Climate-Smart Management of **Forages and Rangelands**

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डॉ. सागर हनुमान सिंह, भा.डा.से.
महानिदेशक

Dr.Sagar Hanuman Singh, IPoS
Director General

MESSAGE

Climate change has emerged as one of the most pressing challenges confronting global agriculture and livestock systems. Forages and rangelands, which provide critical support to livestock-based livelihoods, are particularly vulnerable to climate variability, land degradation, and resource constraints. Strengthening their resilience through climate-smart approaches is therefore essential for ensuring sustainable agricultural growth and food security.

The book Climate-Smart Management of Forages and Rangelands is a timely and valuable contribution that brings together scientific insights, field-based practices, and policy perspectives aimed at promoting sustainable management of forage resources under changing climatic conditions. The chapters comprehensively address climate-resilient forage production, rangeland restoration, resource-use efficiency, and institutional and extension mechanisms for effective adoption.
I am confident that this publication will serve as a useful reference for researchers, academicians, students, extension professionals, policymakers, and development practitioners engaged in climate-smart agriculture and natural resource management. The collective efforts of the editors and contributing authors in compiling this knowledge resource are highly commendable.

I extend my sincere appreciation to all the editors and authors of this book and hope that it will significantly contribute to strengthening resilient forage-based systems and sustainable livelihoods for farming and pastoral communities.

(S.H Singh)

राष्ट्रीय कृषि विस्तार प्रबंध संस्थान (मैनेज)
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Preface

Climate change poses significant challenges to global agriculture, particularly to forage production and rangeland ecosystems that form the backbone of livestock-based livelihoods. Increasing climate variability, land degradation, water scarcity, and declining productivity of natural resources necessitate innovative and sustainable management approaches. In this context, Climate-Smart Management of Forages and Rangelands has emerged as a crucial strategy to enhance productivity, resilience, and environmental sustainability.

This book, Climate-Smart Management of Forages and Rangelands, brings together scientific knowledge, practical experiences, and policy perspectives to address contemporary issues and solutions in forage and rangeland management under changing climatic conditions. The chapters cover a wide range of topics including climate-resilient forage species, sustainable rangeland management practices, soil and water conservation, livestock–forage integration, technological interventions, and extension strategies for effective adoption at the field level.

The book is intended to serve as a valuable resource for researchers, academicians, students, extension professionals, policymakers, and development practitioners working in the areas of agriculture, livestock, and natural resource management. Emphasis has been placed on practical applicability, regional relevance, and capacity building to support climate-smart agriculture initiatives, particularly in developing countries.

We sincerely hope that this publication will contribute to informed decision-making, strengthen climate resilience in forage-based systems, and support sustainable livelihoods for farming and pastoral communities. The editors gratefully acknowledge the contributions of all authors and reviewers whose expertise and commitment made this work possible.

Editors,

Shahaji Phand
Sushrirekha Das
Uday Kumar G
Repalle Naganna

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Chapter-1

Global and Country Climate Change Scenarios-Climate Smart Agriculture: Concepts and Initiations

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ABSTRACT: *Climate change poses profound challenges to global and national agricultural systems through rising temperatures, altered precipitation patterns, and increasing frequency of extreme weather events. Agriculture is simultaneously vulnerable to climate variability and a significant contributor to greenhouse gas emissions, underscoring the need for integrated response strategies. This chapter examines the agriculture–climate change nexus by discussing key concepts, drivers, observed trends, and future climate scenarios, with particular emphasis on IPCC assessment frameworks and climate models. It highlights the principles and pillars of Climate-Smart Agriculture (CSA) as a holistic approach to enhancing productivity, building resilience, and reducing emissions. The chapter further reviews global, national, and sub-national CSA initiatives, policy frameworks, institutional roles, financing mechanisms, challenges, and future pathways, emphasizing CSA's potential to support sustainable and resilient food systems.*

Keywords: Climate change, Climate Scenarios, IPCC, Climate-Smart Agriculture etc.

1. Introduction

Climate change refers to long-term changes in the statistical properties of the climate system, including temperature, precipitation, wind patterns, and the frequency and intensity of extreme weather events, occurring over decades or longer. While natural climate variability has occurred throughout Earth's history, overwhelming scientific evidence now confirms that the current phase of climate change is primarily anthropogenic. The Intergovernmental Panel on Climate Change (IPCC) has stated with high confidence that human influence has warmed the atmosphere, oceans, and land, leading to widespread and rapid changes in the Earth system since the mid-20th century (IPCC, 2021). These changes extend beyond gradual warming and include altered hydrological cycles, melting of glaciers and ice sheets, sea-level rise, and increased climate extremes. The principal driver of contemporary climate change is the enhanced greenhouse effect caused by rising concentrations of greenhouse gases in the atmosphere. Carbon dioxide (CO_2) is the most significant contributor, largely emitted through the combustion of fossil fuels, cement production, and deforestation. Atmospheric CO_2 concentrations have increased from approximately 280 parts per million (ppm) in the pre-industrial era to over 420 ppm in recent years, reaching levels unprecedented in at least the last 800,000 years (NOAA, 2023). Methane (CH_4), primarily emitted from agriculture (especially enteric fermentation and rice cultivation), waste management, and fossil fuel extraction, and nitrous oxide (N_2O), largely from fertilizer use and agricultural soils, further intensify warming due to their high global warming potential (IPCC, 2021). Changes in land use, particularly deforestation and land degradation, reduce natural carbon sinks and amplify climate forcing.

The climate trends clearly demonstrate a warming planet. Global mean surface temperature has increased by approximately 1.1°C above pre-industrial levels, with the last decade being the warmest on record (WMO, 2023). Scientific evidence also indicates a rise in the frequency and severity of extreme events such as heatwaves, floods, droughts, and tropical cyclones, many of which can now be attributed directly to anthropogenic climate change (IPCC, 2021). Another critical trend associated with climate change is the warming of oceans, which absorb more than 90 percent of the excess heat generated by greenhouse gas emissions. Ocean warming contributes to thermal expansion and melting of land-based ice, resulting in global sea-level rise, which has accelerated over the past decades (IPCC, 2021). In addition, increased absorption of CO_2 by oceans has led to ocean acidification, adversely affecting marine ecosystems and fisheries. These interconnected trends highlight that climate change is a systemic phenomenon affecting atmospheric, terrestrial, and oceanic systems simultaneously.

Future climate projections indicate that without substantial and sustained reductions in greenhouse gas emissions, global temperatures are likely to exceed 1.5°C and possibly 2°C above pre-industrial levels during the 21st century. Such warming would substantially increase risks to natural and human systems, particularly agriculture, food security, health, and livelihoods, especially in developing countries (IPCC, 2022). The scientific understanding of climate change thus underscores the urgency of mitigation and adaptation strategies, forming the foundation for concepts such as climate-smart agriculture that seek to address climate risks while ensuring sustainable development.

2. Agriculture–Climate Change Nexus

The relationship between agriculture and climate change is complex and bidirectional, making agriculture both a victim and a contributor to climate change. Agricultural systems are highly sensitive to changes in temperature, precipitation, and the frequency of extreme weather events, which directly influence crop growth, livestock productivity, soil health, and water

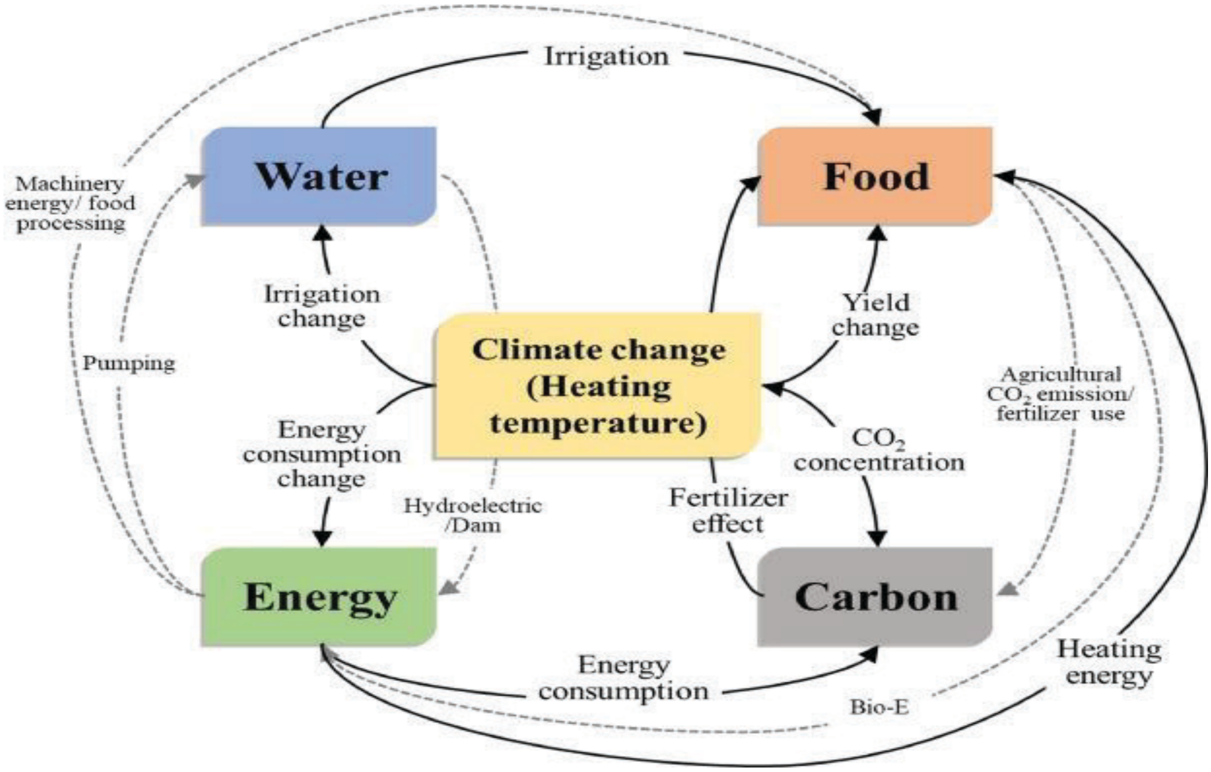

Figure 1: Food-Energy-Water-Carbon Nexus

availability. Climate variability affects crop phenology, growing periods, and yield stability, while extreme events such as droughts, floods, heat waves, and cyclones often result in large-scale crop failures and livestock losses. Rained agriculture, which supports a major share of global food production and livelihoods in developing countries, is particularly vulnerable to erratic rainfall and prolonged dry spells. Climate change also alters pest and disease dynamics, often increasing their incidence and geographic spread, thereby raising production risks and input costs for farmers (IPCC, 2022).At the same time, agriculture significantly contributes to climate change through greenhouse gas emissions. The sector accounts for a substantial share of global emissions, primarily in the form of methane from enteric fermentation and rice cultivation, nitrous oxide from fertilizer application and manure management, and carbon dioxide from land-use change, deforestation, and agricultural mechanization. Unsustainable farming practices, such as excessive tillage, residue burning, and overuse of chemical inputs, further exacerbate emissions and degrade natural resources. However, agriculture also holds considerable potential for climate change mitigation through carbon sequestration in soils and biomass, improved nutrient and water management, agroforestry, and sustainable livestock practices. This dual role places agriculture at the center of climate change adaptation and mitigation strategies, emphasizing the need for integrated approaches that enhance resilience while reducing emissions and ensuring food security (FAO, 2017; IPCC, 2021).

3. Global Climate Change Scenarios

Global climate change scenarios are scientific representations of possible future climate conditions based on different assumptions about greenhouse gas emissions, socioeconomic development, population growth, and technological change. These scenarios are developed using Global Climate Models (GCMs) and Earth System Models, which simulate interactions among the atmosphere, oceans, land surface, and biosphere. The Intergovernmental Panel on Climate Change uses standardized scenario frameworks to project future climate outcomes and assess associated risks. In recent assessments, Shared Socioeconomic Pathways (SSPs) have been adopted to describe alternative development trajectories ranging from sustainable, low-emission futures to fossil-fuel-intensive, high-emission pathways (IPCC, 2021).

Projections under global climate change scenarios consistently indicate continued warming throughout the 21st century, with the magnitude of temperature increase depending on future emission pathways. Under low-emission scenarios, global warming is likely to stabilize around 1.5–2.0°C above pre-industrial levels, whereas high-emission scenarios project temperature increases exceeding 4°C by the end of the century. These scenarios also project significant changes in precipitation patterns, including increased rainfall intensity in many regions and declining rainfall in subtropical and semi-arid areas. In addition, the frequency and severity of extreme events such as heatwaves, heavy rainfall, droughts, and tropical cyclones are expected to increase across most regions of the world. For agriculture, these projected changes imply heightened production risks, shifts in agro-climatic zones, increased water stress, and growing uncertainty in food systems, particularly in climate-vulnerable regions (IPCC, 2021; WMO, 2023).

4. IPCC Assessment Frameworks and Climate Models

The Intergovernmental Panel on Climate Change (IPCC) assessment framework provides a comprehensive and standardized approach for evaluating the scientific understanding of climate change, its impacts, risks, and response options. Established in 1988 by the World Meteorological Organization and the United Nations Environment Programme, the IPCC does not conduct original research but synthesizes peer-reviewed scientific literature to inform policymakers. Its assessment reports are structured around three Working Groups: Working Group I focuses on the physical science basis of climate change, including observed changes and future projections; Working Group II assesses impacts, vulnerability, and adaptation of natural and human systems; and Working Group III examines mitigation options to reduce greenhouse gas emissions.

Climate models form the scientific backbone of IPCC assessments, particularly for understanding past climate behaviour and projecting future climate scenarios. These models are mathematical representations of the Earth's climate system that simulate interactions among the atmosphere, oceans, land surface, cryosphere, and biosphere based on physical laws. Over time, climate models have evolved from simple energy balance models to complex coupled Earth System Models that incorporate biogeochemical cycles, aerosols, and land-use dynamics. The IPCC relies heavily on coordinated international modeling efforts such as the Coupled Model Inter-comparison Project (CMIP), which provides a standardized framework for comparing outputs from multiple climate models developed by research institutions worldwide. CMIP phases, including CMIP5 and the more recent CMIP6, enable systematic evaluation of model performance and uncertainty, and they underpin the climate projections presented in IPCC assessment reports (Taylor et al., 2012; Eyring et al., 2016).

In recent assessments, the IPCC has integrated climate model outputs with Shared Socioeconomic Pathways (SSPs), which describe alternative future development trajectories based on varying assumptions about population growth, economic development, energy use, and technological change. By combining SSPs with different levels of greenhouse gas emissions, climate models generate a range of plausible future climate outcomes. This framework allows policymakers and planners to assess climate risks under different development pathways and to evaluate trade-offs between mitigation, adaptation, and sustainable development goals. Despite inherent uncertainties, climate models have demonstrated robust skill in reproducing large-scale climate patterns and long-term trends, making them indispensable tools for climate risk assessment and long-term planning in sectors such as agriculture, water resources, and disaster management (IPCC, 2021; IPCC, 2022).

5. Pillars of Climate-Smart Agriculture

Climate-Smart Agriculture (CSA) is built on three interlinked pillars: sustainably increasing agricultural productivity and incomes, enhancing resilience and adaptation to climate change, and reducing or removing greenhouse gas emissions wherever feasible. These pillars reflect the need to simultaneously address food security and climate challenges without compromising environmental sustainability. Productivity enhancement is essential to meet the growing food demand of a rising population, particularly in developing countries where agriculture supports livelihoods and rural economies. However, productivity gains must be achieved in ways that conserve natural resources and minimize environmental degradation. The second pillar, adaptation and resilience, focuses on strengthening the capacity of agricultural systems to cope with climate variability and extreme events. This includes developing climate-resilient crops and livestock, improving water and soil management, diversifying farming systems, and enhancing climate risk management through early warning systems and climate services. Adaptation is particularly critical for smallholder farmers who are highly exposed to climate risks and often lack access to resources and safety nets. Building resilience not only reduces vulnerability but also stabilizes production and incomes over time. The mitigation pillar emphasizes reducing greenhouse gas emissions from agriculture and increasing carbon sequestration through improved land management. While agriculture is a significant source of methane and nitrous oxide emissions, it also offers opportunities for

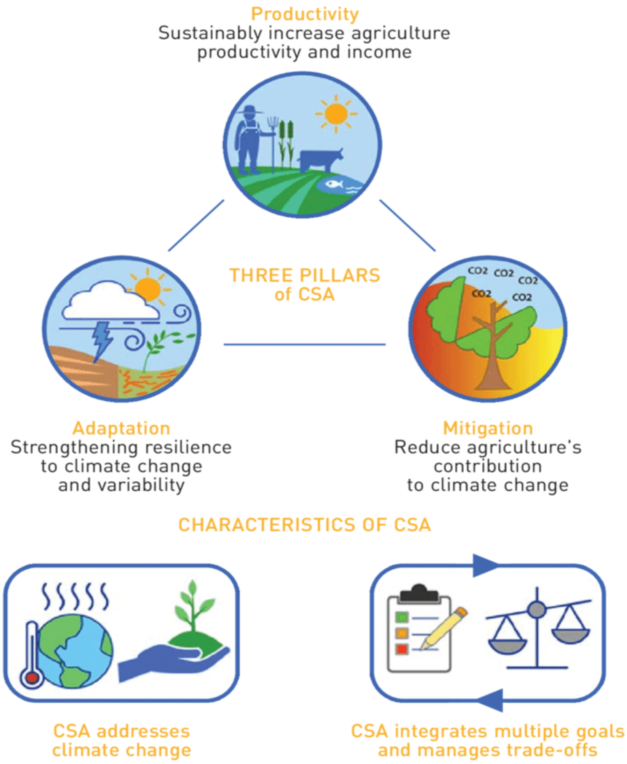

Figure 2: Three Pillars of CSA

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mitigation through practices such as conservation agriculture, agroforestry, improved nutrient management, and sustainable livestock systems. Importantly, CSA recognizes that trade-offs may exist among the three pillars and promotes context-specific solutions that maximize synergies while minimizing negative impacts (FAO, 2013).

6. Global Climate-Smart Agriculture Initiatives

Global climate-smart agriculture initiatives have emerged in response to the growing recognition of agriculture's central role in addressing climate change and food security. These initiatives aim to promote knowledge sharing, policy coherence, capacity building, and investment in climate-resilient agricultural systems. International platforms facilitate collaboration among governments, research organizations, civil society, and the private sector to accelerate the adoption of CSA practices across diverse agro-ecological and socio-economic contexts. One of the key objectives of global CSA initiatives is to integrate agriculture into international climate and development agendas. By aligning agricultural strategies with climate commitments, these initiatives support countries in meeting their adaptation and mitigation goals while ensuring food security and livelihood sustainability. Global efforts also emphasize strengthening climate information systems, enhancing innovation, and promoting inclusive approaches that address gender and social equity concerns. In addition, global CSA initiatives play a critical role in mobilizing financial and technical resources for developing countries. Through partnerships and coordinated action, they help bridge gaps between research, policy, and practice, enabling the scaling of proven climate-smart solutions. These initiatives provide a foundation for translating global climate goals into actionable strategies at national and local levels (FAO, 2017; World Bank, 2021).

7. International Policies and Agreements

International climate policies and agreements provide the overarching framework within which climate-smart agriculture initiatives operate. The United Nations Framework Convention on Climate Change (UNFCCC) and its subsequent agreements recognize the vulnerability of agriculture to climate change and the need for adaptation and mitigation actions in the sector. Agriculture has gained increasing prominence in climate negotiations, particularly due to its role in food security, livelihoods, and sustainable development. The Paris Agreement marked a significant milestone by encouraging countries to include agriculture in their Nationally Determined Contributions (NDCs). Many countries have identified CSA-related actions such as sustainable land management, climate-resilient crops, and improved livestock systems as key components of their climate strategies. These commitments highlight the growing policy consensus that agriculture must be part of the global climate solution. Complementary international frameworks, such as the Sustainable Development Goals (SDGs), further reinforce the importance of CSA by linking climate action (SDG-13) with zero hunger (SDG-2), poverty reduction, and ecosystem conservation. Together, these agreements create an enabling environment for coordinated global action on climate-smart agriculture (UNFCCC, 2015; United Nations, 2015).

8. Global Institutions and Research Networks

Global institutions and research networks play a vital role in advancing the science, policy, and practice of climate-smart agriculture. Organizations such as the Food and Agriculture Organization of the United Nations, the World Bank, and the Consultative Group on International Agricultural Research (CGIAR) provide technical guidance, research evidence, and policy support to countries implementing CSA. These institutions contribute to developing climate-resilient technologies, decision-support tools, and best-practice frameworks. International research networks facilitate collaboration among scientists, policymakers, and practitioners across regions. Through coordinated research programs and global databases, they generate knowledge on climate impacts, adaptation strategies, and mitigation potential in agriculture. CGIAR research centers, for example, focus on climate-resilient crops, sustainable farming systems, and climate risk management, directly supporting CSA objectives. In addition, global institutions act as conveners, bringing together diverse stakeholders to share experiences and lessons learned. By fostering partnerships and knowledge exchange, they help scale successful CSA innovations and ensure that scientific advancements are translated into real-world impacts for farmers and food systems (CGIAR, 2020; FAO, 2018).

9. Financing Mechanisms for Climate-Smart Agriculture

Financing is a critical enabler for the adoption and scaling of climate-smart agriculture. Transitioning to climate-resilient and low-emission agricultural systems often requires upfront investments in technology, infrastructure, and capacity building. International climate finance mechanisms have therefore increasingly recognized agriculture as a priority sector for funding adaptation and mitigation actions. Global funds such as the Green Climate Fund, Global

Environment Facility, and Climate Investment Funds support CSA projects by providing grants, concessional loans, and risk-sharing instruments. These mechanisms aim to leverage public and private investments while ensuring that financial support reaches vulnerable farming communities. Blended finance approaches are increasingly used to attract private sector participation in climate-smart agricultural value chains. Despite these efforts, significant financing gaps remain, particularly for smallholder farmers in developing countries. Addressing these gaps requires innovative financial instruments, improved access to credit, and stronger integration of CSA into national budgetary processes and development planning (World Bank, 2021; GCF, 2022).

10. National and Sub-National Climate-Smart Agriculture Initiatives

National and sub-national governments play a pivotal role in translating global CSA frameworks into locally relevant actions. Many countries have incorporated climate-smart agriculture into national climate policies, agricultural development plans, and rural livelihood programs. These initiatives aim to enhance resilience, improve productivity, and reduce emissions in line with national priorities and capacities. At the sub-national level, state and local governments are increasingly implementing CSA interventions tailored to specific agro-climatic conditions. Decentralized planning allows for more context-specific solutions, such as watershed-based approaches, climate-resilient cropping systems, and location-specific advisories. Such initiatives strengthen local ownership and improve the effectiveness of CSA implementation. The success of national and sub-national CSA initiatives depends on strong institutional coordination, policy coherence, and stakeholder engagement. Integrating CSA into extension services, research systems, and development programs is essential for achieving long-term impacts (FAO, 2017; IPCC, 2022).

11. National Climate Policies and Agricultural Strategies

National climate policies provide the strategic framework for integrating agriculture into climate action. Many countries have developed National Adaptation Plans and long-term low-emission development strategies that explicitly recognize the role of agriculture. These policies emphasize building resilience, enhancing food security, and reducing emissions through sustainable agricultural practices. Agricultural strategies aligned with climate objectives focus on promoting climate-resilient technologies, improving natural resource management, and strengthening institutional capacity. Policy instruments such as subsidies, incentives, and regulatory measures are used to encourage the adoption of CSA practices. Integration of climate considerations into agricultural planning also supports risk-informed decision-making. Effective implementation of these policies requires cross-sectoral coordination among agriculture, environment, water, and rural development agencies. Aligning climate and agricultural policies helps avoid trade-offs and maximizes synergies for sustainable development (FAO, 2018; UNFCCC, 2015).

12. Climate-Smart Agriculture Programs and Missions

Climate-smart agriculture programs and missions operationalize policy commitments through targeted interventions and investments. These programs often focus on scaling climate-resilient technologies, strengthening extension services, and improving access to climate information and financial services for farmers. They serve as platforms for piloting innovative approaches and mainstreaming CSA into development practice. Many CSA programs emphasize participatory approaches, recognizing farmers as key agents of change. By integrating local knowledge with scientific innovations, these programs enhance adoption and sustainability. Missions also prioritize vulnerable regions and communities to address climate-induced inequalities. Monitoring and evaluation are critical components of CSA programs, enabling learning and adaptive management. Evidence generated through program implementation informs policy refinement and supports the scaling of successful models (World Bank, 2021; FAO, 2013)

13. Role of Research, Extension, and Capacity Building

Research, extension, and capacity building form the backbone of climate-smart agriculture implementation. Scientific research generates evidence on climate impacts, adaptation options, and mitigation potential, while extension systems translate this knowledge into practical guidance for farmers. Strengthening the linkages between research and extension is essential for effective CSA adoption. Capacity building efforts focus on enhancing the skills of farmers, extension agents, and policymakers to understand climate risks and implement CSA practices. Training programs, farmer field schools, and digital advisory platforms are increasingly used to disseminate climate-smart knowledge. Building institutional capacity also enables better planning, coordination, and resource allocation.

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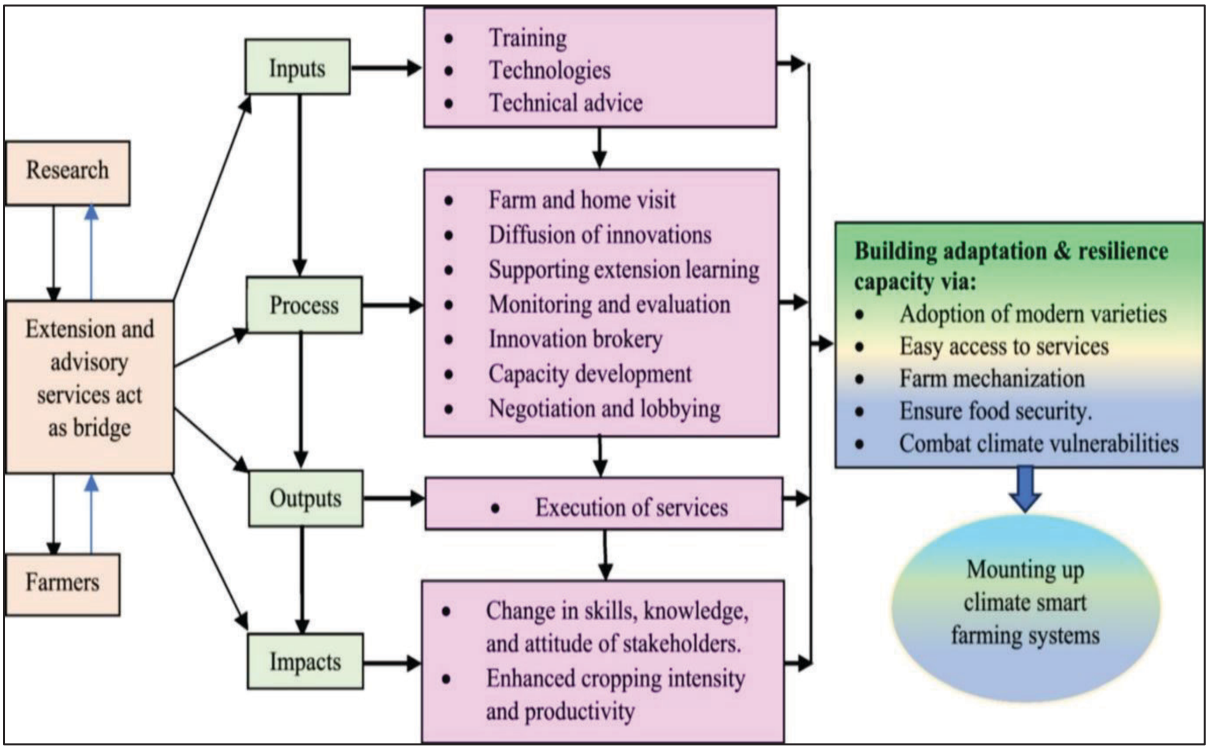

Figure 3: Role of Research, Extension & Capacity Building in CSA

Inclusive capacity building that addresses gender and social disparities is particularly important for equitable CSA outcomes. Empowering women and marginalized groups enhances resilience at household and community levels and contributes to sustainable agricultural transformation (FAO, 2017; CGIAR, 2020).

14. Challenges and Trade-offs in Climate-Smart Agriculture

Despite its potential, climate-smart agriculture faces several challenges and trade-offs. One of the key challenges is balancing productivity, adaptation, and mitigation goals. For example, intensification aimed at increasing yields may lead to higher emissions if not managed sustainably. Institutional and financial constraints also hinder CSA adoption, particularly among smallholder farmers. Limited access to credit, information, and technology reduces the ability of farmers to invest in climate-smart practices. In addition, uncertainty in climate projections and local variability complicate planning and decision-making. Addressing these challenges requires context-specific solutions, supportive policies, and continuous learning. Transparent assessment of trade-offs and inclusive decision-making processes are essential for ensuring that CSA contributes to sustainable and equitable outcomes (IPCC, 2019; FAO, 2013).

15. Opportunities and Pathways for Scaling Climate-Smart Agriculture

Climate-smart agriculture presents significant opportunities for transforming food systems in the face of climate change. Advances in climate science, digital technologies, and agricultural innovation provide new tools for managing climate risks and enhancing productivity. Integrating CSA into value chains and market systems further strengthens incentives for adoption. Scaling CSA requires enabling environments that combine supportive policies, investments, and institutions. Strengthening partnerships among public, private, and civil society actors can accelerate dissemination and adoption of climate-smart solutions. Climate finance and risk-transfer mechanisms also play a crucial role in reducing barriers to scaling. By aligning CSA with broader development objectives, countries can achieve multiple benefits, including poverty reduction, ecosystem conservation, and climate resilience. Strategic investments and knowledge sharing are key pathways for scaling CSA impacts (World Bank, 2021; FAO, 2018).

16. Future Perspectives and Way Forward

The future of climate-smart agriculture lies in its integration into holistic food system approaches that address production, consumption, and sustainability simultaneously. Emerging priorities include nature-based solutions, digital agriculture, and climate-resilient value chains that enhance both adaptation and mitigation outcomes. Strengthening climate governance and data systems will further support evidence-based decision-making. Greater emphasis is needed on local innovation and participatory approaches to ensure that CSA solutions are context-appropriate and socially inclusive. Empowering farmers, especially women and youth, as innovators and leaders in climate action will enhance the long-term sustainability of agricultural transformation. Moving forward, coordinated global and national efforts are essential to scale CSA and meet climate and development goals. By investing in research, capacity building, and inclusive policies, climate-smart agriculture can play a transformative role in building resilient and sustainable food systems for the future (IPCC, 2022; FAO, 2017).

