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Capturing Grasslands in Nationally Determined Contributions and Integrated Assessment Models: Review and Perspective

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Key Points:

- Forward-looking quantitative mitigation targets for ruminant livestock and grasslands remain limited in current NDCs
- IAMs represent grassland-livestock systems in a highly simplified form, limiting their ability to capture management and carbon dynamics
- The dominance of inventory-based accounting and limited forward-looking targets reveals an information imbalance between NDCs and IAMs

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Grasslands support the majority of global livestock production systems while providing vital ecosystem services. Expansion of the livestock sector over recent decades has however placed enormous pressure on grasslands, with increasing greenhouse gas emissions that challenge the aspirations of climate mitigation. Here, we reviewed (a) climate policies pertaining to livestock and grasslands underpinning the Nationally Determined Contributions (NDCs) of 16 countries or regions, and (b) representation of grassland and livestock sectors in five contemporary integrated assessment models (IAMs). We find that mitigation policies reported in NDCs and Biennial Update/Transparency Reports (BURs/BTRs) remain limited in their specification of clearly defined forward-looking quantitative mitigation targets for ruminant livestock and grassland systems, despite their substantial contribution to agricultural emissions. At the same time, many reported policies are articulated in ways that support inventory-compatible, retrospective accounting. Contemporary IAMs, however, employ a highly simplified and aggregated representation of grassland–livestock interactions, with limited consideration of management intensity, degradation, restoration, and management-induced carbon dynamics. Taken together, these features reveal an information imbalance at the interface between policy articulation and model-based quantitative assessment, which may limit the transparency and cross-country comparability of evaluations of mitigation pathways in grassland and ruminant livestock systems.

Plain Language Summary Grasslands support most of the world's livestock production systems and play an important role in climate change mitigation. Many countries include livestock and grasslands in their climate pledges under the Paris Agreement, while integrated assessment models (IAMs) are used to explore future mitigation pathways. In this study, we reviewed climate policies related to livestock and grasslands in the Nationally Determined Contributions and Biennial Transparency/Update Reports of 16 major countries and regions, and examined how these systems are represented in widely used IAMs. We find that policies often focus on tracking emissions after actions are taken, but rarely specify in advance how much mitigation is expected from livestock or grassland management. At the same time, current models represent grassland-livestock systems in a highly simplified way and have limited ability to reflect management practices. These gaps make it difficult to assess future mitigation pathways consistently across countries. Improving both policy descriptions and model representations would support more transparent and robust climate assessments.

1. Introduction

Grasslands, characterized by prevalent grass species and a scarcity of trees or shrubs (Dengler et al., 2014; Suttie et al., 2005; Wilsey, 2018), encompass diverse ecosystems, including open grasslands, open shrublands and savannas (Figure 1). From the perspective of human appropriation, they comprise natural grasslands, semi-natural

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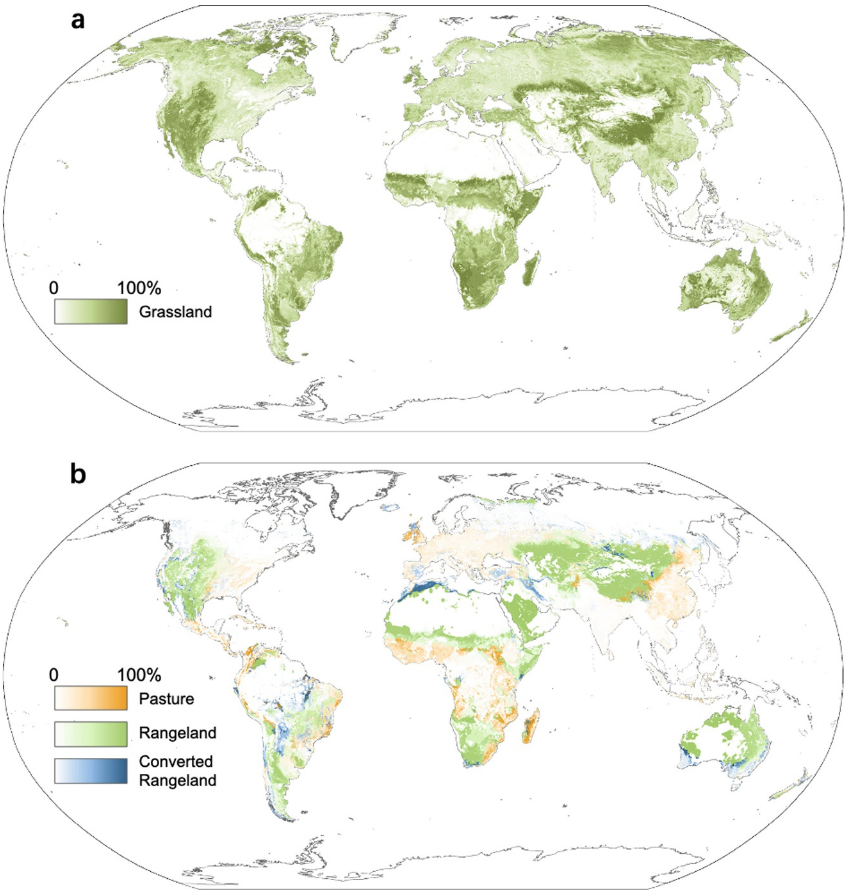

Figure 1. Global grassland distribution (a) and utilization (b) in 2020. Gridded grassland fraction by 2020 (a) obtained by the natural and managed grassland area by 2020 from the plant-functional-type maps consistent with the ESA CCI/C3S Land Cover map (Harper et al., 2023) minus the cropland area by 2020 from HYDE 3.3 (Klein Goldewijk, 2024). Gridded grassland utilization map (pasture with higher utilization intensity, rangeland with lower utilization intensity and converted rangeland from other land types) by 2020 is derived from HYDE 3.3. Proportion of area within each 0.08333° × 0.08333° land grid is shown.

rangelands, and intensively managed grasslands/pastures, constituting approximately 40% of the global ice-free land surface and 69% of agricultural areas (Bardgett et al., 2021). Grasslands, especially those that are extensively managed, are home to a huge amount of biodiversity (Habel et al., 2013; Murphy et al., 2016), harbor many unique species not found in forests (Bond, 2016; Feurdean et al., 2018), and provide numerous ecosystem functions and services (Bengtsson et al., 2019; Yahdjian et al., 2015) including water conservation, flood control, soil erosion regulation, potentially for climate mitigation, and both a habitat and feed for livestock husbandry.

Grasslands play an important role in terrestrial carbon cycling (Chang et al., 2021; Sándor et al., 2020) and comprise a large carbon pool with the majority of grassland carbon stored underground in the form of root biomass and soil organic carbon (White et al., 2000). Recent global syntheses indicate that grassland soils contain approximately 20% of the world's soil organic carbon stocks, underscoring the central role of grassland belowground carbon pools in the global carbon cycle (Dondini et al., 2023). While the direction and magnitude of global net carbon fluxes across all grasslands are uncertain Yang et al. (2022), it has been suggested that some natural and sparsely grazed grassland can serve as a carbon sink (Chang et al., 2021), and substantial carbon sequestration potential can be achieved by restoring biodiversity, improving grazing management and legume sowing (Bai & Cotrufo, 2022).

As the cornerstone for livestock production, grasslands provide livestock feed and husbandry and thus the livelihoods of pastoralists (Matthew T. Harrison et al., 2014, 2021). Ruminants are efficient at converting human inedible fiber and forage (such as grasses) to edible food, and provide milk and meat as critical sources of energy, protein and micronutrient for sustaining food security (Herrero et al., 2023). Global meat production from cattle, buffalo, sheep, and goats reached 93.8 million tonnes, accounting for about 25.8% of total meat production by 2024 (FAOSTAT, 2026) while milk provided twice the energy supply from ruminant meat (O'Mara, 2011). In terms of protein supply, ruminant meat and milk account for 15.6% of the world's total protein supply and 37.1% of animal production by 2023 (FAOSTAT, 2026). Despite the increasing use of concentrate feeds, grasslands remain a major source of feed for ruminant livestock, particularly in extensive and mixed production systems (Herrero et al., 2023; Jiang & Wang, 2022; Wróbel et al., 2025).

The escalating demand for livestock products positions the livestock industry for further expansion, intensifying environmental concerns (Clark et al., 2020; Van Dijk et al., 2021). Livestock husbandry is a key source of anthropogenic greenhouse gas (GHG) emissions, accounting for 14%–18% of global total emissions (Gerber et al., 2013; Steinfeld, 2006), where grassland livestock husbandry is one of the major contributors (Herrero et al., 2013). Considering the entire process of food system production and consumption, food system emissions represent 34% of total anthropogenic GHG emissions (Crippa et al., 2021), while GHG emissions from ruminant products account for 73.2% of animal-based food emissions and 41.4% of total food emissions (Xu et al., 2021). Increasing production of livestock farming on grassland has not only increased CH_4 and N_2O emissions from livestock, and CO_2 emissions from land conversion (Chang et al., 2021), but also caused grassland degradation in many regions (Fetzel et al., 2018; Hilker et al., 2014). On the other hand, improving livestock management, manure spreading and sowing legumes in pasture can reduce and partially offset carbon emissions (Bai & Cotrufo, 2022). Restoration of degraded grasslands has therefore been widely discussed as a potential pathway for enhancing terrestrial carbon sinks and moderating emissions from grassland–livestock systems (Bai & Cotrufo, 2022; Matthew Tom Harrison et al., 2021).

Assessing the future role of grassland–livestock systems in climate mitigation requires analytical frameworks capable of capturing interactions between food demand, land use, and management practices at large spatial scales (Matthew Tom Harrison & Liu, 2024). Process-based grassland models or ecosystem models are often used for simulating the response of grassland productivity to climate change and management practices (Chang et al., 2021; Forster et al., 2022; Rolinski et al., 2018). Land-use components of IAMs are often applied for exploring future pathways in animal-based food demand and livestock development (including feed, forage production, and relevant livestock system and land-use changes) under various scenarios of socio-economic development, climate action, technological change, and policy intervention (Gambhir et al., 2019; Popp et al., 2017). However, the extent to which current IAMs provide sufficiently detailed and policy-relevant representations of grassland management and ruminant livestock systems, especially for assessing climate mitigation measures, remains unclear.

At the international level, Nationally Determined Contributions (NDCs) serve as the primary instruments through which countries communicate their mitigation commitments under the Paris Agreement (Calvin et al., 2023; UNFCCC, 2025). Beyond economy-wide emission targets, NDCs often include sector-specific policies, measures, and strategic directions reflecting national priorities, technological contexts, and development pathways. While some studies have examined the role of agriculture or livestock in NDCs (e.g., Luo et al., 2024; Vyas et al., 2022), systematic assessments focusing specifically on ruminant livestock and grassland ecosystems remain scarce, particularly with regard to the specificity of policy instruments and the potential for cross-country comparison.

The aims of this paper are to (a) summarize existing mitigation measures associated with ruminant livestock farming and grassland systems in the NDCs of 16 predominant agricultural and livestock-producing countries/regions, with particular attention to how these measures are framed and their relevance for quantitative assessment; (b) review the representation of livestock, grassland, and their interactions in a few IAMs or land-use components of the IAMs; and (c) identify structural gaps and opportunities at the interface between policy articulation in NDCs and model-based quantitative assessment in IAMs, with implications for improving the transparency and interpretability of grassland–livestock mitigation pathways.

2. Representation of Mitigation Policies Relating to Livestock and Grassland Systems in the Nationally Determined Contributions (NDCs)

2.1. Selection of Countries/Regions

Following the Paris Agreement, 195 countries have submitted their NDCs outlining their goals and action plans for climate change mitigation. We collected the 2024 National GHG Inventory Reports (NIRs), latest NDCs and 2024 Biennial Transparency/Update Reports (BTRs/BURs) for as selected set of countries and regions.

