopolitical shocks invoke risk of tipping points

We assessed temporal climatic (e.g. extreme events), economic (e.g. hyperinflation) and geopolitical (e.g. international conflict) trends in the global livestock sector over 50 years and found increasing impacts of shocks, particularly on industries producing eggs, meat (chicken, sheep, goat) and cow milk (Fig. 1). In the context of this paper, we define 'shocks' as those disruptive events causing sudden, substantive downturns in livestock production with cascading and detrimental social, economic and environmental implications for society. Examples of climatic, economic and geopolitical shocks are shown in Table 1.

Extreme weather events, such as floods, longer heat waves and droughts periods, have driven more than 65% of these livestock production shocks, causing severe production losses and mortalities in many regions (Cottrell et al., 2019). The Intergovernmental Panel on Climate Change (IPCC) highlights the occurrence of increased length of warm spells or heat waves in Asia, Africa and South America, and more frequently heavy rainfalls and associated flooding events in central North America and North-western Australia (IPCC, 2021). Globally, the frequency of heavy precipitation events, floods and tropical cyclone activity has increased since the 1950s, but with regional and subregional variation (FAO, 2021; IPCC, 2021). Indeed, at the time of writing, southern Queensland in Australia was hit by one of the most severe flash flooding events in history, with total damages caused by a single extreme event estimated at over $AU7.7B (Queensland Goverment, 2022).

In line with these observations, many global circulation models show increasing temperatures in the short and long-term with risks of transgressing irreversible climatic and, by extension, agro-ecological thresholds, edging ever closer (IPCC, 2021). Here and in many other causes, humanity would be much better served preparing the knowledge, forecasting systems (e.g. meteorological models) and infrastructure (storage, drainage and prevention) prior to the extreme event, rather than paying for damage that ensues for impacted unprepared (or ill-equipped) communities. To improve resilience (capacity to recover from adverse events), we solicit advances in forecasting, preparation and fortification for extreme events (Box S1).

At regional and global scales, natural disaster occurrences have almost quadrupled since the 1970s, with more intense damage costing (on average) US$170B per year over the last decade (FAO, 2021). Between 2008 and 2018, agricultural sectors of LMIC absorbed 26% of the impact caused by medium-to large-scale natural disasters that caused US $108B of damage, of which 45% occurred in Asia, 27% in Latin America and the Caribbean, and 28% in Africa (FAO, 2021). Livestock systems accounted for 31%, 20% and 7% of agricultural losses of Latin American and the Caribbean, Asia and Africa, respectively. Although agricultural research has enabled productivity by technical progress around 3% per year, the influence of anthropogenic climate change has slowed gains by 21%, the equivalent of losing 7 years of productivity growth in warm regions within Latin America and the Caribbean (e.g., tropical forage-based livestock systems) and Africa (e.g., pastoral systems in arid and semiarid regions of sub-Saharan Africa) (Ortiz-Bobea, Ault, Carrillo, Chambers, & Lobell, 2021).

A lack of comprehensive understanding of the interaction between climate change and livestock production and vice versa has restricted theoretical exploration, research translation and adoption of sustainable development options of the livestock sector. As well, many prospective interventions designed to reduce GHG emissions may be counterbalanced by trade-offs in other dimensions, potentially for example reducing prosperity, nutrition and inclusivity of food systems (Harrison et al., 2021). Global warming beyond 1.5 °C may elicit abrupt change and new system states, triggered by breaching irreversible thresholds known as "tipping points" (Armstrong McKay et al., 2022). Tipping points invoke cascading effects, transforming states across several scales and regions (Lenton et al., 2019), and may be climatic, socio-economic, humanitarian and/or geopolitical (Fig. 2). A climatic tipping point caused by cessation of the Atlantic Meridional Overturning Circulation or modification of the amplitude/or frequency of the Niño–Southern Oscillation, and may trigger compounding droughts or megadroughts lasting decades, evoking state transitions in global terrestrial ecosystems and driving catastrophic losses in wildlife and domesticated animals, as depicted in Fig. 2 (Duque-Villegas, Salazar, & Rendón, 2019; Nguyen-Huy et al., 2020; Stendel, Francis, White, Williams, & Woollings, 2021). Consecutive droughts amount to large scale biophysical and economic losses (e.g., 30% production losses suffered by ranchers in Utah between 1999 and 2004; over the last 50 years reduced gross farm production in Australia by 27% on average), potentially increasing irrigation demand, which reduces economic income (Duque-Villegas et al., 2019; Nguyen-Huy et al., 2020; Stendel et al., 2021).

Impacts of the climate crisis vary by region, animal species and genotype, production system and enterprise (Henry et al., 2018; Rojas-Downing, Nejadhashemi, Harrigan, & Woznicki, 2017). These include direct impacts on animal physiology, behaviour, production and welfare together with indirect impacts through feed availability, composition and quality, as shown in Fig. 2 (Henry et al., 2018; Twining, Shipley, & Matthews, 2022). In some regions, shifts in seasonal rainfall distribution (within and between seasons) impact ground cover conservation and feed supply (Ara et al., 2020). Direct impacts of the climate emergency will be more profound on grazing systems (outdoor systems where animals graze *in situ*) because of their high dependence on climate for feed supply and thus risk of mismatch between forage supply and livestock demand across seasons (Godber & Wall, 2014; Michalk et al., 2019; Twining et al., 2022; Wolf, Chen, & Asrar, 2021). One potential adaptation to such change is transhumance, the seasonal movement of livestock between summer and winter seasons, depending on forage supply. A Spanish case study of sheep grazing systems demonstrated that transhumance improved grazing management and helped restore ecosystems services, enhancing nutrient-use efficiency and soil carbon sequestration while increasing farm profitability by more than 20% (Box S1).

