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Climate Change–Land Use–Biodiversity Nexus
Impacts and Policy Pathways

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by

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Preface

This Policy Paper is an initiative under the India International Centre (IIC) Sectoral Policy Group on Science and Technology (S&T) to create awareness on contemporary S&T issues relevant to the society. IIC has established several Sectoral Policy Groups (SPGs) to address critical policy concerns across diverse domains. Among these, the SPG–S&T focusses on fostering awareness and informed discourse on contemporary challenges at the science-policy interface.

This Policy Paper explores the linkages of climate change and its effects on land use and land cover (hereafter LULC), biodiversity and agrobiodiversity and the interplay between these are explained in detail chapter-by-chapter. The paper was developed after extensive expert discussions, stakeholder consultations and detailed literature review, and suggests policy level changes as well as sustainable solutions to tackle the issues mentioned. The introductory chapter provides a comprehensive understanding of the issue at hand, the key points of concern and policy gaps, as well as an overview of the extensive discussions carried out to prepare this Policy brief.

The second chapter explains climate change in detail and how it affects the LULC, biodiversity and agrobiodiversity. The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as the change that can be attributed 'directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods. Human activities since the 19th century have drastically increased the atmospheric concentration of greenhouse gases (GHGs), particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These emissions, driven primarily by the burning of fossil fuels, deforestation, and land use changes, have led to a marked rise in global temperatures. The Intergovernmental Panel on Climate Change (IPCC) attributes a 1°C increase in global surface temperatures over the past 150 years to anthropogenic activities. The resulting impacts include glacier-melting, sea level rise, altered temperature and precipitation patterns, and an uptick in extreme weather events. Regional effects, compounded by factors like air pollution and land use changes, are particularly pronounced in a diverse country like India, where vulnerable populations in urban and rural areas face significant challenges. India's climate has witnessed notable changes, with a 0.7°C rise in average temperatures between 1901 and 2018. Over the past six decades, summer monsoon precipitation has declined by approximately 6 per cent, particularly affecting the Indo–Gangetic Plains and Western Ghats. This decline has heightened drought risks and disrupted monsoon patterns, while extreme weather events, such as cyclones, have intensified. The impact of climate change on the availability of fresh water is a critical area of concern for India. Continued global warming through the 21st century, together with the high probability of future reductions in anthropogenic aerosol emissions from North America, Europe and Asia, will likely intensify summer monsoon precipitation and its variability over India. For policymakers, it is important to have a clear, comprehensive view of possible climate change projections. Climate models are often used to project how the world might change in response to scenarios in the future. These models have proven to be reasonably accurate in simulating the climate change that has been experienced so far. The projections indicate a continuation of human-induced climate change during the 21st century and beyond. Climate change simulations, however, may have uncertainties. The largest uncertainty in these projections is the level of GHG emissions in the future. Climate models, like the Indian Institute of Tropical Meteorology Earth System Model (IITM-ESM) contributing to Coupled Model Intercomparison Project Phase 6 (CMIP6) and IPCC's Sixth Assessment Report (AR6), emphasise the need for robust data collection and policy-driven interventions to address uncertainties in future projections. If current GHG emissions persist, the global average temperature could rise by 5°C or more by the end of the 21st century. Emissions of GHGs, aerosols and changes in LULC during the industrial period have substantially altered the atmospheric composition, and consequently the planetary energy balance, that are primarily responsible for the present-day climate change. A detailing of the cause and effects of climate change can be found in Chapter 1.

The third chapter explains the LULC, drivers, impacts and how it changes with anthropogenic activities. Land use and land cover changes are significant drivers of environmental transformations, influencing ecological systems and contributing to climate change. Land cover, which includes vegetation, water bodies and human-made structures; and land use, which pertains to human activities on these lands, are crucial for understanding environmental impacts. Land cover plays a vital role within the United Nations (UN) framework, as it directly impacts sustainable development, climate change mitigation, biodiversity conservation, food security and disaster risk reduction. Recognised as one of the 14 fundamental data themes, land cover shapes ecosystems and influences both human and natural systems, making sustainable land management and the preservation of terrestrial ecosystems essential for meeting the Sustainable Development Goals (SDGs). These changes, coupled with deviations in climatic conditions, impact ecosystems, biodiversity and agricultural productivity. Tools like remote sensing and field surveys play pivotal roles in monitoring LULC changes over time, enabling better resource management and sustainable practices. LULC policies are necessary to ensure that land is used in a way that supports sustainable development, environmental preservation and resource management. These policies influence and define how land is used to find the proper equilibrium between economic growth, social welfare and environmental protection. In fact, effective LULC policies and instruments are necessary to cope with intensifying challenges like urbanisation, deforestation, agricultural expansion, food security and climate change. They are critical for balancing competing claims on land, promoting sustainable development and protecting the environment. LULC policies not only provide a framework for land use practices but also have the potential to reverse some of humanity's worst missteps. Chapter 2 goes into details of the same.