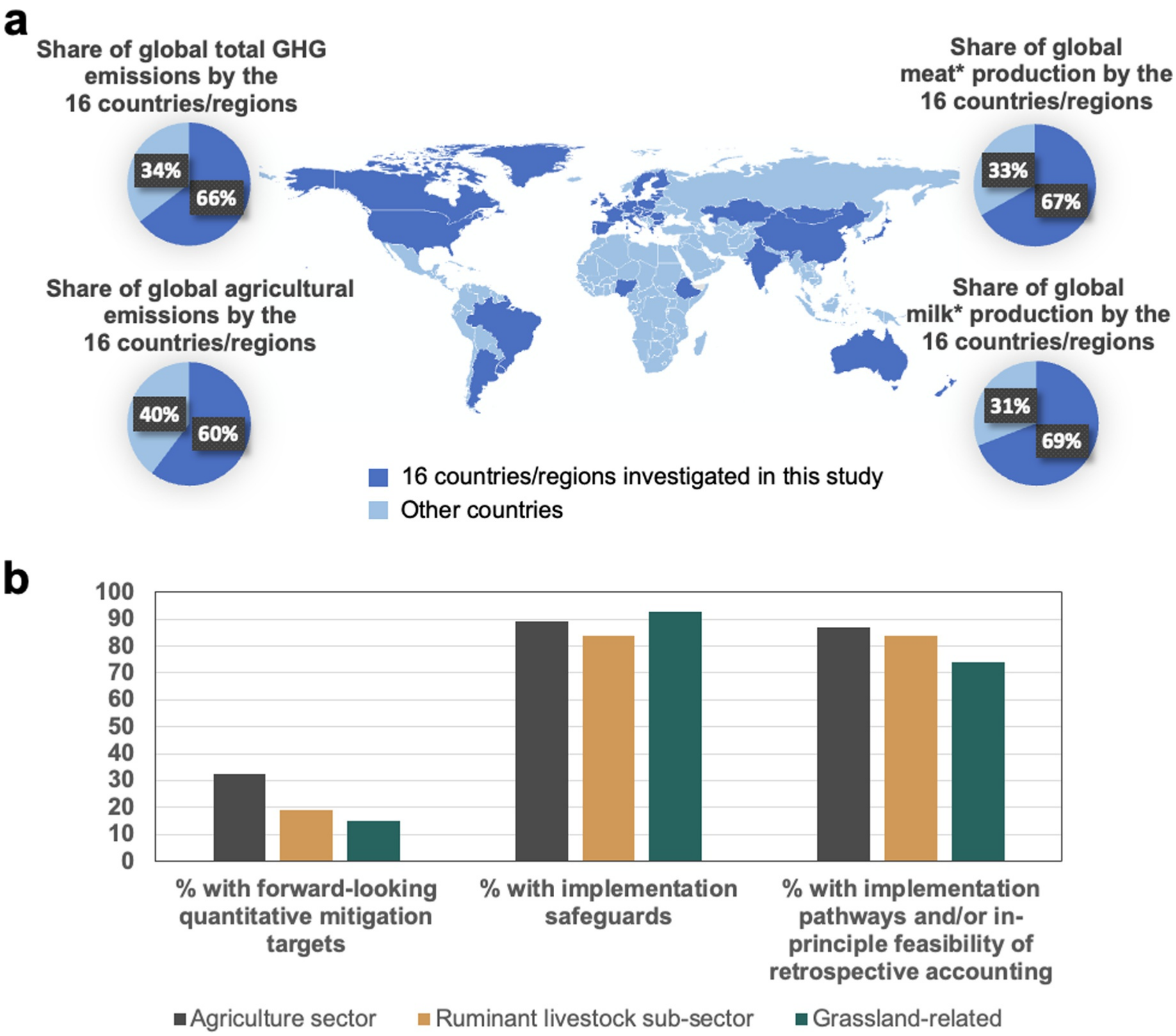

Figure 2. Global coverage of the investigated countries/regions and sectoral articulation of mitigation-related policies in NDCs and BURs/BTRs. Panel (a) global coverage of the 16 countries/regions investigated in this study. Countries and regions included in the analysis are highlighted in dark blue, while all other countries are shown in light blue. The accompanying pie charts illustrate the share of global total greenhouse gas (GHG) emissions, global agricultural emissions, global meat* production, and global milk* production represented by the investigated countries/regions. Shares of global total GHG emissions and global agricultural emissions are derived from the GHG emissions of all world countries—JRC/IEA 2025 Report (Crippa et al., 2025), based on the most recent nationally reported and harmonized inventory data available. Meat and milk production shares (marked with an asterisk) refer exclusively to ruminant production, including cattle, buffalo, sheep, and goats, consistent with the scope of this study. Meat and milk production shares are based on FAOSTAT (2026), using the most recent production statistics available for 2024. Panel (b) sectoral aggregation of mitigation-related policies reported in NDCs and BURs/BTRs for the agriculture sector, ruminant livestock sub-sector, and grassland-related policies. Bars indicate the percentage of assessed policies that specify quantitative mitigation targets, implementation safeguards, and implementation pathways and/or the in-principle feasibility of retrospective accounting, respectively. Percentages are calculated based on the total number of policies assessed for each sector (Table 1), following the analytical framework and level-specific criteria described in Section 2.2 and Text S1 of Supporting Information S1.

Country selection was guided by three complementary criteria. First, global system relevance was considered by including major agricultural and livestock-producing countries/regions accounting for a substantial share of global agricultural output, livestock production, and associated GHG emissions. Second, diversity of livestock production systems and grassland dependence was ensured by incorporating countries representing contrasting livestock systems, ranging from industrialized and mixed crop–livestock systems to grassland-dependent pastoral systems. Third, geographical coverage and developmental representation were taken into account to capture variation across world regions and income levels.

Based on these criteria, the final sample comprises 16 countries/regions: Australia, Argentina, Brazil, Canada, China, Ethiopia, India, Japan, Kazakhstan, Mongolia, New Zealand, Nigeria, Uruguay, the European Union, the United Kingdom, and the United States (Figure 2; Table 1; Table S1). Collectively, these countries/regions

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Table 1
Mitigation Targets, Policies and Measures for Agriculture Sector, Ruminant Livestock Sub-Sector, and Grassland Presented in the Latest NDCs and BURs/BTRs of the 16 Countries/Regions Investigated in This Study

Country/Region	Targets, policies and measures in the nationally determined contributions (NDCs) or the biennial transparency/Update reports (BTRs/BURs)					Source
	Reference year	Mitigation target	Agriculture sector	Ruminant livestock sub-sector	Grassland-related policies	Latest status of NDC Submission/Update
Australia	2005 (incl. LULUCF)	62%–70% below 2005 levels by 2035 (economy-wide, incl. LULUCF)	Australian Carbon Credit Unit Scheme (ACCU)[a] [2,−/+/+/M], Carbon Farming Outreach Program (more than $17.5 + 30.8 million)[1,−/+/+/V], Climate-Smart Agriculture Program under the Natural Heritage Trust ($302.1 million in 2023–2028)[1,−/+/+/V], The National Soil Action Plan 2023 to 2028 ($20 million)[2,−/+/−/V],	ACCU[a] [2,−/+/+/M], Methane emissions reduction in livestock ($29 million) [1,−/+/+/V], Carbon Farming Outreach Program [1,−/+/+/V], Climate-Smart Agriculture Program under the Natural Heritage Trust [1,−/+/+/V]	ACCU[a] [2,−/+/+/M], Nature Repair Market[a] [2,−/+/−/M], Australia's Strategy for International Union for Conservation of Nature, 2024–2030[a] [2,−/+/−/V]	2035 NDC (Australia, 2025), 2024 BTR (Australia, 2024)
Canada	2005 (excl. LULUCF)	45%–50% below 2005 levels by 2035 (economy-wide, excl. LULUCF)	Carbon markets[a] [2,−/+/+/M], Agricultural Clean Technology Program ($429.4 million in 2023-2028)[a] [1,−/+/+/V], Agricultural Climate Solutions—On-Farm Climate Action Fund[a] ($704.1 million in 2021–2031, 2.7 Mt CO2e 2030 expected) [1,+/+/+/V], Agricultural Climate Solutions—Living Labs program ($185 million in 2021–2031, 1 Mt CO2e 2030 expected)[a] [1,+/+/+/V], Resilient Agricultural Landscape Program[a] [1,−/+/+/V]	On-Farm Climate Action Fund[a] [1,+/+/+/V], Living Labs program[a] [1,+/+/+/V], Resilient Agricultural Landscape Program[a] [1,−/+/+/V], Agricultural Methane Reduction Challenge ($12 million)[1,−/+/+/V]	Nature Smart Climate Solutions Fund[a] ($1.4 billion, 5-7 Mt CO2e by 2030) [1,+/+/+/V]	2035 NDC (Canada, 2025), 2024 BTR (Canada, 2024a)
The United Kingdom	1990 (incl. LULUCF)	At least 81% below 1990 levels by 2035 (economy-wide, incl. LULUCF)	ELM (Environmental Land Management)[a]: Sustainable Farming Incentive (SFI)[a] [1,−/+/+/V], Countryside Stewardship (CS)[a] [1,−/+/+/V], Landscape Recovery (LR)[a] [1,−/+/+/V],	ELM-SFI[a] [1,−/+/+/V], ELM-CS[a] [1,−/+/+/V]	ELM-SFI[a] [1,−/+/+/V], ELM-CS[a] [1,−/+/+/V]	2035 NDC (UK, 2025), 2024 BTR (UK, 2024a)
The United States	2005 (incl. LULUCF)	61%–66% below 2005 levels by 2035 (economy-wide, incl. LULUCF)	Partnerships for Climate-Smart Commodities ($3.125 billion, 5834 kt CO2e 2030 expected)[1,+/+/+/V], Environmental Quality Incentives Program (EQIP)[1,−/+/+/V], Conservation Stewardship Program (CStP, $3.25 billion from IRA)[1,−/+/+/V], Regional Conservation Partnership Program (RCPP, $1 billion in 2023)[1,−/+/+/V], Conservation Innovation Grants (CIG, $90 million in 2023)[1,−/+/+/V]	Partnerships for Climate-Smart Commodities [1,+/+/+/V], EQIP [1,−/+/+/V], CStP [1,−/+/+/V], RCPP (115 million in 2024) [1,−/+/+/V]	Conservation Reserve Program [1,−/+/+/V], RCPP [1,−/+/+/V], CIG [1,−/+/+/V]	2035 NDC (US, 2024b), 2024 BTR (US, 2024a)

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Table 1
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Country/Region	Targets, policies and measures in the nationally determined contributions (NDCs) or the biennial transparency/Update reports (BTRs/BURs)					Source
	Reference year	Mitigation target	Agriculture sector	Ruminant livestock sub-sector	Grassland-related policies	Latest status of NDC Submission/Update
Japan	2013 (excl. LULUCF)	60% below 2013 levels by 2035 and 73% by 2040 (incl. LULUCF credits)	Reduction of methane emissions in paddy fields (1040 kt CO2eq 2030 expected)[1,+/+/+/V], Reduction of nitrous oxide associated with fertilization (244 kt CO2eq 2030 expected) [1,+/+/+/V], Policies and measures to increase carbon removals in agricultural soils [1,+/+/+/V]	No policies meeting the inclusion criteria	Policies and measures to increase carbon removals in agricultural soils [1,+/+/+/V]	2035/2040 NDC (Japan, 2025), 2024 BTR (Japan, 2024a)
European Union	1990 (incl. LULUCF)	66.25%–72.5% below 1990 levels by 2035 (incl. LULUCF)	The Effort Sharing Regulation (ESR)[a] [2,+/+/+/M], LULUCF Regulation[a] [2,+/+/+/C], Certification for carbon removals and carbon farming [2,−/+/+/V], CAP Eco-schemes (2023–2027)[1,−/+/+/V], Enhanced CAP conditionality (GAECs) [2,−/+/+/C], Nitrates Directive [2,−/+/+/C], Farm to Fork Strategy (F2F)[2,+/+/−/C]	CAP Eco-schemes (2023–2027)[1,−/+/+/V], F2F [2,−/+/−/C]	LULUCF Regulation[a] [2,+/+/+/C], Certification for carbon removals and carbon farming [2,−/+/+/V], CAP Eco-schemes (2023–2027)[1,−/+/+/V], GAECs [2,−/+/+/C], Nature Restoration Regulation [2,−/+/+/C] Soil Monitoring Law [2,−/+/−/C]	2035 NDC (EU, 2025), 2024 BTR (EU, 2024a)
New Zealand	2005 (excl. LULUCF)	51%–55% below gross 2005 levels by 2035 (incl. LULUCF)	The Second Emissions Reduction Plan (ERP2, 0.2 Mt CO2e)[2,+/+/+/C], On-farm agricultural emissions pricing by 2030 [2,−/+/−/C]	ERP2 [2,+/+/+/C], On-farm agricultural emissions pricing by 2030 [2,−/+/−/C]	No policies meeting the inclusion criteria	The Second NDC (New Zealand, 2025), 2024 BTR (New Zealand, 2024a)
China	Peak year (not specified)	7%–10% below peak net GHG emissions by 2035 (economy-wide), with ambition to exceed	Action Plan for Methane Emission Control[a] [2,−/+/−/C], Carbon Sink Capacity Consolidation and Enhancement Action [2,−/+/−/C], Implementation Plan for Agricultural and Rural Emission Reduction and Carbon Sequestration [2,−/+/−/C]	Action Plan for Methane Emission Control[a] [2,−/+/−/C], Implementation Plan for Agricultural and Rural Emission Reduction and Carbon Sequestration [2,−/+/−/C]	Integrated Protection and Restoration Project of Mountains, Rivers, Forests, Farmlands, Lakes, Grasslands and Deserts[a] [1,−/+/+/C], Implementation Plan for Consolidating and Enhancing Ecosystem Carbon Sink Capacity[a] [2,−/+/−/C], Carbon Sink Capacity Consolidation and Enhancement Action [2,−/+/−/C], Opinions on Strengthening Grassland Protection and Restoration [2,−/+/+/C]	2035 NDC (China, 2025), 2024 BTR (China, 2024)