By leveraging climate analogues (Pugh et al., 2016), a recognized

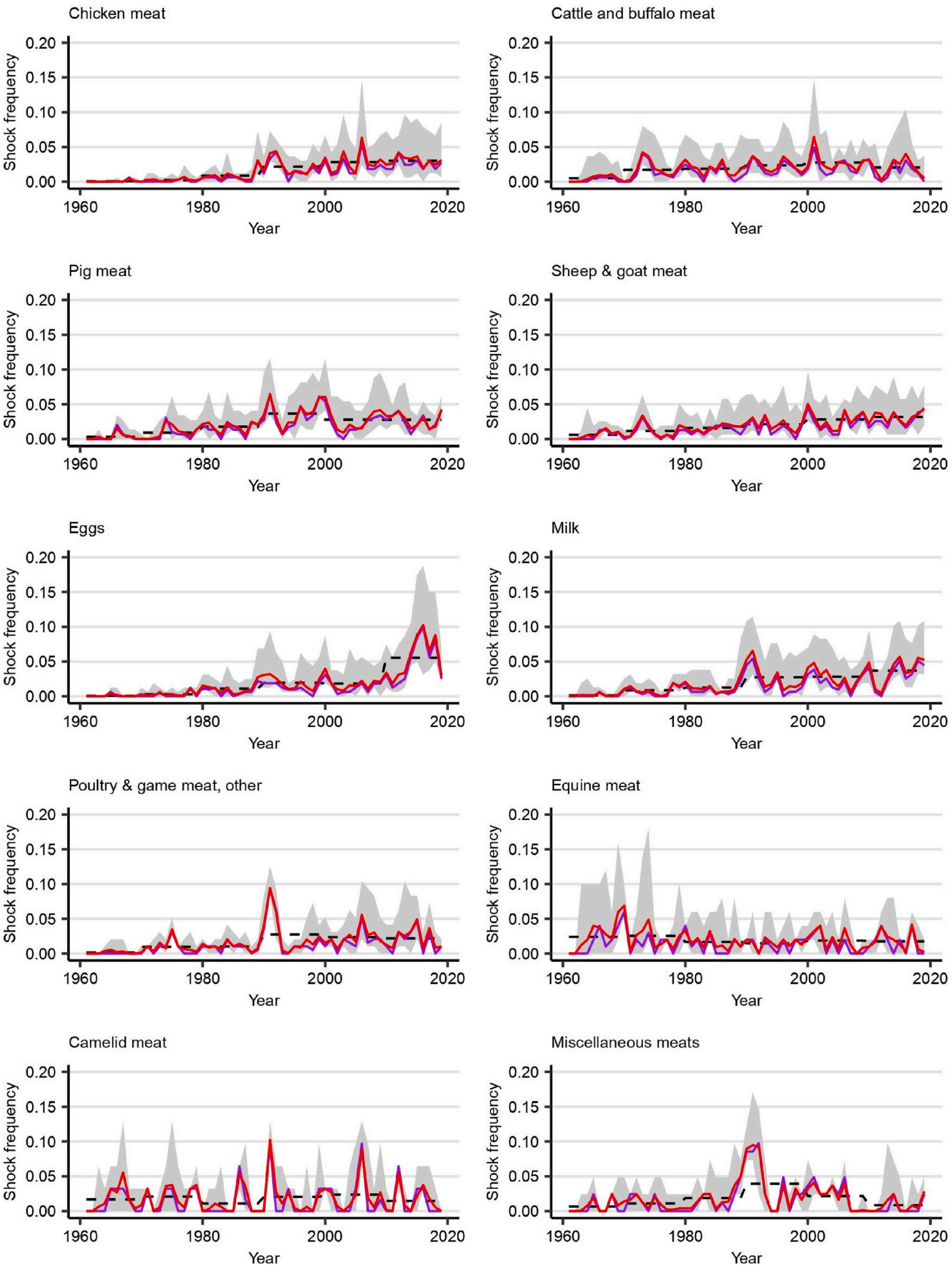


Fig. 1. Time series of climatic, economic and geopolitical shocks on the livestock sector from 1961 to 2019 [adapted from Cottrell et al. (2019)]. The shock frequency here is defined as the number of shocks detected for that livestock product in a given year normalized by the number of time series used to detect those shocks (i.e. the number of nations producing more than 0 Mg that year). Only negative shocks considered (i.e. production losses) relative to average production baselines. Gray shaded area depicts the confidence interval of the shock frequency for a given year and commodity. Red lines indicate the annual frequency of shocks identified; purple line is the median of the shock frequency range; dashed black line is the decadal mean. Regions include North America, Central America, the Caribbean, South America, Northern Europe, Western Europe, Southern Europe, Eastern Europe, North Africa, West Africa, Central Africa, Southern Africa, East Africa, Western Asia, South Asia, East Asia, Southeast Asia, Melanesia, Micronesia, Australia, New Zealand and Polynesia. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Key shock themes with illustrative examples categorised by country, timing and magnitude [adapted from Cottrell et al. (2019)].

Shocks	Definition	Example	Country	Year	Production loss (Mg)	Ref
Policy	Policies and legislation that disincentivise commodity hoarding and export bans, closure or abolition of subsidies	Reformation of the subsidy system to incentivise large-scale farms over smaller businesses in Norwegian agriculture.	Norway	2000	126,861	1
Mismanagement & policy change	Multiple categories, such as erosion of soils on land	Collapse of reindeer herds attributed to mass starvation over the winter and potential issues with data reporting and management across different years.	Greenland	1992	166	2
Geopolitical & economic events	Shock triggered by conflict, state dissolution or financial crises	The conflict in Northern Mali displaced over 300,000 people, causing significant disruptions to agriculture in the region.	Mali	2011 and 2013	105,576	3, 4
		Protests and conflict arising from proposed land reform, coupled with the shutdown of the oil industry, have become major sources of economic disturbances for agriculture.	Venezuela	2004	69,910	5
		During the first Gulf War, sanctions on Iraq resulted in a complete cut-off of imported feed grains. Additionally, the domestic supply of feed grains diminished as it was redirected toward human food consumption.	Iraq	1991	334,354	6
Climate/weather events	Extreme anomalies such as storms, droughts, El Niño Southern Oscillation events or climate-driven ecosystem change	Between 2000-2002 and 2009–2010, Mongolia experienced two mass mortality events, known as 'dzuds', resulting in the loss of 20 million head of livestock. The 'dzuds' were driven by a combination of factors, including summer droughts, heavy snowfall, high winds, and extremely low winter temperatures.	Mongolia	2001 and 2010	134,023	7
		Widespread floods in southern Nigeria have resulted in significant livestock losses.	Nigeria	2011	162,689	8
		Drought driven by El Niño exacerbated with Asian economic crisis.	Indonesia	1998	242,122	9
Compound shocks	When multiple shocks occur in serial and/or concurrently and/or overlap	Consecutive (concatenated) droughts and economic crises from 1986 to 1989.	Mexico	1989	1,627,163	10
		Decline in food production following the floods of 1995–96.	North Korea	1997	85,561	11, 12
Other	Multifaceted pressures from production diseases to geological events, such as tsunamis or volcanic eruptions	The Foot and Mouth Disease outbreak in 2000 resulted in further declines in livestock production until 2003.	Argentina	2003	1,616,044	13
		The economic downturn was induced by the infrastructure damage caused by the eruption of the Soufriere volcano in 2005.	Montserrat	2006	665	14, 15

1: Forbord, Bjørkhaug, and Burton (2014), 2: Cuyler (1999), 3: Kimenyi, Adibe, Djiré, and Jirgi (2014), 4: FAO (2013), 5: Wilpert (2006), 6: Schnepf (2004), 7: Rao et al. (2015), 8: Agbola, Ajayi, Taiwo, and Wahab (2012), 9: FAO (1998), 10: Liverman (1999), 11: Noland (2004), 12: Noland, Robinson, and Wang (2001), 13: Mattion et al. (2004), 14: Pollard and Christ (2008), 15: Hicks and Few (2015).

effective tool to explore potential adaptation options tested in similar agroclimatic conditions, the potential for transhumance may be better explored at the regional and potentially global levels (Henry et al., 2018). Climate analogues can also help identify the type of livestock and genotypes suitable to a given agro-ecological region, and thus how an inter-regional redistribution of livestock populations and breeds may look under future climates.

Climate resilient genotypes too, may play an essential role in maintaining productivity in regions where shifts in livestock production may not be viable, e.g. due to cultural or social reasons. Climate resilient thermo-tolerant animals will play a key role in regions with warmer winters and or warmer annual temperate ecosystems (Osland et al., 2021; Sejian, Bhatta, Gaughan, Dunshea, & Lacetera, 2018). In comparison to conventional British cattle, e.g. *Bos taurus*, tropical breeds (e.g. *Bos indicus* Nellore breeds) can reduce daily water use by up to 11 kg per head per day, while maintaining similar liveweight gain and feed conversion efficiency associated with enhanced sweating capacity and thermotolerance (Ahlberg et al., 2019; Hooper et al., 2019). However, *Bos indicus* breeds are susceptible to gastrointestinal parasites in warm and wetter climates (Navarre, 2020). Extreme weather events that result in extended wet periods such as cyclones and flash flooding have catastrophically damaged crop production in rural villages in the Philippines. Such losses have however given rise to buffalo production, given the morphological and anatomical characteristics of buffalo in engendering adaptive capacity to hot and humid climates, flooded grazing areas and muddy terrain (Escarcha, Lassa, Palacpac, & Zander, 2020). Compared with other Bovidae, water buffaloes are more susceptible to heat waves and associated stress because they have fewer sweat glands (Vilela et al., 2022). As future climate conditions transform agroecosystems, humankind will need to adapt grazing systems and livestock genotypes simultaneously [Box S1, e.g., agroforestry in South America (Peri, Dube, & Varella, 2016), novel shelter belts in the United States (Walston et al., 2018), cooling systems in Italy (Agethen & Weeks, 2020)].