The fourth chapter gives a comprehensive overview of biodiversity and its components. The term 'biodiversity', derived from 'biological diversity', signifies the diversity of life on Earth across all levels, ranging from genetic variation to ecosystems. It also encompasses the evolutionary, ecological and cultural processes that support and sustain life. Biodiversity is a critical component for ecosystem stability and human well-being. The chapter gives a glimpse of hierarchical components of biodiversity such as genetic diversity, species diversity and ecosystem diversity. The characteristics and classifications of flora and fauna are detailed, highlighting their importance in understandings biodiversity, monitoring ecosystem health, and guiding conservation strategies. This section offers a thorough exploration of ecosystem services, their significance and the challenges involved in their preservation and valuation. Policies that promote sustainable land use, pollution control and biodiversity conservation are vital. The IPCC and the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES) emphasise the need for integrated policies that address both issues simultaneously. International agreements such as the Convention on Biological Diversity (CBD) and the Paris Agreement on climate change underscore the global commitment to protecting ecosystem services. Chapter 3 also explains the consequences of biodiversity loss and mitigation strategies.

In the fifth chapter, threats to agrobiodiversity are explained. Agrobiodiversity encompasses the rich biological diversity within agricultural ecosystems. It is a subset of biodiversity within agricultural systems that underpins food security, ecosystem services and cultural heritage. In a global perspective, agrobiodiversity encompasses the worldwide distribution and human utilisation data for all plants, major crops, and their associated wild relatives. Agrobiodiversity has served as the foundation for the development of agricultural systems over millennia. India, with its vast agroclimatic diversity, is a global hotspot for agrobiodiversity, hosting numerous traditional crop varieties and farming systems. Sustainable agricultural practices, bolstered by Payments for Agrobiodiversity Conservation Services (PACS), encourage the preservation of genetic resources critical for food security and climate adaptation. Despite challenges like monoculture dependence, traditional knowledge and community-led initiatives offer pathways for enhancing agricultural resilience and sustainability. The future of agrobiodiversity lies in its ability to create a harmonious balance between productivity, sustainability and equity. By integrating traditional wisdom with modern innovation, fostering community-led initiatives, and strengthening policy frameworks, we can transform agrobiodiversity into a powerful tool for ecological stability, food security, and socio-economic development. The choices we make today will determine whether agrobiodiversity becomes a legacy of abundance or a memory of what was lost.

The sixth chapter details the policy frameworks in place. The framework addressing climate change impacts on LULC, biodiversity and agrobiodiversity is shaped by international agreements, national strategies and regional policies aimed at sustainable land management, conservation and climate adaptation. The interplay of these three factors highlights the need for integrated approaches to address global challenges like sustainability, migration and resource degradation. Revamping land use planning, informed by policies like the National Land Use Policy (NLUP) and National Forest Policy (NFP), is crucial for sustainable development. The institutions like the National Land Use and Conservation Board (NLUCB) play a vital role in guiding national strategies. Global initiatives such as the UNFCCC, the CBD, and the SDGs guide nations in integrating climate considerations into land and biodiversity policies. Similarly, policies promoting agrobiodiversity emphasise the conservation of traditional crop varieties, sustainable farming practices, and genetic resource management to enhance food security in changing climatic conditions. Effective implementation requires interdisciplinary collaboration, scientific research and community engagement to balance development with ecological sustainability.

The seventh chapter examines the international protocols and policy frameworks in place and their significance with respect to the SDGs. It also details how programmes and activities within their ambit need to be aligned to these Goals. In addition, the need for public–private partnerships to drive these initiatives has also been outlined.

Chapter eight summarises key policy recommendations. Drawing upon interdisciplinary insights and ground-level experiences, a set of actionable policy recommendations have been developed, which are aimed at strengthening climate resilience, promoting sustainable land governance, conserving biodiversity and enhancing agrobiodiversity systems. These proposals serve as a roadmap for aligning national strategies with global environmental commitments while ensuring local relevance and community participation.

The final chapter charts the way forward. To tackle the impact of climate change on land use, biodiversity and agriculture, we need a well-rounded approach that combines science, policy and community action. Protecting ecosystems, promoting sustainable land management and adopting climate-smart farming methods are key steps. By aligning policies, leveraging technology and involving local communities, we can build resilience and ensure a sustainable future for both nature and people. Policy coherence at national and international levels, aligned with frameworks like the Paris Agreement and the CBD, will be key in driving effective climate action. Equally important is community participation—empowering local stakeholders, indigenous groups, and farmers through education, capacity building and financial incentives will ensure long-term sustainability. By combining science-driven strategies, policy interventions and grassroots engagement, we can build resilience against climate change while promoting sustainable development.