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References

CGIAR. (2020). *CGIAR research program on climate change, agriculture and food security (CCAFS)*.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 9(5), 1937–1958.

Food and Agriculture Organization of the United Nations. (2013). *Climate-smart agriculture sourcebook*. FAO.

Food and Agriculture Organization of the United Nations. (2017). *Climate-smart agriculture sourcebook* (2nd ed.). FAO.

Food and Agriculture Organization of the United Nations. (2018). *Scaling up climate-smart agriculture*. FAO.

Green Climate Fund. (2022). *GCF in action: Climate-smart agriculture*. GCF.

Intergovernmental Panel on Climate Change (2021). *Climate change 2021: The physical science basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Intergovernmental Panel on Climate Change. (2019). *Climate change and land*. IPCC Special Report. IPCC.

Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Impacts, adaptation and vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

National Oceanic and Atmospheric Administration. (2023). *Trends in atmospheric carbon dioxide*. NOAA Global Monitoring Laboratory.

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, 93(4), 485–498.

United Nations Framework Convention on Climate Change. (2015). *Paris Agreement*. UNFCCC.

United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development*. UN.

World Bank. (2021). *Climate-smart agriculture investment plan*. World Bank.

World Meteorological Organization. (2023). *State of the global climate 2023*. WMO.

Contribution of Fodder and Rangeland Management in Climate Change

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ABSTRACT: *Global climate change poses an escalating threat to livestock-based production systems, particularly those dependent on natural rangelands and rainfed fodder resources. Rangelands occupy approximately 54% of the Earth's terrestrial surface and support the livelihoods of over 500 million people. Traditionally viewed as vulnerable ecosystems, rangelands are increasingly recognized for their role in climate change mitigation. This chapter examines the dual role of fodder and rangeland management as both a casualty of climate variability and a mitigation tool. It synthesizes current research on soil carbon sequestration, climate-resilient fodder species, and enteric methane mitigation. Global case studies demonstrate that climate-smart rangeland management enhances ecosystem services, reduces greenhouse gas emissions, and strengthens pastoral livelihoods.*

Keywords: Climate change, Mitigation, Range land management

1. Introduction:

The contemporary era of climate change has fundamentally altered global agriculture. Livestock-based systems face severe stress from rising temperatures, erratic rainfall, and prolonged droughts. Rangelands comprising grasslands, savannas, shrublands, and open woodlands; form the backbone of extensive livestock production. While livestock are often criticized for their greenhouse gas (GHG) footprint. The challenge of the 21st century lies in balancing the nutritional needs of a growing population with the imperative to sequester carbon. Climate stress, combined with unsustainable grazing, has accelerated rangeland degradation, leading to reduced vegetation cover and soil erosion. However, when managed through regenerative and climate-smart practices, these lands function as effective carbon sinks. This chapter explores how optimized fodder production and rangeland governance can turn a climate vulnerability into a mitigation powerhouse.

2. Rangelands as Strategic Carbon Sinks

Rangelands store nearly 30 % of the world's terrestrial carbon. Unlike forest ecosystems, where carbon is concentrated in aboveground biomass (wood and leaves) and is highly susceptible to wildfires, rangeland carbon is predominantly stored belowground in Soil Organic Carbon (SOC).

2.1. Mechanisms of Soil Carbon Sequestration: Carbon sequestration in rangelands occurs through the photosynthetic capture of CO_2 and its subsequent transfer to the soil via root exudates and the decomposition of plant material. Proper grazing management enhances this process through:

A. **Stimulated Root Growth:** Moderate grazing can stimulate plant regrowth and deeper root penetration.

B. **Rhizodeposition:** Plants release carbon-rich compounds into the rhizosphere, feeding microbial communities that stabilize carbon in soil aggregates.

C. **Litter Incorporation:** Animal hoof action, when managed correctly, incorporates plant litter into the soil surface, preventing oxidation and loss to the atmosphere.

2.2. Restoration Potential: Degraded rangelands represent a significant "carbon debt." Restoring these lands through reseeding and erosion control can sequester up to 0.5 Mg C ha−1 year−1. In addition to mitigation, restoration improves water infiltration and nutrient cycling.

Table 1. Global Extent and Carbon Sequestration Potential of Rangelands

Parameter	Estimated Value	Source
Global land coverage	~54%	FAO (2022)
Population supported	>500 million	Reid et al. (2014)
Share of terrestrial carbon	~30%	IPCC (2019)
SOC sequestration rate	0.1–0.5 Mg C ha^{-1} yr^{-1}	Conant et al. (2017)
Restoration return	USD 35 per USD 1	UNCCD (2024)

3. Climate-Resilient Fodder Systems

To mitigate climate change, livestock must become more efficient. Higher-quality fodder reduces the time animals spend on the range to reach market weight, thereby reducing their lifetime GHG emissions.

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3.1. Physiological Adaptations of Resilient Species: Climate-resilient fodders are selected for their Phenotypic Plasticity the ability to maintain yields under heat, drought, and salinity.

- C4 Photosynthetic Pathway: Species like *Panicum maximum* utilize the C4 pathway, which is more efficient at high temperatures and low CO_2 internal concentrations than the C3 pathway.
- Deep Rooting Systems: *Cenchrus ciliaris* (Buffel grass) can access water at depths exceeding 2 meters, allowing for carbon storage in deeper soil horizons where it is less likely to be disturbed.

3.2. Emerging Fodder Crops: Sustained livestock productivity under climate stress depends on fodder species capable of maintaining yield and nutritional quality under heat, drought, salinity, and elevated CO_2 concentrations. Climate-resilient fodders enhance feed efficiency, stabilize livestock performance, and reduce methane emissions per unit of output.

Table 2 Climate-Resilient Fodder Species and Mitigation Attributes

Species	Climatic Adaptation	Yield Potential	Mitigation Role
Cenchrus ciliaris	Drought, heat	2–18 t DM ha^{-1}	Soil carbon storage
Panicum maximum	Heat, high CO_2	15–30 t DM ha^{-1}	Feed efficiency
Beta vulgaris	Salinity, drought	150–200 t ha^{-1}	Methane reduction
Leucaena leucocephala	Drought	6–12 t DM ha^{-1}	Tannin-based mitigation

4. Enteric Methane Mitigation through Nutritional Intervention

Enteric fermentation in ruminants accounts for nearly 30% of global anthropogenic methane emissions, representing a significant challenge for climate mitigation in livestock systems. Nutritional interventions offer a practical and cost-effective pathway for reducing methane production at the animal level. Leguminous fodder species such as *Leucaena leucocephala* contain condensed tannins that suppress methanogenic archaea in the rumen. Inclusion of such species in livestock diets can significantly reduce methane emissions while maintaining or improving animal performance. Improving overall diet quality by replacing low-digestibility crop residues with nutrient-rich green fodder enhances feed conversion efficiency. Studies indicate that such dietary transitions can reduce methane emissions by more than 30% per unit of digestible dry matter consumed, highlighting the strong mitigation potential of fodder-based strategies. Phytochemicals: Legumes like *Leucaena leucocephala* contain

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condensed tannins that naturally inhibit methanogens in the rumen. Dietary Quality: Transitioning livestock from high-fiber crop residues to high-quality green fodder can reduce methane emissions by over 30% per unit of digestible dry matter.

4.1. The Role of Secondary Metabolites: Leguminous fodders like *Leucaena leucocephala* contain Condensed Tannins. These compounds form complexes with proteins and directly inhibit methanogenic archaea in the rumen.

4.2. Diet Digestibility and Emission Intensity: There is an inverse relationship between fodder quality and methane production. When livestock consume high-fiber, low-quality crop residues, the fermentation process is slow and inefficient, leading to high CH_4per unit of meat or milk. Strategy: Replacing 20% of low-quality residues with green fodder can reduce methane intensity by over 30%. Leguminous fodders such as *Leucaena leucocephala* contain condensed tannins that suppress rumen methanogens. Replacing crop residues with high-quality green fodder improves feed efficiency and can reduce methane emissions by more than 30% per unit of digestible dry matter.

Table 3. Methane Reduction Potential of Fodder-Based Strategies

Strategy	**Methane Reduction**
Tannin-rich legumes	10–25%
Improved digestibility	20–30%
Crop residue replacement	>30%

5. Sustainable Management: The Regenerative Paradigm

The "Regenerative Grazing" movement has transitioned from a niche ecological theory to a scientifically validated mitigation strategy. At its core, it focuses on soil health as the primary indicator of success, utilizing livestock as biological "tools" to stimulate plant growth and microbial activity.

5.1. High-Density Short-Duration (HDSD) Grazing: The HDSD grazing, often referred to as "Adaptive Multi-Paddock" (AMP) grazing, mimics the density and movement of ancestral wild herds. By concentrating animals, we ensure uniform grazing and prevent the selective depletion of high-protein species.

- **Carbon Accrual Rates:** Long-term studies in the North American Great Plains have shown that AMP grazing can sequester significantly more carbon than continuous grazing. Research demonstrated that regenerative systems could increase soil carbon at rates of 1.5 to 3.0 Mg C ha^{-1} yr^{-1} in high-rainfall zones, compared to negligible gains in conventional systems.
- **Water Infiltration:** Evidence from Northern Australia suggests that the "hoof action" associated with HDSD grazing increases water infiltration rates by up to 200%. By breaking the physical crust of the soil, livestock create micro-depressions that capture rainfall, preventing runoff and soil erosion (which otherwise acts as a carbon source).
- **Root Biomass:** Regenerative practices maintain a higher leaf area index, which translates to a larger photosynthetic "solar panel." This sustains a massive root network; for every 1 cm of top growth maintained, a corresponding volume of root exudates is pumped into the soil, feeding the Glomalin-producing fungi that stabilize soil aggregates.

5.2. Silvopastoral Systems (SPS): Silvopastoral systems (the intentional integration of trees and livestock) are considered the "Gold Standard" for carbon sequestration in tropical and sub-tropical regions.

- **Total Carbon Stocks:** In Latin America, research by CIPAV found that traditional open pastures held approximately 60–80 Mg C/ha, whereas intensive silvopastoral systems (including fodder shrubs like *Leucaena*) held over 160 Mg C/ha. This doubling of carbon stock is attributed to the combination of tree trunks and deep-soil carbon accumulation facilitated by tree roots.
- **Nitrogen Fixation:** Evidence from the Indian Council of Agricultural Research (ICAR, 2026) shows that leguminous trees in silvopastures (such as *Prosopis cineraria*) fix atmospheric nitrogen, reducing the need for synthetic nitrogen fertilizers. Since the production of synthetic fertilizer is highly energy-intensive and releases N_2O (a GHG with 298x the warming potential of CO_2), this represents a significant indirect mitigation benefit.
- **Enteric Methane Reduction:** In silvopastures, the availability of high-protein browse (leaves from trees) improves the diet quality of ruminants. Evidence suggests that cattle grazing in SPS have a 20% lower methane emission intensity compared to those on

degraded open ranges, due to the presence of secondary metabolites like condensed tannins in the tree fodder.

5.3. The Role of Biological Nitrogen Fixation (BNF): A critical but often overlooked evidence point is the reduction of Nitrous Oxide (N_2O) emissions. Regenerative systems rely on Biological Nitrogen Fixation from leguminous fodder (e.g., *Medicago sativa*, *Trifolium*). By eliminating synthetic Urea, these systems prevent the volatilization of N_2O, which is a major contributor to the agricultural GHG footprint.

6. Global Case Studies: Evidence from the Field

The theoretical potential of rangeland mitigation is best illustrated through diverse geographical applications. These case studies highlight how localized management can lead to measurable climate benefits.

6.1. India: The Silvopastoral Model in Rajasthan: In the arid regions of Marwar, the integration of *Lasiurus sindicus* (Sewan grass) with *Prosopis cineraria* (Khejri trees) has created a resilient multi-tier system. This "traditional silvopasture" serves as a biological barrier against desertification.

- ***Key Findings***: Studies indicate that soil organic carbon (SOC) under tree canopies is 15–20% higher than in adjacent open grazing lands.
- ***Impact:*** This system provides a year-round fodder bank, reducing the need for external, high-carbon-footprint feed transport (Jatav, 2025).

6.2. Kenya: Community-Based "Dedha" Governance: In Northern Kenya, the Borana community utilizes the *Dedha* system, a traditional legal framework that regulates access to water and grass. By designating specific "drought reserves" and "wet-season" pastures, the system prevents the over-extraction of biomass.

- ***Climate Benefit:*** Regenerative cycles allow the perennial grasses to reach full maturity, maximizing the depth of the root systems.
- ***Methane Reduction:*** Healthy forage ensures animals reach market weight 12 months earlier than those on degraded land, effectively lowering the "lifetime methane yield" per animal (Odhong et al., 2025).

6.3. Australia: High-Density, Short-Duration (HDSD) Grazing: In Northern Australia, the shift toward regenerative grazing involves high-intensity "pulses" of animal impact. The hooves of high-density herds break surface crusts, allowing moisture to penetrate the soil rather than evaporating. Carbon Results: This method has demonstrated an increase in soil water-holding capacity by 25%, which directly correlates with increased microbial activity and carbon stabilization.

7. Emerging Technologies and Future Perspectives

As we enter the International Year of Rangelands and Pastoralists (IYRP 2026), a suite of new technologies is enabling real-time mitigation monitoring.

7.1. Satellite-Driven Precision Management: Remote sensing technologies, specifically Synthetic Aperture Radar (SAR) and NDVI (Normalized Difference Vegetation Index), now allow land managers to calculate "Available Forage Biomass" from space with 90% accuracy. This prevents overgrazing by providing an early warning system to move herds before they damage the "crown" of the grass, which is vital for carbon sequestration.

7.2. Virtual Fencing and AI: Artificial Intelligence (AI) algorithms can now process data from GPS-enabled collars to implement Virtual Fencing. This technology allows pastoralists to exclude livestock from sensitive riparian areas (rivers and streams) or "carbon-heavy" zones without the cost of physical fences, ensuring that grazing is used only as a tool for ecological stimulation.

8. Policy Frameworks for Climate-Smart Pastoralism

For rangelands to contribute significantly to the Paris Agreement goals, they must be integrated into national and international policy frameworks.

1. **Carbon Credit Integration:** Governments must develop standardized protocols for "Soil Carbon Credits." This allows pastoralists to be paid for the carbon they sequester, providing an economic incentive for sustainable management.
2. **Infrastructure Investment:** Mitigation is only possible if livestock can survive extreme weather. Policy must support "Fodder Banks" and community silos to store climate-resilient fodder for use during droughts.
3. **Educational Extension:** Knowledge transfer regarding the use of tannin-rich legumes and high-yield varieties (like fodder beet) must reach the "last mile" to ensure widespread adoption.

9. Conclusion

Sustainable fodder and rangeland management represents one of the most cost-effective and socially inclusive strategies for climate change mitigation. By shifting the paradigm from "exploitation" to "regeneration," rangelands can transition from being victims of climate change to becoming vital carbon-sequestering assets. The integration of climate-resilient fodder species, nutritional methane-reduction strategies, and AI-driven monitoring creates a pathway toward a sustainable livestock sector. As global temperatures continue to rise, the preservation of our grasslands is not merely an agricultural goal it is a planetary necessity.

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References

Almeida, A.K., et al. (2021). Nutritional strategies to mitigate methane emission. *Journal of Animal Science*, 12, 45–58.

Beauchemin, K.A., et al. (2022). Fifty years of research on rumen methanogenesis. *Frontiers in Animal Science*, 3, 100512.

Conant, R. T., et al. (2017). Grassland management impacts on soil carbon stocks. *Ecological Applications*, 27(2), 662–668.

FAO. (2022). *Grasslands and rangelands of the world*. Rome.

ICAR. (2026). *Fodder Beet: A high yielding green fodder crop gaining popularity in arid regions*. ICAR-CAZRI, Jodhpur.

IPCC. (2019). *Climate Change and Land: Special Report*. Geneva.

Jatav, A. (2025). Approaches for Sustainable Livestock Development in Rainfed Regions. *IJNRD*, 25(08), 259–271.

Odhong, C., et al. (2025). Impact of Community-based Rangeland Management on GHG Emissions in Kenya. *ILRI Research Report 42*.

Singh, S., et al. (2023). Evaluation of global Cenchrus germplasm for key nutritional traits. *Frontiers in Nutrition*, 9, 1094763.

UNCCD. (2024). *Global Land Outlook: Rangelands and Drylands*. Bonn.

Indigenous Knowledge Systems in Rangeland and Grassland Management under Climate Change

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ABSTRACT: *Rangelands and grasslands are highly vulnerable to climate change due to their dependence on rainfall variability, temperature extremes, and ecological disturbances. Indigenous knowledge systems have historically enabled pastoral and agro-pastoral communities to manage these ecosystems sustainably under conditions of climatic uncertainty. This chapter examines the role of indigenous knowledge in rangeland and grassland management within the context of climate change, emphasizing its ecological logic, institutional foundations, and adaptive capacity. Traditional practices such as seasonal livestock mobility, flexible stocking strategies, customary governance, and biodiversity stewardship are discussed as coherent management systems rather than isolated techniques. The chapter further explores the complementarities between indigenous knowledge and contemporary range science, highlighting opportunities for policy integration and climate-resilient land management. By adopting a conceptual, textbook-oriented approach, this contribution underscores the relevance of indigenous knowledge for sustainable forage and rangeland management in a changing climate.*

Key words: Rangeland management; grassland ecosystems; pastoralism etc.

1. Introduction

Rangelands and grasslands constitute some of the most extensive terrestrial ecosystems on Earth, supporting livestock-based livelihoods, biodiversity conservation, and ecosystem services such as carbon sequestration and hydrological regulation. In many parts of the world, particularly in arid, semi-arid, and sub-humid regions, these landscapes have been managed for centuries by pastoral and agro-pastoral communities through indigenous knowledge systems. Such systems evolved long before the emergence of formal range science and continue to influence land-use decisions at the local level. Indigenous knowledge in rangeland and grassland management is often misunderstood or undervalued within mainstream scientific and policy frameworks. It is frequently perceived as anecdotal, static, or incompatible with modern management objectives. However, empirical evidence and historical continuity indicate that traditional systems are dynamic, experiment-driven, and capable of sustaining productivity under variable climatic conditions. Recognizing these systems requires a shift from reductionist evaluation toward holistic understanding. This chapter adopts a conceptual and explanatory approach, consistent with textbook-oriented edited volumes. Rather than presenting experimental results or region-specific case studies, the discussion focuses on principles, processes, and institutional arrangements that characterize indigenous rangeland and grassland management. The aim is to provide readers with a structured foundation for appreciating the scientific relevance and practical utility of indigenous knowledge.

2. Conceptual Foundations of Indigenous Knowledge Systems

Indigenous knowledge systems may be defined as cumulative bodies of knowledge, practices, and beliefs that evolve through adaptive processes and are transmitted across generations by cultural means. In the context of rangeland and grassland management, such knowledge is inseparable from daily livelihood activities, social organization, and cosmological worldviews. Unlike codified scientific knowledge, indigenous knowledge is primarily experiential and relational. Observations of plant phenology, animal behavior, soil conditions, and climatic patterns are integrated through repeated interaction with the landscape. Decision-making is therefore guided not by standardized prescriptions but by contextual interpretation of environmental signals. A defining feature of indigenous knowledge systems is their embeddedness within social institutions. Grazing rights, seasonal mobility, and resource access are regulated through customary laws and norms enforced by community authority. These institutional arrangements function as governance mechanisms, ensuring equitable resource distribution and preventing overexploitation.

3. Ecological Logic of Rangeland and Grassland Systems

Rangeland and grassland ecosystems are characterized by high spatial and temporal variability in biomass production. Rainfall uncertainty, frequent disturbances, and heterogeneous soils render equilibrium-based management approaches inadequate in many dryland contexts. Indigenous management systems have historically accommodated this variability through flexible and opportunistic strategies. Traditional grazing systems recognize non-equilibrium dynamics, wherein vegetation change is driven primarily by climate rather than stocking density alone. Mobility of livestock, variable herd composition, and seasonal grazing rotations allow pastoralists to track resource availability while minimizing localized degradation. The ecological rationale underlying indigenous practices aligns with key principles of modern range ecology, including rest-and-recovery cycles, spatial heterogeneity, and disturbance-mediated regeneration. This convergence underscores the scientific legitimacy of indigenous knowledge when evaluated within appropriate ecological frameworks.

4. Historical Evolution of Indigenous Rangeland Management

The historical development of indigenous rangeland management systems reflects long-term co-evolution between human societies and their environments. Archaeological and ethnographic records indicate that pastoral mobility patterns, herd structures, and land-tenure arrangements adapted continuously in response to climatic fluctuations and socio-political change. Colonial interventions often disrupted indigenous governance structures through land alienation, sedentarization policies, and imposed grazing regulations. These interventions not only altered land-use patterns but also undermined knowledge transmission mechanisms, leading to increased vulnerability of rangeland ecosystems. Despite such disruptions, many indigenous practices persist in modified forms. Their resilience demonstrates the adaptive capacity of traditional systems and highlights the importance of historical context in evaluating contemporary management outcomes.

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Table 1. Core Characteristics of Indigenous Knowledge Systems in Rangeland and Grassland Management

Dimension	Description of Indigenous Knowledge Characteristic	Functional Role in Rangeland and Grassland Management
Ecological orientation	Knowledge derived from long-term observation of vegetation, soils, livestock behaviour, and climate variability within specific landscapes	Enables context-specific decision-making under variable and uncertain environmental conditions
Temporal adaptability	Seasonal and inter-annual adjustment of management practices based on rainfall patterns, forage availability, and ecosystem feedback	Maintains productivity and prevents ecosystem degradation during climatic extremes
Spatial flexibility	Dynamic use of heterogeneous grazing landscapes through mobility and rotational access rather than fixed land allocation	Distributes grazing pressure and supports regeneration of grazed areas
Institutional embedding	Management practices governed by customary norms, communal rules, and local authority structures	Regulates resource access, minimizes conflict, and sustains collective stewardship
Knowledge transmission	Intergenerational transfer through oral traditions, apprenticeship, and experiential learning	Ensures continuity and refinement of management practices over time
Risk management strategy	Diversification of livestock species, grazing areas, and livelihood responses	Reduces vulnerability to drought, disease, and forage scarcity
Ethical and cultural grounding	Integration of ecological management with belief systems, taboos, and cultural values	Promotes restraint in resource use and reinforces conservation behaviour

5. Indigenous Grazing Regimes and Seasonal Mobility

Seasonal mobility constitutes a central organizing principle of indigenous rangeland management. Pastoral communities historically structured livestock movement patterns in response to spatial and temporal variability in forage availability, water resources, and climatic conditions. These movements were neither random nor opportunistic in a simplistic sense but followed culturally codified routes, grazing calendars, and access rights. Dry-season and wet-season grazing areas were distinctly recognized within indigenous systems. Wet-season pastures were generally more extensive and accessible, while dry-season reserves were carefully protected through customary restrictions. Such temporal segregation allowed regeneration of highly productive zones and reduced pressure on vulnerable landscapes during periods of ecological stress. Mobility also served as a risk-spreading mechanism. By distributing grazing pressure across heterogeneous landscapes, indigenous systems minimized localized degradation and enhanced ecosystem resilience. This dynamic spatial use aligns closely with contemporary understandings of non-equilibrium rangeland ecology.

6. Indigenous Stocking Strategies and Herd Composition

Indigenous stocking strategies are best understood as flexible, decision-oriented processes rather than fixed stocking rates. Livestock numbers were historically adjusted in response to forage conditions, rainfall variability, and household labor availability. Rather than maximizing animal numbers, pastoralists prioritized herd viability and long-term sustainability. Herd diversification formed a critical element of indigenous risk management. The maintenance of multiple livestock species such as cattle, sheep, goats, and camels enabled efficient utilization of diverse vegetation strata. Grazers and browsers complemented one another, reducing interspecific competition and enhancing overall system productivity. Selective breeding practices further strengthened herd resilience. Indigenous criteria for animal selection emphasized traits such as drought tolerance, disease resistance, and mobility rather than short-term production metrics. These preferences reflect a deep ecological understanding of environmental constraints.

7. Traditional Pasture Resting, Fire Use, and Regeneration

Pasture resting represents a foundational ecological principle embedded within indigenous rangeland management systems. Community enforced grazing bans, rotational access, and seasonal exclusions allowed vegetation recovery and soil moisture replenishment. Unlike externally imposed enclosures, these practices were socially regulated and context-specific. The controlled use of fire played a multifaceted role in traditional grassland management. Indigenous fire regimes were typically low-intensity and seasonally timed, aimed at removing senescent biomass, stimulating fresh growth, and controlling woody

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encroachment. Fire use was governed by communal decision-making and ecological indicators. Regeneration processes under indigenous management were therefore not accidental outcomes but intentional results of integrated practices. The coordination of grazing, resting, and fire reflected an understanding of disturbance as an ecological necessity rather than a destructive force.

8. Indigenous Approaches to Biodiversity Conservation

Biodiversity conservation within indigenous rangeland systems emerged as a functional necessity rather than an explicit conservation objective. Diverse plant communities ensured forage availability across seasons, while heterogeneous habitats supported wildlife co-existence. Indigenous tolerance toward wild herbivores and predators often reflected pragmatic assessments of ecological roles. Sacred landscapes, culturally protected species, and taboo-based restrictions contributed indirectly to biodiversity maintenance. Such cultural mechanisms functioned as informal conservation instruments, limiting exploitation in ecologically sensitive zones. These embedded conservation outcomes underscore the importance of examining indigenous management through an ecological systems perspective, rather than isolating individual practices from their cultural context.

Table 2. Indigenous Management Practices and Their Ecological Implications in Rangeland and Grassland Systems

Management Practice	Operational Description	Ecological Implication
Seasonal mobility	Planned livestock movement across landscapes	Reduces grazing pressure and enhances resilience
Herd diversification	Maintenance of multiple livestock species	Optimizes forage use across vegetation layers
Pasture resting	Temporary exclusion of grazing areas	Facilitates vegetation recovery
Controlled burning	Low-intensity seasonal fire application	Promotes regeneration and controls encroachment
Customary regulation	Community-enforced access norms	Prevents resource overuse

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9. Indigenous Institutions and Customary Governance

Indigenous rangeland and grassland management systems are sustained not merely by ecological understanding but by institutional arrangements that regulate access, use, and stewardship of resources. Customary governance structures, often unwritten yet widely recognized, define grazing rights, seasonal priorities, and conflict resolution mechanisms. These institutions operate at multiple social scales, from household-level decisions to landscape-level coordination. Community authority, typically vested in councils of elders or recognized leaders, plays a central role in enforcing customary regulations. Decisions regarding grazing closures, herd movement timing, and sanctions for rule violations are made through collective deliberation, reinforcing social legitimacy and compliance. Such governance systems differ fundamentally from centralized administrative models. Rather than relying on external enforcement, indigenous institutions depend on shared norms, reciprocity, and long-term social relationships. This institutional embeddedness enhances adaptability and reduces transaction costs in managing common-pool resources.

10. Social Organization and Knowledge Transmission

The continuity of indigenous rangeland management depends on effective mechanisms for knowledge transmission across generations. Learning occurs primarily through observation, participation, and apprenticeship rather than formal instruction. Young community members acquire ecological skills by accompanying elders during grazing, herding, and decision-making activities. Narratives, rituals, and oral histories serve as repositories of ecological memory. Seasonal indicators, historical droughts, and landscape-specific hazards are embedded within stories that reinforce appropriate responses to environmental variability. These cultural forms function as decision-support systems, encoding practical guidance within socially meaningful frameworks. The erosion of traditional learning pathways, often driven by formal education systems and labor migration, poses a significant challenge to indigenous knowledge continuity. Understanding these dynamics is essential for designing interventions that respect and strengthen existing systems rather than replacing them.

11. Gender Dimensions in Indigenous Rangeland Knowledge

Gender roles constitute an integral component of indigenous knowledge systems. Men and women often hold differentiated, yet complementary, domains of ecological expertise

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shaped by labor responsibilities and social norms. While men may predominantly engage in herding and long-distance mobility, women contribute extensive knowledge of fodder species, water sources, and animal health management. Women's roles in processing livestock products, managing small stock, and maintaining household-level resource strategies provide critical insights into system resilience. Their observations of daily environmental conditions frequently inform adaptive decisions, particularly during periods of scarcity. Recognizing gendered knowledge domains is essential for comprehensive understanding of indigenous management systems. Failure to account for these contributions risks undervaluing key adaptive capacities embedded within pastoral societies.

12. Indigenous Strategies for Climate Variability and Resilience

Climatic variability represents a defining constraint for rangeland and grassland systems. Indigenous management strategies have evolved precisely to cope with uncertainty, rather than to eliminate it. Flexibility in mobility, herd structure, and resource use enables rapid response to droughts, floods, and shifting rainfall patterns. Early warning indicators, derived from long-term environmental observation, guide anticipatory decision-making. Changes in vegetation composition, wildlife movement, and atmospheric conditions are interpreted collectively to assess impending stress. These adaptive strategies align closely with contemporary resilience theory, emphasizing diversity, redundancy, and learning-based responses. Indigenous systems therefore offer valuable frameworks for climate adaptation, particularly in data-scarce environments.

Table 3. Institutional and Socio-cultural Components Supporting Indigenous

Component	Institutional or Social Function	Contribution to Resilience
Customary governance	Regulates access and enforces norms	Prevents overuse of common resources
Knowledge transmission	Intergenerational learning systems	Maintains adaptive capacity
Gender expertise	Differentiated ecological roles	Enhances decision diversity
Collective decision-making	Consensus-based rule setting	Strengthens compliance and flexibility
Environmental indicators	Traditional early warning signals	Supports anticipatory action

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13. Indigenous Knowledge and Contemporary Range Science

Contemporary range science increasingly acknowledges that many principles central to indigenous rangeland management align with established ecological theory. Concepts such as non-equilibrium dynamics, adaptive management, and spatial heterogeneity resonate strongly with traditional practices rooted in long-term observation. However, integration does not imply assimilation of indigenous knowledge into formal scientific models without context. Indigenous systems represent holistic frameworks that interlink ecological processes with social institutions and ethical considerations. Effective integration therefore requires epistemological humility and mutual learning.

14. Policy Relevance and Governance Integration

Policy frameworks governing rangeland management have historically emphasized centralized regulation and standardized technical prescriptions. Such approaches often overlook local variability and undermine indigenous governance mechanisms. Recent policy discourse increasingly recognizes the need for participatory and decentralized models. Integrating indigenous institutions into formal governance structures can enhance legitimacy, compliance, and ecological outcomes. Policies that recognize customary tenure, seasonal mobility, and community-based regulation are better suited to managing complex rangeland systems.