More frequent extreme heat exposure constraints pasture quality in extensive grazing systems, with animals exposed to such thermal stress often showing compromised metabolic and digestive functions (Chang-Fung-Martel et al., 2021), and thus greater enteric methane production (Wilkinson & Lee, 2018). Adaption of pasture genotype [e.g., high energy ryegrass (Winichayakul et al., 2020) or plants with higher stomatal regulation (Taylor et al., 2010)] and/or selection of alternative pasture species [e.g., deep-rooted species (Meyer et al., 2021) or "warm-season" grasses known as C_4 plants (Taylor et al., 2010); Box S1] can improve water-use efficiency by up to 15–30% or reduce enteric methane emissions (Taylor, Harrison, Telfer, & Eckard, 2016). Studies conducted in Northern Europe, Canada and Southern Australia have shown that mixing grasses with deep-rooted legumes can increase 7–15% pasture yield and quality compared with monocultures, while offsetting GHG emissions by increasing soil carbon sequestration (Bilotto, Christie-Whitehead, Malcolm, & Harrison, 2023; Sturludóttir et al., 2014). Although such benefit is somewhat undermined by the greater susceptibility of legumes to dry summers, mixed pastures cope

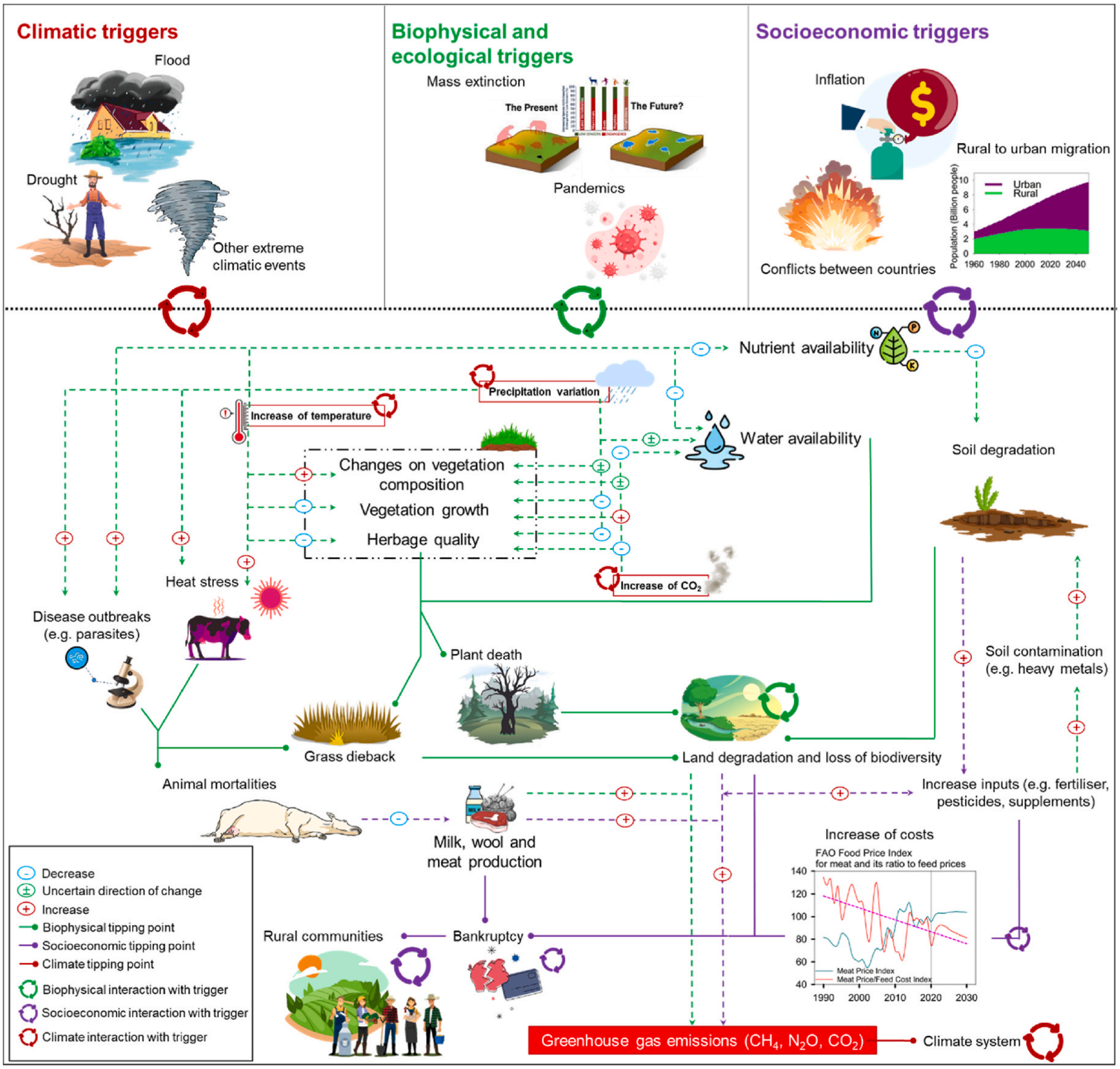


Fig. 2. Biophysical, ecological and socioeconomic tipping points at global, regional and farm scales arising from climatic effects on and from livestock systems. FCE: feed conversion efficiency; CH_4: methane; N_2O: nitrous oxide; CO_2: carbon dioxide. Assumptions underpinning the schematic are based on international research (Baker et al., 2022; Ceballos, Ehrlich, & Dirzo, 2017; Davis, Downs, & Gephart, 2021; Franzke et al., 2022; Gourevitch et al., 2021; Hellegers, 2022; Pritchard, 2011; Rasmussen et al., 2018; Rojas-Downing et al., 2017; Schutze, Tree, Hauxwell, Dickson, & Gullan, 2019; Snow et al., 2021; Sun, Scherer, Zhang, & Behrens, 2022; Thornton, Nelson, Mayberry, & Herrero, 2022; Tollefson, 2020; World Bank, 2021), including relevant databases (FAOSTAT, 2023; World Bank, 2022).

better with flooding stress by taking up nutrients as the soil dries and mitigate flood-induced N_2O emissions (Sturludóttir et al., 2014). Improved understanding of the interannual variation in seasonal forage growth and vegetation composition, as well as the use of complementary forage species, is critical for designing a resilient feedbase.

Global climate change will also impact on the ability to mitigate GHG emissions (Chang-Fung-Martel et al., 2021; Liu et al., 2021). Changes in soil moisture and temperature caused by climate change drive nutrient availability and root development with direct impacts on root surface area, dictating nutrient acquisition and nutrient-use efficiency (Wilkinson & Lee, 2018). Shifts in vegetation structure and composition resulting in lower ground cover have, in some cases, exacerbated soil erosion by water and wind, as depicted in Fig. 2 (Winichayakul et al., 2020). In developed contexts, novel strategies such as soil amendments ("hydrogels") containing potassium polyacrylate and humic complexes offer promising solutions for maintaining growth and ground cover by conserving up to 50% of water (Malik et al., 2023). Biochar in soil binds with metal/metalloids present in flood sediments and improve the sustainability of drainage systems by enhancing soil fertility, porosity and soil organic matter (He et al., 2022). Risch et al. (2019) suggest that higher temperatures together with microbial biomass in wet locations often correlates with greater levels of organic matter mineralized by soil microbes. Elevated atmospheric CO_2 may increase pasture production, potentially raising livestock carrying capacity. Nitrogen (N) mineralisation may 'acclimatise' along climate gradients where warmer and wetter climates lead to depletion of readily available organic N pools compared with soils from cooler climates (Bilotto et al., 2021; Rawnsley, Smith, Christie, Harrison, & Eckard, 2019). It is clear that future climates will negatively impact soil carbon sequestration (Bilotto, Vibart, Mackay, Costall, & Harrison, 2022; Ho, 2023; Kou-Giesbrecht & Arora, 2023).