This Policy Paper gives a detailed analysis of the critical components of the climate change–land use–biodiversity nexus, highlighting their interplay and impact as well as outlining the suggested policy frameworks and the way forward.

RENU SWARUP

Climate Change–Land Use–Biodiversity Nexus
Impacts and Policy Pathways

RENU SWARUP, PARTH SARATHI ROY, SWATI BASU, SANJAY KUMAR, RESHMA M.R.

1. INTRODUCTION

India stands at the confluence of ecological richness and developmental urgency, where the interplay of climate change, land use dynamics, biodiversity loss and agricultural transformation poses an unprecedented policy challenge. Rapid urbanisation, shifting land cover and ecosystem degradation—exacerbated by climate variability—demand holistic responses that transcend sectoral boundaries. With this in mind, a high-level scientific and policy dialogue facilitated by the India International Centre's Sectoral Policy Group (SPG) on Science and Technology was organised. This paper offers a scientific overview of the dialogue to provide an integrated policy-scientific framework, synthesising impacts, feedbacks and strategic interventions needed to secure India's future.

1.1 Why the Interplay of Land Use, Biodiversity and Agrobiodiversity Matters in a Climate Change Scenario

In the era of accelerating climate change, the interplay between land use, biodiversity and agrobiodiversity has become critically important for sustaining ecological balance, ensuring food security, and enhancing climate resilience. Land use change, through deforestation, urban expansion, intensive agriculture and infrastructure development, has been identified as one of the principal anthropogenic drivers of climate change (IPCC, 2022). These alterations contribute significantly to greenhouse gas (GHG) emissions by reducing carbon sequestration capacities of natural ecosystems and increasing emissions from land degradation (Foley et al., 2005). The loss of forests and soil carbon stocks exacerbates atmospheric CO_2 concentrations, while unsustainable land practices accelerate erosion, reduce water retention, and increase vulnerability to floods and droughts (Lal, 2004).

Biodiversity plays a foundational role in maintaining ecosystem functionality and resilience under climate stress. Rich species diversity improves the ability of ecosystems to absorb shocks such as extreme weather events, diseases and invasive species (Hooper et al., 2005). However, biodiversity is increasingly threatened by shifting climatic zones, habitat fragmentation and altered phenological patterns (Parmesan, 2006). The resulting ecological simplification weakens key services such as pollination, nutrient cycling, pest regulation and carbon storage—many of which are critical buffers against climate change impacts (Cardinale et al., 2012). Moreover, the decline of biodiversity reduces nature's capacity to support human well-being, livelihoods and sustainable development, particularly in regions where communities are closely dependent on natural ecosystems.

Agrobiodiversity, the genetic and species-level diversity within agricultural systems, is essential for climate-resilient food production. It provides a broad gene pool that enables crops and livestock to adapt to changing climatic conditions, pests and diseases (Frison et al., 2011). Traditional agricultural practices, especially those of indigenous and smallholder farmers often maintain a rich diversity of plant and animal species, contributing to both environmental sustainability and cultural heritage. Yet, climate change is altering agroecological zones, shortening growing seasons, and intensifying biotic stresses, thereby increasing the reliance on agrobiodiversity for crop adaptation and productivity stability (Jarvis et al., 2011). The erosion of this diversity, due to market-driven monocultures and neglect of local varieties, reduces adaptive capacity and increases vulnerability.

The interlinkages among land use, biodiversity and agrobiodiversity form complex feedback loops that either reinforce resilience or compound vulnerabilities. For instance, biodiversity loss can reduce soil fertility and productivity, leading to land abandonment or conversion pressures elsewhere (Tscharntke et al., 2012). Conversely, land degradation can force shifts to marginal lands, increasing pressure on remaining biodiversity. Sustainable land management approaches such as agroforestry, conservation agriculture, and integrated landscape planning can create co-benefits by conserving biodiversity, improving soil and water retention, and sequestering carbon (Pretty et al., 2006). These approaches are aligned with global climate and biodiversity agendas, including the UNFCCC's Nature-based Solutions (NbS) and the CBD's post-2020 Global Biodiversity Framework.