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Table 1
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Country/Region	Targets, policies and measures in the nationally determined contributions (NDCs) or the biennial transparency/Update reports (BTRs/BURs)					Source
	Reference year	Mitigation target	Agriculture sector	Ruminant livestock sub-sector	Grassland-related policies	Latest status of NDC Submission/Update
Argentina	Absolute target (incl. LULUCF)	Economy-wide emissions capped at 349 Mt CO_2e in 2030 (incl. LULUCF)	National Plan for Climate Change Adaptation and Mitigation (PNAyMCC)[a] [2,+/+/+]	PNAyMCC[a] [2,−/+/−/C]	No policies meeting the inclusion criteria	The Second NDC (Argentina, 2021), 2024 BTR (Argentina, 2024a)
Brazil	2005 (incl. LULUCF)	59%–67% reduction below 2005 levels by 2035 (economy-wide, incl. LULUCF)	The Plan for Adaptation to Climate Change and Low Carbon Emissions in Agriculture (ABC + Plan)[a] [2,+/+/+/C]	National Program for the Conversion of Degraded Pastures into Sustainable Agricultural and Forestry Production Systems (PNCPD)[a] [2,−/+/−/C], ABC + Plan[a] [2,+/+/+/C]	National Plan for the Recovery of Native Vegetation (PLANAVEG)[a] [2,−/+/−/C], ABC + Plan[a] [2,+/+/+/C]	The Second NDC (Brazil, 2024a), 2024 BTR (Brazil, 2024b)
India	2005 (incl. LULUCF)	45% reduction in emissions intensity of GDP below 2005 levels by 2030 (economy-wide, incl. LULUCF)	System of Rice Intensification [1,−/+/+], Direct Seeded Rice [1,−/+/+], Crop Diversification Programm [1,−/+/+], Crop Residue Management (SMAM) [1,−/+/+], Neem Coated Urea [1,−/+/+],	Balanced Ration for Livestock [1,−/+/+/V], Feeding bypass proteins [1,−/+/+/V], Green fodder supplementation [1,−/+/+/V], Silage feeding [1,−/+/+/V]	No policies meeting the inclusion criteria	Updated First NDC (India, 2022), Fourth BUR (India, 2024)
Mongolia	BAU 2035 (base year 2010 excl. LULUCF)	30.3% below BAU emissions by 2035 (unconditional); 46.3% incl. forest removals; up to 52.8% with conditional measures	No policies meeting the inclusion criteria	Regulation of livestock numbers and structural optimization [1,−/−/+/C]	No policies meeting the inclusion criteria	NDC 3.0 (Mongolia, 2025), 2024 BTR (Mongolia, 2026)
Kazakhstan	1990 (incl. LULUCF)	17% reduction below 1990 (unconditional), 25% with international support by 2035 (economy-wide, incl. LULUCF)	Increase the share of manure and crop residues utilized for energy[a] [1,−/−/+], Organic farming conversion[a] [1,−/+/+], Rantional use of arable land (180 kt CO2e) [1,+/+/+/V]	Support of livestock breeding and Rational use of pastures [1,+/+/+/V]	Implementation of practices for restoring degraded pastures, cover cropping and no-till farming [1,−/−/+]	NDC 3.0 (Kazakhstan, 2025) 2024 BTR (Kazakhstan, 2024)
Nigeria	2018 (economy-wide)	32.2% below 2018 levels by 2035 (absolute reduction of 184.9 Mt CO_2e; economy-wide, incl. LULUCF). Indicative sectoral contributions include 2.1 Mt CO_2e from agriculture.	Improved manure management system for production of biogas[a] [1,−/−/+], Lower methane emissions from rice cultivation[a] [1,+/−/+] Adoption of circular economy practices within the Climate Smart Agriculture concept[a] [1,+/−/+]	Upscale adoption of ranching for cattle(enteric fermentation)[a] [1,+/−/+]	No policies meeting the inclusion criteria	Updated NDC (Nigeria, 2025b), 2024 BTR (Nigeria, 2024)

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Table 1
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Country/Region	Targets, policies and measures in the nationally determined contributions (NDCs) or the biennial transparency/Update reports (BTRs/BURs)					Source
	Reference year	Mitigation target	Agriculture sector	Ruminant livestock sub-sector	Grassland-related policies	Latest status of NDC Submission/Update
Uruguay	1990 (only for beef emission intensity)	Unconditional (conditional, more stringent) absolute economy-wide GHG emission cap of 40.65 (37.45) Mt CO_2e by 2035, with a 35% (37%) reduction in CH_4 and a 36% (38%) in N_2O emission intensity from beef production (GWP100 AR5, excluding LULUCF)	National Climate Change Policy (PNCC)[a] [2,−/+/+/C], Good Practices for Nitrogen Fertilization [1,−/−/+/V]	Climate Roadmap for Livestock[a] [2,−/+/+/C], Genetic Improvement in Cattle and Sheep [1,−/−/+/V], Dietary Compounds for Methanogenesis Reduction [1,−/−/+/V] Animal Health, Reproductive Efficiency and Longevity [1,−/−/+/V] Manure and Effluent Management in Livestock Systems [1,−/+/+/M] Good management practices for natural grasslands (under PNCC)[1,−/+/+/V] Implementation of no-till farming/Direct seeding (under PUMS)[1,−/−/+]	Soil Use and Management Plans (PUMS)[a] [2,−/+/+/C], Good management practices for natural grasslands (under PNCC)[1,−/+/+/V] Implementation of no-till farming/Direct seeding (under PUMS)[1,−/−/+]	The Third NDC (Uruguay, 2024), 2024 BTR (Uruguay, 2025a)
Ethiopia	2035 BAU emissions (base 2010, including LULUCF)	Economy-wide GHG emissions 40.7% below BAU by 2035 (unconditional) and 70.3% below BAU (conditional) with international support (including LULUCF).	No policies meeting the inclusion criteria	No policies meeting the inclusion criteria	The Green Legacy and Degraded Landscapes Restoration Special Fund[a] [2,−/+/−/M]	NDC 3.0 (Ethiopia, 2025), 2024 BUR (Ethiopia, 2024)

Note. This table provides a selective, IAM-oriented compilation of mitigation-relevant targets, policies, and measures explicitly referenced in countries' latest NDCs and BURs/BTRs. This table does not aim to provide an exhaustive inventory of climate-, environment-, or agriculture-related policies. Instead, it focuses on policies relevant to agriculture, ruminant livestock, and grassland systems that can be credibly linked to technically feasible mitigation options. Only policies that are, in principle, amenable to quantitative analysis are included. Policies are classified as action-level or rule-/framework-level instruments. The analytical framework, inclusion criteria, and coding logic applied in compiling and assessing the policies are described in Section 2.2 and Text S1 of Supporting Information S1. *"No policies meeting the inclusion criteria" indicates that no policies explicitly referenced in the latest NDCs or BURs/BTRs meet the inclusion criteria of this study, rather than the absence of mitigation-relevant actions at the national level. Policies are classified as either action-level (1) or rule-/framework-level (2) and evaluated across three dimensions: the presence of forward-looking quantitative mitigation objectives, implementation safeguards, and implementation pathways or the in-principle feasibility of accounting. Different evidentiary thresholds are applied to action-level and rule-/framework-level policies in recognition of their distinct roles. Policy assessments are summarized using a bracket notation of the form [level, target/safeguard/pathway/instrument], where "+" and "−" indicate presence or absence under level-specific criteria. The final letter denotes the dominant policy instrument type (C = command-and-control; M = market-based; V = voluntary); where no dominant instrument type can be robustly identified, the instrument code is left unspecified. Policies primarily designed for climate mitigation are underlined. Policies explicitly referenced in the latest NDCs are marked with a superscript "a." Detailed inclusion criteria, evaluation logic, and coding rules are provided in Text S1 of Supporting Information S1.

account for approximately 66% of total global GHG emissions and 60% of global agricultural GHG emissions (Figure 2a). For livestock, they account for 67% of global ruminant meat production and 69% of global milk production, with both aggregates comprising cattle, buffalo, sheep, and goats.

2.2. Analytical Framework for Policy Assessment

Climate policies and measures reported in NDCs and BURs/BTRs for the agricultural sector, ruminant livestock sub-sector, and grassland system are examined with a focus on how they are articulated to support traceable and cross-country comparable analysis, rather than evaluating overall national climate ambition.

Policies are classified as either action-level or rule-/framework-level, reflecting their proximity to implementation. All policies are characterized across three common dimensions: (a) forward-looking quantitative mitigation objectives, referring to explicitly stated emission reduction or sequestration targets, intensity benchmarks, or activity-based goals, (b) implementation safeguards, including funding, legal authority, or governance arrangements and (c) implementation pathways and/or in-principle feasibility of accounting outcomes. These dimensions are assessed using differentiated evidentiary thresholds for action-level and rule-/framework-level policies, in recognition of their distinct roles and levels of abstraction within national mitigation architectures (see Text S1 in Supporting Information S1).

To summarize these assessments consistently, we apply a bracket notation that records policy level, the presence of the three-dimensions, and the dominant policy instrument type, where identifiable. Detailed coding rules, thresholds, and classification criteria are described in Text S1 of Supporting Information S1. This framework allows a structured interpretation of policy signals and their potential to inform quantitative analyses and model-based evaluation of climate mitigation pathways.

Recent studies highlight the diversity of mitigation objectives in the AFOLU sector, including absolute emission targets, intensity targets, activity-based targets, and qualitative commitments (e.g., Luo et al., 2024). In this study, we focus on whether these commitments are articulated with sufficient clarity and specificity to support cross-country comparable assessment, complementing ambition-focused analyses by examining the structural features of policy articulation.

2.3. Agricultural Sector in the NDCs and BTRs (BURs)

Within the 16 countries/regions investigated, agricultural GHG emissions comprise 3%~83% of their total economy-wide emissions (Figure S1 in Supporting Information S1; Table S1). The share reaches 49% in Brazil, 52% in Mongolia, 53% in New Zealand, 83% in Ethiopia, and 73% in Uruguay, highlighting the relevance of the agricultural sector in national mitigation contexts. The corresponding absolute agricultural emissions for these countries are presented in Table S1.

Despite the importance of agriculture in national mitigation contexts, explicitly articulated quantitative mitigation targets at the agricultural sector level remain uncommon in NDCs (Table 1). Among the countries and regions reviewed, only a small number provide sector-specific quantitative commitments. For instance, Nigeria reports an indicative agricultural sector contribution of 2.1 Mt CO_2e, and Uruguay commits to reducing CH_4 and N_2O emission intensities from beef production by at least 35% and 36%, respectively. In most other cases, any quantified agricultural mitigation objectives are embedded within broader economy-wide or cross-sectoral frameworks rather than articulated as stand-alone sectoral targets (Table 1).

Using the analytical framework presented in Section 2.2 and detailed in Text S1 of Supporting Information S1, and based on the coding of policies summarized in Table 1, we further computed simple statistics across the three evaluation dimensions to generate the bar charts shown in Figure 2b. Agricultural policies reported in NDCs and BURs/BTRs exhibit substantial heterogeneity across these dimensions. First, although many action-level policies specify concrete practices or interventions, clearly defined forward-looking quantitative mitigation targets are relatively rare: only 32.6% of the assessed agricultural policies include explicit quantitative objectives (Figure 2b). Notable examples include Japan, where action-level measures specify expected emission reductions from methane mitigation in paddy fields and nitrous oxide reductions associated with fertilization. In addition, selected action-level programs in Canada, the United States, Kazakhstan, and Nigeria report anticipated mitigation outcomes for specific interventions.

Second, implementation safeguards, such as clearly identified funding sources or institutional and governance arrangements, are considerably more prevalent than other dimensions. This is evidenced by their specification in 89.1% of the assessed agricultural policies (Table 1; Figure 2b), particularly in countries with long-standing agricultural support systems (e.g., Canada, the United States, and the European Union). Third, a large share of assessed policies (87%) are coded as having either explicitly articulated implementation pathways or the in-principle feasibility of retrospective accounting based on inventory-consistent methods (Figure 2b). Importantly, this indicator reflects a composite criterion and does not distinguish between policies with clearly specified implementation pathways and those whose mitigation effects are considered quantifiable only retrospectively at an aggregate level. As such, a positive coding in this dimension should not be interpreted as evidence that implementation pathways are uniformly or explicitly articulated across policy types, nor as a normative assessment of retrospective accounting itself.

2.4. Ruminant Livestock and Grassland Systems in the NDCs and BTRs (BURs)

Across the 16 countries and regions investigated, emissions from the livestock sub-sector, estimated from enteric fermentation and manure management, account for a substantial share of total agricultural GHG emissions, ranging from 34% to 83% (Figure S1 in Supporting Information S1), highlighting the importance of this sub-sector for national mitigation efforts. Despite this significant contribution, mitigation-related policies explicitly targeting the ruminant livestock sub-sector and grassland ecosystems are less frequently and less consistently articulated than those addressing crop-based agricultural activities (Figure 2b; Table 1). In most cases, livestock- and grassland-related measures are embedded within broader agricultural or land-use frameworks rather than formulated as stand-alone, sector-specific mitigation policies.

With respect to the ruminant livestock sub-sector, policies specifying forward-looking quantitative mitigation objectives remain relatively uncommon. Across the policies assessed, only 18.9% include explicit quantitative targets, reflecting a limited degree of advance commitment at the sub-sectoral level (Figure 2b). Action-level measures with quantified mitigation expectations are observed in a small subset of cases, most notably in Canada and the United States, where selected programs report expected emission reductions associated with methane mitigation or feed-related interventions.

Implementation safeguards are more frequently articulated for livestock-related policies, with 83.8% specifying at least one form of institutional, financial, or governance support (Figure 2b). A similarly large share of policies (83.8%) are coded as having either explicitly articulated implementation pathways or the in-principle feasibility of retrospective accounting based on inventory-consistent methods. This coding reflects the fact that many livestock-related measures correspond to mitigation actions whose effects can, in principle, be quantified retrospectively at an aggregate level. However, the presence of such accounting feasibility should not be interpreted as evidence that mitigation intentions are consistently translated into clearly specified implementation pathways or forward-looking operational constraints suitable for quantitative modeling.

Policies addressing grassland systems are articulated even more unevenly. Among the assessed grassland-related policies, only 14.8% specify forward-looking quantitative mitigation targets, the lowest proportion across the three sectors examined (Table 1; Figure 2b). Several countries, including China, Brazil, Canada, and the United States, report grassland-related measures primarily in the context of ecosystem protection, restoration, or land-based carbon sinks. These policies are predominantly framed at the rule- or framework-level and frequently specify institutional mandates, regulatory arrangements, or funding mechanisms, but rarely define quantitative mitigation objectives directly attributable to grassland carbon sequestration or avoided emissions.