A biological tipping point imparted by the climate crisis could engender spread of novel diseases (Ceballos et al., 2017; Tollefson, 2020), causing pandemics such as COVID-19 (Fig. 2). The COVID-19 and associated mitigation strategies have disrupted our agricultural systems via shocks to agricultural labor markets, trade and value chains (Hashem et al., 2021; Snow et al., 2021). Many smallholder farms in LMIC countries operate subsistence farming systems that while disconnected from food markets are especially vulnerable to adverse weather conditions (Franzke et al., 2022). Global problems, such as pandemics or conflicts between countries or within countries also compromise livestock production, disrupt downstream processing and distribution due to the reallocation of resources and reduced government capacities to prevent and control animal diseases (e.g. foot and mouth disease), slowing product supply against a hyperinflationary background (Hellegers, 2022; Sun et al., 2022). In the absence of adequate warning systems and defence, teleconnections between intrinsically linked multidimensional triggers can lead to a cascading sequence of socio-economic tipping points, such as individual and organisational bankruptcy, and/or collapse of corporate banking structures, which, as we have seen, sparked the Global Financial Crisis (GFC).

4. Contribution of the livestock sector to the climate emergency

Prior to the Green Revolution from 1960 to 1980, the coexistence of cropping and livestock activities on the same land was common (de Faccio Carvalho et al., 2021). Since 1970, many regions witnessed a decoupling of crop and livestock production (Garrett et al., 2020), driven by a decrease in the areas of natural grasslands and an expansion of grain production (although we acknowledge that many regions still farm crops and livestock on the same land area). This decoupling has been driven by favorable grain prices, new germplasm, low production costs and the emergence of new management practices, such as no-tillage. During the same period, livestock farming in developed countries intensified and translocated, resulting in greater stocking rates on natural grasslands, with a greater focus on rearing and finishing in areas of agricultural expansion. Although processes of intensification and specialisation of agricultural and livestock production systems are thought to have elevated productivity (de Roest, Ferrari, & Knickel, 2018), their implementation has in some cases had deleterious effects on the environment, including deforestation and loss of natural habitat (Kronberg & Ryschawy, 2019; Pretty et al., 2018). Several studies suggest that diversification and integration of mixed crop-livestock operations could enable adaptation to climatic and price variability, and potentially offer solutions to alleviate environmental impacts generated by specialised activities (Martin et al., 2016; Nie et al., 2016).

Intensification of livestock farming has led to the accumulation of organic residues in soil (N and P), pollutants as heavy metals (McDowell, Moss, Gray, Smith, & Sneath, 2021), and N emissions to water and air (Dangal, Tian, Pan, Zhang, & Xu, 2020; Mateo-Sagasta, Zadeh, & Turral, 2018). The lack of whole farm forage planning has in some cases reduced animal welfare and resulted in overgrazing, soil erosion and reduction of grassland species diversity, affecting ecosystem services, which are vital for the resilience of the system (Bardgett et al., 2021; Petz et al., 2014). Intensification of livestock production systems has increased non-CH_4 GHG emissions associated with animal production (Fig. 3 and Fig. S1) (Davis et al., 2015). ‘Circular economies’ are often purported as an avenue for decoupling the tight linear relationship between livestock production and GHG emissions. This includes (1) eliminating waste and pollution, (2) promoting circulation of products and materials, and (3) encouraging natural regeneration (Iijima et al., 2016; Peterson, Bell, Carvalho, & Gaudin, 2020; Velenturf & Purnell, 2021). Smart farming systems can optimize fertilization, minimize nutrient losses (e.g., N leaching, runoff, and denitrification), reduce soil erosion, decrease water use and energy demand, and maximize water storage for times of scarcity (Box S1). Digital twins can further modernize livestock systems by leveraging AI to harness big data, providing timely management information that improves the efficiency of water, energy, and nutrient supply (Neethirajan & Kemp, 2021; Tzachor, Richards, & Jeen, 2022). Although there may be concerns about the initial availability of such technologies in developing countries, promoting and supporting their adoption can help overcome these barriers and eventually lead to significant benefits (see section 6. *Enabling research adoption*).

During the last 50 years, poultry and pork production has grown faster than ruminant production, with drastic changes on the

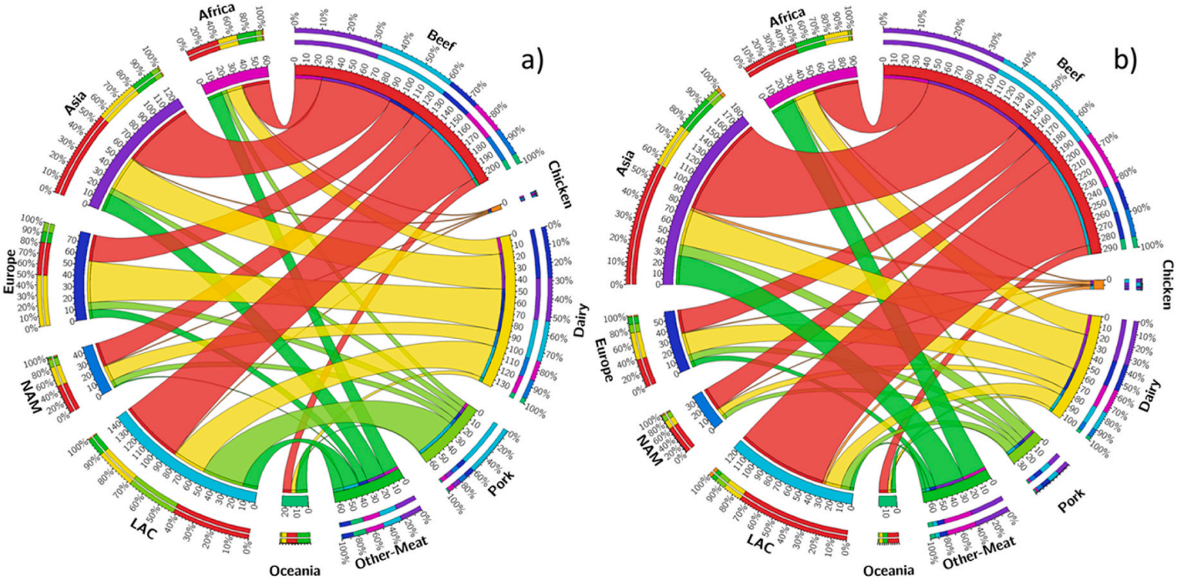


Fig. 3. Absolute and relative greenhouse gas (GHG) emissions associated with livestock industries and regions in 1961 (a) and 2017 (b). Livestock include beef (red), chicken (orange), dairy (yellow), pork (light green) and other meat (green; sheep, buffalo and goat meat). Regions include Africa (pink), Asia (purple), Europe (blue), NAM (Northern America; medium blue), LAC (Latin America and the Caribbean; light blue), Oceania (green). External segments reflect the proportion of each entity (% of total emissions from a specific livestock product in a region or vice-versa). Internal segments reflect cumulative absolute emissions (x 10 Tg CO_2e) for each entity (emissions from a specific livestock product in a region). Values adapted from Hong et al. (2021). For example, absolute GHG emissions for beef production between 1961 and 2017 shifted from ~2000 Tg CO_2e to ~2900 Tg CO_2e (internal red segments). This transformation was primarily attributed to increased GHG from Asia (+300 Tg CO_2e, purple segments) and LAC (+300 Tg CO_2e, light blue segments). These changes raised the relative livestock emission profile in LAC, with the contribution of beef increasing from 40% to 75% (red segments, left external circles) and to a lesser extent in Asia (50%–55%; red segments, left external circles). These changes increased the relative proportion of global beef GHG derived from LAC (light blue segments, external right circles). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

environmental burden per animal calorie over time. The 'land trade' for feed has tripled over the last three decades; 77% of countries currently rely on 'land imports' to support domestic livestock production (Davis et al., 2015). This phenomenon has resulted in the replacement of more than 0.5B ha of forest with pastures and crops, with a concurrent and near linear increase in global GHG emissions between 1961 and 1990 (Ritchie & Roser, 2021; Tzachor et al., 2022). From 1961 to 2017, GHG emissions from predominant livestock products (beef, poultry, pigmeat, sheep, buffalo, goat meat and dairy) increased from 4.7 Gt CO$_2$e (45% from CH$_4$, 36% from land use change; LUC) to 5.1 Gt CO$_2$e (65% from CH$_4$, 6% from LUC) (Fig. S1), peaking in the early 1990s at 5.4 Gt CO$_2$e (Hong et al., 2021). Hong et al. (2022) found that international trade has the most significant impact on land-use emissions, with the top ten net importers of emissions (mostly developed countries) tending to increase global land-use emissions, while imports into Latin American and sub-Saharan African regions tend to reduce global land-use emissions. To prevent inter-regional and international carbon leakage associated with climate mitigation efforts (Dumortier et al., 2012), it is crucial to account for land-use emissions embodied in trade.