1.2 Policy Gaps and the Need for a New Framework

Despite increasing recognition of the climate–biodiversity–agriculture nexus, current policy frameworks often remain fragmented, with land use planning, biodiversity conservation, and agricultural development governed by separate ministries, regulations, and strategies. This sectoral approach leads to conflicting objectives, such as promoting food security through intensive monoculture while simultaneously aiming to protect biodiversity and reduce emissions. Biodiversity strategies rarely integrate agrobiodiversity concerns, while land use plans often prioritise short-term economic gains over long-term ecological sustainability. Similarly, climate policies tend to emphasise energy transitions but neglect land-based emissions, which account for nearly 24 per cent of global GHG emissions (IPCC, 2022). Additionally, data and institutional limitations constrain evidence-based decision-making. In many emerging economies, spatial monitoring of biodiversity and agrobiodiversity remains weak, land use records are outdated or misclassified, and coordination mechanisms across governance levels are not effectively developed (Chaudhuri & Roy, 2021). There is a lack of mainstreaming of climate resilience into local governance, resulting in missed opportunities to integrate nature-based adaptation strategies. To address these gaps, an evolving policy framework must adopt a systems-based approach, recognising the mutual interdependence of land, biodiversity and agrobiodiversity. Key features of such a framework include:

- Integrated land use and biodiversity governance, guided by ecological zoning, ecosystem service mapping, and landscape-level planning;
- Agrobiodiversity mainstreaming in agricultural and climate policies, promoting in-situ and ex-situ conservation, seed banks, and community-based knowledge systems;
- Climate-resilient agricultural landscapes, supported by incentives for agroecological practices, diversified cropping systems, and restoration of degraded lands;

- Cross-sectoral policy platforms to align actions under climate change (National Adaptation Plans/Nationally Determined Contributions), biodiversity (National Biodiversity Strategies and Action Plans), and agriculture (food and nutrition security programmes);
- Investment in geospatial and remote sensing tools to monitor land degradation, ecosystem change and biodiversity status at appropriate scales (Walther, 2010).

Such a framework must also embed local participation, equity, and indigenous knowledge systems to ensure that climate responses are not only ecologically sound but also socially just and culturally appropriate. By bridging disciplinary and institutional divides, countries can strengthen their capacity to design and implement adaptive, inclusive and nature-based climate policies.

1.3 Intersectoral Dialogue

This policy document is the outcome of an interdisciplinary collaboration initiated and developed under the aegis of the India International Centre's S&T Policy Group. It draws upon rigorous peer engagement and critical review by three of India's leading experts in climate science, biodiversity and sustainable land management. The core content was deliberated at a high-level seminar on '*Climate Change: Land Use & Land Cover and Biodiversity—Interplay, Impact, Policy Framework and Way Forward*', hosted on 9 April 2025. The seminar served as a catalytic platform to integrate scientific insights and policy perspectives spanning climate science, land governance, biodiversity and agriculture and underscored the growing interdependencies between climate change, land use dynamics, and biodiversity conservation. The dialogue featured two thematic panels:

- Panel I addressed the climate–land use–biodiversity–agrobiodiversity nexus.
- Panel II explored policy frameworks to respond to these interlinked challenges.

The seminar brought together distinguished experts and institutional representatives from across India, including the Indian Council of Agricultural Research (ICAR), Indian Institute of Technology, (IIT) Delhi, National Centre for Medium Range Weather Forecasting (NCMRWF), India Meteorological Department (IMD), Jawaharlal Nehru University (JNU), The Energy and Resources Institute (TERI), TERI School of Advanced Studies (TERI-SAS), World Resources Institute–Food and Land Use Alliance (WRI), Council on Energy, Environment and Water (CEEW), and ICLEI–South Asia, among others. Through detailed presentations and interactive discussions, the seminar generated actionable insights for developing integrated, climate-resilient policy frameworks. The outcomes and deliberations directly shaped the core findings and recommendations of this paper, promoting cross-sectoral governance and adaptive strategies essential for India's climate and environmental future.

2. CLIMATE CHANGE: HUMAN DRIVERS AND PLANETARY CONSEQUENCES

Since the 19th century, human activities—particularly the burning of fossil fuels, deforestation and land use changes—have led to a significant increase in GHG emissions. Atmospheric carbon dioxide (CO_2) concentrations rose from about 280 ppm in 1850 to over 416 ppm by 2020. This anthropogenic forcing has unequivocally driven global surface warming of approximately 1°C over the past 150 years, as established by successive IPCC assessments. This warming has triggered large-scale environmental changes, including glacier retreat, sea level rise, shifts in precipitation, and increased frequency of extreme weather events. Future scenarios suggest further amplification of these trends, contingent upon emissions trajectories. While global changes are well-identified, regional climate responses—especially over countries like India—are shaped by a mix of GHG forcing, local pollution, and land use dynamics, necessitating enhanced regional observations and modelling.