Implementation safeguards are widespread in grassland-related policies, being identified in 92.6% of cases (Figure 2b), reflecting the strong institutional anchoring of grassland management within conservation, land-use, or ecological restoration programs. By contrast, the share of policies associated with either explicitly articulated implementation pathways or the in-principle feasibility of retrospective accounting is lower (74.1%; Figure 2b) than in the livestock and agricultural sectors. This indicates that grassland-related mitigation is more often articulated through broader land-use or ecosystem restoration objectives, with mitigation outcomes primarily becoming visible at an aggregate level through inventory-based accounting, while sector-specific mitigation pathways are less frequently specified in a forward-looking manner.

Overall, the NDCs and BURs/BTRs reviewed reveal a structurally uneven articulation of mitigation-related policy signals for ruminant livestock and grassland systems across the three evaluation dimensions.

Forward-looking quantitative mitigation targets remain limited, particularly beyond the agricultural sector, while implementation safeguards are comparatively well specified across most policy domains. In parallel, a substantially larger share of reported policies is associated with either articulated implementation pathways or the in-principle feasibility of retrospective accounting, although coverage varies across sectors and is notably lower for grassland-related policies than for agriculture and livestock. Taken together, these patterns point to uneven levels of traceability and cross-country comparability across sectors, highlighting the challenges of systematically assessing mitigation pathways for ruminant livestock and grassland systems based on current NDC and transparency reporting.

3. Representation of Grassland and Livestock Systems in Integrated Assessment Models

Contemporary IAMs are widely used to explore the scenarios and global and/or regional pathways of various economic activities, including AFOLU sector, and their socio-economic, environmental and climate change impacts (Frank et al., 2019; Havlík et al., 2014; Popp et al., 2017). Through analyzing interactions between human and the Earth system (climate and environmental changes) under different scenarios, IAMs are frequently applied to assess the implications of Nationally Determined Contributions (NDCs) and long-term mitigation strategies. Previous studies have used IAMs to examine land-based mitigation options, including bioenergy deployment, afforestation, and agricultural mitigation measures (Frank et al., 2019).

3.1. Models Reviewed and General Structure

Here, we examined five land-use components of widely used IAMs: AIM/CGE7.0, GCAM6, GLOBIOM (as the land-use component of the IIASA IAM MESSAGEix-GLOBIOM), IMAGE3.0, and MAgPIE4 (as the land-use component of the PIK IAM REMIND-MAgPIE). Key characteristics of these models, together with primary documentation sources, are summarized in Table 2. The base years of the models reviewed range from 1990 to 2007. While these base years are relatively distant from the present, they do not directly determine model error or predictive performance. The base year primarily serves to initialize production structures and ensure consistency across historical data sets, whereas model parameters, behavioral responses, and equilibrium dynamics are calibrated and evaluated using observed trends in subsequent periods.

GLOBIOM and MAgPIE are commonly used as partial equilibrium models focusing specifically on AFOLU sectors without modeling the entire economy. When coupled with energy-economic models such as MESSAGE (forming MESSAGE-GLOBIOM) or REMIND (forming REMIND-MAgPIE), they become IAMs that cover all economic sectors. AIM/CGE7.0 and GCAM6 are IAMs with representations of all major economic sectors, although their land-use components may still function as partial equilibrium modules. IMAGE3.0 is a broader modeling framework that integrates various models, including the CGE-based MAGNET model for economic analysis.

In general, the demand for commodities in these IAMs or their land-use components is initially driven by exogenous drivers such as population, GDP growth and diet preference affected by income and price, while agricultural and forestry production are endogenously adjusted to reach market equilibrium and constrained by resources such as land and water (Figure 3). The production system within the model is initialized using historical data from various sources, primarily FAOSTAT. The commodity prices are then adjusted based on the supply and demand situation, which in turn affects production and consumption, ultimately achieving supply demand balance plus maximizing profits or minimizing cost.

3.2. Land-Use Representation

All five models account for major land cover types such as forest, cropland, grassland, other natural vegetation, and build-up/urban land. Some models also include wetland, peatland or bare land (Table 2). Forest representation varies across models: GLOBIOM, MAgPIE4, and GCAM6 distinguish managed and natural forests; AIM/CGE7.0 differentiates primary and secondary forests; IMAGE3.0 represents forest as natural vegetation.

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Table 2
Characteristics of the Land-Use Components of IAMs Reviewed in This Study, and the Crop, Grassland and Livestock Modules of Them

	GLOBIOM	AIM/CGE 7.0	IMAGE3.0	MAgPIE4	GCAM6
Basic characteristics					
Institution	IIASA	NIES	PBL	PIK	JGCRI in PNNL
Model type	Partial equilibrium (PE)	CGE	PE/CGE	PE, recursive dynamic cost-minimization model	Market equilibrium model, dynamic recursive model
Economy coverage	Agriculture and forestry	Full economy	Full economy	Agriculture and forestry	Full economy
Spatial Resolution	5 arc-min/0.5°	0.5°	5 arc-min (LULUC); 0.5° (Plant growth, carbon and water cycles)	0.5°	Downscale FAO data to a subnational level
No. of Regions	37 regions/179 countries	18 AEZ	26 regions	12 regions	32 geopolitical regions; 32 economy and energy; 384 land-water regions
Base year	2000	2005	2007 (land-use model)	2000	1990
Time step	10-year	annual	annual or 5-year	5-year	5-year
Land cover type	Forest, Cropland, Pasture, Other natural land, Short-rotation plantations (for bioenergy), Other land	Primary Forest, Secondary Forest, Primary Grassland, Grazing land, Cropland, Other land	Grassland, Cropland, Bioenergy, Natural vegetation, Bare land	Forestry, Nature vegetation, Cropland, Pasture, Urban, Peatland	Tundra, Rock, Ice, Desert, Non-Pasture, Cropland, Commercial Forest, Forest, Pasture, Urban
Food demand	Calories demand following GDP and population growth (region/country specific), demand structure following	The household consumption is formulated as LES (linear expenditure system) function	Population, GDP per capital, income and price elasticities	Calories demand following GDP and population growth (region/country specific), and with standalone food demand model executed	The population, the income levels, and commodity prices and historical demand for crops from FAO
Crop module					
Crop types[a]	18	5	10	5	7
Crop yield	EPIC crop model	future land input coefficient (yield) from IMPACT, climate change impact from GAEZ	LPJmL	LPJmL	Forecasting yield by historical data and agriculture productivity growth rate from FAO
Livestock module					
Livestock types	Beef Cattle, Dairy Cattle, Cattle followers/heifer, Small ruminant for meat, small ruminant for milk, small ruminant followers, pigs, poultry broiler, poultry hen, poultry mixture	Livestock 1- N	Beef Cattle, Dairy Cattle (Both large ruminants), sheep & goat (small ruminants), Pig and Poultry (both monogastric)	Beef Cattle, Dairy Cattle, Pigs, Broilers and Laying Hens	Reference FAO
Livestock production system	Mixed and industrial system, pastural system for ruminant, urban and other system for pigs and poultry	Not provided	Pastoral system, Mixed and industrial system, and with specific intensities, rations and feed conversion ratios	Beef cattle, dairy cattle, pigs, broilers and laying hens, and every time-step regional and product-specific feed baskets and feed conversion	Using the production system within IMAGE

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Table 2
Continued

	GLOBIOM	AIM/CGE 7.0	IMAGE3.0	MAgPIE4	GCAM6
Livestock production simulation	RUMINANT model for energy requirement, digestibility and feed structure	Assuming to be corresponding to the livestock products demand change	MAGNET provides exogenous data on domestic livestock production per region and management intensity.	In the Livestock model, production is determined by the input population and the per capita consumption derived from the food demand model.	Assuming balance with demand and adjusting through Logit share decision-making method
Feed demand simulation	Feed structure from RUMINANT model	Not provided	In the livestock module, the inputs include: livestock production, and drivers (inferred from SSPs): production system mix, animal productivity, feed conversion rates, and livestock rations.	In the Livestock model, feed demand is calculated based on the production of different livestock products	Using livestock systems module in IMAGE
Feed basket	Grains (concentrates), stover, grass, and others. Differentiate based on region and production system	Not provided	Grass silage, hay, feed crops, processing byproducts, crop residues, fodder crops. Differentiate based on region and production system	Crop residues, considering regional and production system differences. The specific feed structure is not provided.	The feed type is consistent with IMAGE. Using Logit share decision-making method to determine the feed ratio based on the prices of various types of feed
Grassland module					
Grassland types	Pasture, Nature Vegetation	Primary Grassland (unmanaged pasture), Grazingland (managed pasture which feeds marketed livestock)	Intensive Grassland, Extensive Grassland (CLUMondo)	Pasture, Nature Vegetation	Pasture: Pasture, unmanaged Pasture; Non-pasture: Grassland, Shrubland
Grasses production model	CENTURY for unmanaged pasture/EPIC for managed pasture	Not provided	LPJmL	LPJmL	Equivocal, may be similar to the methods in the crop module
Climate impacts on yield	Yes	No	Yes	Yes	No

Note. All model information is sourced from official documentation. Additionally, GLOBIOM refers to IBF-IIASA (2023), AIM/CGE7.0 refers to Fujimori et al. (2017), IMAGE3.0 refers to Stehfest et al. (2014), MAgPIE4 refers to https://rse.pik-potsdam.de/doc/magpie/4.3/ (accessed on 26 May 2025) and Dietrich et al. (2019), and GCAM6 refers to http://jgcri.github.io/gcam-doc (accessed on 26 May 2025) (https://zenodo.org/doi/10.5281/zenodo.11481167). [a]Crop types/groups in each model was listed below: GLOBIOM: Barley, Dry Bean, Cassava, Chickpea, Corn, Cotton, Groundnut, Millet, Potato, Rapeseed, Rice, Soybeans, Sorghum, Sugarcane, Sunflower, Sweet Potato, Wheat, Oil palm. AIM/CGE 7.0: Rice, Wheat, Other grains, Oil crops, Sugar crops. IMAGE3.0: temperate cereals, rice, maize, tropical cereals, roots and tubers, pulses, and oil crops, both rain-fed and irrigated; grass; sugar cane and maize for bioenergy; and woody and non-woody bioenergy. MAgPIE4: temperate and tropical cereals, maize, rice, oilseeds, roots. GCAM6: corn, rice, wheat, sugar crop, oil crop, forest, pasture, and so on.

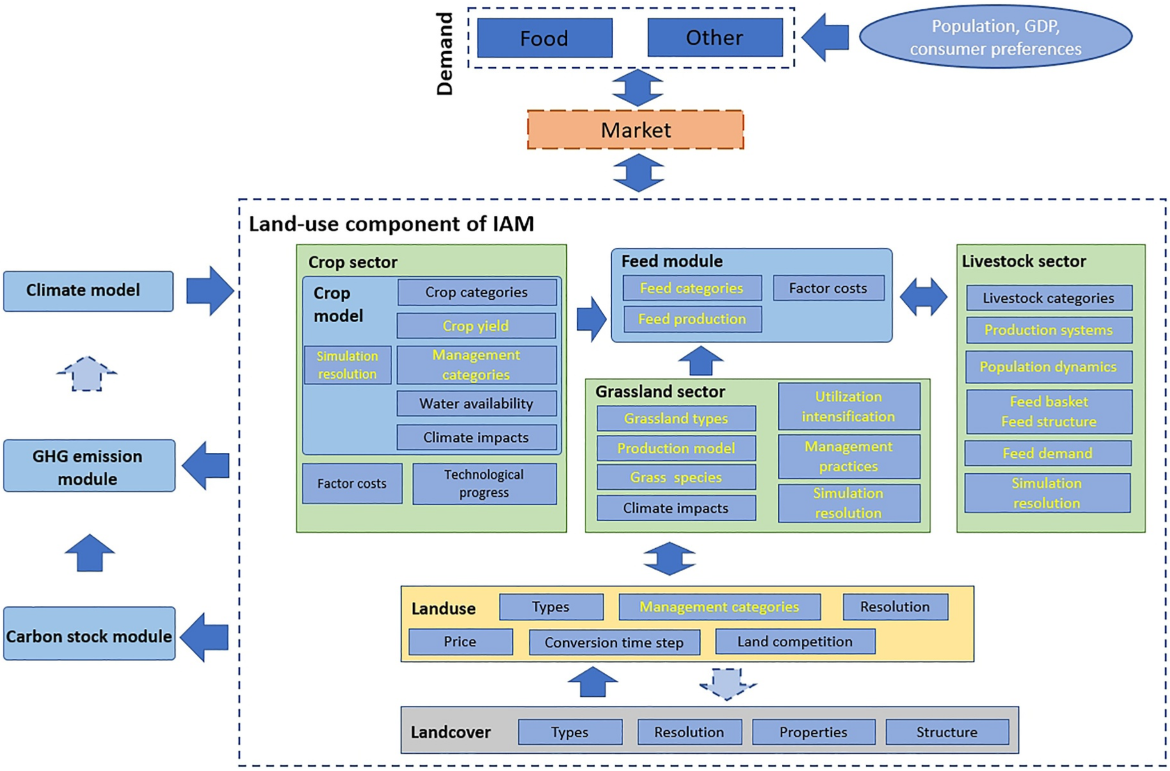

Figure 3. Illustration of the sectors and modules relevant to grasslands and livestock production systems in IAMs. Text in yellow highlights the components and the modules focused in this study.

All five models consider bioenergy plantations. The implementation for BECCS scenarios differs across the land-use components of these models. IMAGE3.0, GCAM6 and AIM/CGE7.0 simulate the entire BECCS chain, while GLOBIOM and MAgPIE4 only provides supply side simulations and needs to be coupled with MESSAGE and REMIND, respectively, for energy pathways.