15. Ethical Considerations and Knowledge Safeguards

The growing interest in indigenous knowledge raises important ethical considerations. Documentation and application must respect community ownership, cultural integrity, and informed consent. Failure to address these concerns risks knowledge extraction without reciprocal benefit. Safeguards should ensure that indigenous knowledge is applied in ways that strengthen, rather than replace, local systems. Collaborative frameworks and benefit-sharing mechanisms are essential components of ethical engagement.

16. Synthesis and Concluding Perspectives

Indigenous knowledge systems in rangeland and grassland management constitute sophisticated, adaptive frameworks developed through centuries of ecological interaction. Their persistence and relevance reflect not cultural inertia, but functional efficiency under

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conditions of uncertainty. This chapter has examined indigenous management as an integrated system encompassing ecological logic, institutional governance, socio-cultural practices, and adaptive strategies. Recognizing and engaging with these systems is essential for developing resilient, inclusive, and sustainable rangeland futures.

References

Angassa A and Oba G (2007) Effects of grazing pressure, age of enclosure and seasonality on bush cover dynamics and vegetation composition in southern Ethiopia. *Journal of Arid Environments* 70: 409–423.

Briske D D, Bestelmeyer B T, Stringham T K and Shaver P L (2008) Recommendations for development of resilience-based state-and-transition models. *Rangeland Ecology and Management* 61: 359–367.

FAO (2012) *Grasslands of the World*. Food and Agriculture Organization of the United Nations, Rome.

FAO (2019) *The State of the World's Biodiversity for Food and Agriculture*. FAO Commission on Genetic Resources for Food and Agriculture, Rome.

Fernández-Giménez M E (2000) The role of mongolian nomadic pastoralists' ecological knowledge in rangeland management. *Ecological Applications* 10(5): 1318–1326.

IPCC (2019) *Climate Change and Land: An IPCC Special Report*. Intergovernmental Panel on Climate Change, Geneva.

Mortimore M (2009) *Dryland Opportunities: A New Paradigm for People, Ecosystems and Development*. IUCN, Gland, Switzerland.

Oba G, Stenseth N C and Weladji R B (2008) Indigenous ecological knowledge of Borana pastoralists in southern Ethiopia and implications for sustainable rangeland management. *Journal of Environmental Management* 88: 1–10.

Pratt D J, Greenway P J and Gwynne M D (1966) *A Classification of East African Rangeland, with an Appendix on Terminology*. Journal of Applied Ecology Monograph No. 5.

Reed M S, Dougill A J and Baker T R (2008) Participatory indicator development: what can ecologists and local communities learn from each other? *Ecological Applications* 18: 1253–1269.

Scoones I (1995) *Living with Uncertainty: New Directions in Pastoral Development in Africa*. Intermediate Technology Publications, London.

Scoones I (2016) The politics of sustainability and development. *Annual Review of Environment and Resources* 41: 293–319.

Thornton P K, van de Steeg J, Notenbaert A and Herrero M (2009) The impacts of climate change on livestock and livestock systems in developing countries: a review of what we know and what we need to know. *Agricultural Systems* 101: 113–127.

Turner M D and Hiernaux P (2008) Changing access to grazing resources in the Sahel: pastoralism, globalization and environmental change. *Human Ecology* 36: 849–867.UNEP (2016) *Global Drylands: A UN System-wide Response*. United Nations Environment Programme, Nairobi.

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Chapter-4

Climate Smart Agriculture in Forage and Rangeland Management

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ABSTRACT: *Forage systems are critical components of livestock sector for providing essential feed and nutrient resources for cattle, sheep, goats, buffaloes, and other animals which is already in deficit. Forage production systems are highly vulnerable to climate change impacts such as erratic rainfall, prolonged droughts, heat stress, cold stress, hailstorms, floods and increased frequency of extreme weather events. Climate smart agriculture (CSA) offers a holistic approach to enhance adaptive capacity, improve resilience, and sustain productivity in forage and rangeland management. This chapter has been formulated to examine the theoretical foundations of CSA, the status of forage and rangeland resources in India, climate vulnerabilities, adaptation strategies, and the role and experiences of the National Innovations in Climate Resilient Agriculture (NICRA) project in promoting climate smart practices highlighting the key achievements, technology interventions, socio-economic impacts, and future pathways for scaling climate smart forage and rangeland management in India.*

1. Introduction

Agriculture in India is predominantly rainfed (48% of net cropped area and 40% of total livestock population) and highly sensitive to climatic variability due to predominance of extensive system of rearing the livestock. Forage systems are integral to livestock production and rural livelihoods, especially in dryland, and semi-arid regions. These ecosystems include natural grasslands, pastures, degraded lands, shrub lands, and community grazing areas that support grazing livestock and provide biomass for feeding the livestock. During 1991, the gap between the availability and requirement of fodder was 67 and 137 million tonnes, respectively in terms of dry and green fodder. By 2020, this demand-supply scenario may be around 69 and 145 million tonnes, respectively. As per the estimate from IGFRI, Jhansi, at present, the country faces a net deficit of 36% green fodder, 21.9% dry crop residues and 32% of concentrate feeds.

Climate change alters precipitation patterns, water availability, vegetation composition, and forage productivity, leading to reduced feed quality and quantity and increased vulnerability of livestock systems. Consequently, there is an urgent need to build climate resilience into forage and rangeland management. Climate Smart Agriculture (CSA) provides a conceptual and operational framework for addressing these challenges. Within this framework, forage and rangeland management must integrate climate risk assessment, participatory planning, resilient forage production systems, water and soil conservation, and community-based resource governance.

2. Forage resources in India: overview and climate vulnerability

India supports one of the world's largest livestock populations, contributing to nutrition, income, employment, and rural resilience. According to national statistics, livestock contributes more than 4.1% to national GDP and provides livelihoods to millions of small and marginal farmers and pastoralists. Forage systems - both cultivated and natural - are vital as feed resources; however, they remain under severe pressure due to:

- Fragmentation and degradation of rangelands due to unsustainable grazing;
- Reduced rainfall (variable rainy days and dry days) and increased temperature stress;
- Soil erosion and nutrient depletion;
- Competing land use for crops and real estate

Natural grasslands and pastures have experienced declining productivity, changing species composition, and reduced nutritive value under climate variability. Such impacts disproportionately affect resource-poor livestock holders who depend on free grazing and local feed resources (Table 1).

Table 1. Status of forage and rangeland resources in India

Resource type	Estimated area/ contribution	Major constraints	Climate sensitivity
Cultivated fodder crops	About 8-9 million ha	Water scarcity, low priority	High
Crop residues	About 60-65% of livestock feed	Low nutritive value	Moderate
Common grazing lands	About 12-14 million ha	Degradation, overgrazing	Very high
Forest-based grazing	Restricted	Policy limitations	High

3. Climate risks to rangelands

Climate change affects forage and rangelands through:

- Temperature rises, which often accelerate forage quantity but reduce forage nutritive quality;
- Erratic rainfall, leading to moisture stress, poor establishment of forage crops, and reduced growth of native grasses;
- Droughts and heat waves, causing pasture degradation, flaring up of diseases and livestock heat stress;
- Floods and waterlogging, especially in lowlands and midlands, damaging perennial grasses and forages;
- Increased frequency of extreme events, which destabilize forage production and pasture regeneration.

  Under these conditions, traditional management often fails, necessitating adoption of climate smart practices.

4. Conceptual framework for climate smart agriculture in forage and rangeland systems

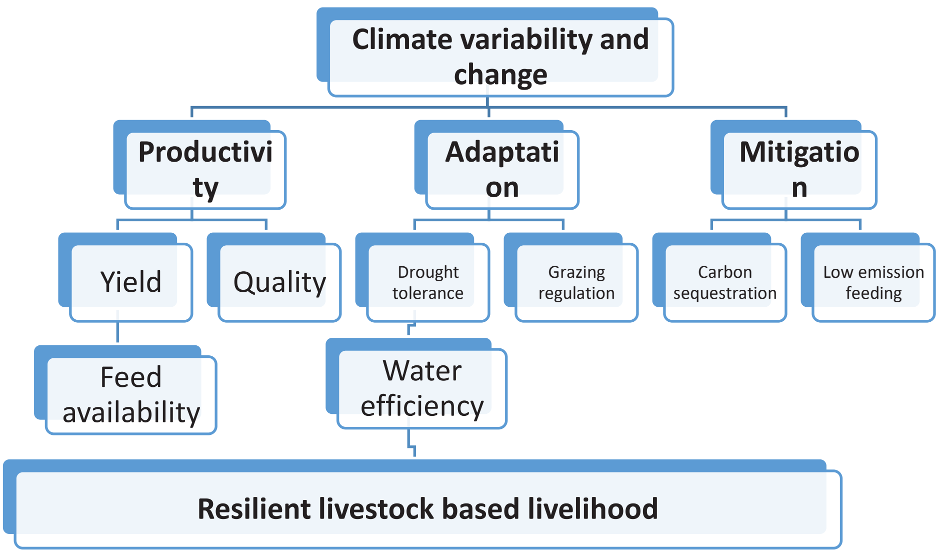

Figure 1. Conceptual framework of climate smart forage

Climate Smart Agriculture in forage and rangeland management integrates three pillars:

(a). Productivity enhancement

CSA seeks to increase forage yields and quality through:

- Selection of stress-tolerant forage species and cultivars;

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- Improved establishment practices such as sowing at optimal climate windows;
- Efficient nutrient and soil fertility management;
- Integrated silvi-pasture systems combining trees, shrubs, and grasses.

(b). Adaptation to change

Adaptation measures include:

- Moisture conservation and drought-proofing (e.g., mulching, contouring);
- Water harvesting and efficient irrigation (micro-irrigation for fodder crops);
- Rotational grazing to prevent overgrazing and restore vegetation;
- Introduction of perennial grasses suited to changing rainfall regimes.

(c). Mitigation and ecosystem services

Although mitigation receives less emphasis in forage systems compared to crops, CSA contributes to:

- Carbon sequestration in soil and biomass (through perennial grasses, agroforestry);
- Reduced methane emissions through improved animal nutrition and feed quality;
- Soil stabilization and reduced erosion.

Effective CSA also relies on institutional support, extension services, data and decision-support tools (such as agro-meteorological advisories), and farmer-to-farmer learning networks.

5. National Innovations in Climate Resilient Agriculture (NICRA): an overview

NICRA was launched by the Indian Council of Agricultural Research (ICAR) in February 2011, as a flagship initiative aimed at enhancing the resilience of Indian agriculture - including crops, livestock, fisheries, and natural resource management - to climate change and variability. The project operates through a multidisciplinary, multi-institutional network that combines strategic research, technology demonstration, capacity building, and competitive research grants. As per the vulnerability atlas prepared by ICAR-CRIDA, Hyderabad, whole country was divided into highly, medium and low vulnerable districts. NICRA-Technology Demonstration Component (TDC) was flagged in these high and very high vulnerable districts by anchoring on respective KVKs under the domain of different ATARI of ICAR.

NICRA's major objectives are:

- To develop and apply improved production and risk management technologies;
- To demonstrate site-specific technology packages to farmers;

- To enhance stakeholder capacity in climate resilient agricultural research and application. The project emphasizes practical, location-specific interventions, implemented through Krishi Vigyan Kendras (KVKs) and other partners in vulnerable districts identified through climate risk analyses.

Table 2. NICRA modules relevant to fodder and rangeland management

NICRA Module	**Key Interventions**	**Relevance to Forage Systems**
Natural Resource Management	Water harvesting, soil conservation	Enhances fodder productivity
Soil Health Management	Organic amendments, mulching	Improves pasture regeneration
Crop Production	Climate-resilient varieties	Fodder crop stability
Livestock Management	Nutrition, housing	Efficient forage utilization

Modules and scope of NICRA

NICRA's interventions are structured around four modules:

1. **Natural Resource Management (NRM)** – Soil and water conservation, moisture retention, water harvesting, and improved irrigation;
2. **Soil Health Management** – Soil amendments, organic matter enhancement, nutrient management;
3. **Crop Production** – Climate-resilient varieties and cropping systems;
4. **Livestock and Fisheries** – Nutrition, health, housing, and resource use improvements. Across these modules, technologies are demonstrated and refined in **Climate Resilient Villages (CRVs)** to maximize local adoption and impact. A total of 151 CRVs were established in highly and very highly vulnerable districts of India.

Forage and rangeland interventions under NICRA

There are many interventions under forage management tested under NICRA-TDC (Table 3).

Table 3. Forage management technologies available under NICRA-TDC

Technology	**Climate risk addressed**	**Benefits**
Perennial grasses	Drought, heat stress	Stable biomass supply
Legume-based fodder	Soil fertility decline	Protein enrichment
Silvi-pasture systems	Land degradation	Biomass + carbon storage
Fodder intercropping	Rainfall variability	Risk diversification
Fodder conservation (hay/silage)	Seasonal scarcity	Feed buffering

6. Climatic assessment and baseline planning

NICRA's approach begins with participatory climate risk assessment in target villages, identifying key vulnerabilities for forage and grazing systems. Villages are clustered into climate-vulnerable regions where technologies are tested in real farmer conditions.

a. **Resilient forage production technologies:** Key technologies demonstrated for climate smart forage production include:
   - Selection of resilient forage species capable of withstanding drought and heat stress;
   - Sowing perennial grasses and legumes suited to local climatic conditions;
   - Rainwater harvesting structures to support fodder production during dry spells;
   - Intercropping fodder crops with legumes to enhance soil fertility.
   - Technologies also promote alternate land use systems, such as integrating agroforestry with pastures (silvi-pasture), which improves soil cover, reduces erosion, and increases biomass production.

b. **Soil and water conservation measures:** Given the strong link between moisture availability and forage growth, NICRA emphasizes:
   - In-situ moisture conservation through mulches, contour bunds, and micro-catchments;
   - Farm pond desiltation and water harvesting to increase supplemental irrigation options;
   - Sprinkler and drip irrigation in fodder plots for efficient water use. Such measures stabilize forage yields under erratic rainfall.

c. **Sustainable grazing and pasture management:** For rangelands, NICRA promotes:
   - Rotational grazing systems with controlled animal movement to prevent degradation;
   - Pasture rest periods to allow regeneration of palatable grasses;
   - Community grazing management committees to regulate access and use of common lands;
   - Fencing and protection of degraded patches for restoration. These interventions improve ecological resilience and long-term pasture productivity.

d. **Livestock nutrition and feeding strategies:** Improved forage availability is combined with strategic feeding practices:

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- Feed conservation techniques such as hay and silage making to buffer seasonal shortages;
- Balanced feed supplementation to enhance animal health and productivity;
- Use of crop residues and by-products in structured feeding systems. This integrated feed strategy enhances livestock resilience to climatic stress.

7. Case studies:

NICRA village experiences: NICRA's field interventions have yielded diverse experiences across India, with notable examples:

Case Study 1: Kamarpara, Darrang District, Assam

In the flood-prone system of Assam's Darrang district, NICRA interventions combined climate-resilient rice varieties, rainwater harvesting, and improved forage practices. While this case focused broadly on crop and livestock integration, perennial grasses and fodder plots supported livestock during post-flood recovery, improving resilience and income diversification. Increased availability of quality forage enhanced livestock productivity and reduced mortality during climatic stress.

Case Study 2: Jharsuguda District, Odisha

Socio-economic analysis in Jharsuguda revealed that NICRA farmers exhibited higher diversification, better adaptive capacity, and improved livelihoods compared to non-NICRA counterparts. Though this primarily measured overall climate-resilient agriculture adoption, improved forage and livestock management contributed to these outcomes.

Adoption and impact on productivity: Empirical studies across NICRA villages report:

- Enhanced adoption of forage technologies (e.g., moisture conservation, short duration crops);
- Increased fodder area and productivity;
- Improved milk yields and livestock condition due to better feed availability;
- Greater awareness and adaptive capacity among farmers.

These reflect measurable impacts of integrated CSA practices in livestock nutrition systems.

Socio-economic and institutional dimensions

Capacity building and knowledge transfer

A cornerstone of NICRA is stakeholder engagement and capacity building:

- Training programs for farmers on climate resilient technologies;
- Farmer field schools and exposure visits;
- Formation of climate risk management committees at village levels.

Capacity building improves decision-making under climate uncertainty, leading to faster adoption of climate smart forage and pasture practices. Almost more than 7.0 Lakhs farmers have been taken training for different aspects of climate change till date under NICRA-TDC.

Institutional linkages and extension support

NICRA leverages:

- Local extension networks (KVKs, agricultural departments);
- Convergence with government schemes (watershed development, employment programs);
- Community organizations for pasture governance.

These institutional arrangements enhance sustainability and scaling potential.

Economic benefits and livelihood resilience

By stabilizing forage production and reducing seasonal feed scarcity, NICRA interventions:

- Lower the cost of feed procurement;
- Increase livestock productivity and income;
- Reduce vulnerability to climatic stress.

Households with access to better forage resources show higher resilience and economic stability.

Challenges in climate smart forage management: Despite successes, several challenges remain:

- Limited adoption in remote or resource-poor areas due to labor and finance constraints;
- Land tenure issues for common rangelands;
- Inadequate access to irrigation and water storage in drought-prone regions;
- Knowledge gaps in advanced forage species selection and silvipasture design;
- Weak market linkages for fodder and livestock products.

Addressing these requires policy support, financing mechanisms, and continued research.

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Table 4. Socio-economic benefits of CRA in rangeland management

Indicator	Conventional System	CSA-based System
Fodder availability	Seasonal	Year-round
Feed cost	High	Reduced
Livestock productivity	Unstable	Stabilized
Climate risk exposure	High	Moderate to low

8. Addressing the fodder shortage

Though the availability of feed and fodder has improved in the last decade, still there exists a substantial gap between the demand and availability of fodder in the country, particularly during the lean periods and at the time of natural calamities including droughts/floods.

A. Alternate land use mode

1. Crop-fodder system

In drylands, we have a restriction with very narrow sowing window apart from land degradation and poor productivity. Thus, to reduce the risk of crop failure and to have a sustainable farming, the farmers often prefer intercropping cropping rather than single crop. However, at least for six months in a year there is no vegetal cover on cultivated soil. Even though dairy is an important component in dryland, availability of availability of fodder from natural grasses or fodder crops are negligible. This problem can be overcome by the inclusion of easily propagated perennial forage legume or grass apart from high yielding fodder varieties. They grow fast and cover the land surface quickly even under low rainfall situations and provide considerable amount of green fodder. They can help in increasing the crop yield and resource use efficiency through their vegetation cover. The perennial system can also help in soil conservation. Earlier many researches were focused to include a fodder crop into a system trying the best to have less diminution in total food crop production.

2. Ley farming

It is rotation in a cropping system in which two or more crops are grown in affixed sequence. In other words, it is a mixture of grass-legume or ley as a farm crop which becomes an integral part of cropping pattern. Here, the benefits are double; the grass apart from providing fodder improves the soil structure, while the legume enriches the soil. This system meets the

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fodder demand of cattle, in addition to food needs. It also helps in soil conservation, improves the soil fertility and reduces the cost of input and thus the cost of cultivation. However, the inclusion of forage legume leys in the cereal crop rotation means that some land is taken out of food crop production for at least one or more season Hence research is needed to determine this loss in production is balanced by enhanced production from the cereal crops following the legumes.

3. Utilization of waste land

Eroded, infertile land could provide significant additional forages. Initial establishment may find difficult, however, once established they can substantially improve upon the provision of fodder during the lean months. The planting method and suitability of suitable species needs to be assessed for its successful implementation.

3. Silvi-pastural system

Plains have the benefit of assured rainfall hence, a successful crop, whereas, dryland has the great risk of crop failure. Here is where trees can play a vital role. Trees are often referred to as 'green blood of mankind'. It is most suited to marginal dryland preferably where the fodder shortage is high. Enough care should be taken to select compatible tree species with forage crops. This system is highly tolerant to drought and extremes of temperature.

4. Alley cropping

It is a system in which food crops are grown in alley formed by hedge rows of trees or shrub. The most important advantage of this system includes higher total biomass per unit area, utilization of off-season precipitation, provision of green fodder during lean period and also a barrier to run off water. The important parameter that should be given due consideration for its management are choice of crops, alley width, cutting height and interval of cutting. Generally, these parameters differ from region to region. Hence, it is highly advisable that a crop and species suitable/recommended for the area/region is followed as to obviate the ill-effect.

B. Extension mode

1. Fodder banks

Keeping surplus fodder for use during crisis periods may be advised. Farmers may be encouraged and trained to popularize high-yielding fodder and forage crops and supported for creating fodder banks through silage or fodder blocks and enrichment of crop residues, etc.

2. KVKs

Extension activities can be strengthened by associating KVKs, which must play a lead role in educating the farmers in maximizing fodder output with limited land and ensuring quality of feed. Progressive livestock farmers may be identified for training through KVKs who can in turn train other farmers.

9. Future directions and policy implications

Strengthening research and innovation

Future priorities include:

- Development of heat, drought, and salinity tolerant forage varieties;
- Precision climate risk modeling for forage planning;
- ICT based advisories linking weather forecasts with forage management decisions.

Scaling CSA in rangelands

Policies should promote:

- Incentives for community pasture restoration;
- Payment for ecosystem services (carbon sequestration, biodiversity protection);
- Integration of livestock-forage management in national climate adaptation plans.

Institutional and financial mechanisms

Success depends on:

- Enhanced funding for local government agencies and KVKs;
- Microcredit and insurance products for climate smart forage enterprises;
- Public-private partnerships for fodder supply chains.

10. Conclusions

Climate smart agriculture holds significant promise for transforming forage and rangeland systems in India amid changing climate patterns. NICRA has provided a pioneering platform for deploying context-specific, multi-disciplinary interventions that enhance resilience, productivity, and livelihoods in vulnerable communities. Through participatory planning, capacity building, innovative forage technologies, and integrated grazing management, NICRA experiences demonstrate how CSA principles can be operationalized in complex agricultural landscapes. However, scaling these successes requires sustained policy commitment, institutional strengthening, and continuous innovation.

References

Food and Agriculture Organization of the United Nations. (2013). *Climate-smart agriculture sourcebook*. FAO.

Indian Council of Agricultural Research. (2011). *National innovations in climate resilient agriculture (NICRA): Project document*. ICAR, New Delhi.

Indian Council of Agricultural Research. (2020). *NICRA annual report*. ICAR, New Delhi.

Journal of International Environment and Climate Change. (2021). Impact of NICRA interventions on livelihood resilience in climate vulnerable districts. *Journal of International Environment and Climate Change, 11*(6), 123-134.

National Research Council. (2015). *Climate change and livestock systems*. National Academies Press.

Pushpanjali, Konda Srinivas Reddy, Josily Samuel, Prabhat Kumar Pankaj, Ardha Gopala Krishna Reddy, Jagriti Rohit, Kotha Sammi Reddy. 2022. Fodder grass strips for soil conservation and soil health. Chemistry Proceedings, 10(1): 58.

Rao, I. M., Peters, M., Castro, A., et al. (2015). Livestock Plus – The sustainable intensification of forage-based agricultural systems to improve livelihoods and ecosystem services in the tropics. *Tropical Grasslands–Forrajes Tropicales, 3*(2), 59-82.

Thornton, P. K., van de Steeg, J., Notenbaert, A., & Herrero, M. (2009). The impacts of climate change on livestock and livestock systems in developing countries. *Agricultural Systems, 101*(3), 113-127.

Visha Kumar Venugopalan, M Prabhakar, KA Gopinath, PK Pankaj, Ch Srinivas Rao. 2016. Community Fodder Banks for addressing forage shortage in rainfed areas. Indian Farming, 66(2): 10-15.

Technological options to mitigate climate change for sustainable forage and rangeland management

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ABSTRACT: *Climate change is becoming an ominous threat to the forage production and ecosystem processes in the range land as temperatures rise, precipitation becomes unpredictable, droughts occur regularly, land is degraded, and biodiversity declines, especially in the arid and semi-arid zones where livelihoods are based on livestock grazing. The chapter examines significant technological alternatives to sustainable forage and rangeland management that improve productivity and resilience with the help of climate change mitigation. Key interventions are climate-resistant forage species and varieties, forage legumes with better nitrogen cycling, livestock genetic enhancement to adapt to climate, adaptive and rotating grazing, silvopastoral and agroforestry integration, fodder conservation and the use of crop residues, rangeland restoration, and soil health and carbon enhancement technologies.*

Keywords: Climate change, forage and rangeland

1. Introduction

Forage production systems and rangeland ecosystems form the foundation of livestock-based agriculture by supplying feed, sustaining biodiversity, regulating hydrological and nutrient cycles, and supporting rural livelihoods. Globally, rangelands occupy nearly 40% of the Earth's terrestrial surface and play a crucial role in ecosystem service provision and carbon cycling. (Boone *et al*., 2019). Climate change has emerged as a dominant driver of stress on forage and rangeland ecosystems, exacerbating pre-existing pressures such as land degradation, overgrazing, and water scarcity. Rising mean temperatures, altered monsoon dynamics, increased frequency of droughts and heat waves, and greater rainfall variability have already begun to significantly influence forage growth patterns, rangeland condition, and ecosystem stability across India (Giridhar & Samireddypalle, 2015). Climate projections indicate a temperature increase of 1.5–2.0 °C by mid-century, accompanied by longer dry spells and more intense rainfall events, particularly in arid and semi-arid regions of the country (O'Leary *et al*., 2018).

In India, forage and rangeland ecosystems covering more than 120 million hectares are under severe stress due to climate variability, soil degradation, invasive species encroachment, and competing land uses (Malaviya *et al*., 2018). These challenges are particularly critical given that nearly 65–70% of India's livestock owners are smallholders who rely heavily on common property grazing lands for feed resources (Shinde and Mahanta, 2020). Climate-induced declines in forage availability and reliability intensify seasonal fodder shortages, increase dependence on purchased feed, and reduce livestock productivity, thereby threatening livelihood security and food systems resilience. Rangeland ecosystems are also experiencing accelerated soil degradation under climate change. Increased erosion, organic matter decomposition, salinization, and nutrient loss reduce soil water-holding capacity and biological activity, thereby lowering ecosystem resilience (Eldridge *et al*., 2011).

Traditional forage production and rangeland management practices are increasingly inadequate to cope with the magnitude and complexity of climate-induced stresses. Consequently, there is an urgent need for integrated, science-based, and technology-driven interventions that enhance both adaptation and mitigation outcomes. Technological options such as climate-resilient forage varieties, improved grazing management, soil and water conservation measures, fodder conservation, and silvopastoral systems have demonstrated substantial potential to stabilize productivity, restore degraded rangelands, and enhance carbon sequestration (Ghosh *et al*., 2017). Recent advances in digital agriculture—including remote sensing, GIS, UAVs, sensor networks, artificial intelligence, and decision-support systems—have further strengthened the capacity for precision rangeland management and climate-smart decision-making (Patel *et al*., 2025).

In this context, the present work synthesizes technological adaptations for mitigating climate change impacts on forage production and rangeland ecosystems, with particular emphasis on the Indian subcontinent. By integrating genetic, management, soil, and digital technologies, sustainable forage and rangeland systems can enhance resilience, reduce greenhouse gas emissions, conserve biodiversity, and support long-term livelihood security under changing climatic conditions.

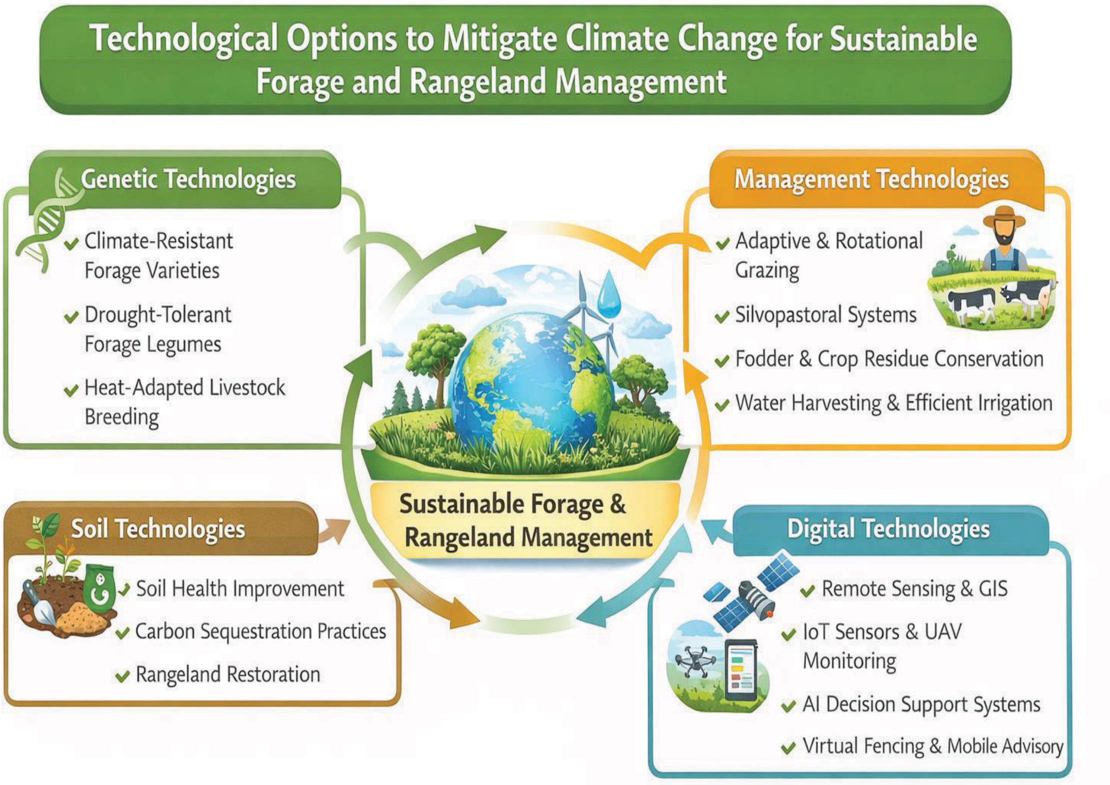

Figure 1. Conceptual framework of technological options for climate change mitigation in sustainable forage and rangeland management.

2. Influence of climate change on forage and rangeland ecosystems

2.1. Effects on forage yield

Global warming has negatively impacted the growth and yields of three prevalent forage plant species: *Cenchrus ciliaris*, *Stylosanthes hamata*, and *Sorghum bicolor*, resulting in lower production of these crops because of an unpredictable monsoon pattern along with higher instances of drought. The increase in temperatures (when they rise above 35ºC) causes the following problems: decreased duration of growth, decreased efficiency of photosynthesis, leaf senescence occurs much earlier than usual (Giridhar and Samireddypalle, 2015). The disruptive changes that have occurred to the global climate due to changing precipitation patterns will continue to affect the availability of soil moisture, therefore affecting the ability of a plant to produce and develop roots, which will inhibit the plant's ability to produce subsequent shoots and leaves (Kakusu, 2022). Using climate simulation models, Dereje *et al.* (2024) predicted that there will be a decrease of 12% to 28% in biomass productivity over the next mid-century time period for rain fed fodder crops (using the RCP 4.5 and 8.5 scenarios).