While global net GHG emissions associated with livestock production systems has increased by 10% (considering SOC changes) over the last six decades (Hong et al., 2021), production of food equivalent units (an index used to standardise edible food) has more than trebled (Hong et al., 2021, 2022). In 1961, beef accounted for 50% of global meat production; by 2017, this value halved to around 25%. Pork and poultry meat production increased by 50% and 400%, respectively, and currently account for 24% and 20% of global meat production (Hong et al., 2021). Despite these trends, beef cattle remain the largest producer of GHG emissions associated with meat (2.9 Gt CO$_2$e or 58% of global livestock GHG emissions), while poultry and pork account for 12% of total GHG emissions (Fig. 3). In food equivalent units, changes in the relative production of major meat types together with evolving dietary preferences over the last 50 years have decreased emission intensities by 69% (kg CO$_2$e/FEU) (Manceron, Ben-Ari, & Dumas, 2014). Remarkably, less than 10% of the reduction in emission intensities has occurred since the early 2000s, with no significant changes over the last decade. Recent studies have examined how replacing ruminants with monogastric livestock may overcome this impasse, suggesting that substituting 12% of global livestock production could reduce nitrogen emissions by 2% and GHG emissions by 5% due to the lower demand for cropland areas for ruminant livestock (Cheng et al., 2022), which could feed up to 525 million people. Alternative protein sources may also play a role. Replacement of 20% of global meat consumption with single-cell protein by 2050 could decrease annual deforestation emissions by 50% (Humpenöder et al., 2022).

Over the coming decade, more than 80% of growth in livestock meat production is expected to occur in LMIC countries (Harrison et al., 2021; OECD, 2021), but more than 60% of potential GHG reduction also needs to occur in these countries if net-zero carbon has to be achieved by 2050 (FAO, 2018, p. 224). To achieve such mitigation quanta by 2050, LMICs would need to transition to abatement rates equal to those seen in developed countries (Fig. S2) even though most LMICs have very low adaptive capacity and high vulnerability to climate change (Godber & Wall, 2014) which undermines GHG mitigation potential. We suggest that decomposing factors that influence GHG emission intensity in the livestock sector may be a useful first step in developing emissions reduction policies. Net emission intensity per unit livestock output value (NEIe) may be decomposed as the product of livestock product per unit livestock output value (EVP), the proportion of regional livestock sector output relative to the global sector value (RLV) and net emissions per unit of livestock product (NEIp), as shown in Fig. 4. Since 1961, GHG emissions per unit of livestock output value (NEIe = kg CO$_2$e/US$) have been driven primarily by decreasing trends in GHG emissions per unit of the product (NEIp) and increasing economic value of the livestock sector (EVP). More than 50% of the reduction in NEIp has occurred in South America and Eastern Asia (FAOSTAT, 2023; Hong et al., 2021), while digestible protein produced per unit gross production value [ΔEVP (variation in livestock product per unit livestock sector output value) = 0.1%], grew steadily b in developed countries including Australia and New Zealand, Europe, North America and Southern Asia (FAOSTAT, 2023), the gross production value decreased given the large shifts in the basket of livestock products.

Geopolitical crises, such as the ongoing economic decentralization in Europe and conflicts in sub-Saharan Africa (Cottrell et al., 2019),

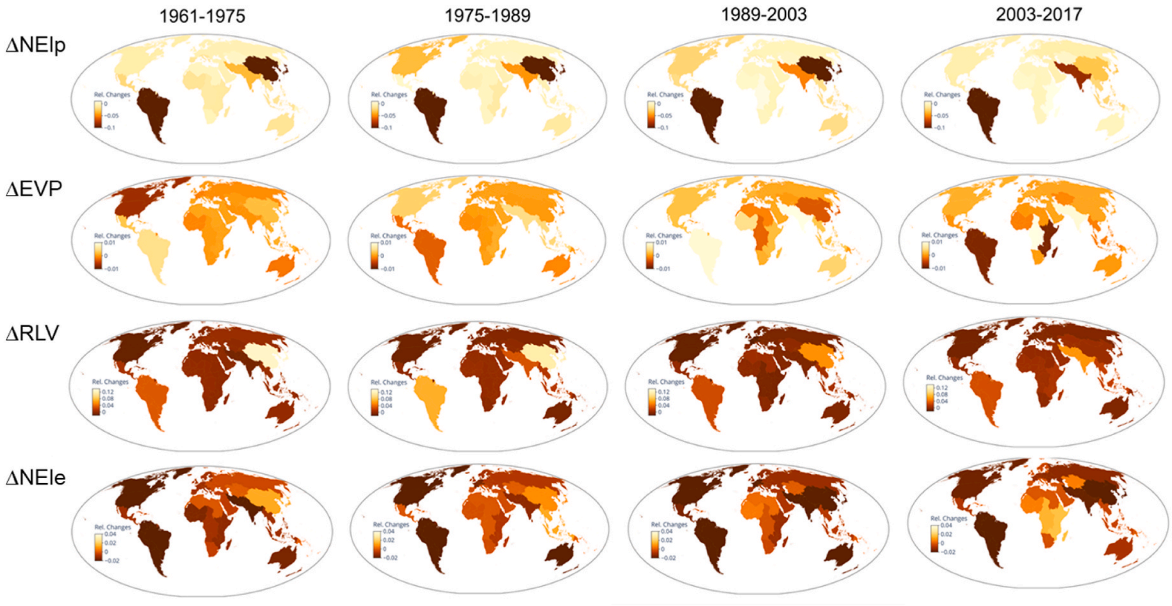


Fig. 4. Decomposition of factors contributing to declining global livestock GHG per unit livestock value (ΔNEIe) from 1961 to 2017. ΔNEIp: net GHG emissions per unit product (kg CO$_2$e/FEU); ΔEVP: livestock product per unit livestock output value (FEU/US$); ΔRLV: proportion of regional livestock sector output (US$r) relative to the global sector output (US$g) value (US$r/US$g); ΔNEIe: emissions per unit livestock output value ΔNEIe (kg CO$_2$e/US$). Negative values indicate that the factor in question drives a decline of NEIe. Values adapted from Hong et al. (2021) and analzsed following Cai, Xia, Yang, Huo, and Zhang (2019). FEU: Food Equivalent Units.

comprise key processes impacting on changes observed in digestible protein, NEIp and NEIe in our analysis. Our results were similarly sensitive to severe summer droughts in Mongolia in 2001 and 2010 that reduced fodder availability and compromised livestock condition and welfare (Cottrell et al., 2019). North America and Southern Asia together account for 20% of total GHG emission reduction and reduction in emissions/output value, although emissions per unit product changed little in North America over the period of the analysis. According to Harrison et al. (2021), Western Europe, Oceania and North America have been transitioning towards extensification/deintensification processes, resulting in reductions in either absolute animal numbers, total GHG emissions and/or GHG emission intensities. While protecting and conserving natural resources of these regions, such trends may drive upward livestock production into developing regions, such as Africa and Latin America, which, given the more premature GHG emissions mitigation policy status in these countries, may result in even greater global GHG emissions and poorer environmental outcomes compared with scenarios wherein livestock production remained in developed countries. Further analyses are required to understand how geopolitical and economic processes, extreme weather events, and livestock management dynamics impact on GHG emissions from the livestock sector.