2.1 Climate Change in India: Observed Trends and Projections

Temperature and Heat Extremes

India has warmed by approximately 0.7°C between 1901 and 2018, largely due to GHGs, tempered by aerosols and land cover change. Projections under high-emissions scenarios (RCP8.5) indicate a rise of approximately 4.4°C by 2100. The Hindu Kush Himalaya (HKH) region has already experienced a warming of 1.3°C since the mid-20th century, with projections indicating up to 5.2°C warming by the end of the century. These changes will intensify heatwaves, reduce cold extremes and exacerbate thermal stress on health, agriculture, and infrastructure (Krishnan et al., 2020).

Rainfall and Monsoon Dynamics

India's monsoon rainfall declined by approximately 6 per cent between 1951 and 2015, mainly over the Indo-Gangetic Plains and Western Ghats. This has been linked to aerosol pollution suppressing convection. However, the frequency of extreme rainfall events has increased. Model projections suggest more intense rainfall and a lengthened monsoon season due to enhanced moisture availability and warming, but with higher variability. Central India has already seen a 75 per cent rise in daily rainfall extremes above 150 mm/day since 1950 (Roxy et al., 2017).

Droughts and Water Stress

Drought frequency and severity have increased, particularly in central and southern India, with a 1.3 per cent rise per decade in affected areas. Climate models foresee a continued rise in drought events, driven by rainfall variability and increased evapotranspiration. These changes portend serious risks to food and water security.

Indian Ocean Warming and Sea Level Rise

Sea surface temperatures in the tropical Indian Ocean have risen by approximately 1°C (1951–2015), exceeding the global average. Ocean heat content has surged, especially post-1998. The North Indian Ocean has seen accelerated sea level rise, from roughly 1.5 mm/year historically to over 3.3 mm/year since 1993. By 2100, regional sea levels are projected to rise by about 300 mm under Representative Concentration Pathway (RCP)4.5, threatening coastal infrastructure, agriculture and freshwater systems (Krishnan et al., 2020).

Cyclones and Coastal Vulnerability

India's 7,500 km coastline faces growing threats from intensified tropical cyclones, driven by rising sea surface temperatures and climate-linked ocean changes. The frequency and strength of extremely severe cyclones, especially in the Bay of Bengal and the Arabian Sea, have increased, as seen with Cyclones Amphan (2020), Tauktae (2021) and Biparjoy (2023), which caused major human, ecological, and infrastructure damage. These events trigger storm surges, heavy rainfall and coastal flooding, leading to farmland salinisation, mangrove loss, and displacement. Rapid urban expansion in cities like Chennai, Mumbai and Visakhapatnam exacerbates this vulnerability by weakening natural buffers. Integrated coastal zone management—combining early warning systems, blue-green infrastructure, and mangrove restoration, is essential for long-term resilience.

Himalayan Region: The Climate Hotspot

The Indian Himalayan Region (IHR), often referred to as the 'Third Pole' is among the world's most ecologically fragile and climate-sensitive zones. Spanning 11 states and two union territories, the Himalayas are warming nearly twice as fast as the global average, triggering major shifts in glacial mass, hydrology, and ecosystem dynamics. Rapid glacier retreat is forming unstable glacial lakes, raising the risk of glacial lake outburst floods (GLOFs), landslides and flash floods. Altered snowfall and the upward shift of vegetation zones are disrupting traditional farming, threatening horticulture and stressing water supplies for millions downstream. The region's rich endemic biodiversity is increasingly at risk from habitat fragmentation, invasive species and climate change. Indigenous communities relying on alpine pastures, forests and mountain agriculture face growing vulnerability due to limited adaptive infrastructure and declining ecosystem services. Protecting the Himalayas requires tailored adaptation strategies, integrated watershed and forest governance, stronger transboundary coordination, and inclusion of traditional ecological knowledge in policy frameworks (Shrestha et al., 2019).

2.2 Climate Change Hotspots (Based on 100 Years of Climate Data)

India's diverse agroecological zones exhibit marked regional differences in climate change impacts. Long-term data (1901–2020) from IMD, Indian Institute of Tropical Meteorology (IITM) Pune, Indian Space Research Organisation (ISRO) and International Centre for Integrated Mountain Development

(ICIMOD) reveal multiple climate hotspots with regions experiencing above-average warming, altered rainfall, extreme events, and ecosystem stress, often coupled with high socio-economic vulnerability. The key hotspots include the Western and Eastern Himalayas, facing glacial retreat, biodiversity loss, and rising flood and landslide risks; the Indo-Gangetic Plains, with heatwaves, erratic rainfall, and groundwater stress; and the Central Indian Plateau, showing warming, forest degradation, and rainfed agriculture vulnerability. The Western Ghats and Eastern Coastal Region face floods, cyclone intensification and saline intrusion. The Sundarbans confront sea level rise and habitat degradation. Northeast India sees flood-prone monsoons and forest loss, while the arid West (Rajasthan and Gujarat) faces drought and declining farm viability. Major cities like Delhi, Mumbai, Chennai and Bengaluru are turning into urban heat island hotspots due to concrete expansion and ecosystem stress. These regions demand urgent, localised adaptation, ecosystem-based resilience, and integrated climate policies (Krishnan et al., 2020).