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Soni and Tripathi (2021) stated that when drought patterns occur more often than previously recorded, it negatively affects how well and quickly perennial grasses regenerate and establish themselves by reducing the reproductive plants in the ground in Central and Peninsular India. The long-term observational studies conducted by the Indian Council of Agricultural Research on Forage Research Institute in Jhansi and Avikanagar support the assertion that the inter-annual variability of forage yields has increased by approximately 35% since the early 1990's largely due to the unpredictability of when the monsoon begins and ends (Balasubramaniyan and Rao, 2023). Meena *et al*. (2022) reported that dry matter yields would decrease by approximately seven percent, for each increase of one degree Celsius, during the development of the reproductive plant stages. There is an expected 10% to 25% decrease in yields of forage on semi-arid rangeland by 2050 based on predictions from the Indian Meteorological Department and Indian Council of Agricultural Research on Forage Research Institute. Areas such as Rajasthan and Bundelkhand have experienced crop losses that were as high as 15% to 20% in terms of forage biomass during drought periods. Under high-emission (RCP 8.5) scenarios, it is possible that the amount of water-stressed crops would decline as much as 23% for forage maize being produced in Central India (Sharma *et al*., 2025).

2.2. Effects on forage quality

The higher the amount of CO_2 in the atmosphere on the Earth the more plants can grow, but the concentration of nitrogen in plants is diluted by CO 2 and this dilution process reduces the content of crude protein and digestible nutrients in plant tissues (Moore *et al*., 2020). A study conducted in semi-arid areas of India established that crude protein content reduced by 10 to 22 percent and total digestible nutrients went down by 15 percent during this period among fodder crops. The heat-stressed conditions promote increased vegetative lignin and cellulose, which lead to a reduction in palatability of fodder crops. A research conducted by Tamboli *et al*. (2023) revealed a reduction of about 2.1-3.5 percent in the crude protein and an increase of 4-7 percent in fibre contents of grasses and maize under heat stress conditions. Drought stress and heat stress are adversely affecting nutritive value of forages due to climate change. Sandhu *et al*. (2015) established that heat stress above 38 C led to a reduction in crude protein content of *Cenchrus ciliaris* and *Dichanthium annulatum*, both varieties of tropical grasses, by 18-24 percent. It is also established that increased CO_2 levels have led to dilution of nitrogen, increased levels of neutral detergent fiber (NDF) and decreased levels of metabolizable energy in Indian tropical forage, which in turn has increased emission of methane in livestock production by research conducted by Knapp *et al*. (2014). A study in Tamil Nadu and Karnataka established that when forage sorghum and maize were grown under drought stress, it accumulated an extra 6 to 10 percent of lignin relative to forage grown under normal conditions (Kanthaswamy *et al*., 2025). The aggregate impact of these developments has widened an already scarcity of good quality forages with which livestock can be produced in India.

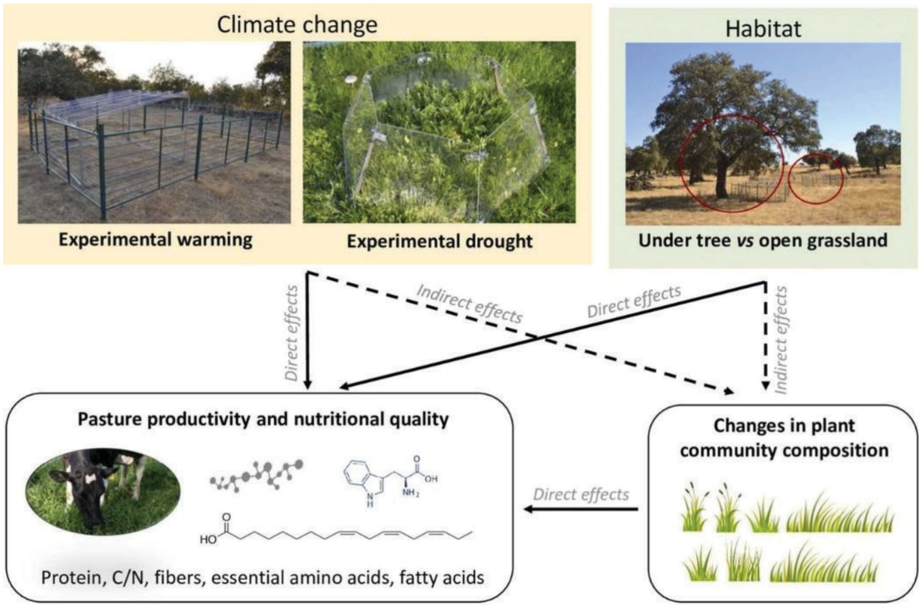

Figure 2. Direct and indirect effects of climate change and habitat conditions on plant community composition, pasture productivity and forage nutritional quality.

2.3. Soil degradation and carbon loss

Extreme weather enhances soil erosion, organic materials, and loss of nutrients (Kulkarni, 2021). The rangelands are degraded and could lose 2050 percent of the initial soil organic carbon (SOC) and become an offset source of greenhouse gases (Lal, 2002). There is a common loss of 0.2-0.5 Mg C ha -1 per year in degraded systems, which lead to loss of water-holding capacity, infiltration, and nutrient availability (Lal, 2018). In dry parts of Rajasthan and Gujarat, salinity and desertification has been exacerbated through enhanced evapotranspiration. According to Safriel and Kumar (2021), there was a 10 percent rise in barren land between the years 2001 and 2020 that was majorly caused by the degradation of pastures and the intrusion of invasive species. Remote sensing studies, conducted by Rawat and Adhikar (2021) have found more than 30 million hectares of grassland dominated topographies degraded, especially in the states of Rajasthan, Gujarat, Maharashtra and Telangana. In the aridland areas where

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rangelands are located, elevated temperatures amplify the demand of evapotranspiration thus aggravating desertification.

2.4. Biodiversity loss

Climate change gives preference to the invasive, unpalatable species, instead of the native forage grasses and legumes. Prosopis juliflora, Parthenium hysterophorus, Lantana camara and Opuntia spp. are the dominating species on degraded rangelands, lowering the biodiversity and forage. In India, Prosopis juliflora alone has invaded 810 million hectares and this decreases the biomass of grass by 6070 percent and changes the properties of the soil (Mworia, 2011). Invasive species lead to soil biogeochemistry, decrease diversity of the microbial community, and raise the risk of erosion (Gibbons *et al*., 2017). Recent ecology researches indicate that warming and changes in rainfall favor aggressive invasive species like Prosopis juliflora and Parthenium hysterophorus that outcompete native forage grasses and legumes. Kibet and Van Wilgen (2024) revealed that herbaceous biomass is decreased by up to 70 percent by the invasion of Prosopis, and soil nutrient cycling changes, which complicates the restoration efforts of rangelands under climate stress. There are also climate induced vegetation changes that are being experienced in high altitude rangelands in Ladakh and Himachal Pradesh. Jarque-Bascunana (2021), reported that shrub species were found to be increasing in altitude and alpine forage grasses were decreasing in abundance, making them less grazable to pastoral systems.

3. Genetic and Biological Technologies

3.1 Climate-Resilient Forage Species and Varieties

Climate-resilient forage varieties are among the most scalable interventions for stabilizing biomass supply under climate stress. Stress-tolerant grasses and legumes are selected or bred to withstand drought, heat, salinity and temporary flooding, while maintaining forage yield and nutritive value (Kara and Surmen, 2023). Such varieties reduce the yield gap in dry years and ensure stable fodder supply, particularly in rainfed and rangeland-based livestock systems. Field experiments in semi-arid India showed that improved varieties of *Cenchrus ciliaris* and *Panicum maximum* produced 18–35% higher biomass under water-limited conditions than local landraces (Hussain *et al*., 2020). Similarly, drought-tolerant sorghum and pearl millet hybrids maintained stable yields even under temperatures above 38°C, indicating suitability for hot environments (Srivastava *et al*., 2022). Recent evaluations also emphasize the importance of using locally adapted ecotypes/cultivars, because ecological adaptation strongly influences persistence and recovery after drought. Perennial forage systems contribute to mitigation through increased soil carbon storage. Deep-rooted perennial grasses improve soil aggregation, reduce erosion, and increase microbial activity, leading to SOC accumulation. Perennial forage systems increased SOC by 0.4–1.2 Mg C ha^{-1} yr^{-1} compared with annual forage systems (Gamble *et al*., 2019). Biodiversity-based strategies, especially grass–legume mixtures, enhance stability and productivity under variable rainfall. Mixed swards can outperform monocultures by 20–30% under rainfall variability while improving forage quality and soil nitrogen availability (Stanciu, 2025). These mixtures also improve nutrient cycling and reduce external input dependency.

Table 1: Climate-resilient forage species and key traits

Forage species	Stress tolerance	Added advantage
Sorghum	Drought, heat	High biomass
Pearl millet	Drought	Fast growth, high nutritive value
Stylo (Stylosanthes)	Low rainfall	Nitrogen fixation
Napier hybrid	Heat, moisture stress	Perennial fodder
Cowpea	Heat tolerant	Early maturity
Guineagrass(Panicum maximum)	Drought, heat	High palatability
Cenchrus (Buffel grass)	Drought	Good pasture persistence
Lucerne (Alfalfa)	Drought (deep root)	High protein fodder
Desmanthus	Drought, low fertility	Perennial legume
Para grass	Waterlogging	Lowland suitability

3.2 Role of Forage Legumes in Climate Mitigation

Forage legumes are central components of climate-smart rangeland systems because they enhance nitrogen cycling, improve forage quality, and reduce dependence on industrial fertilizers. Biological nitrogen fixation (BNF) by legumes contributes approximately 50–300 kg N ha^{-1} yr^{-1} depending on species, climate, and management (Barbieri *et al*., 2023). This reduces synthetic N fertilizer requirement and its associated emissions from manufacturing and field application. Long-term trials in Australia and sub-Saharan Africa reported that legume-based pastures reduced nitrous oxide (N_2O) emissions by 35–60% compared to fertilized grass monocultures (Nyameasem, 2021). Since N_2O has a high global warming potential, this represents a major mitigation gain. Legumes also increase crude protein content and digestibility, improving animal productivity. In India, inclusion of Stylosanthes, cowpea and Desmodium increased crude protein by 15–25%, improving livestock weight gain and milk yield (Singh *et al*., 2018). Improved forage quality enhances feed conversion efficiency, reducing enteric methane emission intensity per unit of product (Dong *et al*., 2019). Thus, forage legumes provide both mitigation and adaptation benefits: they increase pasture resilience, reduce reliance on chemical fertilizers, improve productivity under rainfall variability, and stabilize livestock performance.

3.3 Climate-Smart Livestock Genetic Improvement

Climate-smart livestock genetic improvement complements forage technologies by reducing the emission intensity of livestock production. Animals with improved feed efficiency, faster growth, and enhanced fertility produce more output per unit feed, thereby lowering methane per unit milk or meat. Meta-analyses suggest that genetic selection can reduce enteric methane emissions by 10–20% over multiple generations (Worku, 2024). Heat tolerance is increasingly important because heat stress reduces feed intake, milk yield, fertility and survivability. Climate-smart breeding strategies include:

- selection for heat tolerance and thermo-resilience
- structured crossbreeding using indigenous adaptive traits
- selection for disease resistance and longevity

Indigenous breeds and composites often perform better under low-input rangeland systems, showing greater tolerance to heat and feed scarcity. Therefore, genetic improvement should prioritize balanced breeding objectives (productivity + resilience), rather than yield alone.

4. Improved Management-Based Technologies

4.1 Adaptive and Rotational Grazing Systems

Grazing management is one of the most validated approaches for rangeland sustainability. Rotational, deferred and adaptive multi-paddock (AMP) grazing systems prevent overgrazing, allow vegetation recovery, and maintain ground cover. These systems support deeper rooting, improved biomass regeneration and better soil function. Long-term grazing studies show that rotational grazing increases SOC by 0.3–1.0 Mg C ha^{-1} yr^{-1} compared with continuous grazing (Liu *et al*., 2024). Improved grazing also reduces bare soil, strengthens infiltration and lowers runoff. Indian studies from semi-arid regions reported 25–40% higher forage biomass under controlled grazing regimes, along with reduced land degradation (Shinde and Mahanta, 2020). Improved grazing increases infiltration and reduces runoff by 30–50%, thereby enhancing drought resilience (Tracy *et al*., 2018). Adaptive grazing systems further improve resilience because recovery periods can be adjusted based on rainfall and pasture growth rate. Overall, grazing management is essential for conserving rangelands, maintaining carrying capacity and sustaining livestock livelihoods.

4.2 Integrated Agroforestry and Silvopastoral Systems

Integrated agroforestry and silvopastoral systems combine trees/shrubs + pasture + livestock**,** improving land productivity and ecosystem services. These systems contribute strongly to mitigation through carbon sequestration in woody biomass and soils. Reported sequestration rates range from 1.5–4.0 Mg C ha^{-1} yr^{-1} depending on system type and climate (Ortiz *et al*., 2023). Silvopastoral systems also deliver major adaptation benefits. Tree shade lowers heat stress and improves animal comfort. Trees enhance soil fertility through litter addition, improve biodiversity and stabilize microclimate. Studies indicate that silvopastoral systems can improve milk yield by 10–25% and reduce mortality during heat waves (Goncherenko *et al*., 2024). These systems are particularly suitable for tropical environments where heat stress is a major livestock constraint. Comparison of ecosystem service indices (SES) among secondary vegetation, pasture, and silvopastoral systems, showing enhanced carbon storage, nutrient cycling, erosion control, and water regulation in silvopastoral land-use systems.

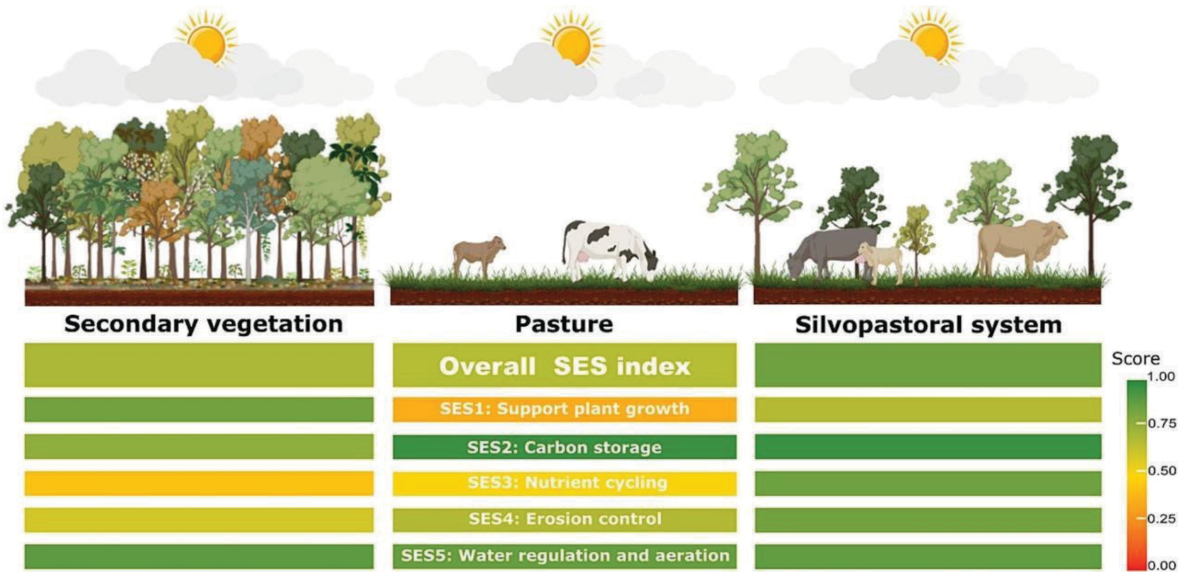

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Figure 3. Ecosystem services of secondary vegetation, pasture and silvopastoral systems.

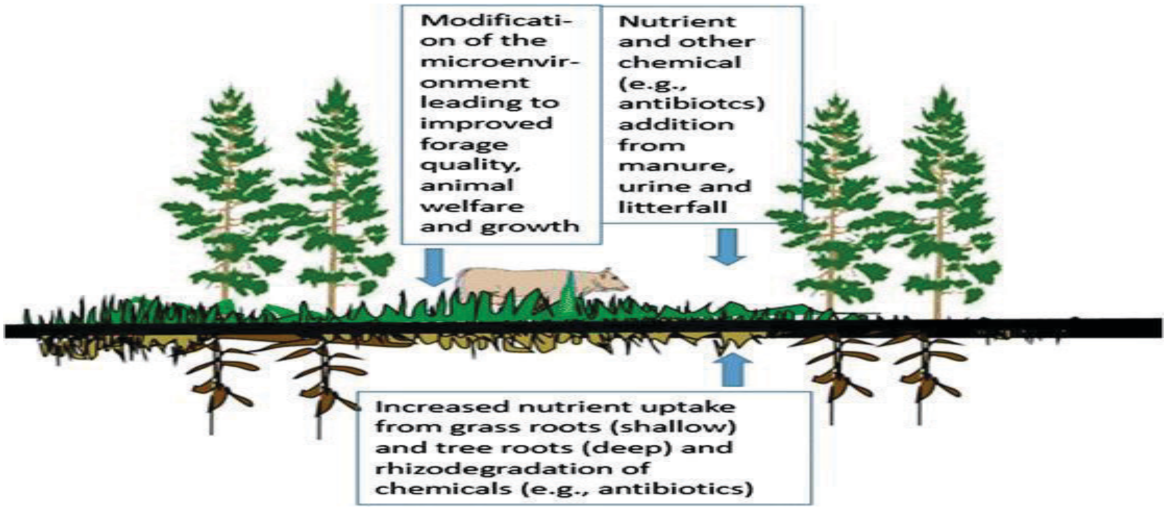

Figure 4. Nutrient cycling and microclimate regulation in silvopastoral systems.

4.3 Fodder Conservation and Crop Residue Utilization

Climate variability increases fodder shortages during dry seasons and extreme rainfall events. Conserving surplus forage through silage, hay and densified fodder blocks ensures feed availability during stress periods. Silage-based systems reduce dry-season feed gaps by up to 40% and help maintain milk yield (Tóthi *et al*., 2024). For smallholders, silage also reduces dependence on purchased concentrates and improves economic stability (Balehegn *et al*., 2022). Crop residues such as straw and stover constitute an important feed resource. However, residues are low in digestibility due to lignocellulose. Chemical and biological treatments can increase digestibility by 15–30%, improving intake and productivity. Residue utilization also avoids open-field burning, reducing CO_2 and particulate emissions while supporting soil organic matter maintenance.

4.4 Rangeland Restoration and Rehabilitation

Restoration and rehabilitation aim to reverse rangeland degradation and recover productivity. Technologies include reseeding, invasive weed management, grazing regulation and soil–water conservation structures (Teague and Kreuter, 2020). reseeding degraded rangelands with adapted perennial grasses can restore 60–80% productivity within 3–5 years, especially when combined with controlled grazing (Rapiya *et al*., 2025). Soil and water conservation measures such as contour bunds, trenches and check dams reduce runoff, increase infiltration, and improve vegetation recovery. In arid India, these interventions increased forage availability by 20–35% under rainfed conditions (Reddy *et al*., 2022). Restoration success depends on long-term grazing regulation; without controlled grazing, degradation can recur rapidly.

4.5 Crop Residue Management

Crop residue management refers to the scientific utilization of post-harvest by-products such as straw, stover, stalks and leaves for livestock feed or soil conservation. Residues provide a critical feed source during dry seasons when green fodder is scarce. Upgrading practices such as chopping, soaking, and urea treatment improve palatability and nutritive value (Kamal *et al*., 2025). Residues may also be retained on the soil surface as mulch, reducing erosion and moisture loss while improving soil quality. Avoiding residue burning prevents GHG and particulate emissions and reduces nutrient loss, supporting climate-smart farming under changing climatic conditions.

4.5 Water Harvesting and Efficient Irrigation

Water harvesting and efficient irrigation stabilize forage production in drought-prone regions. Water harvesting structures such as farm ponds, bunds, small tanks and check dams store rainfall runoff for protective irrigation. Efficient irrigation ensures adequate moisture for forage crops without wastage, improving water productivity and yield stability (Walia *et al*., 2024). These practices are particularly important for multicut fodder crops like Napier and guinea grass, which require continuous moisture for optimal productivity.

Table 2: Soil and water conservation technologies and benefits (fodder crops)

Technology	Benefits
Mulching	Moisture conservation
Contour bunds	Erosion control
Trenches / staggered trenches	Rainwater harvesting
Farm ponds	Drought irrigation
Check dams	Groundwater recharge
Vegetative barriers	Runoff reduction
Rotational grazing	Prevents overgrazing
Reseeding	Pasture recovery
Gully plugging	Stops erosion
Percolation tanks	Recharge storage

5. Soil Health and Carbon Enhancement Technologies

Soil health improvement is essential for sustainable fodder productivity because healthy soils store more water, improve nutrient cycling and support pasture persistence. Conservation tillage, organic amendments and cover crops improve soil structure and microbial activity, contributing to both adaptation and mitigation. Reduced tillage reduces CO_2 emissions by limiting soil organic matter oxidation and reducing fuel use (Lal, 2020). Organic amendments such as FYM, compost, vermicompost and biochar increase SOC stocks and enhance microbial biomass. Biochar offers long-term carbon storage, with SOC increases of 10–40% depending on application rate and soil type (Das *et al*., 2024). Cover crops maintain soil cover, reduce erosion and improve nitrogen availability. Meta-analyses show cover crops increase SOC by 0.3–0.8 Mg C ha^{-1} yr^{-1}, and in mixed systems they can provide additional forage biomass during dry periods.

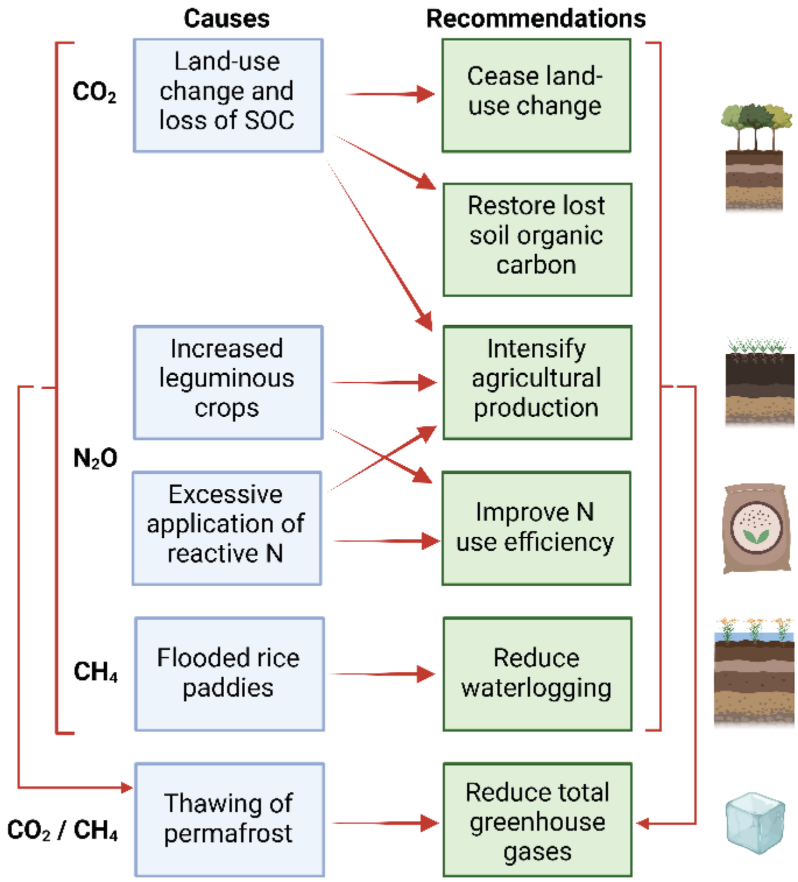

Figure 5. Causes of greenhouse gas emissions from land-use and soil processes and recommended mitigation measures.

6. Digital Technologies in Forage and Rangeland Management

Advances in digital and smart technologies are increasingly transforming forage and rangeland management by enabling real-time monitoring, precision decision-making, and rapid response to climatic and ecological changes. Traditional rangeland management mainly relies on periodic field observations and experience-based estimates. However, climate variability has increased the risk of drought, heat stress, irregular rainfall, invasive species spread, and rangeland degradation. Digital technologies address these challenges by generating continuous and location-specific information on soil–plant–animal interactions, which supports timely and precise interventions.

Digital tools improve rangeland sustainability through four major functions:

1. Continuous monitoring of soil, vegetation and livestock movement
2. Early warning of drought, forage deficit and degradation risk
3. Precision interventions for grazing, water and restoration management
4. Decision support and documentation for adaptive planning and reporting

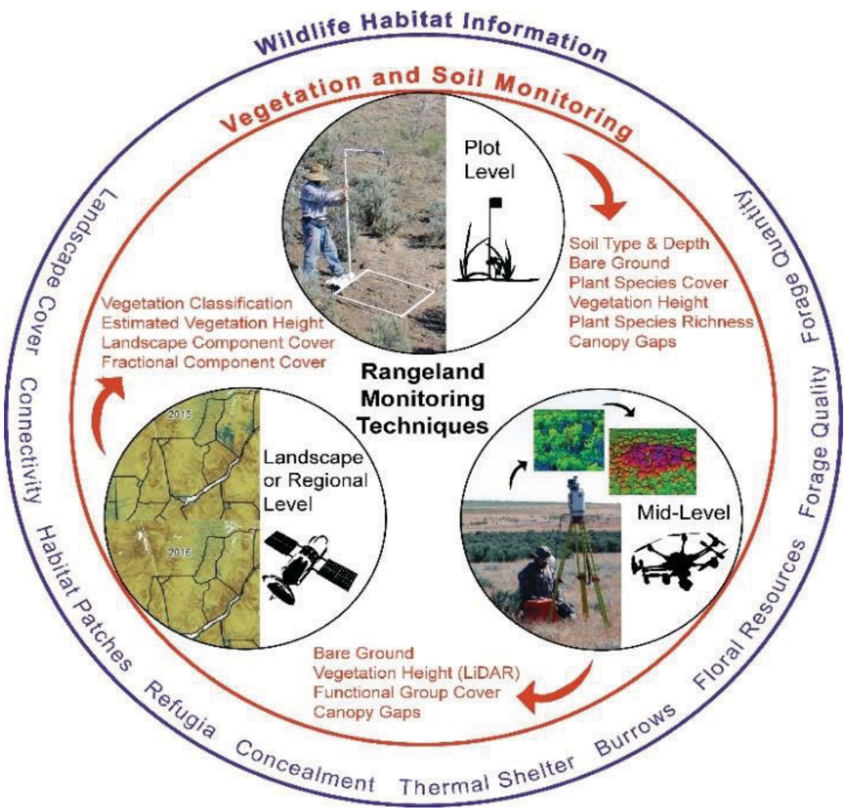

Figure 6. Integrated Rangeland Monitoring for Vegetation, Soil, and Habitat Assessment

6.1 Smart Field Monitoring Devices (IoT and Sensor Systems)

Smart monitoring devices include interconnected sensors that measure and transmit field-level data in real time. In forage and rangeland systems, sensors are used to monitor soil moisture, soil temperature, salinity, nutrient status, pasture growth, microclimate conditions, and water availability. Sensors installed across grazing zones transmit data through wireless networks to centralized dashboards or mobile interfaces. These systems support management by identifying moisture stress and pasture decline early, guiding protective irrigation in fodder plots, and improving grazing allocation. Microclimate monitoring also supports livestock comfort management by indicating heat stress risk periods. Overall, sensor-based monitoring improves pasture utilization efficiency and reduces degradation risks by enabling adaptive and evidence-based decisions.

6.2 Landscape Monitoring Tools (Satellite and Drone-Based Assessment)

Landscape monitoring tools use satellite imagery and drone platforms to provide large-area assessment of rangeland condition. Remote sensing generates spatial information on vegetation cover, biomass, land degradation patterns, seasonal forage availability, and weed/shrub invasion. Multispectral imagery supports mapping of forage condition and trend analysis across seasons. Satellite-based monitoring is suitable for regional planning, while drone-based surveys provide detailed local assessment for pasture improvement and restoration. These tools support identification of overgrazed patches, bare soil expansion, erosion risk, and restoration priority zones. Therefore, landscape monitoring strengthens rangeland planning through evidence-based zoning and targeted interventions.

6.3 Predictive Decision Support Systems (AI and Data Analytics)

Predictive decision support systems use artificial intelligence and data analytics to convert complex datasets into actionable recommendations. AI models process data from sensors, satellite imagery, weather records and livestock tracking tools to predict:

- forage growth trends and biomass availability
- soil moisture deficits and drought risk
- grazing pressure and pasture recovery time
- risk of degradation, erosion or invasive spread

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Such forecasts help in planning stocking rate adjustments, rotational grazing schedules, and restoration strategies. AI also strengthens climate resilience by improving early warning capacity and reducing uncertainty in forage-based production systems.

6.4 Digital Grazing Control Systems (Virtual Fencing and GPS Tracking)

Digital grazing control uses GPS-enabled collars and virtual boundaries to guide livestock movement without physical fences. Animals receive warning signals near boundaries and are redirected to permitted grazing zones. These boundaries can be updated regularly to support dynamic grazing schedules. Virtual fencing enables better rotational grazing, prevents overuse of preferred patches, and protects sensitive areas such as wetlands, riparian zones, and regenerating pasture blocks. It improves uniform grazing distribution, reduces soil compaction in fragile locations, and supports real-time livestock monitoring across large grazing lands.

6.5 Precision Operations and Automated Tools (Robotics and Smart Mechanization)

Precision operations involve the use of automated technologies and drones for operational tasks in rangelands and forage lands. Robotics and autonomous tools can be used for:

- Reseeding and pasture renovation in degraded patches
- Targeted weed and shrub management
- Soil sampling and pasture condition assessment
- Precision spraying of nutrients or biocontrol agents

These technologies reduce labour dependency and enhance operational efficiency, especially in large or remote rangeland areas. Targeted operations also reduce unnecessary chemical use and disturbance, improving long-term ecosystem stability.