5. Towards sustainable livestock farming

Development of systems with improved agility calls for advanced analytical frameworks that allow integrated assessment of social, economic, environmental and climatic interactions within and across regions. Popp et al. (2017) implemented a suite of Integrated Assessment models (IMAGE, MESSAGE-GLOBIOM, AIM/CGE, GCAM4, REMIND-MAGPIE) to translate shared socioeconomic pathways into quantitative projections (SSP; pathways in which global socioeconomic factors might evolve), accounting for how land-use dynamics and agricultural production systems influenced GHG emissions. These projections showed that the most optimistic scenario (SSP1: net zero CO_2 emissions by 2050) would reduce GHG emissions while enhancing ecosystems services based on lower demand for agricultural products and improved correlation between global markets. Conversely, the most pessimistic scenarios (SSP5: CO_2 emissions trebled by 2075) would result in continuous expansion of cultivated agricultural area (replacing forests, native grasslands, and shrubs), intensification (machinery, supplements, irrigation water, fertilizers and pesticides) and higher livestock densities, eliciting further environmental degradation. Regardless of the approach applied, modelled pathways may give an overly optimistic picture of the mitigation potential for agriculture to limit global warming to 1.5 °C by 2050 (Leahy, Clark, & Reisinger, 2020), because many assumptions have been based on growth in livestock production in LMIC associated with large scale adoption of technologies (Godde et al., 2020; Harrison et al., 2021).

Adaptations to climate change should be contextualized using local knowledge (Berrang-Ford et al., 2021). Rickards and Howden (2012) suggest that incremental adaptations are short-term adjustments to a given practice (e.g. pasture management, irrigation and fertilization schedules). These modifications may be extended to the medium-term through systems transitions, such as the adoption of new crops or pasture types or precision agriculture with triple bottom-line benefits (economic, environmental and social benefit, Fig. S3). Scaling up in complexity, dimensionality and risk, transformational adaptations of livestock systems (values, goals, location, system attributes) focus on building capacity for monitoring and learning, coevolving with the environment and proactively looking at emerging opportunities (Fig. S3). For example, cooperativism ensures that voluntary members obtain greater benefits through connected socioeconomic movements as opposed to acting individually (Box S1). In India, social networking institutions such as cooperatives are being used as an adaptation strategy. Cooperatives are said to elicit positive impacts on households who desire access to timely information pertaining to weather and climatic parameters for irrigation, soil and water conservation (Funk, Raghavan Sathyan, Winker, & Breuer, 2020). Only 20 countries, 10% of the parties to the UNFCCC and 30% of the parties who specify livestock as a subsector, submitted *Nationally Determined Contributions* describing adaptations that could be considered transformative for livestock production (Richards et al., 2016; Salman, Ferdinand, Carter, & Choularton, 2019).

Here, we suggest that the need to classify interventions as "transformational" is perhaps another example of the obsessive need of the scientific community to categorize, similar to other contemporary catch phrases including "climate-smart farming", "regenerative agriculture" and "agroecology". An intervention that results in a step change in only one dimension could well result in maladaptive changes in another, which would be neither useful in name nor function. We opine that the scientific community would better serve society by developing 'BIC' interventions that elicit *beneficial integrated changes* in the social, environmental, economic and biophysical dimensions; we need to move beyond reductionist interventions focusing on a siloed discipline to applied, integrated and transdisciplinary research initiatives.

Nascent adaptation opportunities may include relocating livestock production systems from regions that become uninhabitable to regions with increasing rainfall (Pugh et al., 2016), introducing new livestock species (e.g. replacement of cattle with camel breeding in Kenya with cultural awareness raising and market developments for camels) or applying new technologies and practices that facilitate both adaptation and mitigation (feeding biochar to livestock as a supplement, agrivoltaics, enhanced weathering). Adaptations may include rehabilitation of degraded grazing lands in Ethiopia or Mongolia by excluding livestock (i.e., spelling grazing) allowing improvement of soil organic matter and carbon removals (Vermeulen, Dinesh, Howden, Cramer, & Thornton, 2018). By 2050, there is global potential for around 190–296 Mha to be restored and converted to regenerative annual cropping or other productive, resilient farming systems sequestering 12–20 Gt CO_2e per year (Fig. 5). To lessen the risk of maladaptation (e.g., replacing climate-sensitive cattle with climate-resilient small ruminants or camels), breeding efforts may account for greater tolerance to climate extremes and disease risks under climate change, such as the incidence of heat stress, pests and pathogens (introducing transgenic livestock, e.g. tick resistance in *Bos indicus* cattle) (Henry et al., 2018; Zhang, McCarl, & Jones, 2017). Incremental adaptations, such as improving current breeds for climate resilience, can become transformative adaptation, securing genetic diversity of livestock breeds (tropical, subtropical and semi-arid), new species or animal types by a transformation of the breeding infrastructure itself (Salman et al., 2019). Compound climate extremes in livestock systems across different countries with varying levels of exposure (Box S1) will also necessitate comprehensive multi-stress adaptation strategies (Lesk et al., 2022).

In regions such as Middle Africa, Melanesia, Micronesia, Polynesia and Eastern Europe, climate change may have positive impacts on grasslands due to a combination of increased moisture availability and CO_2 fertilization (Hou et al., 2022). This may provide an opportunity for relocating livestock production systems from degraded lands, with limited natural capital, adverse climate change and socially unacceptable regions to new viable areas (Pugh et al., 2016; Salman et al., 2019). Farming new species or changing types of livestock rearing (e.g., transhumant to sedentary) or livestock production systems (e.g., mixed crop-livestock systems) requires new skills, knowledge, technologies and labour, which if limited, constrain the ability and value of the redesigned system (Fig. S3). Weindl et al. (2015) suggest that transitioning from livestock to cropping-only or mixed systems would reduce agricultural production costs by 0.3–3.0% globally and would reduce tropical deforestation by 76 million ha over the next 20 years.

Global cross-sector land-use opportunities for mitigation and adaptation abound, though again potential adoptability is limited by economic, land-use type and infrastructure constraints. Renewable energies on farm and onshore wind farms for example hold significant promise (Fig. 5) although require substantive capital investment and need to be