3.3. Cropland and Crop Productivity

Cropland is represented using between five and 18 crop types across models. In most models except GCAM6, crop productivity and associated resource requirements like irrigation water and fertilizer were derived from gridded simulations of process-based crop models (18 crop types by EPIC-IIASA for GLOBIOM, and 18 crops by LPJmL for IMAGE3.0, 6 grain crops by LPJmL for MAgPIE4). Climate impacts can therefore be explicitly assessed in the process-based model simulations, while yield growth from technological progress were implemented exogenously.

GCAM6 uses GAEZ data (Fischer et al., 2021) to initialize regional crop yields for 15 crops and considers exogenous technological progress, but its approach to climate impacts on agricultural production is less detailed compared to process-based models.

None of the reviewed models explicitly includes crop classification of managed forages such as silage corn, alfalfa, oats, and ryegrass, which poses difficulties in simulating the intensification of livestock production with non-grain forage production.

3.4. Livestock Systems and Feed Representation

All models represent major livestock categories (ruminants and monogastric) and their associated animal products (milk and meat) that are broadly consistent with FAOSTAT's classification, including beef cattle, dairy cows, small ruminants (sheep and goats), pigs and poultry, but with different level of complexity.

AIM/CGE7.0 and MAgPIE4 only include livestock numbers and production without differentiating production systems. IMAGE3.0 differentiate pastoral, mixed and industrial systems, and GCAM6 directly adopts the same classification. GLOBIOM is more detailed and adopted the Serre and Steinfeld production system (Robinson et al., 2011) with two production systems for poultry and pigs, and eight production systems for ruminants.

Accordingly, regional specific feed baskets are used in AIM/CGE7.0 and MAgPIE4, while feed structures are specified for each region and production system in IMAGE3.0 and GLOBIOM. Crop for feed and grass biomass were accounted by all models in their feed basket, while some models include more feed categories such as crop residues (GLOBIOM, MAgPIE4 and IMAGE3.0), byproducts (GLOBIOM, MAgPIE4 and IMAGE3.0), fodder crops (e.g., MAgPIE4).

In particular, region- and system-specific feed structure for ruminant in GLOBIOM was derived from a mechanistic model of digestion in ruminants called RUMINANT (Herrero et al., 2013), and included four major categories of grains, crop residues, grass biomass, and occasional feed.

3.5. Grassland Representation and Management

In all models, grass feed demand and supply at regional level are matched with balance. Only three models (GLOBIOM, IMAGE3.0 and MAgPIE4) account for grass biomass productivity at grid cell level derived from process-based models (CENTURY and EPIC-IIASA for GLOBIOM and LPJmL for IMAGE3.0 and MAgPIE4), while the type of management and changes in grazing intensity are typically not represented.

Across models, grassland management practices, ranging from intensification measures such as fertilization, irrigation, reseeding, and forage cultivation, to extensification measures such as reduced grazing intensity, grazing exclusion, and the restoration of degraded grasslands, are generally not represented explicitly.

In the five land-use components of IAMs, forage used for feed is treated as a natural output of pasture, rather than results of human agricultural activities, or is only considered when grown on cropland (e.g., cultivated forage crops or supplementary feeds). An exception is IMAGE3.0, which incorporates policies to improve grassland productivity by planting alfalfa and applying fertilizers (Stehfest et al., 2014).

3.6. Emissions/Removals Accounting

All five models explicitly estimate the GHG emissions from the AFOLU sector following the IPCC guidelines (IPCC, 2006). Tier 1 methods in the IPCC guidelines are widely used by the IAMs with regional emission factor applied to the specified activity level, while Tier 2 or Tier 3 methods are used for some activities and emissions by the models. For example, enteric fermentation CH_4 emissions from ruminants in GLOBIOM is estimated with a mechanistic model of digestion (Tier 3), while other models usually apply regional emission factors for different livestock categories (Tier 1 or Tier 2).

Carbon emissions and sinks in LULUCF only focus on carbon stock changes resulting from conversions between forests, cropland, grassland, and other land types, while carbon stock changes without land-use conversion are not considered. For example, emissions from grassland remaining as grassland are not accounted for, as all models neither distinguish between extensive and intensive grazing nor consider management practices or pasture degradation. Grassland fires are represented only in IMAGE3.0.

While these accounting approaches ensure consistency with national greenhouse gas inventories, they do not necessarily translate management-specific mitigation actions into decision-relevant variables within IAM optimization frameworks.

4. Discussion

4.1. Agriculture, Livestock, and Grasslands in National Mitigation Contexts

Across the 16 countries and regions investigated, agricultural greenhouse gas (GHG) emissions constitute a substantial share of economy-wide emissions, highlighting the importance of agriculture, and particularly livestock and grassland-based systems, for achieving national climate targets. At the global level, food system emissions contribute approximately 34% of total anthropogenic GHG emissions (Crippa et al., 2021), indicating substantial mitigation potential within agricultural systems. Despite this relevance, our review of the latest NDCs and BURs/BTRs indicates that mitigation policies targeting the agricultural sector are frequently articulated without clearly defined quantitative objectives. While all investigated countries have adopted economy-wide emission reduction targets, explicit sector-specific mitigation targets for agriculture remain uncommon.

This pattern was particularly evident in earlier NDC submissions around the second NDC cycle (around 2020), when agriculture-related mitigation measures were sparse, fragmented, and often articulated only in general or aspirational terms (Table S2). A comparison with more recent submissions indicates incremental progress in the coverage and specificity of agricultural mitigation policies across the sample, as reflected in the latest NDC updates and 2024 BURs/BTRs (Table 1; UNFCCC, 2025). These developments, however, are uneven across countries and have not been accompanied by a commensurate increase in clearly articulated, sector-wide quantitative mitigation targets or enforceable implementation strategies.

Moreover, at least half of the policies recorded in Table 1 are not primarily designed as climate mitigation instruments, but instead take the form of environmental management, land-use, or adaptation-oriented policies, whose stated objectives can be expected, with high confidence, to deliver directionally consistent mitigation co-benefits. While such policies may contribute meaningfully to mitigation outcomes at an aggregate level, their mitigation relevance is often indirect and secondary to broader ecological or resilience objectives. As a result, agriculture's contribution to national mitigation pathways remains predominantly framed qualitatively or embedded within broader economy-wide or cross-sectoral objectives, limiting the transparency and cross-country comparability of sector-specific mitigation ambition.

4.2. Livestock and Grassland Mitigation: Articulation Gaps Relative to Emission Profiles

The divergence between emission profiles and policy articulation becomes more pronounced when focusing on livestock and grassland systems. Emissions from animal-based foods are approximately twice those from plant-based foods (Xu et al., 2021), and national GHG inventories show that emissions from enteric fermentation and manure management account for more than half of agricultural emissions in most countries examined. In Australia and New Zealand, livestock-related emissions exceed 80% of agricultural emissions; in Brazil, the United Kingdom, Uruguay, and Argentina they exceed 70%; and China, Canada, the European Union, India, Kazakhstan, Nigeria, and Mongolia they exceed 50% (Figure S1 in Supporting Information S1; Table S1).

Despite this central role, almost none of the countries reviewed explicitly specify in their NDCs the expected contribution of livestock emission reductions or grassland carbon sequestration toward achieving overall mitigation targets, with Uruguay representing a notable exception. Only a small subset of countries, including Australia, Canada, the United States, Kazakhstan, Brazil and New Zealand, report mitigation measures with indicative emission reduction estimates (Table 1). In several cases, livestock- or grassland-related measures are absent altogether or articulated at a level of generality that limits their traceability and cross-country comparability.

Where mitigation policies are articulated, a clear thematic asymmetry emerges. Livestock-related measures predominantly focus on methane reduction, often through feed management, productivity improvements, or manure-related interventions, whereas grassland-related measures are more frequently framed in terms of ecological protection and restoration embedded within broader land-use, biodiversity, or ecosystem conservation strategies. While such grassland policies may deliver mitigation co-benefits, their mitigation relevance is often implicit and becomes visible primarily through retrospective inventory-based accounting, rather than being explicitly quantified or linked to forward-looking national emission targets.

Across both the livestock and grassland domains, implementation safeguards are consistently more prevalent than forward-looking quantitative mitigation targets, while a large share of policies is associated with the in-principle feasibility of retrospective accounting (Figure 2). This configuration should not be interpreted as indicating that countries explicitly prioritize retrospective accounting as a policy objective. Rather, it reflects a reporting structure in which mitigation relevance is more often established through inventory-compatible, aggregate accounting than through the articulation in advance of sector-specific mitigation targets grounded in estimated technical mitigation potential, a pattern that is particularly pronounced for rule- or framework-level policies. Such an orientation limits the transparency of sectoral mitigation strategies and constrains cross-country comparability, particularly for ruminant livestock and grassland systems where mitigation outcomes depend strongly on management intensity, spatial heterogeneity, and system-specific dynamics.

These findings align with broader global assessments. According to the CGIAR 2024 synthesis (Dittmer et al., 2024), among the 176 countries that submitted new or updated NDCs since 2020, only 14% explicitly referenced grassland soil carbon, 56% mentioned livestock-related mitigation policies, and only 14 countries allocated dedicated financial budgets to support such policies. This suggests that the patterns observed in our sample reflect a more general structural feature of NDC reporting rather than country-specific anomalies.

4.3. Structural and Institutional Constraints Shaping Livestock and Grassland Mitigation

Importantly, the patterns identified above do not imply an absence of mitigation-relevant actions in livestock and grassland systems. Rather, they reflect a set of structural constraints that shape how mitigation is conceptualized and articulated within national climate reporting frameworks. These constraints operate across institutional, economic, and technical dimensions, and collectively limit the extent to which mitigation in ruminant livestock and grassland systems can be translated into clearly specified, forward-looking policy commitments.

A first source of constraint arises from the interaction with broader land-use, land-use change, and forestry (LULUCF) frameworks. Across countries, pasture expansion remains a major driver of deforestation and associated emissions, while grasslands are simultaneously treated as potential land reserves for afforestation or bioenergy crop deployment. Consequently, LULUCF strategies predominantly prioritize forest conservation and afforestation, as reflected in initiatives such as REDD+, the EU LULUCF Regulation, the UK Environmental Land Management scheme, and various international forest pledges. Within these frameworks, however, grassland management on land remaining as grassland—including grazing intensity, degradation, and restoration—is rarely articulated in detail. As a result, mitigation impacts associated with changes in grassland management are weakly represented and difficult to trace within both policy reporting and accounting systems.

A second set of constraints relates to the economic and technical characteristics of livestock mitigation options. Many mitigation technologies for livestock, such as feed additives, improved feed efficiency, and advanced manure management, face high costs, adoption barriers, and uncertainties regarding long-term effectiveness. As a result, their economically feasible mitigation potential is substantially lower than their technical potential, with estimates ranging from less than 10% (Herrero et al., 2016) to approximately 26% (US Environmental Protection Agency, 2022). These challenges are particularly pronounced in low- and middle-income countries, which collectively account for around 66% of global livestock-related emissions and are projected to contribute the majority of future growth in the sector (Herrero et al., 2013; Matthew Tom Harrison, 2021). Such conditions complicate the formulation of credible, forward-looking mitigation targets at the sectoral level.

Together, these constraints explain why mitigation in livestock and grassland systems is often articulated through fragmented or indirect policy instruments. While many policies specify implementation arrangements or enable mitigation-relevant actions, very few explicitly integrate emission reduction and carbon sequestration objectives within grassland–livestock systems, despite growing evidence that such integrated approaches are critical for achieving economically viable net-zero pathways (Bilotto et al., 2023, 2024; Pham-Kieu et al., 2025). Instead, mitigation outcomes are frequently recognized only retrospectively through inventory-based accounting, rather than being incorporated in advance into coherent, management-sensitive mitigation strategies.

4.4. Structural Limitations in Current IAM Representations of Grassland–Livestock Systems

Our review of the land-use components of widely used Integrated Assessment Models reveals that grassland–livestock systems are systematically simplified relative to their importance for both emissions and land-use dynamics. While all models examined recognize grasslands as a major land cover type and include livestock production as a core component of the AFOLU sector, the representation of managed grasslands is largely reduced to an aggregated feed supply constraint operating at regional scale. Grass biomass is typically treated as a quasi-natural output of pasture, with limited or no explicit linkage to management intensity, degradation status, or restoration practices. As a result, IAMs remain unable to assess whether grasslands are undergoing ecological functional damage, such as overgrazing or degradation, or to simulate management-driven shifts in productivity under changing food demand and policy signals.

This limitation is reinforced by a pronounced imbalance between the detailed treatment of croplands and the coarse representation of grasslands. Crop productivity, irrigation, and fertilizer use are commonly derived from gridded simulations of process-based models and supported by increasingly rich spatial data sets (e.g., Kebede et al., 2025; Nguyen et al., 2024; Potapov et al., 2022; Tian et al., 2025; Yu et al., 2020). However, comparable information on managed grasslands, covering their distribution, management practices, and use intensity, is largely absent at the global scale. Although some IAMs incorporate grass biomass productivity at the grid level, changes in grazing intensity, reseeding, fertilization, mowing, or restoration are typically not represented. Consequently, IAMs cannot capture management-driven changes in soil carbon stocks or distinguish between intensive, extensive, and degraded grassland systems. This limitation persists even though these distinctions are central to both mitigation potential and ecosystem integrity.

Carbon accounting practices within IAMs reinforce these limitations. While AFOLU emissions are generally estimated following IPCC guidelines, emissions and removals from grasslands remaining as grasslands are usually excluded from carbon stock change calculations. Management-induced carbon gains or losses, arising from altered grazing pressure, fertilization, reseeding, or degradation, are therefore omitted, despite growing evidence that such practices can substantially influence soil carbon dynamics. This omission constrains IAMs' ability to assess mitigation strategies that rely on improved grassland management rather than land-use conversion alone.