6.5 Digital Advisory and Communication Platforms (Mobile Apps and ICT Services)

Digital advisory tools include mobile apps and web-based ICT platforms that provide farmers and rangeland managers access to:

- Real-time weather forecasts and early warnings
- Grazing advisories and pasture updates
- Fodder planning tools and ration guidance
- Market and livestock information

These platforms also support record keeping of grazing schedules, forage production, livestock movement, and pasture condition. In community-managed rangelands, ICT systems enable knowledge sharing, participatory planning and coordination of grazing and restoration

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activities. Digital advisory services therefore strengthen adaptive management and improve the effectiveness of extension support.

5. Conclusion

To achieve productivity amid climate change, climate-smart forage and rangeland management entails an interdependent alliance of genetic, biological, management-based, soil-water conservation as well as digital technologies. Forage species and varieties that are climate-resilient stabilize the supply of biomass during drought, heat, salinity and variability of rainfall, and forage systems that are perennial increase organic carbon storage in soils and minimize land degradation. Forage legumes enhance mitigation by biological nitrogen fixation, reduce reliance on synthetic fertilizers, and enhance the quality of forage which boosts performances of livestock and reduces the intensity of methane emissions per unit of product. The genetic enhancement of livestock through climate-smartness also helps by enhancing feed efficiency and heat tolerance, thus the reduction in emissions per unit output. The application of better grazing systems like adaptive and rotational grazing stops the occurrence of overgrazing, enhances vegetation recovery and increases the moisture content of the soil and SOC levels. Agroforestry and silvopastoral systems have further mitigation and adaptation advantages such as capturing carbon, enhancing of the micro climate and mitigating heat stress in livestock. Fodder conservation processes, crop remnant use, rangelands recovery, and water harvesting treatments improve fodder security and stability in the face of drought, and other extreme weather incidences. Lastly, the implementation of digital technologies such as IoT sensors, remote sensing, AI-driven decision support, virtual fencing and ICT platforms allow implementing precision monitoring, early warming and effective management that will guarantee long-term sustainability and resiliency of forage and rangeland ecosystems.

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References

Balasubramaniyan C and Rao M N. 2023. Meteorology and agriculture. *Madras Agricultural Journal* 37: 1.

Balehegn M, Ayantunde A, Amole T, Njarui D, Nkosi B D, Müller F L and Adesogan A T. 2022. Forage conservation in sub-Saharan Africa: Review of experiences, challenges, and opportunities. *Agronomy Journal* 114(1): 75–99.

Barbieri P, Starck T, Voisin A-S and Nesme T. 2023. Biological nitrogen fixation of legume crops under organic farming as driven by cropping management: A review. *Agricultural Systems* 205: 103579.

Boone R B, Conant R T, Sircely J, Thornton P K and Herrero M. 2018. Climate change impacts on selected global rangeland ecosystem services. *Global Change Biology* 24(3): 1382–1393.

Das S K, Choudhury B U, Hazarika S, Mishra V K and Laha R. 2024. Long-term effect of organic fertilizer and biochar on soil carbon fractions and sequestration in a maize–black gram system. *Biomass Conversion and Biorefinery* 14(19): 23425–23438.

Dereje F, Mengistu A, Geleti D, Feyissa F, Diba D, Pequeno D and Tesfaye B. 2024. Calibration and evaluation of a CROPGRO perennial forage model for *Brachiaria humidicola* yield simulation under future climate in subhumid environments of Ethiopia. *African Journal of Range & Forage Science* 41(4): 235–243.

Dong L, Li B and Diao Q. 2019. Effects of dietary forage proportion on feed intake, growth performance, nutrient digestibility, and enteric methane emissions of Holstein heifers at various growth stages. *Animals* 9(10): 725.

Eldridge D J, Greene R S and Dean C. 2011. Climate change impacts on soil processes in rangelands. In *Soil Health and Climate Change*, pp. 237–255. Springer, Berlin, Heidelberg.

Gamble A V, Howe J A, Balkcom K B, Wood C W, DiLorenzo N, Watts D B and van Santen E. 2019. Soil organic carbon storage and greenhouse gas emissions in a grazed perennial forage–crop rotation system. *Agrosystems, Geosciences & Environment* 2(1): 1–9.

Ghosh P K, Kumar S, Palsaniya D R, Dixit A K and Rai S K. 2017. Climate resilient strategies for sustainable forage production. *Current Advances in Agricultural Sciences* 9(2).

Published by National Institute of Agricultural Extension Management (MANAGE), Hyderabad

Gibbons S M, Lekberg Y, Mummey D L, Sangwan N, Ramsey P W and Gilbert J A. 2017. Invasive plants rapidly reshape soil properties in a grassland ecosystem. *mSystems* 2(2): 10–1128.

Giridhar K and Samireddypalle A. 2015. Impact of climate change on forage availability for livestock. In *Climate Change Impact on Livestock: Adaptation and Mitigation*, pp. 97–112. Springer, New Delhi.

Goncherenko G A, Báez F, Fedrigo J K, Santa Cruz R, Claramunt M, Mercadante V R G and Viñoles C. 2024. Silvopastoral systems as a strategy to attenuate the negative effects of heat stress on productivity of beef cows grazing natural grassland. *Agroforestry Systems* 98(7): 1995–2011.

Hussain M I, Farooq M, Muscolo A and Rehman A. 2020. Crop diversification and saline water irrigation as potential strategies to save freshwater resources and reclamation of marginal soils—A review. *Environmental Science and Pollution Research* 27(23): 28695–28729.

Jarque-Bascuñana L. 2021. Alpine grasslands, grazing and climate change.

Kakusu E M. 2022. *Effects of soil moisture variability on morphological and anatomical attributes of roots and buds of selected rangeland grasses of southern rangelands of Kenya*. PhD thesis, University of Nairobi, Kenya.

Kamal M, Aldhalmi A K, Abd El-Hack M E, Elsherbeni A I, Youssef I M, Hussein S and Cheng Y. 2025. Enhancing the feed efficiency of crop residues in ruminants: A comprehensive review. *Annals of Animal Science* 25(2): 529–545.

Kanthaswamy H, Das A, Venkatachalam S, Ramasamy A, Radha A K and Kumar S. 2025. Strengthening livestock systems through sorghum-based fodder value chain innovations in southern India. *Agricultural Systems* 225: 104273.

Kara E and Sürmen M. 2023. Forage yield and quality characteristics of winter legume/grass mixtures harvested at different phenological stages. *Türk Doğa ve Fen Dergisi* 12(4): 147–153.

Kibet S and van Wilgen B W. 2024. Prosopis invasions in Eastern Africa’s rangelands: Impacts and management challenges. In *The Ecology and Management of Invasive Prosopis Trees in Eastern Africa*, pp. 108–120.

Published by National Institute of Agricultural Extension Management (MANAGE), Hyderabad

Knapp J R, Laur G L, Vadas P A, Weiss W P and Tricarico J M. 2014. Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. *Journal of Dairy Science* 97(6): 3231–3261.

Kulkarni S. 2021. Climate change, soil erosion risks, and nutritional security. In *Climate Change and Resilient Food Systems: Issues, Challenges, and Way Forward*, pp. 219–244.

Lal R. 2002. Soil carbon dynamics in cropland and rangeland. *Environmental Pollution* 116(3): 353–362.

Lal R. 2018. Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. *Global Change Biology* 24(8): 3285–3301.

Liu Y, Zhang M, Wang X and Wang C. 2024. The impact of different grazing intensity and management measures on soil organic carbon density in Zhangye grassland. *Scientific Reports* 14(1): 17556.

Malaviya D R, Roy A K and Kaushal P. 2018. Rangelands/grasslands of India: Current status and future prospects. In *Grasslands of the World*, pp. 235–252.

Meena R K, Kumar R, Ram H and Saxena A. 2022. *Basics of climate-smart technologies of fodder production and conservation*.

Moore K J, Lenssen A W and Fales S L. 2020. Factors affecting forage quality. In *Forages: The Science of Grassland Agriculture*, Vol. 2, pp. 701–717.

Mworia J K. 2011. Invasive plant species and biomass production in savannas. In *Biomass and Remote Sensing of Biomass*. IntechOpen.

Nyameasem J. 2021. *Diverse forage production systems and their potential for greenhouse gas mitigation*. PhD thesis.

O'Leary G J, Aggarwal P K, Calderini D F, Connor D J, Craufurd P, Eigenbrode S D and Hatfield J L. 2018. Challenges and responses to ongoing and projected climate change for dryland cereal production systems throughout the world. *Agronomy* 8(4): 34.

Ortiz J, Neira P, Panichini M, Curaqueo G, Stolpe N B, Zagal E and Gupta S R. 2023. Silvopastoral systems on degraded lands for soil carbon sequestration and climate change mitigation. In *Agroforestry for Sustainable Intensification of Agriculture in Asia and Africa*, pp. 207–242.

Patel A, Shukla C, Trivedi A, Balasaheb K S and Sinha M K. 2025. Smart farming: Utilization of robotics, drones, remote sensing, GIS, AI and IoT tools in agricultural operations and water management. In *Integrated Land and Water Resource Management for Sustainable Agriculture*, Vol. 1, pp. 127–151. Springer Nature, Singapore.

Rapiya M, Mndela M, Truter W and Ramoelo A. 2025. Assessing the economic viability of sustainable pasture and rangeland management practices: A review. *Agriculture* 15(7): 690.

Rawat G S and Adhikari B S. 2015. Ecology and management of grassland habitats in India. *ENVIS Bulletin: Wildlife & Protected Areas* 17.

Reddy M B, Kumar A, Meena R K, Ram H, Kumar R, Saxena A and Rani A. 2022. Role of agro-interventions in fodder production in the face of climate change. In *Basics of Climate-Smart Technologies of Fodder Production and Conservation*, p. 215.

Safriel U N and Kumar V V. 2021. Land degradation and restoration driven by invasive alien *Prosopis juliflora* and the Banni grassland socio-ecosystem (Gujarat, India). *Global Journal of Science Frontier Research: H Environment & Earth Science* 21(3): 1–10.

Sandhu J S, Kumar D, Yadav V K, Singh T, Sah R P and Radhakrishna A. 2015. Recent trends in breeding of tropical grass and forage species.

Sharma M, Joshi S, Gupta P and Joshi T. 2025. Climate, crops and communities: Modeling the environmental stressors driving food supply chain insecurity. *Earth* 6(4): 121.

Shinde A K and Mahanta S K. 2020. Nutrition of small ruminants on grazing lands in dry zones of India. *Range Management and Agroforestry* 41(1): 1–14.

Singh T, Ramakrishnan S, Mahanta S K, Tyagi V C and Roy A K. 2018. Tropical forage legumes in India: Status and scope for sustaining livestock production. *Forage Crops* 2: 166.

Soni A K and Tripathi J N. 2024. Temporal trends of dry spells in Indian meteorological subdivisions during southwest monsoon 1951–2023. *International Journal of Climatology* 45: e8712.

Srivastava R K, Yadav O P, Kaliamoorthy S, Gupta S K, Serba D D, Choudhary S and Varshney R K. 2022. Breeding drought-tolerant pearl millet using conventional and genomic approaches: Achievements and prospects. *Frontiers in Plant Science* 13: 781524.

Stanciu A Ș. 2025. Sustainable forage yield improvement through perennial grass–legume intercropping in degraded grasslands. *Turkish Journal of Agriculture and Forestry* 49(2): 215–241.

Tamboli P, Chaurasiya A K, Upadhyay D and Kumar A. 2023. Climate change impact on forage characteristics: An appraisal for livestock production. In *Molecular Interventions for Developing Climate-Smart Crops: A Forage Perspective*, pp. 183–196. Springer Nature, Singapore.

Teague R and Kreuter U. 2020. Managing grazing to restore soil health, ecosystem function and ecosystem services. *Frontiers in Sustainable Food Systems* 4: 534187.

Tóthi R, Orosz S, Somfalvi-Tóth K, Babinszky L and Halas V. 2024. Effect of climate change on strategy of forage feeding in cattle farms under dry continental conditions. In *Latest Scientific Findings in Ruminant Nutrition: Research for Practical Implementation*, p. 57.

Tracy B F, Foster J L, Butler T J, Islam M A, Toledo D and Vendramini J M B. 2018. Resilience in forage and grazinglands. *Crop Science* 58(1): 31–42.

Walia S S, Kaur K and Kaur T. 2024. Water harvesting: Importance and techniques. In *Rainfed Agriculture and Watershed Management*, pp. 125–137. Springer Nature, Singapore.

Worku, D. 2024. Unraveling the genetic basis of methane emission in dairy cattle: A comprehensive exploration and breeding approach to lower methane emissions. *Animal Biotechnology,* 35(1), 2362677.

Chapter-06

Climate Resilience through Agroforestry

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ABSTRACT: *Climate change poses unprecedented challenges to agricultural sustainability, food security, and rural livelihoods through increased temperature extremes, erratic rainfall, prolonged droughts, floods, land degradation, and biodiversity loss. Agroforestry, the deliberate integration of trees with crops and/or livestock on the same land management unit, has emerged as a climate-resilient land-use system capable of addressing both adaptation and mitigation goals. This chapter synthesizes concepts, mechanisms, systems, and empirical evidence demonstrating how agroforestry enhances climate resilience of farming systems. It discusses biophysical and socio-economic pathways, carbon sequestration potential, ecosystem services, and policy relevance, with special emphasis on tropical and subtropical regions such as India. The chapter concludes by highlighting research gaps and strategic directions for scaling up agroforestry as a cornerstone of climate-smart agriculture.*

Keywords: Agroforestry, climate resilience, climate change adaptation, mitigation,

1. Introduction

Climate change has become one of the most critical threats to global agriculture and natural resource management. Rising atmospheric temperatures, altered precipitation regimes, increased frequency of extreme weather events, and shifting pest and disease dynamics are severely affecting crop productivity and farm incomes. Smallholder farmers in developing countries are particularly vulnerable due to their dependence on rainfed agriculture, limited adaptive capacity, and fragile natural resource bases. Agroforestry is increasingly recognized as a viable land-use system that enhances resilience to climate variability while simultaneously contributing to mitigation through carbon sequestration. By integrating woody perennials with annual crops and/or livestock, agroforestry systems mimic natural ecosystems, improve resource-use efficiency, and diversify production. These systems are deeply rooted in traditional farming practices and indigenous knowledge, yet they are now being re-evaluated in the context of modern climate challenges. This chapter explores the role of agroforestry in building climate-resilient agricultural landscapes. It examines theoretical foundations, mechanisms of resilience, types of agroforestry systems, evidence from research studies, and policy implications, providing a comprehensive understanding suitable for students, researchers, and practitioners.

2. Concept of Climate Resilience in Agriculture

Climate resilience in agriculture refers to the capacity of agricultural systems to anticipate, absorb, adapt to, and recover from climate-related shocks and long-term stresses while sustaining productivity, ecosystem functions, and livelihoods. In the context of accelerating climate change, resilience is not merely the ability to withstand disturbances but also the capacity for transformation toward more sustainable and adaptive production systems. Resilient agricultural systems are characterized by diversity, redundancy, flexibility, and learning capacity, which together reduce vulnerability to climatic extremes such as droughts, floods, heat waves, and erratic rainfall. Unlike conventional monocropping systems that are highly sensitive to climate variability, diversified systems distribute risk across multiple components and temporal scales. The key dimensions of agricultural climate resilience include:

- **Biophysical resilience**, which encompasses soil health, water availability, microclimate regulation, and biodiversity. Healthy soils with higher organic matter content improve water-holding capacity and nutrient cycling, while diversified vegetation buffers temperature extremes and reduces land degradation.
- **Economic resilience**, which refers to income diversification, risk reduction, and livelihood stability. Farming systems that generate multiple outputs—such as food, fodder, timber, and non-timber forest products—are better able to withstand market and climate shocks.
- **Social resilience**, which includes access to knowledge systems, institutional support, social networks, and adaptive governance. Community-based resource management, extension services, and policy support play a crucial role in enhancing farmers' adaptive capacity.

Agroforestry contributes to all these dimensions simultaneously by enhancing on-farm diversity, strengthening ecosystem services, and providing socio-economic buffers against climate risks. By integrating trees with crops and/or livestock, agroforestry creates multifunctional landscapes that are inherently more resilient than simplified agricultural systems (Jose, 2009; Lasco et al., 2014).

2.1. The Mechanics of Climate Resilience through Agroforestry: Agroforestry supports climate resilience through a set of interconnected biophysical and socio-economic mechanisms that stabilize agricultural environments and reduce exposure to external climatic shocks. These mechanisms operate across spatial and temporal scales, contributing to both climate change mitigation and adaptation**.**

2.1.1 Carbon Sequestration and Climate Change Mitigation: Agroforestry is widely recognized as a cost-effective and sustainable approach to mitigating climate change through the capture and storage of atmospheric carbon dioxide (CO_2) in plant biomass and soils. The integration of perennial woody components into agricultural landscapes significantly enhances carbon stocks compared to conventional annual cropping systems. Aboveground carbon sequestration occurs as trees and shrubs absorb CO_2 through photosynthesis and store carbon in trunks, branches, leaves, and other woody tissues. Long-lived tree species contribute to stable carbon pools, with sequestration rates varying depending on species composition, stand age, and management practices (Albrecht & Kandji, 2003; Nair et al., 2010). Belowground carbon sequestration is facilitated through extensive root systems, litterfall, and root turnover, which increase soil organic carbon over time. Decomposing leaf litter and fine roots enrich soil organic matter, improve aggregation, and enhance nutrient availability, thereby strengthening both mitigation and soil fertility functions (Lorenz & Lal, 2014; Oelbermann et al., 2006).In addition to carbon storage, agroforestry systems contribute to greenhouse gas emission reduction. Improved nutrient cycling and biological nitrogen fixation reduce dependence on synthetic nitrogen fertilizers, leading to lower nitrous oxide (N_2O) emissions. Furthermore, silvopastoral systems enhance forage quality and digestibility, which can reduce methane (CH_4) emissions per unit of livestock product (Jose et al., 2014; Kim et al., 2016). Collectively, these processes position agroforestry as a key nature-based solution for climate change mitigation.

2.1.2 Climate Change Adaptation and Microclimate Regulation: Beyond mitigation, agroforestry plays a crucial role in climate change adaptation by modifying the immediate microclimate and enhancing the capacity of farming systems to cope with environmental stressors. Temperature regulation is one of the most significant adaptive benefits of agroforestry. Tree canopies provide shade and reduce incoming solar radiation, thereby lowering surface and ambient temperatures. Empirical studies have shown that agroforestry systems can reduce field-level temperatures by up to 2 °C, which significantly decreases heat stress on crops and livestock (Chavan et al., 2015; Mbow et al., 2014). Wind and erosion protection are achieved through shelterbelts, hedgerows, and boundary plantations. These tree structures reduce wind velocity, prevent crop lodging, and minimize soil erosion caused by wind and water. Improved soil stability is particularly important under increasing rainfall intensity and extreme weather events associated with climate change (Nair et al., 2021). Water conservation and hydrological regulation are enhanced through improved infiltration, reduced runoff, and increased soil moisture retention. Deep-rooted trees access subsoil water and, in some cases, redistribute moisture to upper soil layers through hydraulic lift, benefiting associated crops. In semi-arid regions such as the Sahel, agroforestry interventions have been shown to significantly raise local groundwater levels and improve water availability compared to treeless agricultural systems (Garrity et al., 2010; Lasco et al., 2014).Through these mechanisms, agroforestry creates buffered and stable microenvironments that enhance crop productivity, livestock performance, and overall system resilience under variable and uncertain climatic conditions.

3. Agroforestry Systems and Their Characteristics

Agroforestry encompasses a wide range of systems varying in structure, function, and scale. Major agroforestry systems include:

3.1 Agri-silviculture:

Integration of trees with annual or perennial crops. Examples include alley cropping, boundary plantations, and scattered trees on cropland.

3.2 Silvopastoral Systems:

Combination of trees with pasture and livestock, improving fodder availability, animal welfare, and land productivity.

3.3 Agrosilvopastoral Systems:

Complex systems integrating trees, crops, and livestock, offering multiple products and enhanced resilience.

4. Mechanisms of Climate Change Adaptation through Agroforestry

Agroforestry enhances adaptive capacity of farming systems through several interconnected mechanisms.

4.1 Microclimate Regulation:

Trees moderate temperature extremes by providing shade, reducing wind speed, and lowering evapotranspiration. This buffering effect protects crops and livestock from heat stress and reduces moisture loss from soil.

4.2 Soil Health Improvement:

Tree roots enhance soil structure, increase organic matter, and promote biological activity. Leaf litter and root turnover improve nutrient cycling, water infiltration, and soil moisture retention, making farms more resilient to droughts and heavy rainfall.

4.3 Water Regulation:

Agroforestry systems improve hydrological functions by reducing surface runoff, enhancing groundwater recharge, and stabilizing stream flows. Deep-rooted trees access subsoil water and redistribute it to upper layers through hydraulic lift.

4.4 Biodiversity and Pest Regulation:

Increased plant and animal diversity in agroforestry systems supports natural enemies of pests and pollinators, reducing vulnerability to pest outbreaks that may intensify under climate change.

4.5 Livelihood Diversification:

Trees provide timber, fuelwood, fodder, fruits, medicines, and other non-timber forest products. Diversified income sources reduce farmers' dependence on a single crop and spread climate-related risks.

5. Climate Change Mitigation Potential of Agroforestry

Agroforestry contributes significantly to climate change mitigation by sequestering carbon in both biomass and soils and reducing net greenhouse gas (GHG) emissions relative to conventional agricultural systems. Its mitigation benefits arise from long-term storage of carbon dioxide (CO_2) and reductions in nitrous oxide (N_2O) and methane (CH_4) emissions through improved nutrient and land management.

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5.1 Carbon Sequestration:

One of the strongest mitigation benefits of agroforestry lies in its capacity to capture atmospheric CO_2 and store it over long periods. Trees and shrubs in agroforestry systems act as carbon sinks, accumulating carbon in their aboveground and belowground biomass. This carbon is stored in trunks, branches, leaves, and extensive root systems, which are continually replenished as trees grow and shed organic material. Empirical studies show that when land is converted from traditional agriculture to agroforestry, soil organic carbon (SOC) stocks increase significantly. For example, a synthesis of 53 global studies found that converting cropland to agroforestry raised SOC by about 34% on average, and conversion from pasture/grassland to agroforestry also increased SOC, particularly when perennial plants were included in the system. This increase contributes directly to long-term carbon storage in agricultural landscapes. Research from India likewise documents that agroforestry has notable carbon sequestration potential. Studies estimate tree component carbon sequestration between 0.25 to 76.55 Mg C/ha/yr and soil carbon sequestration between 0.003 to 3.98 Mg C/ha/yr under different agroforestry systems, depending on species, site quality, and management. These figures illustrate the substantial mitigation potential in tropical and subtropical contexts if agroforestry adoption is scaled up. Quantitative global reviews also confirm that agroforestry increases SOC relative to monocultures, often by 10–20 % or more, with particularly high gains in arid regions. This enhanced SOC results from increased inputs of litter, roots, and organic matter, which foster microbial activity and soil nutrient cycling. Field-based research in diverse agroforestry models—such as horti-silvipasture and boundary plantations—shows that these systems can sequester more atmospheric carbon than traditional agriculture and provide ancillary benefits such as improved soil health and higher biomass production.

5.2. Soil Carbon Storage:

Soil organic carbon (SOC) is a major reservoir of terrestrial carbon and plays a central role in climate mitigation and soil fertility. In agroforestry systems, continuous litter inputs from leaves, branches, and roots, along with reduced soil disturbance, enhance SOC accumulation relative to annual monocropping systems.The presence of woody perennials increases the amount of root biomass and root turnover, which contributes stable carbon to deeper soil layers. Over time, this process can transform soils from net carbon sources into net carbon sinks, particularly when combined with minimal tillage and organic management. Studies indicate that different agroforestry configurations (e.g., alley cropping, integrated tree orchards, and homestead agroforestry) vary in their SOC outcomes, but all tend to store more carbon than adjacent non-forestry agricultural plots. For instance, agroforestry systems in Bangladesh showed higher SOC and soil organic matter (SOM) compared to traditional systems, suggesting enhanced carbon storage potential when perennials are incorporated. Beyond carbon mitigation, increased SOC improves soil structure, water retention, and nutrient cycling, which reinforces resilience to drought and erosion while supporting sustained agricultural productivity.

5.3 Reduced Greenhouse Gas Emissions: Agroforestry also contributes to mitigation by reducing net emissions of potent greenhouse gases:

- **Nitrous oxide (N_2O)**:
  Perennial vegetation and tree components in agroforestry systems often lead to lower N_2O emissions than conventional cropland due to improved nutrient uptake and reduced reliance on synthetic nitrogen fertilizers. Field measurements indicate that N_2O emissions can be markedly lower in perennial tree systems compared to annual grassland or cropland.
- **Methane (CH_4)**:
  Soil carbon enrichment in certain agroforestry settings enhances conditions for methane oxidation by soil microbes, effectively increasing CH_4 uptake and reducing its net emission potential. Some intercropping systems have functioned as effective CH_4 sinks under field conditions.
- **Fertilizer reduction**:
  Agroforestry systems often integrate nitrogen-fixing tree species or legumes, which enhance soil nitrogen availability naturally and reduce the need for synthetic fertilizers—thereby lowering the N_2O emissions associated with fertilizer production, transport, and use.

  In addition, by producing on-farm sources of wood fuel, agroforestry reduces pressure on native forests and decreases the need for fossil fuel–based energy. This substitution effect further contributes to net emission reductions and supports broader climate mitigation goals.

6. Evidence from Research and Case Studies

Numerous studies conducted across tropical, subtropical, and temperate regions clearly demonstrate the resilience and climate benefits of agroforestry systems. Evidence from South

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Asia shows that poplar–wheat agroforestry systems in north-western India recorded 113% higher biomass production and ~34.6 t C ha^{-1} carbon storage, compared to ~18.7 t C ha^{-1} under sole wheat cultivation, highlighting their superior productivity and mitigation potential (Rohit et al., 2019). Similarly, mango-based intercropping systems improved overall land productivity and ensured income stability for farmers during years of erratic rainfall (Dagar et al., 2014). At the national scale, agroforestry systems in India exhibit an average carbon sequestration potential of ~25 t C ha^{-1}, contributing significantly to climate change mitigation goals (Zomer et al., 2016). In dryland and semi-arid regions, tree-based systems have been shown to increase soil organic carbon (SOC) by 18–40% compared to fallow or monocropping systems, thereby improving soil quality and resilience to drought (Singh et al., 2020). Long-term evidence from a 37-year study in semi-arid India further revealed higher SOC stocks under agroforestry (~39.3 Mg C ha^{-1}) compared to fallow land (~30.6 Mg C ha^{-1}), underscoring the sustainability of such systems (Saha et al., 2018). In humid and sub-humid tropical regions, multistrata agroforestry systems, including home gardens and tree–crop mixtures, were found to store 12–228 Mg C ha^{-1}, approaching carbon levels observed in secondary forests while simultaneously enhancing biodiversity conservation, nutrient cycling, and long-term ecosystem stability (Montagnini & Nair, 2004; Udawatta et al., 2019). Globally, agroforestry systems store approximately ~40.9 Mg C ha^{-1} in biomass and ~159 Mg C ha^{-1} in soil (0–100 cm depth), with annual carbon sequestration rates ranging from 0.29 to 15.2 Mg C ha^{-1} yr^{-1}, depending on species composition and management practices, confirming agroforestry as a robust nature-based solution for climate change adaptation and mitigation (Nair et al., 2010; Zomer et al., 2016)

7. Socio-Economic and Policy Dimensions

Despite its benefits, adoption of agroforestry faces constraints such as land tenure insecurity, delayed economic returns, limited access to quality planting material, and lack of awareness. Supportive policies, extension services, and market linkages are essential for scaling up agroforestry. In India, national agroforestry policies and climate action plans increasingly recognize agroforestry as a strategic intervention for achieving climate targets, livelihood enhancement, and sustainable land management.

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8. Challenges and Research Gaps

Key challenges include:

- Quantification of long-term resilience benefits under diverse agroecological conditions
- Species-site matching under changing climates
- Trade-offs between tree–crop competition and facilitation
- Monitoring, reporting, and verification of carbon benefits

Addressing these gaps through interdisciplinary research will strengthen the scientific basis for agroforestry-based climate solutions.

9. Conclusion

Agroforestry represents a powerful, multifunctional approach to building climate resilience in agriculture. By integrating ecological principles with farming practices, agroforestry enhances adaptive capacity, mitigates climate change, and supports sustainable livelihoods. As climate risks intensify, mainstreaming agroforestry into agricultural development and climate policies is both a necessity and an opportunity for resilient and sustainable food systems.

References

Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. Agronomy for Sustainable Development, 35, 869–890.

IPCC. (2019). *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Intergovernmental Panel on Climate Change.

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems, 76*(1), 1–10. https://doi.org/10.1007/s10457-009-9229-7

Montagnini, F., & Nair, P. K. R. (2004). Carbon sequestration: An underexploited environmental benefit of agroforestry systems. *Agroforestry Systems, 61*(1–3), 281–295. https://doi.org/10.1023/B:AGFO.0000029005.92691.79

Nair, P. K. R. (2011). Carbon sequestration studies in agroforestry systems: A reality-check. *Agroforestry Systems, 86*(2), 243–253. https://doi.org/10.1007/s10457-011-9434-z

Nair, P. K. R., Nair, V. D., Kumar, B. M., & Showalter, J. M. (2010). Carbon sequestration in agroforestry systems. *Advances in Agronomy, 108*, 237–307. https://doi.org/10.1016/S0065-2113(10)08005-3

Rao, C. A. R., Kareemulla, K., Krishnan, P., & Murthy, M. R. K. (2017). Agroforestry for resilience building in smallholder farming systems. *Indian Journal of Agroforestry, 19*(2), 1–12.

Rohit, K., Panwar, P., & Singh, V. (2019). Biomass production and carbon sequestration potential of poplar-based agroforestry systems in north-western India. *International Journal of Current Microbiology and Applied Sciences, 8*(6), 156–165. https://doi.org/10.20546/ijcmas.2019.806.019

Singh, A. K., Rai, A. K., & Meena, R. K. (2020). Carbon sequestration and soil fertility under agroforestry systems in semi-arid regions of India. *Agroforestry Systems, 94*(4), 1503–1515. https://doi.org/10.1007/s10457-020-00505-8

Udawatta, R. P., Rankoth, L. M., & Jose, S. (2019). Agroforestry and biodiversity. *Sustainability, 11*(10), 2879. https://doi.org/10.3390/su11102879

Verchot, L. V., van Noordwijk, M., Kandji, S., et al. (2007). Climate change: Linking adaptation and mitigation through agroforestry. *Mitigation and Adaptation Strategies for Global Change, 12*(5), 901–918. https://doi.org/10.1007/s11027-007-9105-6

Zomer, R. J., Neufeldt, H., Xu, J., Ahrends, A., Bossio, D., Trabucco, A., & van Noordwijk, M. (2016). Global tree cover and biomass carbon on agricultural land: The contribution of agroforestry to global clima.