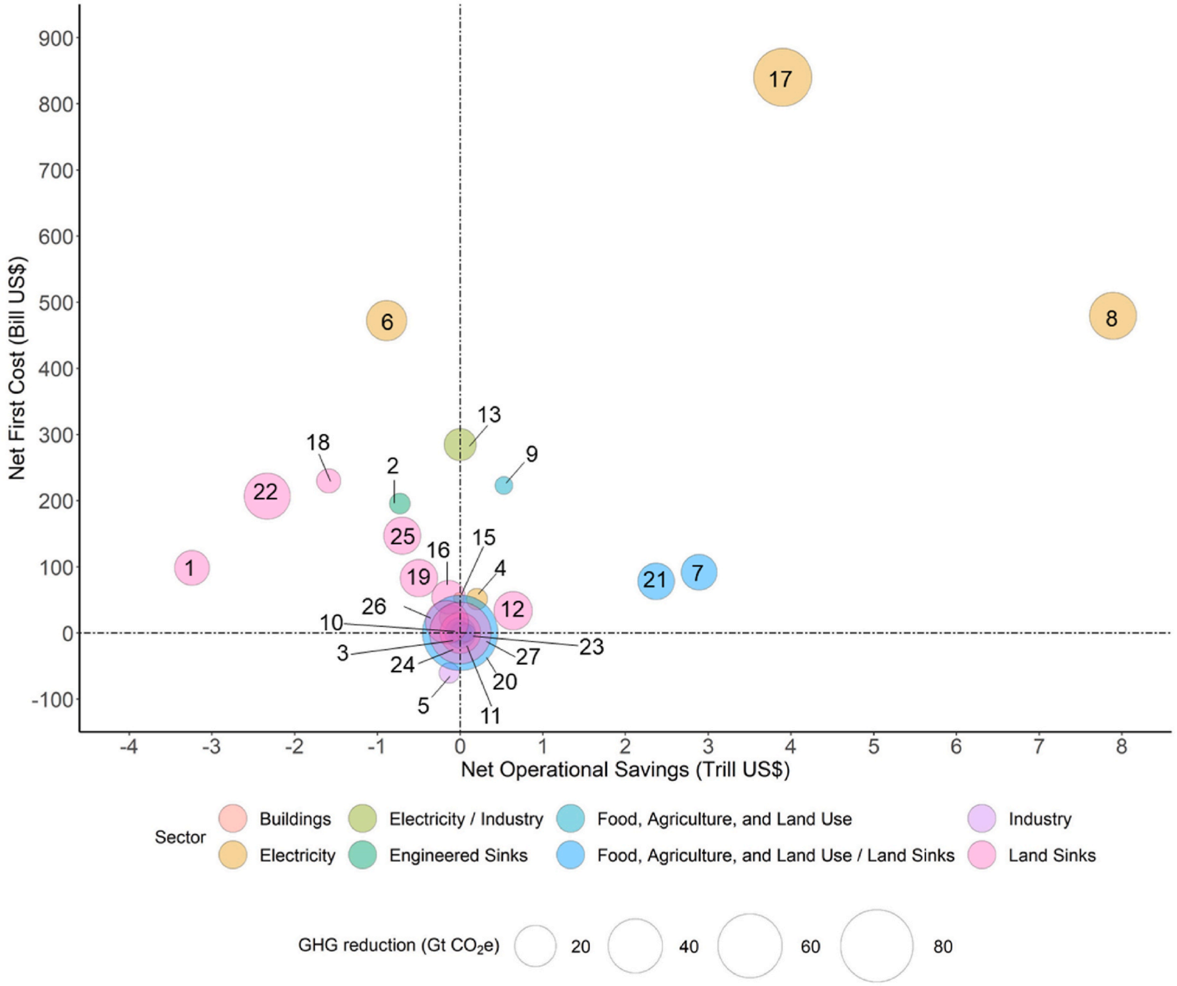


Fig. 5. Trade-offs between global agri-food mitigation, initial capital outlay and net operational savings assuming a 2 °C temperature rise by 2050.1: degraded farmland restoration, 2: biochar production, 3: biogas for cooking, 4: biomass for power, 5: composting, 6: concentrated solar power, 7: conservation agriculture, 8: distributed solar photovoltaics, 9: farm irrigation efficiency, 10: grassland protection and conservation, 11: indigenous peoples' forest tenure, 12: managed grazing, 13: methane digesters, 14: micro wind turbines, 15: agroforestry, 16: nutrient management, 17: onshore wind turbines, 18: perennial biomass production, 19: perennial staple crops, 20: reduced food waste, 21: regenerative annual cropping, 22: silvopastoral systems, 23: sustainable intensification for smallholders, 24: temperate forest restoration, 25: tree intercropping, 26: tree plantations (on degraded land), 27: tropical forest restoration. Data sourced from https://drawdown.org/solutions/table-of-solutions.

placed adjacent to appropriate powerline infrastructure (McKenna et al., 2022; Salman et al., 2019). The forestry sector too, offers substantial climate change mitigation opportunity through restoration of tropical forest and integration with livestock through silvopastoral systems (as the highest ranked solution) with increased biodiversity and removal of 26–54 Gt CO_2e by 2050 with access to carbon markets (Project Drawdown, 2020), but the irreversibility of this option could discourage adoption. Compost application, green manure, and organic production (through conservation and regenerative agriculture) could offset a further 5 Gt CO_2e, providing $US2-4 trillion. To be effective, climate change adaptations from multiple sectors should be mainstreamed in long-term national policies and actively embraced by governments, industry and institutional structures.

Addressing future land use changes towards healthier diets and sustainable agricultural systems necessitates a holistic approach, particularly in the context of livestock systems. Policies aimed at reducing greenhouse gas emissions by curtailing the production and export of certain livestock products must consider the broader socio-economic implications. While such measures may benefit the environment, they could adversely impact employment and income in rural areas, making healthy foods less affordable (Mehrabi, Gill, Wijk, Herrero, & Ramankutty, 2020). A comprehensive assessment of these benefits and trade-offs is essential to ensure that efforts to create sustainable food systems do not unintentionally harm economic stability and public health. Balancing environmental goals with socio-economic realities will be crucial for the success of these initiatives. This requires more research into the transitions needed to achieve these goals, rather than merely analyzing the impacts of implementing such changes. By understanding the pathways and necessary adjustments, policies can be better tailored to support both environmental and socio-economic objectives. This approach allows for future planning to anticipate desirable changes, such as improved livestock management practices, intended consequences like reduced GHG emissions, and potential unintended consequences, such as job losses in the agricultural sector, along the transitioning pathways. This in-depth understanding is crucial for fostering resilient and sustainable livestock systems.

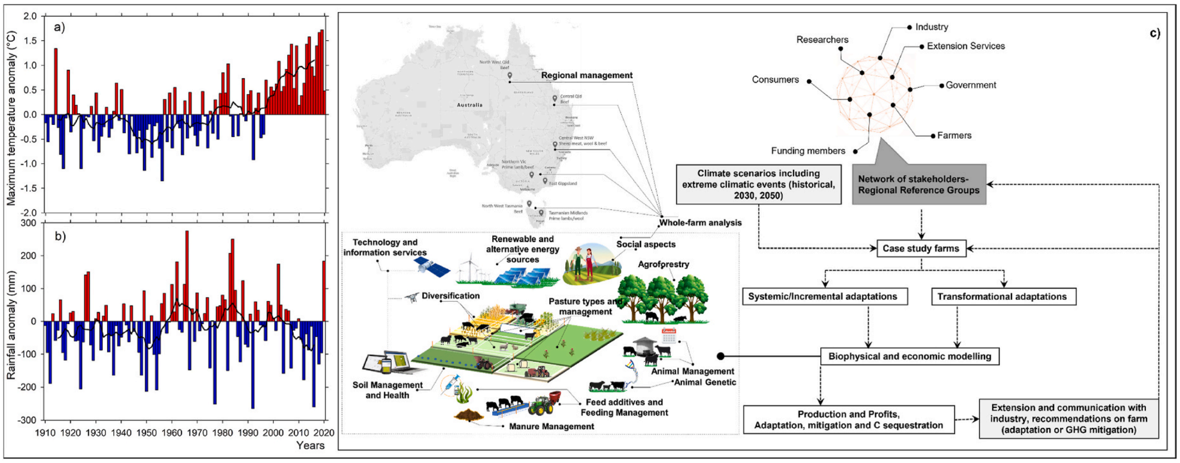
6. Enabling research adoption

Uptake and implementation of new technologies varies according to their readiness, technology-push, cost, complexity, level of systems change required for effective adoption through to end-user pull (Herrero et al., 2020). Technology readiness depends on (1) practical application and concept (foundational research), (2) critical analysis of strengths,

Box 1

End-user people-centric co-design of adaptation-mitigation bundles: the "NEXUS project"

Since 2000, climate change in south-eastern Australia has seen more frequent drought and heat waves, necessitating re- and co-design of many contemporary production systems (panels **a** and **b**). The NEXUS project (www.utas.edu.au/tia/research/research-projects/projects/nexus-project-exploring-profitable,-sustainable-livestock-businesses-in-an-increasingly-variable-climate) explores the intersection between profitability, productivity, greenhouse gas mitigation, carbon sequestration and consumer perceptions of livestock businesses under increasing climate variability (panel **c**). The project has shown that by 2030, impacts of climate change together with potential for significant carbon sequestration on grazing lands may be serious, with sequestration rates declining by 55–133%. Through people-centric learning, NEXUS assured end-user co-design to improve financial and biophysical outcomes, as well as social licence. Such methods build on extreme events frameworks implemented in Harrison, Cullen, and Rawnsley (2016) and Bilotto et al. (2023) for beef, sheep and dairy farming systems.



opportunities, weaknesses and threats for new technologies (proof of concept), (3) analysis of the market, available technology and potential adopters' behaviour, (4) whole-farm analysis of new interventions, (5) validation and demonstration in laboratory and field experiments, (6) industrial scale application studies.