Taken together, these features indicate that current IAM representations treat grasslands primarily as a passive land pool or feed source, rather than as actively managed socio-ecological systems. This structural simplification limits the capacity of IAMs to capture the diversity of grassland–livestock management pathways and their associated mitigation outcomes.

4.5. Implications for Land-Use Trajectories and Opportunities to Strengthen Policy–Model Coherence

The simplified representation of grassland–livestock systems in IAMs has important implications for scenario outcomes and their interpretation. In IAM-based analyses, variations in how grassland is allocated to livestock feed can lead to fundamentally different land-use trajectories, particularly with respect to forest dynamics and bioenergy deployment. Under baseline or weak mitigation scenarios, pasture expansion has been identified as a major driver of deforestation, whereas under mitigation-oriented pathways, reductions in pasture area may create apparent opportunities for afforestation or bioenergy crop cultivation (Bayer et al., 2021; Popp et al., 2017). However, the credibility of these projections critically depends on assumptions about grassland productivity and management that are currently weakly constrained.

Estimates of grassland productivity and use intensity remain highly uncertain Fetzel et al. (2018); Stanimirova et al. (2019), and these uncertainties propagate through IAMs to undermine confidence in assessments of land-use competition, mitigation potential, and food-security trade-offs (Forster et al., 2022; Kriegler et al., 2017). By treating grasslands primarily as a passive land pool or feed source, models risk overstating the availability of grassland for afforestation or bioenergy expansion, while understating the mitigation potential achievable through sustainable intensification, restoration, or improved grazing management. Conversely, they may also underestimate the risks of overgrazing, degradation, and uncontrolled pasture expansion under rising demand for animal-based foods.

Recent advances in grassland science highlight that these limitations are not inevitable. Empirical studies and dynamic models have demonstrated the sensitivity of grassland productivity and carbon dynamics to climate variability, biodiversity, and management practices (Gang et al., 2015; Gao et al., 2016; Zarei et al., 2021). New data sets and modeling tools, including remote-sensing-based yield estimates (Reinermann et al., 2025), grazing-intensity data sets (Wang et al., 2024), and grassland-specific dynamic models such as BASGRA_N, LPJmL, ORCHIDEE-GM, and G-Range, provide increasingly robust, spatially explicit, and management-sensitive information. Integrating such developments into IAM frameworks would substantially reduce uncertainty in assumptions on grassland productivity and management, and improve the capacity of models to evaluate whether overgrazing and disordered pasture expansion can be avoided under different socio-economic and policy scenarios.

More broadly, strengthening the representation of grassland condition, management intensity, and livestock–feed interactions would enable IAMs to move beyond binary land-use trade-offs and toward a more realistic assessment of mitigation pathways that combine emissions reduction with ecosystem stewardship. This includes evaluating extensification options for degraded grasslands, management-driven soil carbon restoration, and the integration of emerging technologies such as optimized feed structures, improved manure management, and cultivated forage systems. Without such advances, both IAM-based scenario analyses and the policy signals derived from them will remain poorly aligned with the biophysical and socio-economic realities of grassland–livestock systems.

4.6. Feedbacks Between NDC Articulation and IAM Representation

Beyond their individual limitations, the NDCs and IAMs reviewed in this study appear to reinforce each other through a mutually constraining feedback. On the policy side, the articulation of mitigation measures for agriculture, ruminant livestock, and grassland systems is characterized by a pronounced imbalance between implementation readiness and advance commitment. As shown in Figure 2b, implementation safeguards are specified for more than 80%–90% of assessed policies across all three sectors, and a large share of policies are associated with either explicitly articulated implementation pathways or the in-principle feasibility of retrospective accounting. By contrast, clearly articulated forward-looking quantitative mitigation targets are specified for only 32.6% of agricultural policies, 18.9% of ruminant livestock policies, and 14.8% of grassland-related policies.

This configuration reflects a policy orientation in which inventory-compatible, retrospective accounting plays a more prominent role than the forward-looking specification of sector-specific mitigation targets grounded in estimated technical mitigation potential. However, in the absence of clearly defined sectoral targets or management-sensitive policy signals, IAMs are left with limited information that can be operationalized as model constraints or levers. As a result, mitigation is often represented through land-use conversion options, such as afforestation or bioenergy expansion, that are more readily quantifiable within existing modeling architectures.

On the modeling side, the simplified representation of grassland management and livestock–feed interactions further constrains the evidence base available to policymakers. When IAMs cannot simulate management-driven changes in grassland productivity, degradation, or soil carbon stocks, the mitigation potential of sustainable grazing, restoration, and grassland intensification remains largely invisible in scenario analyses. This limits the confidence with which such measures can be translated into quantified commitments or prioritized within national climate strategies.

This bidirectional disconnect contributes to a self-reinforcing cycle in which grassland–livestock mitigation options remain underrepresented in both policy articulation and model-based assessments. Policies tend to focus on measures that are feasible in retrospect but difficult to parameterize in advance, whereas models favor mitigation pathways that are easy to represent but often misaligned with management-intensive realities. As a result, IAM scenarios may systematically overstate the availability of grassland for land-use conversion while understating the mitigation potential achievable through improved management of existing grassland systems. Breaking this cycle requires coordinated advances in both domains: clearer and more traceable articulation of grassland–livestock mitigation measures in NDCs, and enhanced IAM representations capable of capturing management-sensitive grassland dynamics and their emissions and removal implications.

5. Perspectives

Recent advances in policies addressing grassland and livestock systems, as well as in associated mitigation technologies, indicate growing recognition of their relevance for climate mitigation (Matthew Tom Harrison & Liu, 2024). Nevertheless, global assessments suggest that current policy trajectories remain insufficient to meet temperature goals, even under full implementation of conditional NDCs (AR6; Calvin et al., 2023; UNEP, 2024). This gap highlights not only challenges related to ambition, but also the importance of how mitigation strategies are articulated, operationalized, and assessed in agriculture, ruminant livestock, and grassland systems.

Within this context, NDCs and IAMs serve complementary but distinct roles: NDCs articulate national mitigation intentions, while IAMs explore the feasibility and system-wide implications of alternative pathways. Consistent with this division of roles, the mitigation information reported for ruminant livestock and grassland systems in NDCs is predominantly oriented toward inventory-compatible, retrospective accounting, while explicitly articulated forward-looking quantitative parameters remain relatively limited. This articulation pattern, while well aligned with transparency and accountability requirements, provides only a partial basis for forward-looking, model-based analysis, which can affect the transparency and cross-country comparability of mitigation pathway evaluations for management-intensive systems such as livestock and grasslands.

From a policy articulation perspective, strengthening livestock and grassland mitigation within NDCs would benefit from clearer specification of sector-relevant mitigation objectives, implementation arrangements, and accounting interfaces. Improved articulation does not necessarily require harmonized mitigation targets or policies across countries, but clearer and more transparent links between stated measures, anticipated mitigation outcomes, and accounting approaches. In particular, degraded and ecologically fragile grasslands represent important opportunities for mitigation through restoration and conservation-oriented interventions (e.g., prohibiting grazing and enclosure, grass resowing, fertilization, pest and disease control), which are already widely implemented in practice but remain weakly translated into forward-looking policy commitments (Matthew Tom Harrison et al., 2021).

From a modeling perspective, addressing the simplified and aggregated representation of grassland–livestock systems in contemporary IAMs requires coordinated advances across data inputs, process representation, and the interface between scenarios and policy signals. At the data and parameter level, this includes improving empirical information on the spatial extent and management of grasslands, grazing intensity, and feed composition, including the role of cultivated forages and region-specific feed structures. At the level of process representation, models need to better capture management-sensitive dynamics, such as responses of grassland productivity, livestock feed allocation, and associated emissions and removals to changes in grazing pressure, restoration, and feeding practices, moving beyond static formulations and Tier 1/2-type carbon accounting approaches. At the scenario and policy interface, IAMs would benefit from representing grassland restoration, grazing constraints, and feed intensification as explicit policy levers or scenario constraints, rather than treating them as indirect or residual outcomes of land-use change.

Finally, we call upon IAM developers to leverage these scientific advances to improve the representation of grassland systems in models, particularly in terms of their coupling with livestock systems and land-use change. We also call for funding to support global grassland monitoring and modeling, similar to existing crop mapping programs, to establish a solid empirical foundation for enhancing the role of IAMs in advancing the UN's Sustainable Development Goals.

6. Conclusion

This study examined how mitigation-related policies for grassland and ruminant livestock systems are articulated in NDCs and BURs/BTRs, and how these systems are represented in the land-use components of widely used integrated assessment models. Rather than evaluating national ambition levels, our analysis focused on the structure and clarity of policy articulation, specifically the specification of forward-looking quantitative objectives, implementation safeguards, and accounting feasibility, and on the extent to which these policy signals can be interpreted within model-based quantitative assessment frameworks.

Taken together, our findings point to structural gaps at the interface between policy articulation and model-based quantitative assessment. Ruminant livestock and grassland systems account for a substantial share of agricultural emissions and land-use dynamics, yet the mitigation-related information reported in NDCs for these systems is predominantly designed to support inventory-compatible, retrospective accounting, with relatively limited specification of forward-looking quantitative parameters relevant for ex ante modeling. At the same time, contemporary IAMs represent grassland–livestock interactions in a highly simplified and aggregated representation, with limited sensitivity to management intensity, degradation, restoration, and management-induced carbon dynamics. These parallel simplifications limit the transparency and cross-country comparability of evaluations of mitigation pathways for ruminant livestock and grassland systems.

More broadly, this analysis highlights the importance of improving the interface between policy articulation in NDCs and quantitative representation in IAMs. Clearer specification of sector-relevant mitigation objectives and management pathways in policy documents, together with enhanced model representations that are responsive to grassland and livestock management, could improve the interpretability of mitigation assessments and support more robust cross-country and scenario-based analyses. Strengthening this interface may help better contextualize the role of grasslands in addressing land-use change, climate mitigation, food security, and biodiversity conservation, as conceptually illustrated in Figure 4.

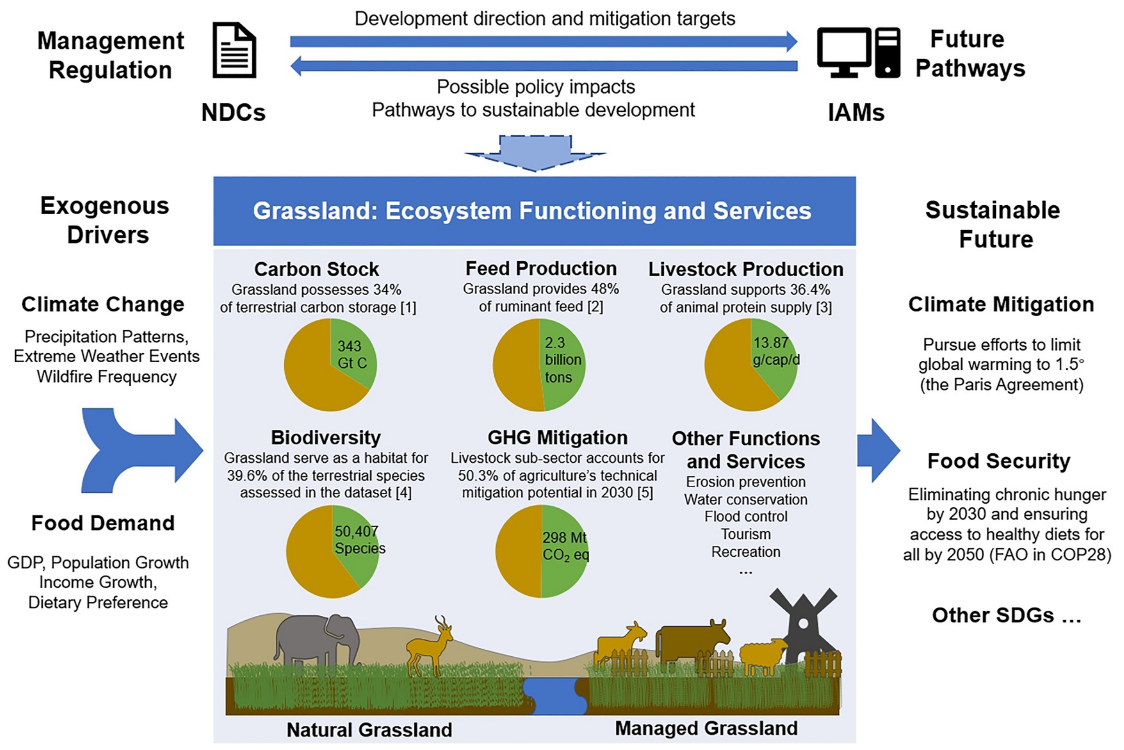

Figure 4. Conceptual framework linking the Nationally Determined Contributions (NDCs) and integrated assessment models (IAMs) in supporting a future sustainable grassland system. [1] Deriveds from FAO's 2007 estimates (Conant, 2010). [2] Derived from Herrero et al. (2013) [3] Derived FAO 2022 (FAOSTAT, 2026) [4] Derived from IUCN Red List of Threatened Species (International Union for Conservation of Nature, 2024) [5] Derived from EPA non-CO_2 GHG projections and mitigation assessments (US Environmental Protection Agency, 2022).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

This review did not generate new data and relies exclusively on publicly available sources. Key sources include official submissions and reports archived by the UNFCCC, namely Nationally Determined Contributions (NDCs), National Greenhouse Gas Inventory Reports, and Biennial Update and Biennial Transparency Reports. Global land-cover and land-use information was drawn from the ESA CCI/C3S plant functional type maps (Harper et al., 2023) and the HYDE 3.3 database (Klein Goldewijk, 2024). Auxiliary statistics were obtained from FAOSTAT, the IUCN Red List, and the U.S. EPA Non-CO_2 Greenhouse Gas Data Tool. All data sources are cited in the text, tables, or reference list. Policy-coding summaries and country lists supporting the results are provided in the manuscript and the supplementary information (see Section 2.2 and Text S1 in Supporting Information S1).