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Climate Risk Management and Finance

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ABSTRACT: *Climate change is the most significant environmental challenge threatening global livestock production and rangeland sustainability. This chapter explores the critical intersection of climate risk management and innovative agricultural finance within the framework of Climate Smart Agriculture (CSA). It provides an in-depth analysis of the multi-dimensional climate risks—physical, transition, and liability—that impair forage quality, animal health, and rural livelihoods. The discussion identifies deep-seated barriers to financial inclusion, such as high transaction costs and information asymmetry, while proposing a robust architecture of innovative finance mechanisms. By integrating blended finance, weather-indexed insurance, and public-private partnerships, the sector can catalyze private investment for adaptation. Furthermore, the chapter details the roles of digital technologies and supportive institutional policies in fostering a resilient rangeland ecosystem. Ultimately, this comprehensive study offers a roadmap for stakeholders to secure the financial health and long-term productivity of the forage and livestock sector in a warming world.*

Keywords: Climate change, Finance, Risk, Forage etc.

1. Introduction

The global livestock sector serves as a cornerstone of agricultural development, contributing 40% of the world's gross domestic agricultural product and supporting the livelihoods of over one billion people. Livestock products are vital to global food security, providing 33% of global protein and 17% of total kilocalorie consumption. However, this vital sector faces systemic threats from climate change, characterized by erratic rainfall, rising surface temperatures, and a higher frequency of extreme weather events such as droughts and floods. These impacts are particularly severe in low- and middle-income countries (LMICs), where communities are disproportionately dependent on climate-sensitive agricultural sectors. Climate Smart Agriculture (CSA) has emerged as a holistic framework to address these challenges by sustainably increasing productivity, enhancing resilience, and reducing greenhouse gas emissions. A critical yet often neglected pillar of CSA adoption is the effective management of climate risks and the mobilization of targeted climate finance. Currently, finance for agriculture, forestry, and land use remains disproportionately small, accounting for only a marginal fraction of global climate investment despite the sector's high vulnerability. Transitioning to resilient rangelands requires a paradigm shift from traditional lending to integrated risk-sharing models that protect both lenders and forage producers.

2. The Multi-Dimensional Spectrum of Climate Risk

Climate risks in the agricultural and livestock sectors are not uniform and manifest through various channels.

2.1. Physical Risks: Direct and Indirect Impacts: Physical risks arise from climate- and weather-related events, which can be categorized as acute (extreme events like storms) or chronic (long-term shifts like sea-level rise).

- Forage and Nutrition Degradation: Increasing temperatures and CO_2 levels significantly alter the quantity and quality of pasture. While higher CO_2 can stimulate growth in certain species, rising heat increases lignin and cell wall components in plants, reducing digestibility and nutrient availability for grazing livestock.
- Heat Stress and Productivity: High-producing animals are highly sensitive to thermal stress, which leads to reduced feed intake, lower milk production, and decreased conception rates.
- Water Scarcity: Livestock production is constrained by increased competition for fresh water, as rising temperatures can increase animal water consumption by a factor of two to three.

2.2 Transition and Liability Risks: Transition risks emerge from the process of adjusting to a low-carbon economy, involving changes in policy, technology, and market preferences. These may lead to "stranded assets" investments in fossil-fuel-dependent technologies that become unviable under new regulations. Liability risks stem from legal actions or the escalating cost of insurance as climate impacts manifest more frequently, potentially making protection unaffordable for smallholders.

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3. Barriers to Financing Resilient Rangelands

Expanding finance for rangeland management is hindered by three primary barriers: the enabling environment, risk management capacity, and transaction costs.

3.1. Information Asymmetry and Moral Hazard: Information asymmetry occurs when lenders lack data on a farmer's credit history or the climate-smartness of their operations. This uncertainty leads to credit rationing, where financial institutions restrict loan amounts or set high interest rates for agricultural clients.

3.2. High Transaction Costs and Financial Fragility: Rangelands are often located in remote areas with poor infrastructure, making it expensive for financial institutions to process and monitor small loans. Furthermore, climate-induced disasters increase financial vulnerability, potentially triggering a default dilemma for rural banks as their clients lose livestock assets to drought or disease.

4. Innovative Climate Finance Architecture:

To bridge the funding gap, new financial structures must leverage public resources to catalyze private capital.

4.1. Blended Finance and Public-Private Partnerships (PPPs): Blended finance utilizes public or philanthropic capital to "de-risk" investments, thereby attracting commercial investors into markets they would otherwise avoid. Public climate funds can provide first-loss guarantees or junior equity, absorbing initial losses to protect senior private debt holders. PPPs further enhance these efforts by leveraging the diverse expertise and networks of donors, research institutions, and private companies.

4.2. Green Bonds and SDG Impact Bonds: Green bonds have emerged as an effective tool for raising large-scale capital for environmental projects, such as sustainable land management and reforestation. Smaller SDG impact bonds can be issued more rapidly and are increasingly advocated for listing under CSR rules or social stock exchanges to drive down interest rates for smallholder-focused lending institutions.

5. Strategic Tools for Climate Risk Management

Managing climate risk requires moving beyond reactive measures to proactive, integrated strategies.

5.1. Risk Mitigation: Diversification and Breeding: Species Diversification: Keeping multiple species (e.g., cattle, sheep, and goats) allows farmers to utilize varying forage resources and reduces the likelihood of total production failure: Genetic Improvement: Selecting for indigenous, heat-tolerant breeds—such as the Red Maasai sheep or Boran cattle—provides inherent resilience to harsh climates and local diseases.

5.2. Technical Interventions: Irrigation plays a dual role by raising forage yields and reducing sensitivity to droughts and heat stress. Additionally, climate-smart feed strategies, including the use of tannins or seaweed additives, can mitigate methane emissions while improving feed efficiency.

6. The Critical Role of Agricultural Insurance

Insurance serves as an indispensable buffer that transfers production risk from the farmer to the financial market.

6.1. Weather-Indexed and "Nat-Cat" Insurance: Traditional insurance is often slow to process in rural areas; however, weather-indexed insurance triggers automatic payouts based on measurable thresholds like rainfall deficiency or wind speed. Innovative "Nat-Cat" (Natural Catastrophe) insurance is being piloted to cover installment liabilities for farmers during unexpected high-loss weather events, ensuring they do not fall into a poverty trap.

6.2. Insurance as Credit Enhancement: The presence of valid insurance significantly improves a farmer's creditworthiness. Banks are more likely to offer larger loan amounts and favorable terms when they are confident that the farmer's repayment capacity is protected by a robust insurance mechanism.

7. Technology-Driven Risk Assessment and Advisory

Rapid advancements in Information and Communication Technology (ICT) are transforming the risk landscape.

7.1. Big Data and Precision Livestock Farming: Digital footprints from mobile phone usage and IoT-enabled sensors can be leveraged to develop alternative credit-scoring models for farmers without formal documentation. Precision livestock farming allows for real-time

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monitoring of animal health parameters, enabling timely interventions before heat stress or disease leads to financial loss.

7.2. Digital Advisory Services: Localised digital platforms provide real-time weather forecasts and agromet advisories via SMS, which can reduce cultivation costs by 25% and significantly increase net returns for dairy and rangeland farmers.

8. Institutional Policies and Coordination

Resilient rangeland management requires an enabling policy environment and better vertical coordination between administrative levels.

8.1. Mainstreaming CSA into National Policy: Governments should integrate climate-smart principles into national development plans, offering structured subsidies and grants for the adoption of drought-tolerant crops and efficient manure management. Policies should also prioritize gender equality, as women farmers in LMICs often have the least access to financial resources.

8.2. Decentralized Governance: Effective risk management should move toward decentralization, empowering village-level institutions like panchayats to coordinate with higher administrative levels for funding and skill development. Better coordination ensures that context-specific contingency plans are successfully implemented at the grassroots level.

9. Conclusion

Climate change poses an existential threat to the stability of forage and rangeland systems, but it also creates an opportunity to modernize agricultural management and finance. Addressing these risks requires a multi-pronged approach: technical innovations such as stress-tolerant genetics, precision farming, and silvopastoral systems must be matched with sophisticated financial instruments like blended finance and indexed insurance. While barriers like information asymmetry and transaction costs persist, the emergence of digital finance and supportive institutional frameworks offers a path to build the resilience of the millions of people dependent on livestock. Ultimately, the transition to climate-smart rangelands depends on the collective ability to mobilize diverse capital flows and ensure that every actor along the agricultural value chain is equipped to navigate the complexities of a changing climate. In summary Climate finance functions as the "economic immune system" for the rangeland landscape; just as a healthy immune system identifies and neutralizes threats before they cause

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systemic failure, innovative finance identifies climate risks and provides the necessary resources to protect the farmer's livelihood before a shock leads to financial collapse.

References

Abay KA, Koru B, Chamberlin J and Berhane G (2022) Does rainfall variability explain low uptake of agricultural credit? Evidence from Ethiopia. *European Review of Agricultural Economics* 49: 182–207.

Bashiru HA and Oseni SO (2025) Simplified climate change adaptation strategies for livestock development in low- and middle-income countries. *Frontiers in Sustainable Food Systems* 9: 1566194.

Gerber PJ, Steinfeld H, Henderson B et al (2013) Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. *FAO Animal Production and Health Paper*, FAO, Rome.

Liu B, Ren B and Jin F (2025) Does climate risk affect the ease of access to credit for farmers? Evidence from CHFS. *International Review of Economics & Finance* 97: 103813.

Massé J, Gerber PJ, Halpern C and Baedeker T (2020) Climate finance readiness of the animal protein sector. *Animal* 14: 1–9.

Paisley J and Nelson M (2019) Climate risk management at financial firms: Challenges and opportunities. *GARP Risk Institute Journal*.

Rojas-Downing MM, Nejadhashemi AP, Harrigan T and Woznicki SA (2017) Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management* 16: 145–163.

Thornton PK and Gerber PJ (2010) Climate change and the growth of the livestock sector in developing countries. *Mitigation and Adaptation Strategies for Global Change* 15: 169–184.

Birthal PS (2021) Climate change and risk management in Indian agriculture. NABARD Research and Policy Series No. 4/2022, NABARD, Mumbai.

Buchner B, Clark A, Falconer A, Macquarie R, Meattle C and Wetherbee C (2019) *Global landscape of climate finance 2019*. Climate Policy Initiative, London.

Falconer A and Stadelmann M (2014) What is climate finance? Definitions to improve tracking and scale up climate finance. Climate Policy Initiative, London.

FWWB/GIZ (2022) Dialogue series on challenges and opportunities in managing climate risk and monitoring adaptation for financial institutions. Report on Dialogue–2: MFIs and NBFCs, GIZ, India.

Sadler MP, Millan A, Swann SA et al (2016) Making climate finance work in agriculture. Discussion Paper, World Bank Group, Washington DC.

Resilient Roots, Sustainable Fruits: The NICRA Roadmap to India's Climate-Smart Agricultural Future

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1. Introduction

Climate change is defined as prolonged alterations in temperatures and atmospheric conditions, primarily driven by human actions like the combustion of fossil fuels. Globally, the Earth is now approximately 1.1 °C warmer than it was in the late 1800s, with the last decade being the warmest on record. India is uniquely vulnerable to these shifts due to its massive population, heavy reliance on natural resources, and the fact that a substantial portion of its livelihoods depends on rainfall-dependent agriculture. Over the past century, India has already witnessed a temperature rise of 0.60 °C, which has adversely affected crop yields and food security. To address these multi-faceted challenges, the Indian Council of Agricultural Research (ICAR) launched a flagship project in February 2011: National Innovations in Climate Resilient Agriculture (NICRA). Initiated with an initial budget of Rs. 650 crores, the scheme aims to bolster the adaptive capacity of Indian agriculture through advanced research, technology demonstrations, and intensive capacity building.

2. The Strategic Architecture of NICRA

NICRA is structured around four primary components designed to bridge the gap between scientific innovation and field-level application:

1. **Strategic Research:**
   Long-term research conducted to generate a wide foundation of knowledge for addressing current and future issues across crops, livestock, fisheries, and natural resources.

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2. **Technology Demonstration Component (TDC):**
   On-field application of proven technologies in climatically vulnerable districts to help farmers adapt to real-time climate variability.
3. **Capacity Building:**
   Training scientists, extension agents, policymakers, and farmers in climate-resilient methodologies.
4. **Sponsored/Competitive Research:**
   Funding for identified institutions to fill critical knowledge gaps in climate research. The lead institute for this massive undertaking is the Central Research Institute for Dryland Agriculture (CRIDA) in Hyderabad, overseen by ICAR's Natural Resource Management (NRM) Division.

3. Strategic Research: Building a Foundation for Resilience

Strategic research serves as the engine of NICRA, involving 21 to 41 ICAR institutes to create a strategic reservoir of knowledge.

- State-of-the-Art Infrastructure: The project has established cutting-edge facilities, including High Throughput Plant Phenomics for screening crop germplasm, Free Air Temperature Elevation (FATE) facilities, and CO2 Temperature Gradient Chambers (CTGC) to study the impacts of elevated CO2 and temperature on crops and pests.
- Vulnerability Assessments: Researchers conduct in-depth evaluations of agro-climatic zones to determine their susceptibility to climatic stresses, extreme events, and rainfall variability.
- GHG Monitoring: State-of-the-art flux towers are used in field areas to continuously measure greenhouse gas (GHG) emissions, helping scientists understand the impact of various management practices on the environment.
- Modeling and Projections: Integrated systems modeling is used to downscale climate change projections and identify regional adaptation strategies for the near and long term.

4. Technology Demonstration Component (TDC): On-Field Realities

The TDC is a participatory model implemented in 121 to 151 climatically vulnerable districts across India. This component is categorized into four essential modules:

A. **Natural Resource Management (NRM):**

This module focuses on augmenting water availability and improving soil health. Key interventions include:

- **In-situ Moisture Conservation:**
  Practices like summer ploughing, ridge and furrow methods, and broad bed furrow practice help conserve rainwater and reduce soil erosion.
- **Water Harvesting and Recycling:**
- Construction and renovation of farm ponds, check dams, and open wells have created millions of cubic meters of storage capacity, providing protective irrigation to thousands of hectares.
- **Conservation Tillage:**
  The use of zero tillage (ZT) in wheat and other crops reduces energy needs and allows for earlier planting to avoid terminal heat stress.

B. **Crop Production:**

This module introduces technologies that foster stability against seasonal variations:

- **Resilient Varieties:**
  Introduction of drought-tolerant (e.g., Sahbhagi Dhan), salt-tolerant (e.g., Jarava), and flood-tolerant (e.g., Swarna Sub-1) varieties.
- **Staggered Community Nurseries:**
  To combat delayed monsoons, nurseries are established so that seedlings are ready for transplanting as soon as rain arrives.
- **Climate-Smart Practices:**
  Promoting water-saving methods such as SRI (System of Rice Intensification), aerobic rice, and direct-seeded rice.

C. **Livestock and Fisheries Management:**

Livestock are vital assets for resource-poor farmers but are highly vulnerable to heat stress and disease.

- **Fodder Banks and Cafeterias:**
  Establishment of village-level fodder banks with high-yielding, multi-cut varieties (e.g., Hybrid Napier, Sorghum) ensures year-round availability of green fodder.

- **Heat Stress Mitigation:**
  Improving animal shelters with better ventilation, reflective roofing, and the use of Temperature-Humidity Index (THI) alerts to advise farmers on cooling strategies.
- **Prophylaxis:**
  Preventive vaccination camps against diseases like Foot and Mouth Disease (FMD) and PPR have reduced livestock mortality rates by up to 90–98%.

D. Institutional Interventions:

NICRA evolves innovative village-level mechanisms to help communities respond to climate shocks:

- **Village Climate Risk Management Committee (VCRMC):**
  A community-led body that manages project funds, coordinates interventions, and maintains a bank account.
- **Custom Hiring Centres (CHCs):**
  These centers provide small and marginal farmers access to essential farm implements (e.g., power tillers, reapers, seeders) at reasonable hire rates, ensuring timely field operations.

5. Forage and Rangeland Management in a Changing Climate

In arid and semi-arid regions where traditional crop production often fails, livestock and forage management become the primary security for farmers. Livestock systems serve as a "living bank," providing flexible financial reserves in times of emergency.

- **Integrated Farming Systems (IFS):**
  NICRA promotes IFS models that combine crops with livestock (e.g., goatery, poultry) and fisheries. In these systems, the byproduct of one enterprise becomes the input for another, maximizing resource efficiency.
- **Silage Making:**
  Demonstrations of silage making ensure that green fodder is stored effectively for use during dry seasons when natural pastures fail.
- **Revitalizing Common Resources:**
  The project focuses on improving the productivity of degrading common pastures and common fodder resources to support small ruminants.

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6. Capacity Building and Extension Tools

Building scientific and community expertise is central to the project's sustainability.

- **Training and Awareness:**
  Scientists are trained in the latest research methodologies, while over 5.5 lakh farmers have participated in training programs on climate-resilient technologies.
- **Extension Methodologies:**
  Tools such as Climate Farmers Field Schools (FFS), Climate-Smart Villages (CSVs), and Climate Awareness Mass Media Campaigns prioritize participatory learning.
- **Digital Empowerment:**
  The VIACC app (Risk and Vulnerability Assessment of Indian Agriculture to Climate Change) provides users with information on climate change risk and indicators for specific districts, aiding policymakers and extension workers.

7. Cross-Cutting Themes: Gender, Natural Farming, and Impact

- **Gender Perspective:**
  Since two-thirds of the world's 600 million poor livestock keepers are women, NICRA emphasizes their empowerment. Climate change often increases women's workloads as men migrate, making the adoption of small ruminants and low-drudgery tools essential.
- **Natural Farming:**
  This ecological approach prohibits chemical inputs, relying instead on formulations like Jeevamrit (cow dung and urine based) to restore soil biology and enhance carbon sequestration.
- **Quantifiable Impacts:**
  In villages like Khagribari, implementation led to a 90% reduction in migration and a 66.66% increase in farmer income. Village-level carbon balance studies have shown significant reductions in GHG emissions due to the adoption of resilient practices.

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8. Conclusion

NICRA is not merely a research project; it is a vital government initiative designed to ensure the enduring productivity of Indian agriculture in a warming world. By integrating high-tech strategic research with community-driven technology demonstrations, the project has built a robust "reservoir of resilience". Moving forward, the successes of NICRA must be further scaled up through the National Mission for Sustainable Agriculture (NMSA) to ensure a secure and sustainable future for India's 140 million hectares of net sown area. In summary if climate change is an unpredictable and powerful storm, NICRA acts as both a weather-proof bunker (demonstrating immediate protective technologies) and a sophisticated radar system (conducting strategic research to predict and prepare for future impacts), ensuring that the Indian farmer is never left entirely at the mercy of the elements.

References

Extension approaches for climate resilient livestock farming, ICAR-CRIDA & MANAGE, Hyderabad, 2023.

ICAR-CRIDA Annual Report 2023.

International Journal of Agriculture Extension and Social Development, Vol 7; Issue 2; Feb 2024.

National Innovations in Climate Resilient Agriculture (NICRA) Brief, ICAR, 2018.

NICRA-Technology Demonstration Component Annual Reports (2016-17, 2017-18, 2018-19, 2019-20, 2020-21).

Press Information Bureau Release: Ministry of Agriculture & Farmers Welfare, Aug 2021.

Nutritional Management of Dairy Animals in Various Climatic Conditions

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ABSTRACT*: Climate change is the invisible driver reshaping the future of livestock farming, with rising temperatures, droughts, and extreme weather events severely disrupting feed quality, animal health, fertility, and productivity. Heat stress lowers feed intake and immunity, while droughts shrink fodder availability and degrade nutrient density. Climate-resilient smart feeding strategies offer a sustainable path forward as balancing productivity, animal welfare, and environmental stewardship. Rooted in Climate-Smart feeding, these approaches integrate precision feeding, drought-tolerant forages, functional additives (e.g., antioxidants, postbiotics, seaweeds), and innovative systems like TMR, silvopasture, hydroponics, and insect-based proteins. These solutions optimize nutrient efficiency, reduce methane and nitrogen waste, and build resilience to climate extremes. Technologies such as ration-balancing tools, hyperspectral monitoring, and emergency feed/fodder banks further strengthen adaptability. Smart feeding isn't just about nutrition it's about securing livestock livelihoods, ensuring food security, and building climate-proof dairy systems. In this changing climate, smart nutrition is no longer optional,it's the new frontier of sustainable livestock production.*

Keywords: Dairy, Nutrition, Climatic Conditions

1. Introduction

Climate is the unseen force behind every drop of milk. From scorching heat to freezing cold, shifting weather patterns directly affect the feed consumption, animal health, fertility, and milk production in dairy herds. Heat stress, fodder scarcity due to drought, and climate induced disease pressures collectively threaten dairy productivity, underscoring the critical role of climate stability in sustaining dairy systems. Climate change refers to long-term shifts in local, regional, and global weather patterns, primarily driven by human activities such as greenhouse gas emissions, global warming, urbanization, and deforestation (Sahoo et al., 2024). In livestock systems, its consequences particularly heat stress during extreme summers in arid tropics and cold stress in temperate or high-altitude regions are increasingly severe. Rising temperatures, droughts, and declining forage quality are undermining feed efficiency and animal productivity (Sahoo, 2021). Heat stress increases plant lignin content, reducing digestibility and nutrient release in the rumen (NAAS, 2016), which disrupts the rumen microbiome, elevates lactate levels, and triggers metabolic disorders that severely impact milk and meat yields (Kim et al., 2022). Coupled with reduced feed intake and hormonal imbalances, reproductive performance also suffers, highlighting the widespread impact of climate change on livestock health and production.

2. Impact of Climate Change on Dairy Nutrition and Health

Climate change results in global warming and extreme weather which disrupt ecosystems and shift species distribution (IPCC, 2007; Pankaj et al., 2013). Animal agriculture itself contributes significantly 18% of global greenhouse gas emissions including 9% CO_2, 37% CH_4, and 65% N_2O thereby intensifying climate impacts (Pankaj et al., 2013). Livestock health is affected by both directly, through heat stress, and indirectly, via changes in feed quality and disease patterns (Chauhan et al., 2014). Directly, heat stress impairs thermoregulation, lowers feed intake, fertility, milk yield, and immunity, while increasing disease susceptibility and mortality, particularly in high-yielding crossbreds (Vitali et al., 2015; Hooda et al., 2010). Indirectly, climate change reduces forage quality and water availability, forcing animals onto nutritionally poorer diets, leading to deficiencies and weakened immune systems (Lacetera, 2019; Thornton et al., 2009). Combined, these impacts reduce productivity and livestock resilience under a changing climate (Chauhan et al., 2014). Nutritional strategies tailored to withstand the extreme weather as it heat, cold, or drought, are essential for sustaining the health, productivity, and welfare of dairy animals. In hot conditions, cooling diets and electrolyte supplements help combat heat stress. Cold weather calls for energy-rich feeds to support thermoregulation and maintain body warmth. During droughts, resilient forages and alternative feed resources ensure nutritional balance despite forage scarcity. Climate-resilient feeding strategies are essential for sustaining livestock productivity, improving animal health, ensuring food security, and minimizing environmental impact (FAO, 2018). Rooted in the Climate-Smart Agriculture (CSA) framework, these approaches enhance resilience to climate variability and disruptions (Germer et al., 2023). At the heart of CSA, nutrition is the role of diet in thermoregulation and mitigating heat stress, with strategies like precision feeding, drought-resilient forages, and supplementation with electrolytes and bioactive compounds showing promise (Sammad et al., 2020). Functional feeds rich in antioxidants, phytogenics, and essential minerals strengthen immunity, stabilize metabolism, and improve oxidative balance. Additionally, the use of sustainable, low-emission, drought-tolerant feed resources, combined with practices like feeding during cooler hours, low heat increment diets, genotype-specific formulations, and methyl donor supplementation for epigenetic support, enhances thermal tolerance and nutrient efficiency, boosting livestock resilience under climate stress (Sammad et al., 2020).

3. Key Components of Climate-Resilient Smart Feeding

3.1 Precision Feeding: Climate-smart nutrition holds strong potential for enhancing the performance of high-yielding dairy animals, particularly during early lactation and rapid growth phases. Although these animals utilize dietary protein efficiently, they still excrete 2–3 times more nitrogen in manure than is secreted in milk. This inefficiency can be minimized by formulating diets based on rumen degradable protein (RDP) and undegradable protein (UDP or bypass protein) rather than relying solely on crude protein. Such targeted feeding strategies can sustain or boost productivity while reducing nitrogen waste. Optimizing microbial protein synthesis and providing adequate bypass protein and essential amino acids is key to improving growth, reproduction, and milk yield (Chandrashekharaiah et al., 2024). Additionally, supplementing protected (bypass) fat under field conditions has been shown to enhance milk production and reproductive outcomes. The recommended dose is 20 g/kg of milk yield for cows and 15 g/kg for buffaloes, not exceeding 200 g/day for cows and 150 g/day for buffaloes to prevent adverse effects on rumen fermentation.

3.2 Smart feeding is a climate-resilient strategy ideal for developing countries, aimed at meeting animals' nutritional needs while minimizing costs and environmental impact. A key approach is shifting toward fodder-based diets and reducing dependence on protein-rich concentrates. These rations are both cost-effective and efficient in low- to moderate-yield systems without compromising milk protein output (Makkar, 2016). Utilizing on-farm resources like fodder and crop by-products lowers reliance on external inputs, prevents nutrient excess, and supports manure recycling. In semi-arid areas, integrating local by-products into dairy feed has cut feeding costs and greenhouse gas emissions by up to 14% (Alqaisi et al., 2014). Technologies such as densified straw-based TMR blocks, forage chopping, and harvesting at optimal stages further boost feed efficiency, reduce emissions, and enhance the sustainability and resilience of smallholder livestock systems.

3.3 Balanced Ration Formulation: It involves creating diets tailored to the specific nutritional requirements of dairy animals, taking into account factors such as their age, breed, and stage of production. It enhances animal health, productivity, and fertility, while also lowering greenhouse gas emissions per unit of milk produced. Feed represents over 70% of operational costs in dairy production, making least-cost ration formulation a major challenge for farmers. Imbalanced diets can result in nutrient deficiencies or oversupply especially of costly nutrients leading to reduced productivity and increased expenses. Maintaining a balanced ration is crucial for optimizing milk yield, reproductive performance, and cost-efficiency. To address this, ration balancing tools have gained popularity, with user-friendly mobile and computer-based platforms now widely available to help farmers fine-tune nutrition and manage costs effectively. Examples: FAO Ration Tool, ILRI On Farm Feed Advisor, NDDB Ration balancing, ICAR-NIANP Software- 1. Feed Assist 2. TMR Maker 3. Feed Chart on print, web and mobile media 4. Ration balancing tools for small ruminants.

4. Complete Feed System/TMR

Blending locally available concentrate agro industrial by-products with roughage to form a total mixed ration (TMR) is a proven, cost-effective strategy in livestock nutrition. This complete feed system enhances feed intake, improves nutrient utilization, and boosts animal performance by enabling the efficient use of fibrous crop residues and non-conventional feed resources. TMR prevents selective feeding, allowing inclusion of less palatable but nutrient-rich components make feeding more economical. It also promotes the use of agro-industrial by-products and farm waste like cottonseed hulls, lentil straw, mesquite pods, oilcakes, sugarcane bagasse, poultry droppings, and tree foliage. Incorporating these into livestock diets not only reduces feeding costs but also supports sustainable and resource-efficient animal production.

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Table 1 Inclusion levels of Crop residue (%) in complete ration	
Crop residue	**(%)Level in TMR**
Sorghum stover	20-60
Maize stover	20-50
Paddy straw	Up to 50
Wheat straw	Up to 60
Pulse straw	Up to 50
Sweet sorghum stover	Up to 60
Maize cobs	Up to 50
Sunflower straw	30-50
Sunflower heads	33.5-50
Cottonseed hulls	Up to 50
Cotton straw	Up to 45
Sugarcane bagasse	Up to 40
Sweet sorghum bagasse	Up to 60

5. Use of Climate-Resilient Feed Resources

It includes drought-tolerant and heat-resistant fodder species, like sorghum and millet, which can thrive in challenging climatic conditions. It improves feed security and lowers reliance on water-intensive crops. Climate-resilient feed resources are vital for maintaining sustainable livestock production amid climate change. They are specifically developed to endure environmental stresses like drought, heat, and water scarcity, ensuring consistent nutrition for animals and supporting farmers' livelihoods.

5.1 Drought-Resistant Crops:

Sorghum and millet are standout examples of climate-resilient feed crops. With origins in Africa, these cereals thrive in dry, arid conditions thanks to their deep root systems and efficient water use. They not only provide nutritious feed for livestock but also offer economic benefits for farmers in regions where traditional crops often fail, making them valuable assets in climate-smart agriculture.

5.2 Indigenous Fodder Plants:

Mexican sunflower (*Tithonia diversifolia*) is a tropical herb or shrub cultivated in many countries of Africa, Asia, and South America and it is a fast-growing plant that tolerates heat and drought and can rapidly form large herbaceous shrubs (CABI, 2014). It is rich in protein and it can be used as valuable fodder for ruminants. In regions like Ethiopia and the Peruvian Andes, farmers are turning to indigenous plants such as *Ficusthonningii* and cactus pears as

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resilient livestock feed. Rich in nutrients and excellent at retaining moisture, these plants are especially vital during dry periods. In Ethiopia, integrating them into silvopastoral systems has reduced water use by up to 83% while significantly increasing forage biomass highlighting their role in sustainable, climate-smart feeding.

5. 3 Top feeding:

Tree leaves are a valuable feed resource, especially during forage-scarce periods, offering green biomass with moderate to high digestibility and good protein content. Their dry matter typically ranges from 20–40%, with crude protein levels of 10–15% and calcium content 2–3% higher than common fodder crops. Rich in protein, vitamins, and minerals, tree leaves are the most nutritious part of the tree. They play a crucial role in hilly regions during winter and summer, when both the quality and quantity of green forage are limited, helping sustain livestock nutrition year-round.