Climate Change Predictions for India by 2070 Using IPCC RCP Scenarios

Based on Intergovernmental Panel on Climate Change (IPCC) RCPs—which represent different GHG concentration trajectories—the Indian subcontinent is projected to experience significant climatic shifts by the 2070s. The scenarios most commonly analysed are RCP2.6 (low emissions), RCP4.5 (moderate stabilisation) and RCP8.5 (high emissions/business-as-usual). These pathways are used in Earth System and Regional Climate Models (e.g., CORDEX-SA, IITM-ESM, INCCA) and align with recent national assessments by IITM Pune, IMD and the Ministry of Earth Sciences (MoES, 2020).

Climate Change Projections for India by 2070

Based on IPCC RCP scenarios (RCP2.6, RCP4.5, and RCP8.5), the following paragraphs cover the seven thematic areas:

- **Temperature Rise:** By 2070, India is expected to witness a significant rise in average annual temperatures, with the extent of warming varying across the IPCC RCPs. Under the high-emission scenario RCP8.5, temperatures may rise by 4–5°C above the 1971–2000 baseline, especially in northwest and central India. Even under the moderate stabilisation scenario RCP4.5, warming of 2.5–3°C is projected, intensifying heatwaves across the Indo-Gangetic plains, Gujarat and interior Maharashtra. Urban centres such as Delhi, Nagpur and Ahmedabad are projected to face over 30 additional heatwave days annually. Night-time minimum temperatures are expected to rise faster than daytime maxima, contributing to persistent heat stress and lower recovery rates for vulnerable populations.
- **Monsoon and Rainfall Patterns:** Monsoonal rainfall is projected to become more erratic and intense by 2070. Under RCP8.5, the frequency of extreme rainfall events is expected to rise by 20–30 per cent, especially in central India, the Konkan coast and the North-East. Despite a projected increase in total rainfall in some regions, the number of rainy days will decline, leading to longer dry spells punctuated by short-duration deluges. This increased intra-seasonal variability could severely affect rainfed agriculture and water resource planning. Under RCP4.5, seasonal shifts and spatial dislocation of

the monsoon trough may occur, increasing the unpredictability of monsoon onset and withdrawal. These changes raise the risk of both flash floods and hydrological droughts within the same season.

- **Sea Level Rise and Coastal Impacts:** Sea level rise is a major threat for India's coastal regions by 2070. Projections indicate a global sea level increase of 0.8 to 1.0 metres under RCP8.5, with localised sea level rise in the Bay of Bengal and the Arabian Sea affecting cities like Mumbai, Chennai, Kochi and Kolkata. The Sundarbans, Gulf of Khambhat and coastal Odisha are particularly vulnerable to permanent inundation, saline intrusion, and cyclone-driven storm surges. Without adequate adaptation, tens of millions could be displaced from low-lying areas, especially in the Ganga–Brahmaputra–Meghna delta. Under RCP2.6, sea level rise may be limited to 0.3–0.45 metres, highlighting the benefits of mitigation.
- **Glacier Retreat and Himalayan Hydrology:** The Himalayan region is projected to undergo substantial glacial loss by 2070, especially under RCP8.5. Glaciers could lose up to 60–70 per cent of their volume, particularly in the western Himalayas. Initially, increased meltwater may lead to higher flows in rivers like the Ganga and Brahmaputra, but in the long run, flow will decline, affecting downstream water availability. The region also faces elevated risks of GLOFs, especially in Sikkim, Himachal Pradesh and Uttarakhand. These hydrological shifts could severely affect agriculture, hydropower generation and ecological stability across northern India and Bangladesh.

- **Agriculture and Crop Yields:** Indian agriculture will face major productivity losses due to climate change by 2070. Under RCP4.5 and 8.5, wheat yields in northern India are projected to decline by 15–25 per cent due to reduced chilling hours and increased heat stress during grain-filling stages. Similarly, maize and pulses in central India may suffer from shortened crop durations and soil moisture stress. Though CO_2 fertilisation may offer some temporary yield benefits for rice and other C_3 crops, these are likely to be offset by high temperatures, erratic rainfall and pest outbreaks. Crop calendars will need significant revision, and climate-resilient seed varieties and precision farming will be critical.
- **Water Resources and Droughts:** India's water security is expected to deteriorate significantly by 2070. Rising temperatures and shifting rainfall will reduce surface water availability in river basins like the Godavari, Krishna and Mahanadi by 10–40 per cent, especially under RCP8.5. Groundwater recharge will be hampered due to increased evapotranspiration and intense rainfall that limits infiltration. Semi-arid regions such as Bundelkhand, Vidarbha and Marathwada are projected to experience twice the current frequency of droughts. Per capita water availability will decline sharply, exacerbating inter-state water conflicts and threatening food and livelihood security across rural India.
- **Biodiversity and Ecosystem Disruption:** By 2070, India's biodiversity will face severe threats from shifting climate zones, habitat loss and altered species interactions. The