Adoption and diffusion of technologies depends on the characteristics of each farm. The degree of intervention influencing relative advantage, ease and speed of learning, the characteristics and perception of rural communities and potential adopters will define the ability to learn and amplify these practices (Kuehne et al., 2017). Feeding of seaweed (*Asparagopsis* spp.) as a livestock supplement is often claimed a panacea for reducing enteric methane emissions (up to 90%) (Black, Davison, & Box, 2021), but further research is needed to develop supplement delivery options (e.g. lick-blocks) at scale, particularly for extensively grazing industries (Vijn et al., 2020).

Rickards and Howden (2012) articulate several characteristics that should be considered in the design of climate change adaptation strategies. These include (1) cross-scale and cross-sectorial shifts, (2) interconnectedness in entrepreneurial ecosystems (social capital), (3) natural capital (land, biodiversity, water, nutrient dynamics, etc), (4) education and health (human capital), (5) infrastructure and technology (physical capital) and (6) financial capital. Adaptive capacity is often dependent on end-user engagement and co-design, with ensures that proposed research solutions are fit for purpose, credible and legitimate (Box 1). Governments must support existing strategies and emerging technologies to enhance adaptive capacity in transforming the livestock sector and mitigating climate change impacts. Effective policies like subsidies, grants, and tax incentives can boost food security, conserve resources, and reduce GHG emissions (Laborde, Mamun, Martin, Piñeiro, & Vos, 2021). The Australian red meat industry aims for Carbon Neutral status by 2030, reducing net GHG emissions by 78% since 2005 (Mayberry, 2024). This significant decrease is due to improved carbon storage, reduced deforestation, and lower livestock emissions. The industry promotes carbon credits and sustainable practices, offering both environmental and financial benefits. Demand-side policies affecting market dynamics, labelling, and consumer awareness are crucial for effective GHG mitigation (Moran & Blair, 2021; Rondoni & Grasso, 2021). As demand for animal protein rises, there is a significant opportunity to promote sustainable practices and achieve 2050 climate targets (Arndt et al., 2022).

Artificial intelligence (AI) can revolutionize livestock systems by accelerating processes and enabling virtual testing of interventions across farms, food supply chains, and industries. The U.S. Department of Agriculture's National Institute of Food and Agriculture (USDA-NIFA) and the National Science Foundation (NSF) announced a US$220 million investment in 11 new NSF-led AI Research Institutes to enhance food security and resilient agriculture (USDA, 2021). The main goal of this initiative is to leverage AI for societal benefits, promote equitable access, and enhance education, with partners like Google, Amazon, Intel, and DHS. As a prime example of AI applied to livestock systems, digital twins—virtual representations of physical systems—can assist monitor health data through sensors to detect early signs of illness, allowing timely interventions and reducing disease risks (Mishra & Sharma, 2023; Neethirajan & Kemp, 2021). This technology can optimize nutrition, herd sizes, and management strategies, improving productivity and reducing costs (Chen, Zheng, Chen, Zhang, & Huang, 2024; Raba, Tordecilla, Copado, Juan, & Mount, 2022; Zhang et al., 2023). For breeding, digital twins analyze genetic data and environmental factors to select optimal breeding pairs, enhancing traits like milk production and disease resistance (Sagwa Barasa, 2021). Additionally, digital twins can enhance market and supply chain optimization by predicting trends, managing inventory, and optimizing logistics (Gallego-García, Gallego-García, & García-García, 2023). Overall, AI can help to improve animal health, productivity, resource management, and sustainability, contributing to more efficient and profitable farm operations. This technology enables equitable access and inclusivity, ensuring that people, regardless of whether they are in developed or developing countries, can benefit from these advancements and break barriers to adoption.

7. Summary and future perspectives

Extreme weather events, such as longer heat waves and droughts, floods and tropical cyclone activity have quadrupled over the last 50 years, causing severe losses in agricultural livestock production. Anthropogenic climate change has slowed productivity growth by 21%, with more severe impacts in the warmer regions of Africa, Latin America and the Caribbean. The lack of early warning systems, inadequate representation of extreme weather events, poor infrastructure and insufficient response planning has meant that impacts of extreme events have historically imparted substantially more economic and environmental damage than they ought to. Improved forecasting of extreme events with greater lead times would allow for better preparation of food systems, although current technologies are neither accurate nor affordable enough for widespread, equitable use.

In a broader context, tipping points such as climatic events (e.g. Antarctic ice sheet melting), economic crises (e.g. the Global Financial Crisis), ecological disasters (e.g. mass extinction due to deforestation), humanitarian health crises (e.g. COVID-19) and geopolitical conflicts (e.g. the Russia-Ukraine conflict), require further consideration. Processes for predicting and preparing for tipping points would potentially help avoid irreversible change. It is ironic that although gradual climate change receives significantly more attention due to its long-term and permanent effects, it is the associated shocks, extreme events, and tipping points that often cause catastrophic damage. This is perhaps because climate change is more amenable to prognostication, while tipping points and extreme events are difficult to predict in frequency, location and magnitude. Similar concepts apply to tipping points in the economy, humanitarian health systems and geopolitics.

Concurrently, changes in livestock production systems supply chains, together with evolving dietary preferences, have helped reduced emission intensities by 69% over the last 50 years. However, emission intensities over the last decade have stagnated, suggesting a need for innovations that sustainably raise productivity per unit GHG emissions. Despite falling global numbers of sheep and beef, beef cattle remain the largest producer of GHG emissions (58% of global GHG emissions), while poultry and pork account for less than 10% of total GHG emissions. Over the coming decade, LMIC are expected to produce more than 80% of total livestock meat growth, yet these nations often have the lowest adaptive capacity. Consequently, prioritizing research, development, and extension in LMICs could have the greatest impact on global climate change mitigation, agri-food production improvement and poverty alleviation.

Therefore, in response to the escalating effects of climate change with livestock emissions as a significant part of the equation, the realization of adaptation-mitigation interventions relies on stakeholder engagement to contextualize and refine proposed solutions. Integrating strategies into sectoral development plans and policy wis crucial for ensuring food security, sustainable resource use and GHG reduction in the medium- and long-term. Relocating livestock production systems from climate-vulnerable regions to those with more favorable conditions could represent a transformational solution, but it requires extensive participatory development to address local needs, capabilities, cultural and socio-economic context. To leverage societal benefits and promote equitable access, the use of digital twins to optimize breeding and enhance traits like milk production and disease resistance in local conditions is just one example of how artificial intelligence can help transform our livestock systems. The incorporation of climate-resilient livestock and plant species, the integration of forestry, energy, and agricultural sectors (e.g., silvopastoral systems and agrivoltaics), and the adoption of new management practices and technologies (e.g., feeding biochar or *Asparagopsis* spp. to livestock) are promising cross-sectoral and cross-scale regional adaptation-mitigation interventions. These initiatives will need robust government support, effective policies, and incentives to enhance food security, conserve natural resources, and reduce GHG emissions.

Author contributions

F.B., M.T.M., R.V., A.M., K.M.C–W., C.S.S.F., R.C., D.F., J.C. conceiving and/or designing the research output. F.B., M.T.M., K.M. C–W. acquired research data where the acquisition has required significant intellectual judgement, planning, design or output. F.B., M.T.M., R. V., A.M., K.M.C–W contributing knowledge, where justified, including indigenous knowledge. F.B., M.T.M., R.C. analysing and/or interpreting databases. F.B., M.T.M., R.V., A.M., K.M.C–W., C.S.S.F., R.C., D.F., J.C. drafting significant parts of research output/s or critically revising output/s to contribute to interpretation.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tifs.2024.104668.

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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