Table 2 Chemical composition of different forage leaves

Forage leaves	DM	OM	Ash	CP	NDF	ADF	ADL
Neem leaves leaf meal (*Azadirachta indica*)	92.8	90.5	9.5	28.2	31.8	21.9	4.9
Pigeon pea leaf meal (*Cajanuscajan*)	94.4	92.5	7.5	16.7	54.0	39.7	13.7
Acacia karro leaves	97.1	92.1	7.9	12.7	38.0	32.5	--
Air-dried *Moringastenopetala* leaf	94.4	88.0	-	29.5	17.8	16.5	-
Khejari leaves	45.09	--	--	17.89	48.11	40.41	--
Leucaenaleucochepala leaf	96.2	--	9.92	20.26	50.05	19.98	15.52
Moringa oleifera	22.8	--	9.14	22.8	30.8	22.8	--
Cow-pea leaves (*Vigna unguiculata)*	91.0	--	--	13.0	46.2	19.5	--
Water hycinth leaf protein (*Eichhornia crassipes*)	15.33	86.67	13.43	20.80	--	--	--
Bamboo leaves (*Bambusa vulgaris*)	45.0	--	11.5	14.15	68.8	42.3	--
Berseem leaves (*Trifolium Alexandrium*)	23.8	85.58	15.4	29.80	43.91	27.5	--
Cassia obtusifolia Leaves	97.0	95.26	13.00	27.84	40.32	17.28	--
Sweet potato leaf (*Ipomea batatas*)	91.8	95.3	--	26.5	25.8	15.2	--
Ber leaves (*Ziziphusmauritiana*)	48.9	--	9.8	13.3	35.8	25.5	--

5.4 Dual purpose varieties:

Growing dual-purpose (DP) crops and using their residues as livestock feed is a widely adopted strategy in dryland farming systems (Sprague et al., 2021). Around 70% of crop residues come from cereals like maize, sorghum, and pearl millet, as well as legumes such as cowpea and groundnut. Recently developed high-yielding DP varieties of cowpea, millet, and sorghum offer both nutrient-rich grains for humans and quality fodder for livestock. These crops are especially valuable during the dry season when grasses lose nutritional value. DP varieties with "stay-green" traits retain leaf biomass at maturity, providing nutrient-rich feed when it's most needed. For instance, DP cowpea varieties retain over 50% of their leaves, enhancing fodder quality and feed efficiency (Martens et al., 2012).

5.5 Insect farming for protein:

Black soldier fly larvae and mealworms are emerging as valuable alternative protein and mineral sources for livestock feed. These insects can be reared on organic waste, promoting a circular economy by converting waste into nutrient-rich biomass (Newton et al., 2005). Other species like grasshoppers, houseflies, beetles, silkworms, earthworms, and crickets are also gaining traction as sustainable feed ingredients, particularly for poultry (Belhadj et al., 2023). Rich in protein and essential amino acids, insect-based feeds are highly digestible, animal-friendly, and boast a low carbon footprint with excellent feed conversion efficiency. By reducing reliance on conventional feed crops, insect protein offers a sustainable solution for future feed demands. Though processing is needed to make insects more suitable for food and feed, they are increasingly recognized as a promising component of sustainable livestock nutrition (Lange, 2021).

Table 3 Protein content of insects

Name	Scientific name	Crude protein (%)
Black soldier fly	*Hermetiaillucens*	32-61
Grasshoppers	*Orthoptera*	48-65
Silkworm	*Bombyx mori*	46-72
Earthworm	*Eiseniafetida*	41-66
Housefly	*Musca domestica*	40-64

(Ojediran*et al.,* 2024)

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5.6 Aquatic plants and algae as a supplement to nutrition:

Duckweed and spirulina are excellent examples of protein- and mineral-rich aquatic plants and algae that offer sustainable feed alternatives, especially in areas with limited arable land (Van der Spiegel et al., 2013). Grown in ponds or water bodies, they serve as efficient, nutrient-dense supplements for animal diets. Marine and freshwater algae enhance feed quality due to their high levels of essential nutrients (Wan et al., 2018). As climate-resilient crops, they require minimal land and water, making them ideal for sustainable and low-impact livestock feeding systems.

Table 4 Proximate composition of aquatic plants

Proximate composition	CP (%)	EE (%)	CF (%)	Ash (%)	Moisture (%)
Hyacinth(*Eicchorniacrassipes*)	8.20	2.21	21.42	18.10	89.21
Algae (*Botryococcusbraunii*)	25-26	2-22	-	-	--

(Ojediran*et al.,* 2024)

5.7 Microalgae:

Microalgae are a diverse group of unicellular or simple multicellular organisms with highly variable nutrient profiles. Their amino acid compositions are generally comparable to those of soybean and rapeseed meals (Becker, 2013), though they tend to be lower in histidine often the first limiting amino acid for milk production in animals on grass silage and cereal-based diets. Supplementing microalgae via drinking water has shown promising results in growing cattle grazing on low-quality grasses, improving rumen microbial protein synthesis and enhancing overall diet digestibility (Panjaitan et al., 2015).

5.8 Seaweeds:

Seaweeds are complex multicellular marine organisms that thrive in saltwater and coastal zones (van der Spiegel et al., 2013). They have a high moisture content of 700 to 900 g/kg dry matter necessitating quick use or preservation through drying or ensiling. Though low in cellulose (~40 g/kg DM), seaweeds are rich in unique carbohydrates like alginate, laminarin, and fucoidan. Introducing seaweed gradually into livestock diets allows rumen microbes to adapt and efficiently utilize these complex compounds (Makkar et al., 2016), making seaweed a promising functional feed ingredient.

5.9 Single-cell protein:

Single-cell protein (SCP) is composed of microbial cells from yeast, bacteria, fungi, or microalgae. Its protein content varies depending on factors such as culture conditions, species, and strains (Lindberg et al., 2016), but generally falls within a similar range as soybean expeller.

5.10 Hydropogenic feed production:

Hydroponically produced fodder offers a sustainable, soil-free method of growing fresh, nutrient-rich feed year-round using minimal water an ideal solution during droughts or when climate change limits traditional forage (Jan et al., 2020). Grown in greenhouses or polyhouses over 6–8 days, this system relies only on seeds, water, sunlight, and nutrients. In India, cereals like barley, oat, wheat, sorghum, maize, and legumes like alfalfa and cowpea are successfully cultivated hydroponically (Raghvendran et al., 2020). The resulting dense green mats, 20–30 cm tall, are highly palatable, digestible, and beneficial for livestock health. Producing 1 kg of hydroponic maize fodder needs just 1.5–3.0 liters of water, with seed cost making up nearly 90% of the total expense. A recommended daily supplement is 5–10 kg per cow (Naik et al., 2015). Hydroponic crops grow up to 50% faster, yielding high-quality fodder with lower environmental impact making it a rising global solution to land, water, and climate challenges (Kide et al., 2015).

Table 5 Proximate composition of hydroponically produced maize fodder

CP%	**EE%**	**CF%**	**Ash%**	**Moisture%**
12.42	2.67	9.50	2.77	83.22

(Ojediran*et al.,* 2024)

5.11 Food-Not-Feed Resources:

Utilizing non-human-edible feed resources such as biofuel co-products, protein isolates, leaf meals, food and slaughterhouse waste, and spineless cactus is a promising strategy for building climate-resilient and sustainable livestock systems. These alternative feeds reduce reliance on arable land and minimize competition with human food sources. This approach aligns with the FAO's Sustainable Animal Diets (StAnD) framework, which emphasizes environmental, economic, and ethical sustainability in livestock feeding practices.

5.12 Agro-industrial by-products:

Reviving technologies such as urea-molasses blocks and treating straw with urea or CaO improves nutrient utilization from low-quality forages, which is vital for sustaining productivity in climate-stressed grazing systems (Makkar, 2016).

Together, these food-not-feed innovations minimize feed-food competition, boost nutrient recycling, and contribute to making livestock production more resilient, ethical, and climate-smart.

Table 6 Proximate composition of agro-industrial by products

Agro-industrial by products	**CP%**	**EE%**	**CF%**	**Ash%**	**Moisture%**
Brewery waste	24.30	5.20	19.66	5.77	79.19
Rice bran	17.50	13.10	23.33	4.92	4.3
Wheat bran	17.10	2.11	11.25	6.11	3.10
Palm kernel cake	15.75	12.23	21.42	1.4	9.42
Biscuit waste dough	19.4	3.87	4.18	7.00	9.91
Cashew kernel waste meal	21.10	35.09	6.83	4.10	9.20
Cassava distillers waste	11.82	2.83	34.86	3.54	10.10
Cassacavinnase	19.26	3.72	7.96	9.33	5.68

(Ojediran*et al.,* 2024)

5.13 Supplementation with Feed Additives: Incorporates additives such as antioxidants, minerals, and plant-based products to enhance digestion, lower methane emissions, and improve overall animal health. Nutritional compounds such as antioxidants (vitamin E, selenium, polyphenols, flavonoids), amino acids (methionine, glutamine), electrolytes (Na, K, Cl, Mg), carotenoids (beta-carotene, lutein), and trace minerals (Zn, Cu, Mn) play a crucial role in combating oxidative stress and enhancing cellular resilience under heat stress. These nutrients help preserve cellular function and integrity during challenging conditions. Additionally, innovative feed additives such as algae, probiotics, prebiotics, postbiotics, phytogenic extracts, and enzymes are gaining attention for their ability to enhance metabolic health and strengthen stress resilience in livestock (Shaik et al., 2020). As climate change intensifies, integrating these advanced nutritional strategies with effective heat stress prevention measures will be key to maintaining profitable, welfare-oriented, and environmentally sustainable ruminant production systems.

a) **Eubiotics**: Eubiotics are feed additives designed to maintain or restore a healthy gut microflora, promoting better digestion, immunity, and overall animal performance. This group includes probiotics, prebiotics, organic acids, and essential oils. By enhancing nutrient digestibility and feed conversion efficiency, eubiotics help reduce methane emissions and support sustainable livestock production especially under heat stress and other environmental challenges. Examples:Probiotics: Bacillus subtilis, Lactobacillus spp., Organic acids: Formic acid, butyric acid

b) **Postbiotics:** Postbiotics are non-living microbial-derived functional compounds such as enzymes, peptides, short-chain fatty acids, and cell wall fragments that confer health benefits to the host.Postbiotics improve gut immunity and stress resistance, helping animals cope better with heat stress and oxidative damage during climatic extremes. Examples:Heat-killed Lactobacillus plantarum, Short-chain fatty acids (SCFAs) like acetate and butyrate

c) **Precision Biotics :**Precision biotics are specifically designed microbial metabolites or interventions that modulate defined microbial pathways in the gut to achieve targeted health or performance outcomes.They reduce waste nitrogen and methane emissions by precisely enhancing nutrient metabolism and immune response under variable climates. Examples: Microbiome metabolic modulators targeting SCFA production, Customized oligosaccharides influencing microbiota function.

d) **Enzymes**: Exogenous enzymes will improve the nutritive value of ruminant feeds through improving the fiber degradation and efficiency of feed utilization by enhanced nutrient utilization and reduce the wastage. Exogenous enzymes are capable of breaking down specific bonds in carbohydrates, starch, protein, fats, cellulose, hemicellulose, pectin, glycoproteins, and lignin (Kholif et al. 2024). Examples: Cellulase, Xylanase, Amylase etc.

e) **Plant Extracts**: Plant extracts are bioactive compounds sourced from herbs or plants, including essential oils, saponins, flavonoids, and tannins, that are used to boost animal health and performance. With their antioxidant and anti-inflammatory properties, these extracts help alleviate heat stress, enhance feed intake and productivity, and reduce the need for synthetic additives. The key advantages of phytogenic additives in livestock production include improved feed digestibility, antimicrobial effects, replacement of feed antibiotics, and stimulation of growth. Additionally, their anti-inflammatory benefits

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contribute to better feed conversion and increased feed consumption by animals (Ignatovich, 2017). Examples: Thymol (from thyme), carvacrol (from oregano), Curcumin (from turmeric), saponins (from *Yucca schidigera*).

Table 7: Use of different feed additives in the diet of different animals to reduce the heat stress

Item	Species	Dose	Duration
Betaine	Dairy cow	15g/d	60d
Polyherbal vitamin C	Dairy cow	20g/d	131d
Organic acid and pure botanical	Dairy cow	75mg/kg	131d
Immunomodulatory feed ingredient	Beef cattle	56g/d	106d
Phytogenic feed additive	Heifers	0.25g/d	7d
Citrus extract	Dairy cow	4g/cow/d	28d
Dihydropyridine	Dairy cow	3g/d	104d
Probiotic compounds	Dairy cow	-	60d

(Shah et al., 2025)

f. Seaweed Additives for Emission Reduction: Incorporating small amounts of *Asparagopsistaxiformis*, a red seaweed, into cattle feed has been shown to reduce methane emissions by over 98%, offering a powerful tool for climate change mitigation and more sustainable livestock farming (Dubois et al., 2013). In addition to their methane-lowering effects, seaweeds supply vital nutrients that support ruminant health. For monogastric animals, high-quality protein alternatives such as single-cell proteins, protein hydrolysates, and plant-based protein isolates reduce reliance on conventional feed crops, promoting more resilient and resource-efficient feeding systems.

6. Silvipastoral systems

The term *'silvo'* refers to trees, while *'pasture'* denotes grasses or grass-legume mixtures. Silvopastoral systems (SPS) are agroforestry practices that integrate trees, forage crops, and rotational livestock grazing to create a sustainable, three-dimensional source of nutritious fodder. These systems not only supply feed but also offer fuelwood, timber, and improve land productivity while conserving soil, water, and biodiversity. By providing shade and improving

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microclimates, trees in SPS reduce heat stress, enhance soil fertility, and support better forage growth. Overall, SPS ensures climate-resilient, nutrient-rich, and consistent feed supplies, promoting both animal health and environmental sustainability. There are three basic components in SPS viz., Agriculture, Forestry and Livestock where they form two important systems with livestock:

a) Silvipastoral system (Fodder Trees + Fodder Grasses)

b) Agrisilvipastoral system (Agriculture + Fodder Trees + Fodder Grasses)

c) Hortipastoral system (Horticulture+ Fodder Grasses)

Table 8: Favourable grasses, legumes, shrubs and tree species for development of SPS

Grasses	Legumes	Shrubs	Trees
Lasiurussindicus, Cenchrusciliaris, C.setigerus, Heteropogoncontortus Sehimanervosum, Cicer, Melilotus, Trifoliumspp., Cenchrus spp., PennisetumpedicellatumDichanthiumannulatum, Brachiariamutica, CynodondactylonPanicum maximum, Pennisetumpolystachyon, P. pedicellatum P. clandestinum, Brachiariamutica,	*Clitoriaternatea, Lablab purpureus,Atylosiascarabaeoides, Stylosantheshamata, Macroptiliumlathyroides, Lablab purpureus, Clitoriaternatea, Alysicarpusmonilifer,Stizolobiumdeeringianum, Clitoriaternatea, Mimosa invisa, M. atropurpureum, Centrosemapubescens, Stylosanthesguianensis, Desmodium spp., Sesbania spp.,*	*Zizyphusnumularia, Dichrostachys Spp., Zizyphusnumularia, Cappariazeylanica, Sesbania, Atriplex, Acacia spp.*	*Prosopis cineraria, Azadirachtaindica, Acacia tortilis, Dalbergiasissoo, Leucaenaleucocephala, Emblicaofficinalis,, Acacia spp., Ficus spp., Bauhinia purpurea, Ficusnumeralis, Albiziachinensis Moruscerrata, Salix tetrasperma,*

7. Creation of Feed & Fodder Bank

To tackle livestock feed shortages during droughts and floods, this timely proposal suggests setting up dedicated Feed Banks stocked with safe, alternative feed resources. Ingredients stored in warehouses often rejected for human use due to aflatoxins, pesticides, or drug residues can be repurposed for livestock after clearance by State and Central labs. Once certified, these feeds can be stored for emergency use, ensuring cost-effective, sustainable nutrition while reducing food-feed competition and wastage (Makkar et al., 2016).

Fodder Banks: *Grasses*: Grasses growing around forest edges, wastelands, and farmlands can be harvested and preserved as hay, either compressed into briquettes or stored in high-density stacks for efficient use. *Crop Residues***:** Key crop residues such as rice and wheat straw play a vital role in feed banks. Additionally, residues from coarse cereals, legumes, and haulms left after grain harvesting can also be collected and stored to support livestock feeding during emergencies.

8. Benefits of Climate-Resilient Smart Feeding

- Enhanced Productivity: Optimized feeding leads to better growth rates and higher milk yields.
- Environmental Sustainability: Reduces greenhouse gas emissions and minimizes resource wastage.
- Economic Viability: Decreases feed costs and improves farm profitability.
- Animal Welfare: Promotes better health and reduces stress, leading to improved fertility and longevity.
- Adaptation to Climate Change: Builds resilience against climate-induced challenges like heat stress and feed scarcity.

6. Challenges

- Limited Adoption at Farmer Level: Despite proven benefits, adoption of climate-resilient feeding strategies remains low, particularly among smallholder farmers, due to limited awareness, technical knowledge, and access to advisory services
- Cost and Availability of Advanced Inputs: Precision feeding tools, bypass nutrients, specialty feed additives, and novel protein sources (insects, algae, SCP) may be expensive or inconsistently available, restricting their widespread use.
- Infrastructure and Policy Constraints Establishing hydroponic units, silvopastoral systems, and feed/fodder banks requires initial investment, land, and institutional support. Inadequate policy incentives and regulatory frameworks can slow large-scale implementation
- Knowledge Gaps and Research Limitations. Long-term effects of many novel feeds and additives on animal health, product quality, and environmental impact are not fully understood, especially under diverse agro-climatic conditions.

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7. Conclusion and Future Directions

In a world of rising temperatures and shrinking resources, smart nutrition is the lifeline for dairy animals. Climate-resilient feeding is not just a strategy, it is a necessity to protect productivity, health, and sustainability of dairy animal production. By embracing precision diets, drought-proof fodders, and eco-friendly feed solutions, climate challenges can be turned into opportunities. Future research should focus on feed efficiency, genetic improvements, and climate adaptability to ensure sustainable ruminant production systems.

References:

Alqaisi O, Hemme T, Latacz-Lohman U and Susenbeth A (2014). Evaluation of food industry by-products as feed in semi-arid dairy farming systems: the case of Jordan. Sust. Sci. 9, 366–377.

Becker E W (2013). Microalgae for human and animal nutrition. In Handbook of microalgal culture: applied phycology and biotechnology (2nd edition, ed. A Richmond and Q Hu), pp. 461–503. Wiley-Blackwell, Chicester, UK.

Belhadj, S.I., H. Yerou, M. Ben Larbi, N. M'Hamdi, T. Najar. (2023). Insects as an alternative protein source for poultry nutrition: a review. Frontir in Vet. Sci., 10: 1200031.

CABI, (2014). Invasive Species Compendium. Wallingford, UK: CAB International

Chandrasekharaiah M., N.M. Soren, S.B.N. Rao, and A. Sahoo (2024). Precision feeding by Strategic supplementation of bypass nutrients for optimizing the productivity of dairy animals and nitrogen use efficiency. Climate Resilient Livestock Farming: Role of Technologies and Extension Strategies [E-book] Hyderabad: ICAR – National Institute of Animal Nutrition and Physiology, Bengaluru and National Institute of Agricultural Extension Management (MANAGE), Hyderabad, India.

Chauhan, D.S. and Ghosh, N. (2014). Impact of climate change on livestock production: A review. J. Ani. Res., 4(2), pp.223-239.

Dubois B, Tomkins NW, Kinley RD, Bai M, Seymour S, Paul NA and de Nys R (2013). Effect of tropical algae as additives on rumen in vitro gas production and fermentation characteristics. Amer. J. Plant Sci. 4, 34–43.

FAO, (2018), Climate Smart Agriculture Sourcebook, http://www.fao.org/3/i6310e/i6310e.pdf .

Published by National Institute of Agricultural Extension Management (MANAGE), Hyderabad

Germer LA, Van Middelaar CE, Oosting SJ, Gerber PJ. (2023) When and where are livestock climate-smart? A spatial-temporal framework for comparing the climate change and food security synergies and tradeoffs of sub-Saharan African livestock systems. Agric Syst. 210:103717. doi: 10.1016/j.agsy.2023.103717

Hooda, O.K. and Singh, G. (2010). Effect of thermal stress on feed intake, plasma enzymes and blood biochemicals in buffalo heifers. Ind. J. Anim. Nutri. 27(2): 122-127.

Ignatovich L.S. Dal'nevostochnyiagrarnyivestnik, (2017), 2(42): 75-81 (doi: 10.24411/1999-6837 2017-00012)

IPCC (Intergovernmental Panel on Climate Change) Climate Change (2007): impacts, adaptation and vulnerability. Summary for policy makers. See http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ spm.html.

Jan, S., Rashid, Z., Ahngar, T. A., Iqbal, S., Naikoo, M. A., Majeed, S., Bhat, T. A., Gull, R., & Nazir, I. (2020). Hydroponics— A review. Int. J. Curr. Microb. Appl. Sci., 9(8), 1779–1787. https://doi.org/10.20546/ ijcmas.2020.908.206

Kazemi, M., Elghandour, M.M.M.Y. and Salem, A.Z. M., (2025). Toward climate-smart Ruminat Production: Best practices and future directions. Hand book of climate change mitigation and adaptation. https://doi.org/10.1007/978-1-4614-6431-0_212-1

Kholif, A.E., Patra, A.K. (2024). Dietary Applications of Exogenous Enzymes to Improve Nutrient Utilization and Performance in Ruminants. In: Mahesh, M.S., Yata, V.K. (eds) Feed Additives and Supplements for Ruminants. Springer, Singapore. https://doi.org/10.1007/978-981-97-0794-2_1

Kide, W., Desai, B., & Kumar, S. (2015). Nutritional improvement and economic value of hydroponically Sprouted maize fodder. Life Sciences Int. Res. J., 2(2), 76– 79. https://doi. org/10.11648/ j.aas.20190 401.13

Kim, S.H., Ramos, S.C., Valencia, R.A., Cho, Y.I. and Lee, S.S. (2022). Heat stress: effects on rumen microbes and host physiology, and strategies to alleviate the negative impacts on lactating dairy cows. Front. in Microb., 13, p.804562.

Lacetera, N. (2019). Impact of climate change on animal health and welfare. Anim. Front. 9(1): 26-31.

Lange, K.W., Y. Nakamura. (2021). Edible insects as future food: chances and challenges. J. Future Foods, 1(1): 38-46.

Published by National Institute of Agricultural Extension Management (MANAGE), Hyderabad

Lindberg JE, Lindberg G, Teräs J, Poulsen G, Solberg SØ, Tybirk K, Przedrzymirska J, Sapota GP, Olsen ML, Karlson H, Jóhannsson R, Smárason BÖ, Gylling M, Knudsen MT, Dorca-Preda T, Hermansen JE, Kruklite Z and Berzina I (2016). Nordic alternative protein potentials: mapping of regional bioeconomyopportunities. Nordic Council of Ministers. Retrieved on 26 July 2017 from http:// www.nordic-ilibrary.org/environment/nordic-alternative-protein-potentials_ tn2016-527.

Makkar HP, Tran G, Heuzé V, Giger-Reverdin S, Lessire M, Lebas F and Ankers P (2016). Seaweeds for livestock diets: a review. Anim. Feed Sci. Tech. 212, 1–17.

Martens, S. D., Tiemann, T. T., Bindelle, J., Peters, M., & Lascano, C. E. (2012). Alternative plant protein sources for pigs and chick ens in the tropics– nutritional value and constraints: A review. J. Agri. Rural Develop. in the Tropics and Subtropics, 113(2), 101–123.

NAAS. (2016). Climate Resilient Livestock Production, Policy Paper 81, National Academy of Agricultural Sciences, New Delhi. Pp1-26.

Naik, P. K., Swain, B. K., & Singh, N. P. (2015). Production and utilisation of hydroponics fodder. Indian Journal of Animal Nutrition, 32(1), 1– 9.

Newton, L., D.C. Sheppard, D.W. Watson, E.E. Thelen. (2005). The black soldier fly, Hermetiaillucens, as a manure management/resource recovery tool. In Symposium on the state of the science of Animal Manure and Waste Management, 1: 57.

Ojediran, T. K., Olofintuyi, O. S., &Ojediran, T. J. (2024). Alternative feed resources in the era of climate change: A review. *Aceh Journal of Animal Science*, *9*(3).

Panjaitan T, Quigley SP, McLennan SR, Swain AJ and Poppi DP 2015. Spirulina (Spirulina platensis) algae supplementation increases microbial protein pro duction and feed intake and decreases retention time of digesta in the rumen of cattle. Anim. Prod. Sci. 55, 535–543.

Pankaj, P.K., Ramana, D.B.V., Pourouchottamane, R. and Naskar, S. (2013). Livestock management under changing climate scenario in India. World J. Vet. Sci., 1(1), pp.25-32.

Raghavendran, V. B., Alex Albert, V., & Tamilselvan, N. (2020). Hydroponic maize fodder production Need for small and marginal farmers. Biotica Research Today, 2(7), 601–603.

Sahoo A, ShahajiPhand, Letha Devi G, AnjumoniMech&Sushrirekha Das (2024). Climate Resilient Livestock Farming: Role of Technologies and Extension Strategies [E-book] Hyderabad: ICAR – National Institute of Animal Nutrition and Physiology, Bengaluru and National Institute of Agricultural Extension Management (MANAGE), Hyderabad, India.

Sahoo, A. (2021). Climate smart small ruminant production. In: Impact of Climate Change on Livestock Health and Production. New India Publishing Agency, New Delhi. Pp. 53-59.

Sammad A, Wang YJ, Umer S, Lirong H, Khan I, Khan A, et al. Nutritional physiology and biochemistry of dairy cattle under the influence of heat stress: consequences and opportunities. Animals. (2020) 10:793. doi: 10.3390/ani10050793

Shah AM, H Zhao, RM Nikzaad, C Zhang, U Aziz, N Goswami, Q Zhou, H He, A Sikiru, J Pan (2025). Exploration of the relationships between production performance and heat stress response by ruminant animals due to feed additives. Intl J Agric Biol 33:33208. https://doi.org/10.17957/IJAB/15.2268

Shaik L, Kashyap R, Thotamgari SR, Singh R, Khanna S. Gut-brain axis and its neuro-psychiatric effects: a narrative review. Cureus. (2020) 12:11131. doi: 10.7759/cureus.11131

Sprague, S. J., Lilley, J. M., Bullock, M. J., Virgona, J. M., Kirkegaard, J. A., Hunt, J. R., Hopwood, M. D. A., Faulkner, M. G., & Angus, J. F. (2021). Low nitrogen use efficiency of dual- purpose crops: Causes and cures. Field Crops Res., 267, 108129. https:// doi.org/10.1016/j.fcr.2021.108129

Thornton, P.K., van de Steeg, J., Notenbaert, A. and Herrero, M. (2009). The impacts of climate change on livestock and livestock systems in developing countries: a review of what we know and what we need to know. Agric. Syst. 101, 113–127.

Van der Spiegel, M., M.Y. Noordam, H.J. Van der Fels-Klerx. (2013). Safety of novel protein sources (insects, microalgae, seaweed, duckweed, and rapeseed) and legislative aspects for their application in food and feed production. Comprehensive Reviews in Food Science and Food Safety, 12(6): 662-678.

Vitali, A., Felici, A., Esposito, S., Bernabucci, U., Bertocchi, L., Maresca, C., Nardone, A. and Lacetera, N. (2015). The effect of heat waves on dairy cow mortality. J. Dairy Sci. 98, 4572–4579.

Fodder banks and feed resources management

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ABSTRACT: *Livestock providing food and financial security, employment, and insurance against crop failure for the small and marginal farmers. Whereas, livestock sector is facing serious constraint of feed and fodder, drastic decline in forages, seasonality, availability of quality fodder, reduction in grazing land and high cost of feeds, causing huge economic loss to the livestock sector. In-spite of genetic potentiality, the economic viability and profitability of livestock rearing depend upon the efficient feeding and feeding management. 60-65 percent of the total cost of production is attributed to feeding cost. The fodder production and supply in India is having huge gap, the availability and deficiency of green and dry fodder is increasing day by day, while situation of concentrates is worse. These chronic situations of shortage of feed and fodder during last few decades shows that most of the animals are underfed, hence there is tremendous pressure of livestock on available feed and fodder resources and similarly there is little scope for increasing the area under fodder cultivation. Hence, establishment fodder bank may promise the availability nutrient rich fodder all-round the year, thereby increases the productivity of livestock.*

Keywords: Fodder banks, Forages, feed resources

1. Introduction

Fodder banks are valuable crops, nutrient rich fodder trees and shrubs to supplement conventional fodder production which support productive farming systems. Intensified plots of quality forages like legumes or trees grown for supplemental livestock feeding, especially during the lean period. Fodder trees serve as a potential source of quality green fodder to livestock especially during lean periods, crop residues and agricultural waste are prime sources of feed to the livestock in India. The resource poor livestock owners most often lose their livestock to the fodder scarcity caused by these natural disasters and during lean period.

Seasonal feed scarcity during the dry season is a common feature of semi-arid regions of India. In this context fodder banks will serve the purpose of easing these scarcities and utilization of surplus forages efficiently. Whereas, feed resource management are well defined planning, strategy and conservation of available feed and fodder (crop residues, cultivated grasses, tree leaves) to ensure year-round supply by using techniques such as silage making, bailing, fodder blocks preparation, community storage, to avoid the shortage of nutritious fodder and to increase the livestock productivity. Further, it was aimed to provide quality nutrition, reduction in feed cost and mitigating risks from droughts or floods with integrating various production systems.

2. Key Objectives of fodder banks

- To provide optimum protein and energy when the livestock deprived from nutrient under natural grazing.
- To support the health and improve productivity of the livestock (milk, meat, wool and reproduction).
- To reduce the cost of feeding through reduction of expenses of commercial concentrates.
- To improve the soil health and reduction of soil erosion
- To reduce the pressure on natural lands through improvement in grazing areas.

3. Management of Fodder Bank

- **Continuous availability Fodder:**
  Prepare a specific plan, area wise to match the fodder supply continuously throughout the year as per livestock demand.
- **Storage and Conservation:**
  By application of techniques for production, storage and conservation of available fodder and agricultural byproducts create a fodder blocks or store surplus feed in to hay, silage to use in lean period.
- **Augmentation of production:**
  Bring larger area of fallow and cultivable wasteland, grass lands in to forage production by using high-yielding varieties and seeds.

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- **Approaches:**

  Establish need-based fodder banks as per the surplus fodder is available and store them to distribute during lean period by involving communities.

- **Extension and Technology Transfer**.

  Involvement of different agencies and coordination of different organization for promotion of fodder production and conservation of forages in the villages through demonstration, field visit and trainings.

- **Management:**

  Maximize fodder production through intensified fodder cultivation and allow them to regenerate. The forage crops/trees can be combined with crop fields at multi-strata for production of fodder across different seasons. Made the availability of quality seed and inputs to the farmers on subsidies base throughout the year for dry land and irrigated land.