Himalayan and Western Ghats ecosystems—both global biodiversity hotspots—will experience upward migration of species and treelines, potentially leading to extinction of endemic flora and fauna. Coral reefs in Lakshadweep and the Gulf of Mannar may suffer bleaching under prolonged ocean warming. Mangrove ecosystems in the Sundarbans will be degraded by saline intrusion and coastal erosion. Invasive species such as *Lantana camara* (West Indian Lantana) and *Parthenium hysterophorus* (carrot grass) will likely expand their range, displacing native species and altering fire regimes.

2.3 Climate Modelling and Research Efforts in India

India's participation in global climate modelling has advanced through the development of the IITM-Earth System Model (IITM-ESM), contributing to CMIP6 and IPCC AR6. This model integrates atmospheric, oceanic, land surface, and sea ice components tailored to simulate regional phenomena like the monsoon (MoES, 2020). However, significant knowledge gaps remain, particularly in simulating convective processes, land-atmosphere interactions, and aerosol-cloud feedbacks. There is also a pressing need to better capture phase transitions in monsoon convection and understand the evolving El Niño–Monsoon relationship. Improving model resolution, enhancing observational networks, and advancing land–surface and ocean–atmosphere coupling are essential for refining projections and guiding adaptation strategies.

Impact, Policy Implications and Adaptive Pathways for India: Key Sectoral Impacts

- **Agriculture and Food Security:** Rising temperatures, erratic monsoons and increase in weather extremities threaten rain-fed agriculture, reduce crop yields, and increase risk to food systems. Droughts and floods will further destabilise agricultural productivity and rural livelihoods.

- **Water Resources:** Shifts in rainfall patterns and increased monsoon variability threaten both surface and groundwater availability. Reduced recharge, greater evapotranspiration and saline intrusion in coastal aquifers will intensify water insecurity.
- **Public Health:** Increased frequency of heatwaves and climate variability raises risks of heatstroke, cardiovascular disorders and vector-borne diseases like dengue and malaria. Urban heat islands and poor air quality compound these vulnerabilities.
- **Energy Infrastructure:** Rising cooling demands, climate-sensitive thermal power generation, and coastal vulnerability to sea level rise and cyclones threaten energy security. Inland thermal plants face water shortages, while coastal plants face flooding and storm surges.
- **Biodiversity and Ecosystems:** India's biodiversity hotspots, including the Western Ghats and the Himalayas, face rapid habitat shifts. Endemic species may not adapt fast enough, and ecosystems risk collapse from cascading events like cyclone-induced saline floods.
- **Policy-Relevant Insights:** The IPCC's Special Report emphasises that exceeding 1.5°C of warming will have disproportionately severe impacts on tropical nations like India. Climate projections indicate worsening scenarios unless rapid emission reductions are enforced. India must localise climate

strategies based on geography—mountains, coasts, arid zones—and integrate regional risk assessments into national plans.

2.4 Way Forward: Adaptation, Mitigation and Social Equity—Strategic Recommendations

A robust climate resilience strategy should advance high-resolution regional climate models, integrate satellite and in-situ data, and address urban risks like heat islands and floods. Strengthening water and agriculture involves rainwater harvesting, drought-resilient crops and sustainable groundwater use. Urban and coastal resilience requires heat-adaptive infrastructure, mangrove restoration and early warning systems. A low-carbon transition calls for phasing out fossil fuels, expanding renewables, improving public transport and adopting carbon pricing. Crucially, community-based approaches must empower vulnerable groups, enhance climate literacy and ensure equity-driven local adaptation.

India's climate trajectory will significantly influence its development path and global environmental stability. Climate change is already altering the subcontinent's weather systems, water cycles and ecosystems. Without robust adaptation, inclusive governance and low-carbon transitions, these shifts could deepen poverty, destabilise livelihoods, and erode long-term growth. *India must act decisively—with science, justice and resilience at the core of its climate strategy.*

3. LAND USE AND LAND COVER (LULC) DYNAMICS: INTERACTIONS WITH CLIMATE, BIOGEOCHEMICAL CYCLES, AND POLICY IMPLICATIONS

Land use and land cover (LULC) form the physical and functional footprint of anthropogenic and natural processes on Earth's surface. While 'land cover' refers to the observed physical characteristics of the land surface—such as forests, grasslands, water bodies, croplands, or built-up areas—'land use' captures the human dimensions, including agriculture, settlements, conservation, and industrial use. This distinction, though subtle, is vital in environmental monitoring and policy formulation. Understanding LULC dynamics is essential for tracking ecosystem health, carbon cycling, agricultural trends and urbanisation, especially in countries like India where the pressure on land is intense due to a growing population and economic development.