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References

Argentina. (2021). *Second nationally determined contribution (nationally determined contribution)*. Buenos Aires, Argentina: United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/NDC/2022-05/Actualizacio%CC%81n%20meta%20de%20emisiones%202030.pdf

Argentina. (2024). *First biennial transparency report of the Argentine republic to the United Nations framework convention on climate change (biennial transparency report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/645001

Australia. (2024). *Australia's first biennial transparency report (biennial transparency report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/644997

Australia. (2025). *Australia's 2035 nationally determined contribution (nationally determined contribution)*. Australian Government. Retrieved from https://unfccc.int/sites/default/files/2025-09/Australias%20Second%20NDC.pdf

Bai, Y., & Cotrufo, M. F. (2022). Grassland soil carbon sequestration: Current understanding, challenges, and solutions. *Science*, *377*(6606), 603–608. https://doi.org/10.1126/science.abo2380

Bardgett, R. D., Bullock, J. M., Lavorel, S., Manning, P., Schaffner, U., Ostle, N., et al. (2021). Combatting global grassland degradation. *Nature Reviews Earth & Environment*, *2*(10), 720–735. https://doi.org/10.1038/s43017-021-00207-2

Bayer, A. D., Fuchs, R., Mey, R., Krause, A., Verburg, P. H., Anthoni, P., & Arneth, A. (2021). Diverging land-use projections cause large variability in their impacts on ecosystems and related indicators for ecosystem services. *Earth System Dynamics*, *12*(1), 327–351. https://doi.org/10.5194/esd-12-327-2021

Bengtsson, J., Bullock, J. M., Egoh, B., Everson, C., Everson, T., O'connor, T., et al. (2019). Grasslands—More important for ecosystem services than you might think. *Ecosphere*, *10*(2), e02582. https://doi.org/10.1002/ecs2.2582

Bilotto, F., Christie-Whitehead, K. M., Malcolm, B., & Harrison, M. T. (2023). Carbon, cash, cattle and the climate crisis. *Sustainability Science*, *18*(4), 1795–1811. https://doi.org/10.1007/s11625-023-01323-2

Bilotto, F., Harrison, M. T., Vibart, R., Mackay, A., Christie-Whitehead, K. M., Ferreira, C. S., et al. (2024). Towards resilient, inclusive, sustainable livestock farming systems. *Trends in Food Science & Technology*, *152*, 104668. https://doi.org/10.1016/j.tifs.2024.104668

Bond, W. J. (2016). Ancient grasslands at risk. *Science*, *351*(6269), 120–122. https://doi.org/10.1126/science.aad5132

Brazil. (2024). *Brazil's nationally determined contribution: National determination to contribute and transform (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/2024-11/Brazil_Second%20Nationally%20Determined%20Contribution%20%28NDC%29_November2024.pdf

Brazil. (2024). *First biennial transparency report of Brazil to the United Nations framework convention on climate change (biennial transparency report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/644852

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., et al. (2023). IPCC, 2023: Climate change 2023: Synthesis report. In H. Lee & J. Romero (Eds.), *Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change [core writing team, IPCC]*. Intergovernmental Panel on Climate Change (IPCC). (First). https://doi.org/10.59327/IPCC/AR6-9789291691647

Canada. (2024). *Canada's first biennial transparency report under the Paris agreement: Developed in accordance with the Paris agreement's enhanced transparency framework (biennial transparency report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/645162

Canada. (2025). *Canada's 2035 nationally determined contribution (nationally determined contribution)*. Ottawa, Canada: Environment and Climate Change Canada. Retrieved from https://unfccc.int/sites/default/files/2025-02/Canada%27s%202035%20Nationally%20Determined%20Contribution_ENc.pdf

Chang, J., Ciais, P., Gasser, T., Smith, P., Herrero, M., Havlík, P., et al. (2021). Climate warming from managed grasslands cancels the cooling effect of carbon sinks in sparsely grazed and natural grasslands. *Nature Communications*, *12*(1), 118. https://doi.org/10.1038/s41467-020-20406-7

China. (2024). *First biennial transparency report on climate change (biennial transparency report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/645296

China. (2025). *China's nationally determined contribution under the Paris agreement (2035) (nationally determined contribution)*. Ministry of Ecology and Environment of the People's Republic of China. Retrieved from https://unfccc.int/sites/default/files/2025-11/2035%E5%B9%B4%E4%B8%AD%E5%9B%BD%E5%9B%BD%E5%AE%B6%E8%87%AA%E4%B8%BB%E8%B4%A1%E7%8C%AE%E6%8A%A5%E5%91%8A.pdf

Clark, M. A., Domingo, N. G., Colgan, K., Thakrar, S. K., Tilman, D., Lynch, J., et al. (2020). Global food system emissions could preclude achieving the 1.5 and 2 C climate change targets. *Science*, *370*(6517), 705–708. https://doi.org/10.1126/science.aba7357

Conant, R. T. (2010). *Challenges and opportunities for carbon sequestration in grassland systems* (Vol. 9). FAO. Retrieved from https://roar-assets-auto.rbl.ms/documents/35915/i1399e.pdf

Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf, E., et al. (2025). *GHG emissions of all world countries – JRC/IEA 2025 report (Report No. JRC143227)*. Joint Research Centre (JRC) and International Energy Agency (IEA). https://doi.org/10.2760/9816914

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, *2*(3), 198–209. https://doi.org/10.1038/s43016-021-00225-9

Dengler, J., Janišová, M., Török, P., & Wellstein, C. (2014). Biodiversity of Palaearctic grasslands: A synthesis. *Agriculture, Ecosystems & Environment*, *182*, 1–14. https://doi.org/10.1016/j.agee.2013.12.015

Dietrich, J. P., Bodirsky, B. L., Humpenöder, F., Weindl, I., Stevanović, M., Karstens, K., et al. (2019). MAgPIE 4–a modular open-source framework for modeling global land systems. *Geoscientific Model Development*, *12*(4), 1299–1317. https://doi.org/10.5194/gmd-12-1299-2019

Dittmer, K. M., Rose, S. C., Khatri-Chhetri, A., Stier, M., Trang, V. H., & Nelson, K. (2024). Agricultural sub-sectors in new and updated NDCs: 2020–2024. *Harvard Dataverse*. https://doi.org/10.7910/DVN/4PO5Z0

Dondini, M., Martin, M., De Camillis, C., Uwizeye, A., Soussana, J.-F., Robinson, T., & Steinfeld, H. (2023). *Global assessment of soil carbon in grasslands: From current stock estimates to sequestration potential*. Food & Agriculture Org. Retrieved from https://books.google.com/books?hl=zh-CN&lr=&id=U0zfEAAAQBAJ&oi=fnd&pg=PR3&dq=Global+Assessment+of+Soil+Carbon+in+Grasslands:+From+Current+Stock+Estimates+to+Sequestration+Potential&ots=tNC_6zxzwl&sig=RF7g5T41-xjukpwki9-bxdRv0wc

Ethiopia. (2024). *Ethiopia's first biennial update report under the united nations framework convention on climate change (biennial update report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/resource/Ethiopia_First%20BUR.pdf

Ethiopia. (2025). *Ethiopia's nationally determined contribution 3.0 (2025–2035) (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/2025-09/Ethiopia%20NDC%203.0%20Final.pdf

EU. (2024). *First biennial transparency report from the European union (biennial transparency report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/644477

EU. (2025). *The nationally determined contribution of the European union and its member states (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/2025-11/DK-2025-11-05%20EU%20NDC.pdf

FAOSTAT. (2026). FAOSTAT statistical database [Dataset]. *Food and Agriculture Organization of the United Nations*. Retrieved from https://www.fao.org/faostat/en/#data

Fetzel, T., Petridis, P., Noll, D., Singh, S. J., & Fischer-Kowalski, M. (2018). Reaching a socio-ecological tipping point: Overgrazing on the Greek island of Samothraki and the role of European agricultural policies. *Land Use Policy*, *76*, 21–28. https://doi.org/10.1016/j.landusepol.2018.04.042

Feurdean, A., Ruprecht, E., Molnár, Z., Hutchinson, S. M., & Hickler, T. (2018). Biodiversity-rich European grasslands: Ancient, forgotten ecosystems. *Biological Conservation*, *228*, 224–232. https://doi.org/10.1016/j.biocon.2018.09.022

Fischer, G., Nachtergaele, F., Prieler, S., van Velthuizen, H., Verelst, L., & Wiberg, D. (2021). Global agro-ecological zones (GAEZ v4)—Model documentation. Retrieved from https://gaez.fao.org

Forster, D., Helama, S., Harrison, M. T., Rotz, C. A., Chang, J., Ciais, P., et al. (2022). Use, calibration and verification of agroecological models for boreal environments: A review. *Grassland Research*, *1*(1), 14–30. https://doi.org/10.1002/glr2.12010

Frank, S., Havlík, P., Stehfest, E., van Meijl, H., Witzke, P., Pérez-Domínguez, I., et al. (2019). Agricultural non-CO_2 emission reduction potential in the context of the 1.5°C target. *Nature Climate Change*, *9*(1), 66–72. https://doi.org/10.1038/s41558-018-0358-8

Fujimori, S., Kainuma, M., & Masui, T. (Eds.) (2017). *Post-2020 climate action*. Springer Singapore. https://doi.org/10.1007/978-981-10-3869-3

Gambhir, A., Butnar, I., Li, P.-H., Smith, P., & Strachan, N. (2019). A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCS. *Energies*, *12*(9), 1747. https://doi.org/10.3390/en12091747

Gang, C., Zhou, W., Wang, Z., Chen, Y., Li, J., Chen, J., et al. (2015). Comparative assessment of grassland NPP dynamics in response to climate change in China, North America, Europe and Australia from 1981 to 2010. *Journal of Agronomy and Crop Science*, *201*(1), 57–68. https://doi.org/10.1111/jac.12088

Gao, Q., Zhu, W., Schwartz, M. W., Ganjurjav, H., Wan, Y., Qin, X., et al. (2016). Climatic change controls productivity variation in global grasslands. *Scientific Reports*, *6*(1), 26958. https://doi.org/10.1038/srep26958

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., et al. (2013). *Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization of the United Nations (FAO). Retrieved from https://www.cabdirect.org/cabdirect/mobile/abstract/20133417883

Habel, J. C., Dengler, J., Janišová, M., Török, P., Wellstein, C., & Wiezik, M. (2013). European grassland ecosystems: Threatened hotspots of biodiversity. *Biodiversity & Conservation*, *22*(10), 2131–2138. https://doi.org/10.1007/s10531-013-0537-x

Harper, K. L., Lamarche, C., Hartley, A., Peylin, P., Ottlé, C., Bastrikov, V., et al. (2023). A 29-year time series of annual 300 m resolution plant-functional-type maps for climate models [Dataset]. *Copernicus GmbH*, *15*(3), 1465–1499. https://doi.org/10.5194/essd-15-1465-2023

Harrison, M. T. (2021). Climate change benefits negated by extreme heat. *Nature Food*, *2*(11), 855–856. https://doi.org/10.1038/s43016-021-00387-6

Harrison, M. T., Christie, K. M., Rawnsley, R. P., & Eckard, R. J. (2014). Modelling pasture management and livestock genotype interventions to improve whole-farm productivity and reduce greenhouse gas emissions intensities. *Animal Production Science*, *54*(12), 2018–2028. https://doi.org/10.1071/an14421

Harrison, M. T., Cullen, B. R., Mayberry, D. E., Cowie, A. L., Bilotto, F., Badgery, W. B., et al. (2021). Carbon myopia: The urgent need for integrated social, economic and environmental action in the livestock sector. *Global Change Biology*, *27*(22), 5726–5761. https://doi.org/10.1111/gcb.15816

Harrison, M. T., & Liu, K. (2024). Holistic systems analyses accelerate progress towards sustainable development goals. *Nature Food*, *5*(7), 544–545. https://doi.org/10.1038/s43016-024-00989-w

Havlík, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M. C., et al. (2014). Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences*, *111*(10), 3709–3714. https://doi.org/10.1073/pnas.1308044111

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M. C., Thornton, P. K., et al. (2013). Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences*, *110*(52), 20888–20893. https://doi.org/10.1073/pnas.1308149110

Herrero, M., Henderson, B., Havlík, P., Thornton, P. K., Conant, R. T., Smith, P., et al. (2016). Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change*, *6*(5), 452–461. https://doi.org/10.1038/nclimate2925

Herrero, M., Mason-D'Croz, D., Thornton, P. K., Fanzo, J., Rushton, J., Godde, C., et al. (2023). Livestock and sustainable food systems: Status, trends, and priority actions. *Science and Innovations for Food Systems Transformation*, *375*. https://doi.org/10.1007/978-3-031-15703-5_20

Hilker, T., Natsagdorj, E., Waring, R. H., Lyapustin, A., & Wang, Y. (2014). Satellite observed widespread decline in Mongolian grasslands largely due to overgrazing. *Global Change Biology*, *20*(2), 418–428. https://doi.org/10.1111/gcb.12365

IBF-IIASA. (2023). Global biosphere management model (GLOBIOM) documentation 2023—Version 1.0. Laxenburg, Austria: Integrated biospheres futures. *International Institute for Applied Systems Analysis (IBF-IIASA)*. Retrieved from https://pure.iiasa.ac.at/18996