4. Strategies for Establishment of Fodder Bank and Feed Resources

Fodder bank establishment includes forage production systems and management of available resources in befitting manner to make availability of feed and fodder to the livestock throughout the year and during lean period including legumes and fodder trees in forage production systems. The system of forage production varies from region to region, place to place and farmer to farmer, depending upon the availability of resource and inputs. An ideal forage production system is that which gives the maximum output of digestible nutrients per hectare or maximum livestock products from a unit area and should ensure the availability of succulent, palatable and nutritious fodder throughout the year for livestock. Legumes usually maintain their quality better than grasses even at maturity, and being rich in protein, enhance the forage value, and also add substantially the much-needed nitrogen to the soil.

4.1 Forage Production under Agroforestry:

An integrated approach of growing grasses, fodder trees and shrubs with crops and livestock on the same land to create diversified, productive and environmentally sound system to improve the productivity. Under agroforestry it is an ideal combination of different grasses, (legumes and non-legumes) shrubs, fodder trees for optimizing land productivity, conserving plants, soils and nutrients and producing quality forages, and fuel wood. Orchard grass, stylo hamata, Anjan grass, golden timothy grass, dinanath grass and trees like sesbania, prosopis leucaena, acasia subabool could be grown under the agroforestry system to produce forages with ought interruption.

4.2 Horti-Pastoral System:

Integration of orchard (fruit bearing tree species) with livestock and forage production is an potential for maintenance of different livestock species as they usually planted on a wide spacing. The shade level is generally regulated by lopping of trees, which are fed to livestock. The high yielding suitable species of fodder can be grown are APBN-1, hybrid -napier, guinea grass, golden timothy grass, anjan grass, Dinanath grass, sweet sudan grass, maize, stylo, cowpea, sirato, hosrsegram, in the orchards of orange, guava, mango and lemon during early phase of plantation. Similarly these legume forage crop also have symbiotic effect on fruit tree.

4.3 Silvi-pastoral system:

Planting of multipurpose trees with grasses and legumes in an integrated system and heir utilization through cut and carry of forage in early years followed by in situ grazing is known as silvi-pastoral system. This system aims at optimizing land productivity, conserving plants, soil and nutrients and producing forage, timber and firewood on a sustainable basis. The technology is also useful for ecological restoration and improvement of soil, environment and biodiversity, because it transforms the degraded lands into fodder and fuel producing land. The selection of suitable perennial grasses, legumes and trees for specific agro climatic condition is important for increasing forage as well as animal productivity. The selection of tree is based on its easy regeneration capacity, coppicing ability, fast growth, nitrogen fixing ability, palatable leaves (fodder) with high nutritive value and less toxic substances, short rotation and high fuel value. The grasses and legumes should have easy colonizing ability, high shade tolerance, high production efficiency, palatability and high nutritive value with strong regeneration ability through roots or self-sown seeds.

Symingtonia populnea, Bauhinia sp. and nevaro (Ficus hookerii) as silvi component and congo signal grass, bamboo grass and broom grass as herbage are useful for both monsoon and winter season. During monsoon congo signal grass are useful. However, tree leaves and broom grass can be used in winter season

5. Conservation of forages

Conservation is a preservation technique of forages during the availability of surplus fodder. The best way to ensure the supply of palatable and nutritious feed during the lean period is to conserve the surplus fodder in the form of hay or silage for sustainable production of livestock.

5.1 Silage Making:

During the availability of surplus forages and maize strovers can be preserved as silage. The silage can be made by making use of chaffed maize stover and surplus grasses/local grasses or mixing hybrid napier in equal quantity on fresh basis. Broom grass and indigenous grass are available in plenty during rainy season locally. However, farmers do not use these grasses in rainy season but in scarcity period during winter. It will be cut only once in a year when plant mature. If it is cut once during first week of August and used for silage making along with maize stover or paragrass, it can give good quality silage. During rainy season paragrass/napier should be harvested in such a stage that it contains the dry matter of about 25% or more. At this stage it could be totally used for silage making. Jungle grass is abundantly available during rainy season up to October. If jungle grasses are cut time to time its biomass production is much higher than cutting once at the end of the rainy season. So its potentiality is to be exploited and maize stover and other fodder plants to be preserved as silage for winter.

5.2 Hay Making:

Hay is made by cutting grasses or legumes (like alfalfa, clover, timothy) and letting them dry in the sun over several days, then raking them into rows (windrows) and compressing them into bales for livestock feed. The process involves mowing, "tedding" (fluffing to speed drying), raking, and baling, requiring multiple sunny days to reduce moisture for proper storage and prevent rot.

5.2.1 The Haymaking Process

5.2.1.1 Mowing: Tall grasses and legumes are harvested, usually in the morning when the plant is still damp from dew.

5.2.1.2Tedding/Conditioning: The cut hay is spread out or "fluffed" to expose more surface area to the sun and wind, helping it dry faster. This might be done multiple times.

5.2.1.3 Raking: Once dried, the hay is gathered into long, narrow rows called windrows, making it easy for the baler to pick up.

5.2.1.4 Baling: Picks up the windrowed hay, compresses it into dense blocks (small squares or large rounds), and wraps it with twine or netting.

5.2.1.5 Storage: The finished bales are transported and stored in barns or covered to protect them from moisture, which can cause mold.

6. Utilization of crop residue

In India the most common sources of fodder for livestock are crop residue, and agro-industrial byproducts. More than 54% of the total fodder is met from crop residues, while 18% fodder is met from grasslands and only 28% fodder is met from cultivated fodder crops. Seasonal feed scarcity during the dry season is a common feature of semi-arid regions of India. Hence promotion of special varieties of food crops which have high forage yield and evaluation of nutritional values of crop residues and pricing based on quality may improve the availability of fodder year-round. Similarly, identification of areas where crop residues are burnt/destroyed or diverted for other uses, for establishing fodder banks and demonstrate process of nutritional enrichment of crop. Encourage the farmers to establish fodder banks with the help off government organization, co-operative society and NGOs through provision of incentives and subsidies to the interested farmers or unemployed youth by trainings in the process of collection, chaffing, compressing, bailing, preparation of complete feed and total mixed ration, which may create employment and reduce the nutritional scarcity to the livestock.

6.1 Fodder Trees:

Fodder trees serve as a potential source of quality green fodder to livestock in most of the time especially during scarce periods. Tree leaves are cheaper source of available nutrient to the livestock in bulk with high density and can easily cultivated by the small-holder farmers in the available fields and banks of agricultural plots. Among the fodder tress leucaena, gliricidia, subabool, mulberry, kadamba, calliandra, acacia, agathi, and moringa are promising fodder tress by virtue of their nutritive foliage, fast growing nature with higher biomass production, amenable to heavy pruning, good coppicing ability and easy management. Moreover, these trees can be grown in close hedgerows as fodder banks in integration with existing crops to maximize productivity in land crunch humid tropical areas. Enhancing tree cover in cropping systems also offers ecosystem services like enhanced carbon storage and associated global warming issues. Tree fodders are another type of rescue biomass in the region for feed scarcity. Tree leaves may contain some antinutritional substances which may be easily manageable. About 300 plant species mostly native and few introduced one constitute the green forage resources for the livestock. The nutritive value in terms of DCP and TDN contents were not yet known. Many native plants are yet to explore for use as fodder.

6.2 Weed fodder:

Most of the part in our country farmers feed weeder grass as fodder to their livestock and it plays an important role as a source of nutrients in livestock feeding in rural area in the rainy and winter season. Nutrient values of many weeder grass has at to be explore. Weeds like Alligator weed (Alternanthera philoxeroides), Dicanthium anulatum, Cynodon dactylon, Avena fatua. Convolvulus arvensis, Sorghum halepense and Amaranthus Viridis. Oxalis debils, Rumex crispus, Medicago polymorpha, P. oleracea and A. viridis. Overall are good-quality forage plants as they meet most of the recommended values for cattle maintenance. Alligator weed (Alternanthera philoxeroides) locally known as Kabo Napi is one of the most weed fodder used by the farmers both in summer and winter. The protein content was found to be more than 23%, which result in high milk yield. A proper agronomic technique is need of the hour to increase the production.

6.1 Improvement of Quality and Utilization of Forages:

Majority of the farmers feed crop residues to their animals in a long form which may lead 60-70 percentage of wastage. The crop residues in long form such as maize strover, sorghum, and millets strover needs chopping before feeding to livestock to reduce the wastage. Chopping of fodder reduce wastage and improves digestibility with available nutrient. Since the crop residues/dry roughages are poor in their nutrient which can be enriched with chemical treatment and molasses. All the chemical treated dry roughages can be stored and fed during the lean period. The chopped and treated dry roughages needs less place to store as compared to long farm.

6.3 Urea treatment of low-grade roughages:

Low grade roughages such as paddy straw, sorghum (kadabi), maize stover, dry grasses and other edible farm waste contain negligible amount of digestible, protein and higher amount of non-digestible cell wall constituents can be enriched through urea treatment. The nutritive values, palatability and digestibility of poor quality roughages improve. For this purpose, 4kg urea for 100 kg paddy straw is needed for the treatment.

6.4 Urea-molasses mixture:

Low-grade roughage/fodders can be fortified with molasses (sugar industry waste), urea, salt and mineral mixture. Urea-molasses mixture contains soluble and fermentable nitrogen from urea. Highly fermentable energy from molasses, and essential minerals. The mixture consists of: Water-1.5 kg. Urea-1.5 kg. Molasses-10 kg and Salt- 1.0 kg

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6.5 Urea molasses mineral block (UMMB):

UMMB commercially available and can be used to supplement the low quality roughages in place of urea molasses mix to balance the deficient nutrients in the ration. Similar to urea-molasses mix, block contains soluble and fermentable nitrogen form of urea, highly fermentable energy from molasses and essential minerals. Natural protein sources such as groundnut cake have also been added to provide preformed peptides and amino acids. UMMB has been found to improve the dry matter intake of the basal roughage and the feed digestibility. The nutrients from the block are well utilized by the animals and UMMB supplementation improves productivity of livestock. This not only enhances the available nutrient but reduces the storage space and utilization of UMMB during scares period, this also make nutrient rich fodder bank to feed the productive livestock.

7. Hydroponics

Hydroponic fodder cultivation is a soil-less method to rapidly grow nutrient-rich animal feed, typically barley, wheat, or maize, in just 7-10 days using minimal water and controlled environments, ideal for drought-prone areas to ensure year-round supply, significantly reducing water use and land requirements compared to traditional farming. The process involves soaking seeds, germinating them in trays, and providing water and light for quick sprouting into edible green shoots with root mats, offering improved animal health and productivity.

8. Azolla

Azolla farming is the cultivation of the fast-growing aquatic fern *Azolla* (mosquito fern) as a highly nutritious, low-cost, and sustainable resource for farmers, used primarily as protein-rich animal feed for cattle, poultry, fish, and pigs, and as a biofertilizer to enrich soil with fixed atmospheric nitrogen. It's a simple, eco-friendly practice that requires minimal investment, offering significant savings on commercial feeds and improving soil health, making it popular in sustainable agriculture.

9. Establishment of Fodder Banks

Fodder banks are also maintenance of high-quality, high yielding fodder species both legume and non-legumes under perennial and annual variety suitable to agro-climatic conditions of the area with a goal to maintain productivity of the animal and availability of seed material to the farmers for propagation in larger areas. They can be utilized year the round and also designed to bridge the forage scarcity during the lean period. Fodder banks do not provide 100% of feed requirements, but supplement the available dry season forage. Fodder banks under cultivated fodder crops are important to support sustainable fodder production which should be managed intensively. Cultivation of fodder crops should be planned according to topography of soil, moisture and seasons. Fodder crops with the following characters are more suitable for this purpose: establish easily, grow quickly, compete with weeds, produce high-quality forage with maximum foliage, remain productive under repeated harvest, withstand dry season with limited water sources, survive on poor soils. For this purpose quality of fodder planting material is crucial. Seeds like fodder sorghum (jowar), multi cut jowar, fodder maize, bajra as annual non legume variety, cowpea, berseem, sunhemp, etc, legume annual variety and IGFRI-S, NB-21 , NB-37, PBN-223, KKM-1 , APBN-1, Co-2, Co-3, Co-4, Phule Jaywanth, Super napier and other grasses like dinanth grass, sudan grass, guinea grass and para grass etc. as perennial non legume fodder grass, and stylo, hedge lucern, lucern are the perennial legume fodder varities can be grown to ensure the year round fodder production.

10. Conclusion

Livestock is an integral part of human life. Livestock rearing in our country generally depend upon available scaresed resources such as deficit feed and fodder availability, natural grazing land and agricultural waste, which causes low level of nutrient availability for optimum production. Scarcity of the fodder, high cost of feed and low net returns are major hurdles for the livestock rearing. Hence to make round the year availability of feed and fodder, management of fodder bank and feed resources is very important during the time period to supply the good quality forages each and every corner of the country to make livestock rearing sustainable. Most of the crop residues, cultivable fodder, non-cultivable local grasses, fodder trees, conservation technology, emerging new technology can address the deficiency of feed and fodder under scientific management of fodder banks, which will supplement and serves adequate nutrition to improve the production.

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GIS and Remote Sensing in Rangeland Monitoring

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ABSTRACT*:* *Indian grasslands are vital socio-economic and ecological assets, supporting the livelihoods of approximately 70% of the rural population through animal husbandry. Despite maintaining a livestock population of over 535 million, the sector faces a significant "efficiency gap," characterized by low milk yields and a chronic shortage of quality feed. Traditional ground-based monitoring methods have proven insufficient for capturing the spatial heterogeneity and rapid ecological changes of these vast rangelands. This chapter explores the paradigm shift toward advanced technological frameworks for grassland monitoring. By integrating multi-platform Remote Sensing (RS), Geographic Information Systems (GIS), and Unmanned Aerial Vehicles (UAVs), managers can now achieve near real-time assessments of biomass, sward height, and forage quality. Furthermore, the deployment of In-Situ IoT devices, on-harvester sensors, and NIR spectroscopy provides granular data necessary for precision yield mapping. These hardware solutions are increasingly enhanced by Artificial Intelligence (AI) and Machine Learning (ML) algorithms that automate crop classification, stress detection, and predictive modeling. Ultimately, these technologies facilitate a proactive management framework that addresses overgrazing and land degradation while ensuring national fodder security.*

Key words*:* Remote Sensing (RS), Geographic Information Systems and Monitoring

1. Introduction

India's grasslands are vast, dynamic ecosystems that represent a profound intersection of ecological health and economic stability. Occupying a central role in the national agrarian landscape, these rangelands form the bedrock of animal husbandry that supports the livelihoods of approximately 70% of the rural population. Beyond their economic utility, these ecosystems are critical biodiversity hotspots that have evolved under diverse bioclimatic conditions, harbouring unique flora and fauna and serving as significant terrestrial carbon sinks. However, the equilibrium of these "unassuming giants" is under severe threat. The convergence of direct grazing pressures and indirect anthropogenic influences, such as land-use conversion and invasive species, has triggered a cycle of degradation. Effective conservation is no longer possible through traditional means alone; there is now a strategic imperative to adopt advanced geospatial technologies to ensure accurate, large-scale, and near real-time monitoring. The value of Indian grasslands is best understood through the lens of the livestock sector. India maintains a staggering livestock population of over 535.78 million animals, contributing more than 4% to the national GDP (Ministry of Fisheries, Animal Husbandry and Dairying , 2019). Despite these impressive numbers, a critical efficiency gap persists:

- Yield Disparity: The average milk yield per cow in India is approximately 4.87 kg, significantly lower than the global average of 7.2 kg (Singh et al., 2023).
- The Nutritional Deficit: This underperformance is primarily attributed to a chronic shortage of quality feed. Current estimates indicate a shortfall of 11.24% in green forage and 23.4% in dry forage.
- Grazing Pressure: Remote sensing studies reveal intense stocking rates, reaching as high as 3.17 Adult Cattle Units (ACU) per hectare in states like Himachal Pradesh far exceeding the sustainable carrying capacity of typical rangelands (Roy & Singh, 2021).

Table 1: India's Annual Fodder Resource Base

Source	Area (Million Ha)	Dry Matter (MMT)	Contribution (%)
Rangelands/Pastures	11.5	37	23%
Cultivated Fodder	9.0	123	77%
Total	**20.5**	**160**	**100%**

(Singh *et al.,* 2023)

2. Evolution of Monitoring Methodologies

The discipline of grassland assessment has undergone a profound paradigm shift, transitioning from localized, labor- intensive field plots to high-frequency, multi-sensor satellite surveillance. Historically, the foundational understanding of India's rangelands relied upon traditional "Pace Transect" methods and reconnaissance surveys, most notably the landmark national survey conducted between 1954 and 1962. While these ground-based efforts

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provided essential baseline data, they were fundamentally limited by their inability to capture the immense spatial heterogeneity of the Indian landscape, their poor repeatability for seasonal monitoring, and the prohibitive requirements for manpower and time. Consequently, these static, point-in-time snapshots struggled to keep pace with the rapid ecological changes occurring across the subcontinent. The technological leap toward Geographic Information Systems (GIS), Global Positioning Systems (GPS), and Remote Sensing (RS) began in earnest during the 1990s, spearheaded by the ICAR–Indian Grassland and Fodder Research Institute (ICAR-IGFRI). This era marked a transition from physical measurement to digital observation, utilizing satellite platforms ranging from the early IRS-1A/1B series to the sophisticated Resourcesat-2. Today, current mapping standards utilize national mosaics generated from AWiFS imagery at a 56m resolution. By applying the Normalized Difference Vegetation Index (NDVI) alongside supervised classification algorithms, researchers can now quantify biomass and map grassland extent with unprecedented accuracy. Furthermore, the integration of advanced sensors like Sentinel-1 Synthetic Aperture Radar (SAR) represents the latest frontier in rangeland monitoring. Unlike traditional optical sensors that are often hindered by India's heavy monsoon cloud cover, SAR provides all-weather, high-frequency data. This capability allows for consistent, year-round assessments of vegetation health and soil moisture, offering a robust solution to the limitations of historical methodologies and ensuring a more resilient framework for national fodder security (Rapiya et al., 2025).

3. Drivers of Degradation and the Role of Precision Agriculture

Despite their ecological and economic significance, Indian grasslands are currently besieged by multifaceted threats that jeopardize their long-term viability. The most pervasive of these is chronic overgrazing, where livestock consumption rates drastically outpace natural biomass regeneration, leading to severe soil compaction and loss of palatable species. This is compounded by systematic encroachment, as vast tracts of rangeland are converted into intensive croplands or industrial zones to meet the needs of a growing population. Furthermore, biological invasions most notably the rapid proliferation of *Prosopis juliflora*, have fundamentally altered ecosystem structures, displacing indigenous forage and reducing the quality of available grazing land. These pressures are further exacerbated by habitat fragmentation; the expansion of infrastructure and the emergence of rampant landfills have disrupted traditional migratory grazing routes, forcing livestock into smaller, already-depleted

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areas. To mitigate these systemic threats, Precision Agriculture (PA) offers a sophisticated, data-driven pathway to bridge the national forage gap. By leveraging ISRO's Bhuvan Geoportal, land managers can now monitor Land Use/Land Cover (LULC) changes in near real-time, providing the necessary intelligence for proactive intervention (NRSC, 2024). This technological framework facilitates Variable-Rate Application (VRA), which optimizes the delivery of water and nutrients based on the specific requirements of localized soil patches identified through GIS analysis. Additionally, geospatial tools enable "hotspot identification," pinpointing low-productivity rangelands within specific Agro-climatic Zones that require urgent ecological restoration. By quantifying the forage resource base at a granular level, these technologies foster seamless value chain integration, informing strategic investments in the dairy, meat, and feed sectors. Ultimately, the transition from static, point-in-time surveys to dynamic, continuous monitoring represents a landmark evolution in grassland science. By integrating Remote Sensing and GIS, India is moving toward a proactive management framework that successfully balances the intense demands of the livestock sector with the vital necessity of ecological preservation.

4. Advanced Technological Frameworks for Rangeland Monitoring

Modern rangeland management relies on a hierarchical approach to data collection. By integrating multi-platform remote sensing with ground-based IoT (Internet of Things) technologies, researchers can achieve a comprehensive understanding of ecosystem health across varying spatial and temporal scales. There are various Remote Sensing Approach:

4.1 Satellite-Based Earth Observation (EO):

Satellite platforms provide the longitudinal data necessary for regional monitoring and historical trend analysis.

- **Multispectral Imagery (e.g., Sentinel-2):** Publicly accessible high-revisit data (5 days) from ESA (European Space Agency) is instrumental for calculating the Leaf Area Index (LAI), tracking phenological transitions and biomass of the crop though the NDVI index. When integrated with Radiative Transfer Models (RTM), these data points facilitate the modeling of gross primary productivity.
- **Synthetic Aperture Radar (SAR) (e.g., Sentinel-1):** Unlike optical sensors, SAR backscatter penetrates cloud cover, allowing for all-weather monitoring. This is particularly

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effective for detecting biomass removal events, such as mowing or intensive grazing, which are critical indicators of land-use intensity.

- **Spaceborne LiDAR:** Light Detection and Ranging (LiDAR) provides 3D structural data. By measuring vegetation height and canopy density, LiDAR serves as a robust input for volumetric biomass estimation models.

4.2 Unmanned Aerial Vehicles (UAVs):

UAVs, or drones, bridge the "scale gap" between satellite observations and ground-truth data.

- **High-Resolution Mapping:** UAVs deliver millimeter-to-centimeter scale imagery, enabling field-level sward heterogeneity mapping.
- **Sensor Payload Versatility:** Equipped with RGB, multispectral, or hyperspectral sensors, UAVs can identify localized nutrient deficiencies, water stress, and species-specific health markers that exceed the spatial resolution of current satellite constellations.

4. 3. In-Situ and Proximal Sensing Systems: Ground-based technologies provide the calibration and real-time precision necessary for operational decision-making in forage production.

- **Proximal Sensors and IoT Integration**
- Internet of Things (IoT) devices deployed in-field offer high-frequency data on forage quantity and animal-environment interactions.
- **Rising Plate Meters (RPMs):** Measure grass height to estimate forage biomass. They provide rapid, on-the-spot assessments of available forage, supporting grazing and stocking decisions (Fig 1.).
- **Livestock Telemetry:** Smart collars and wearable IoT devices monitor animal behavior and movement patterns, allowing managers to map grazing pressure and optimize pasture utilization (Fig 2.).

Fig.1. Rising Plate Meters

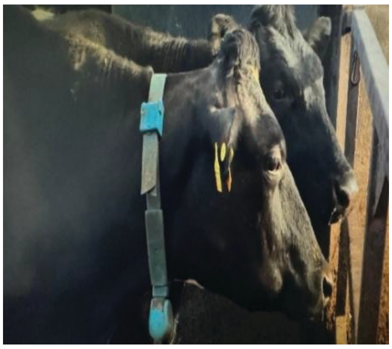

Fig. 2. Smart Collars

4. 4. On-Harvester Sensing and Precision Yield Mapping:
Real-time data acquisition during harvest operations is essential for identifying spatial variability in forage yield and quality.
4.4. 1 Mass and Volume Flow Measurement: These sensors are crucial for creating detailed yield maps. By continuously measuring the weight and speed of crop material as it moves through the harvester, they quantify the real-time yield, revealing high- and low-performing zones within a field. Shinners *et al*. 2024 used a self-propelled forage windrower machine on forage cutting, equipment, with a prediction accuracy of R^2 = 0.83–0.90. These sensors form the basis for high-resolution yield mapping and identification of spatial variability in forage production.
4.4.2 Volume flow sensors and impact sensors: Volume flow sensors measure the flow rate of harvested biomass based on the movement speed of crop material through the harvester. Volume flow depends on crop thickness, growth conditions, and machine operation. Volume alone does not represent true yield; mass density and moisture content must also be considered. Accurate estimation requires integration of flow speed, moisture content, harvester speed and cutting width Impact sensors estimate biomass flow by measuring the force exerted by crop material striking an impact plate. This force measurement is then calibrated to accurately quantify the crop's mass flow rate.

5. Forage Quality and Moisture Analysis

Accurate determination of dry matter (DM) content is essential for silage quality assessment and yield estimation.

- **Moisture Sensors**: Capacitance, microwave, and Near-Infrared (NIR) sensors provide continuous, on-the-go moisture measurements, eliminating labor-intensive oven-drying methods.
- **Near-Infrared (NIR) Spectroscopy**: NIR sensors enable real-time assessment of both moisture and forage quality parameters, including:
  - Protein
  - Fiber
  - Starch

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NIR systems mounted on self-propelled forage harvesters have been widely adopted and validated for real-time estimation of moisture and DM yield.

6. Computational Analytics: AI and Machine Learning

The transformation of raw sensor data into actionable intelligence is driven by Artificial Intelligence (AI) and Machine Learning (ML) algorithms.

a. **Crop Classification:** Algorithms such as **Random Forest (RF)** utilize unique spectral signatures and phenological cycles to distinguish between forage species, such as Alfalfa (*Medicago sativa*), Clover, and small grains like Oats.

b. **Deep Learning for Stress Detection:** Advanced Neural Networks scan high-resolution UAV imagery to automate the identification of invasive species or localized pathological outbreaks.

c. **Predictive Modeling:** By synthesizing historical climatic data with real-time sensor inputs, ML models forecast seasonal yields, providing stakeholders with critical lead time for resource allocation.

d. **Spatiotemporal Change Detection:** AI-driven analysis of multi-temporal satellite imagery facilitates the monitoring of land-cover conversion, aiding in the conservation of permanent grasslands against urban encroachment or agricultural intensification.

framework will balance the nutritional demands of over 535 million livestock with vital ecological preservation.

Table.2 Technological Frameworks for Grassland Monitoring and Biomass Estimation

Category	Technologies/ Methods	Key Applications	Advantages	Challenges/Limitations
Remote Sensing & UAVs	Satellite (Sentinel-2), UAV multispectral imaging	Biomass, forage quality, canopy characteristics, grass height, dry matter yield	High coverage, precise estimation via ML integration (e.g., random forest, CNNs)	Spectral similarities in mixed grasslands; NDVI limitations
LiDAR & Laser Scanning	Terrestrial, airborne LiDAR	Plant height, structure, canopy volume	Accurate 3D structure capture	High cost, complexity in data processing

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Category	Technologies/ Methods	Key Applications	Advantages	Challenges/Limitations
		(horizontal/vertical)		
Hyperspectral & Photogrammetry	Hyperspectral sensors, aerial photogrammetry, spectral unmixing (e.g., super-pixel segmentation, Sentinel-2 fusion)	Dry matter (DM), nitrogen content, and sward heterogeneity delineation	Species differentiation in mixed grasslands: biomass cover estimation	Data processing intensity requires hyperspectral imaging
On-Harvester & Machine-Mounted Sensors	Load cells, mass flow/impact sensors, capacitance oscillators (on SPFHs); John Deere HarvestLab™ (with GPS); pendulum/forage-throughput sensors	Real-time biomass flow, moisture, mass flow	On-the-go accuracy; yield mapping integration	Calibration needs: machine-specific
Windrower, Mower, Baler & Wagon Methods	Constant weighing (windrowers), torque/pressure (mowers), curved plate sensors; bale-weighing + GPS; wagon silage mapping	Biomass estimation, yield maps	Practical for harvesting operations	Environmental variability affects accuracy
Feed Roller & Silage Chopper Sensors	Spring force measurement on feed rollers	Biomass during harvesting	Direct integration in choppers	Limited to specific machinery

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Category	Technologies/ Methods	Key Applications	Advantages	Challenges/Limitations
NIR Spectroscopy & Field Methods	Portable field spectrometers, on-harvester NIR; transfection for liquids	Moisture, DM crude protein fiber (NDF/ADF/ADL), lipids; fodder quality (e.g., switchgrass, Napier grass, soybean)	Rapid, non-destructive, in situ; ML-enhanced (e.g., neural networks)	Calibration essential (species-specific, dried/ground samples); moisture/temperature interference; overfitting; yearly retraining
Machine Learning & Predictive Modeling	Random forest, neural networks, SVM, gradient boosting; integrated with optical/SAR (Sentinel-1/2), UAV data	Biomass, height, yield, mowing frequency, management intensity (intensive vs. extensive)	High accuracy; distinguishes land use/environmental impact	Large datasets needed; model robustness
Decision Support Systems (DSS)	Crop-modeling DSS integrating N fertilizers, defoliation, species, weather; remote sensing (S1/S2/Landsat-8) + ML/regression	Grazing rotation, fertilization, LAI/biomass, nutrient/pest/livestock management	Timely precision management; simulation of regimes	Low adoption due to cost/complexity; needs farmer training

17. Conclusion

The transition from traditional, labour-intensive field surveys to advanced multi-sensor frameworks represents a pivotal shift in India's ability to manage its vast rangeland resources. While current technologies ranging from Sentinel-1 SAR for all-weather monitoring to AI-driven predictive modelling provide unprecedented accuracy in estimating biomass and forage quality, their full potential remains untapped due to adoption barriers. To bridge the chronic

11.24% green forage deficit and restore ecosystems besieged by overgrazing and invasive species, strategic policy intervention is essential. Policymakers should prioritize the institutionalization of a "National Fodder Intelligence System" using the Bhuvan Geoportal for near real-time tracking. Furthermore, the government must incentivize the adoption of precision hardware, such as on-harvester NIR sensors and smart livestock telemetry, through subsidies to dairy cooperatives. Addressing the low adoption of Decision Support Systems (DSS) requires targeted digital literacy programs for extension workers. Finally, by leveraging high-resolution UAV mapping to target invasive removal and enforcing carrying capacities derived from LiDAR and SAR data, India can move toward a proactive management framework. Integrating these tools into a formal policy

References

Ministry of Fisheries, Animal Husbandry & Dairying. (2019). *20th Livestock Census-2019: All India Report*. Department of Animal Husbandry and Dairying, Government of India.

National Remote Sensing Centre [NRSC]. (2024). *Thematic services and land use land cover (LULC) mapping: Third cycle technical document*. ISRO Bhuvan Geoportal.

Rapiya, S., et al. (2025). Sentinel-1 SAR as a tool for forage productivity assessment in rangeland ecosystems. *Journal of Applied Geomatics* (In Press).

Roy, A. K., & Singh, J. P. (2021). Grasslands in India: Current status, challenges and future strategies for management. *Indian Journal of Grassland and Fodder Research*, 27(1), 1–15.

Singh, V. K., et al. (2023). *Status of Fodder Resources in India: National Assessment and Strategic Framework*. ICAR-Indian Grassland and Fodder Research Institute (IGFRI).

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