India. (2022). *India's updated first nationally determined contribution under the Paris agreement (2021–2030) (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/NDC/2022-08/India%20Updated%20First%20Nationally%20Determined%20Contrib.pdf

India. (2024). *India: Fourth biennial update report to the united nations framework convention on climate change (biennial update report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/645149

International Union for Conservation of Nature. (2024). The IUCN red list of threatened species – Statistics [Dataset]. Retrieved from https://www.iucnredlist.org/

IPCC. (2006). IPCC guidelines for national greenhouse gas inventories. Retrieved from https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

Japan. (2024). *Japan's first biennial transparency report (biennial transparency report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/642069

Japan. (2025). *Japan's nationally determined contribution (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/2025-02/Japans%202035-2040%20NDC.pdf

Jiang, X., & Wang, L. (2022). Grassland-based ruminant farming systems in China: Potential, challenges and a way forward. *Animal Nutrition*, *10*, 243–248. https://doi.org/10.1016/j.aninu.2022.04.007

Kazakhstan. (2024). *The first biennial transparency report of the Republic of Kazakhstan (biennial transparency report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/642798

Kazakhstan. (2025). *Kazakhstan NDC 3.0 (third nationally determined contribution) (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/2025-11/NDC%20Kazakhstan%203.0%20russ.pdf

Kebede, E. A., Oluoch, K. O., Siebert, S., Mehta, P., Hartman, S., Jägermeyr, J., et al. (2025). A global open-source data set of monthly irrigated and rainfed cropped areas (MIRCA-OS) for the 21st century. *Scientific Data*, *12*(1), 208. https://doi.org/10.1038/s41597-024-04313-w

Klein Goldewijk, K. (2024). History database of the global environment (HYDE) 3.3 [Dataset]. *Utrecht University*. https://doi.org/10.24416/UU01-94FNH0

Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., et al. (2017). Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Global Environmental Change*, *42*, 297–315. https://doi.org/10.1016/j.gloenvcha.2016.05.015

Luo, C., Li, S., Hua, E., Forsell, N., & Chen, M. (2024). Synthesizing mitigation ambitions and implementation of the agriculture, forestry, and other land use (AFOLU) sector. *Ecosystem Health and Sustainability*, *10*, 0217. https://doi.org/10.34133/ehs.0217

Mongolia. (2025). *Mongolia NDC 3.0 (third nationally determined contribution) (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/2025-09/Mongolia%20NDC3_0%20under%20UNFCCC_PA%20FINAL.pdf

Mongolia. (2026). *2024 biennial transparency report (biennial transparency report)*. Ulaanbaatar, Mongolia: United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/655311

Murphy, B. P., Andersen, A. N., & Parr, C. L. (2016). The underestimated biodiversity of tropical grassy biomes. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1703), 20150319. https://doi.org/10.1098/rstb.2015.0319

New Zealand. (2024). *New Zealand's first biennial transparency report under the Paris agreement (biennial transparency report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/644974

New Zealand. (2025). *Submission under the Paris agreement: New Zealand's second nationally determined contribution (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/2025-01/New%20Zealand%27s%20second%20Nationally%20Determined%20Contribution.pdf

Nguyen, T. H., Tang, F. H. M., Conchedda, G., Casse, L., Obli-Laryea, G., Tubiello, F. N., & Maggi, F. (2024). NPKGRIDS: A global georeferenced data set of N, P_2O_5, and K_2O fertilizer application rates for 173 crops. *Scientific Data*, *11*(1), 1179. https://doi.org/10.1038/s41597-024-04030-4

Nigeria. (2024). *Biennial transparency report (biennial transparency report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/645210

Nigeria. (2025b). *Nigeria NDC 3.0 (third nationally determined contribution) (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/497790

O'Mara, F. P. (2011). The significance of livestock as a contributor to global greenhouse gas emissions today and in the near future. *Animal Feed Science and Technology*, *166*, 7–15. https://doi.org/10.1016/j.anifeedsci.2011.04.074

Pham-Kieu, M., Ives, S., Badgery, W., & Harrison, M. (2025). Stacking interventions enhances carbon removals and profitability of livestock production systems. *Advanced Science*. https://doi.org/10.1002/advs.202503382

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., et al. (2017). Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, *42*, 331–345. https://doi.org/10.1016/j.gloenvcha.2016.10.002

Potapov, P., Turubanova, S., Hansen, M. C., Tyukavina, A., Zalles, V., Khan, A., et al. (2022). Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. *Nature Food*, *3*(1), 19–28. https://doi.org/10.1038/s43016-021-00429-z

Reinermann, S., Boos, C., Kaim, A., Schucknecht, A., Asam, S., Gessner, U., et al. (2025). Grassland yield estimations – Potentials and limitations of remote sensing, process-based modelling and field measurements. *EGUsphere*, 1–34. https://doi.org/10.5194/egusphere-2024-4087

Robinson, T. P., Thornton, P. K., Franceschini, G., Kruska, R. L., Chiozza, F., Notenbaert, A., et al. (2011). *Global livestock production systems*. FAO and ILRI. Retrieved from https://cgspace.cgiar.org/bitstream/10568/10537/1/faoglobalLivestock.pdf

Rolinski, S., Müller, C., Heinke, J., Weindl, I., Biewald, A., Bodirsky, B. L., et al. (2018). Modeling vegetation and carbon dynamics of managed grasslands at the global scale with LPJmL 3.6. *Geoscientific Model Development*, *11*(1), 429–451. https://doi.org/10.5194/gmd-11-429-2018

Sándor, R., Ehrhardt, F., Grace, P., Recous, S., Smith, P., Snow, V., et al. (2020). Ensemble modelling of carbon fluxes in grasslands and croplands. *Field Crops Research*, *252*, 107791. https://doi.org/10.1016/j.fcr.2020.107791

Stanimirova, R., Arévalo, P., Kaufmann, R. K., Maus, V., Lesiv, M., Havlík, P., & Friedl, M. A. (2019). Sensitivity of global pasturelands to climate variation. *Earth's Future*, *7*(12), 1353–1366. https://doi.org/10.1029/2019EF001316

Stehfest, E., van Vuuren, D., Bouwman, L., & Kram, T. (2014). Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications. *Netherlands Environmental Assessment Agency (PBL)*. Retrieved from https://research-portal.uu.nl/files/8219332/PBL_2014_Integrated_Assessment_of_Global_Environmental_Change_with_IMAGE_30_735.pdf

Steinfeld, H. (2006). *Livestock's long shadow: Environmental issues and options*. Food & Agriculture Org.

Suttie, J. M., Reynolds, S. G., & Batello, C. (2005). *Grasslands of the world* (Vol. 34). Food & Agriculture Org.

Tian, F., Wu, B., Zeng, H., Zhang, M., Zhu, W., Yan, N., et al. (2025). GMIE: A global maximum irrigation extent and central pivot irrigation system data set derived via irrigation performance during drought stress and deep learning methods. *Earth System Science Data*, *17*(3), 855–880. https://doi.org/10.5194/essd-17-855-2025

UK. (2024). *United Kingdom's first biennial transparency report (biennial transparency report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/645089

UK. (2025). *United Kingdom of Great Britain and Northern Ireland's 2035 nationally determined contribution (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/2025-01/UK%27s%202035%20NDC%20ICTU.pdf

UNEP. (2024). Emissions gap report 2024. Retrieved from https://www.unep.org/resources/emissions-gap-report-2024

UNFCCC. (2025). *Nationally determined contributions under the Paris agreement. Synthesis report by the secretariat (synthesis report No. FCCC/PA/CMA/2025/8)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/650664

Uruguay. (2024). *Third nationally determined contribution to the Paris agreement (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/2025-01/20241220_Uruguay_NDC3.pdf

Uruguay. (2025a). *2024 Biennial transparency report (biennial transparency report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/645269

US. (2024). *2024 U.S. biennial transparency report: First biennial transparency report of the United States of America (biennial transparency report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/645032

US. (2024). *The United States of America nationally determined contribution: Reducing greenhouse gases in the United States: A 2035 emissions target (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/2024-12/United%20States%202035%20NDC.pdf

US Environmental Protection Agency. (2022). Non-CO_2 greenhouse gas data tool [Dataset]. Retrieved from https://cfpub.epa.gov/ghgdata/nonco2/

Van Dijk, M., Morley, T., Rau, M. L., & Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nature Food*, *2*(7), 494–501. https://doi.org/10.1038/s43016-021-00322-9

Vyas, S., Khatri-Chhetri, A., Aggarwal, P., Thornton, P., & Campbell, B. M. (2022). Perspective: The gap between intent and climate action in agriculture. *Global Food Security*, *32*, 100612. https://doi.org/10.1016/j.gfs.2022.100612
Wang, D., Peng, Q., Li, X., Zhang, W., Xia, X., Qin, Z., et al. (2024). A long-term high-resolution data set of grasslands grazing intensity in China. *Scientific Data*, *11*(1), 1194. https://doi.org/10.1038/s41597-024-04045-x
White, R. P., Murray, S., Rohweder, M., Prince, S. D., & Thompson, K. M. (2000). *Grassland ecosystems*. World Resources Institute.
Wilsey, B. (2018). *The biology of grasslands*. Oxford University Press.
Wróbel, B., Zielewicz, W., & Paszkiewicz-Jasińska, A. (2025). Improving forage quality from permanent grasslands to enhance ruminant productivity. *Agriculture*, *15*(13), 1438. https://doi.org/10.3390/agriculture15131438
Xu, X., Sharma, P., Shu, S., Lin, T.-S., Ciais, P., Tubiello, F. N., et al. (2021). Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. *Nature Food*, *2*(9), 724–732. https://doi.org/10.1038/s43016-021-00358-x
Yahdjian, L., Sala, O. E., & Havstad, K. M. (2015). Rangeland ecosystem services: Shifting focus from supply to reconciling supply and demand. *Frontiers in Ecology and the Environment*, *13*(1), 44–51. https://doi.org/10.1890/140156
Yang, Y., Shi, Y., Sun, W., Chang, J., Zhu, J., Chen, L., et al. (2022). Terrestrial carbon sinks in China and around the world and their contribution to carbon neutrality. *Science China Life Sciences*, *65*(5), 861–895. https://doi.org/10.1007/s11427-021-2045-5
Yu, Q., You, L., Wood-Sichra, U., Ru, Y., Joglekar, A. K., Fritz, S., et al. (2020). A cultivated planet in 2010: 2. The global gridded agricultural production maps. *Earth System Science Data Discussions*, *2020*, 1–40.
Zarei, A., Chemura, A., Gleixner, S., & Hoff, H. (2021). Evaluating the grassland NPP dynamics in response to climate change in Tanzania. *Ecological Indicators*, *125*, 107600. https://doi.org/10.1016/j.ecolind.2021.107600

References From the Supporting Information

Argentina. (2019). *National inventory report of the third biennial update report of the Argentine republic to the united nations framework convention on climate change (national inventory report (biennial update report))*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/201965
Argentina. (2024). *National inventory report (national inventory report)*. Buenos Aires, Argentina: United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/645002
Australia. (2022). *Australia's nationally determined contribution communication 2022 (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/NDC/2022-06/Australias%20NDC%20June%202022%20Update%20%283%29.pdf
Australia. (2024b). *National inventory document (national inventory document)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/637882
Brazil. (2024). *National inventory report (national inventory report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/644855
Canada. (2021). *Canada's 2021 nationally determined contribution under the Paris agreement (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/NDC/2022-06/Canada%27s%20Enhanced%20NDC%20Submission1_FINAL%20EN.pdf
Canada. (2024). *National inventory document (national inventory document)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/638317
China. (2021). *China's implementation of nationally determined contributions and new targets and initiatives (nationally determined contribution implementation report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/NDC/2022-06/%E4%B8%AD%E5%9B%BD%E8%90%BD%E5%AE%9E%E5%9B%BD%E5%AE%B6%E8%87%AA%E4%B8%BB%E8%B4%A1%E7%8C%AE%E6%88%90%E6%95%88%E5%92%8C%E6%96%B0%E7%9B%AE%E6%A0%87%E6%96%B0%E4%B8%BE%E6%8E%AA.pdf
China. (2022). *Progress report on the implementation of nationally determined contribution targets (nationally determined contribution progress report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/NDC/2022-11/Progress%20of%20China%20NDC%202022.pdf
EU. (2023). *The update of the nationally determined contribution of the European union and its member states (nationally determined contribution update)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/NDC/2023-10/ES-2023-10-17%20EU%20submission%20NDC%20update.pdf
EU. (2024). *National inventory document (national inventory document)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/644896
Japan. (2024). *National inventory document (national inventory document)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/637879
Kazakhstan. (2023a). *Kazakhstan national inventory report 2023 (national inventory report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/627844
Kazakhstan. (2023b). *Updated nationally determined contribution of the Republic of Kazakhstan to the global response to climate change (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/630387
Mongolia. (2020). *Mongolia's nationally determined contribution to the united nations framework convention on climate change (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/NDC/2022-06/First%20Submission%20of%20Mongolia%27s%20NDC.pdf
Mongolia. (2023). *Mongolia's national inventory report 2023 (national inventory Report)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/sites/default/files/resource/20231112_NIR_MGL.pdf
New Zealand. (2024). *National inventory document (national inventory document)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/642192
Nigeria. (2021). *Nigeria's nationally determined contribution (nationally determined contribution)*. United Nations Framework Convention on Climate Change. Retrieved from https://climate-laws.org/documents/nigeria-first-ndc-updated-submission_9e31
Nigeria. (2025a). *National inventory document (national inventory document)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/645211

UK. (2024). *National inventory document (national inventory document)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/645088

Uruguay. (2025b). *2024 National inventory document (national inventory document)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/645270

US. (2024). *2024 national inventory document (national inventory document)*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/637881