3.1 Scientific Foundation of LULC and its Dynamics

LULC information is derived either from field-based surveys or satellite remote sensing. These datasets inform models to track temporal changes and assess environmental impacts. However, inconsistent definitions across agencies, such as varying criteria for 'forest' based on canopy cover, height or replanting intention, often create confusion. For example, the same patch of land may be classified differently by the Forest Survey of India and the Ministry of Environment, Forest and Climate Change, depending on their functional interpretation. To overcome such discrepancies, standardised hierarchical classification systems like Anderson et al. (1976) were introduced. This United States Geological Survey (USGS)-based system has gained global recognition due to its multi-level structure, allowing classification from broad categories (e.g., forest, agriculture) to specific sub-classes (e.g., irrigated rice, tropical moist deciduous forest, dry deciduous forest and so forth). In India, agencies such as the National Remote Sensing Centre (NRSC), Indian Council of Agricultural Research (ICAR), and Forest Survey of India (FSI) have adopted this hierarchical approach in regional and national assessments.

Natural grasslands in India are ecologically diverse ecosystems that predominantly occur as transitional zones across climatic and elevational gradients. They manifest in two broad ecological contexts: (1) climatic ecotones between Dry Deciduous forests and Tropical Savannahs, and (2) altitudinal gradients spanning from Subalpine meadows to Alpine pastures and Cold deserts. Across central and peninsular India, grasslands frequently occur within deciduous–savannah–grassland landscape mosaics, notably in the Deccan Plateau and the Vindhyan uplands. These tropical grasslands are often maintained by fire, grazing and climatic seasonality. In contrast, Himalayan grasslands—ranging from the Subalpine zones (approximately 3,000 m) to Alpine meadows and Cold deserts beyond 4,500 m are characterised by short grasses and herbaceous diversity. These high-altitude grasslands support seasonal pastoralism and exhibit adaptations to low temperature, high radiation and nutrient-poor soils.

The uniqueness of Indian grasslands lies in their role as biodiversity reservoirs, carbon sinks, and drought-buffering systems in semi-arid regions. Despite their ecological value, grasslands in India have long been undervalued and often classified as 'wastelands' in the National Wasteland Atlas developed by the National Remote Sensing Centre (NRSC, 2019). Labels such as 'gullied and ravine lands', 'scrublands' and 'underutilised degraded pastures' frequently overlap with biologically rich grasslands, encouraging policies that support afforestation or land conversion. Recent remote sensing analyses using Sentinel-2 and Indian Remote Sensing (IRS) datasets reveal fragmentation and decline of semi-arid grasslands, particularly in Gujarat, Madhya Pradesh and Rajasthan—highlighting the need for urgent conservation attention and legal recognition.

3.2 Land–Atmosphere Interactions and Hydrological Considerations

LULC changes significantly influence land-atmosphere feedbacks. Vegetation plays a key role in modulating energy exchange via evapotranspiration, surface albedo and roughness. Forests, for instance, enhance humidity through transpiration and can lead to localised rainfall, while urban surfaces amplify the urban heat island effect by absorbing solar radiation and reducing surface moisture. These interactions directly affect cloud formation, temperature profiles and rainfall patterns. Hydrologically, LULC alterations impact surface runoff, infiltration, groundwater recharge and evapotranspiration. Urbanisation, by replacing permeable surfaces with concrete, leads to higher runoff and reduced aquifer recharge, while deforestation accelerates soil erosion and disrupts local water cycles. The hydrological cycle, composed of processes such as precipitation, infiltration and evaporation, is sensitive to land use. Degradation of wetlands and riparian buffers has reduced nature's ability to store and purify water, affecting both human and ecological water demands.

3.3 Biogeochemical Cycles and LULC Impact

Land cover governs biogeochemical cycles of carbon, nitrogen, phosphorous and sulphur. These cycles maintain the balance of life-supporting elements in the biosphere and are deeply intertwined with LULC change.

- **Carbon Cycle:** Forests sequester large amounts of carbon; deforestation releases this stored carbon, turning sinks into sources. The carbon exchange between land, atmosphere and oceans is altered drastically through land conversion, with tropical forest losses having the most severe climate consequences.

- **Nitrogen Cycle:** Agriculture, particularly the use of synthetic fertilisers, contributes to nitrogen enrichment in soils and water bodies, causing eutrophication and releasing potent greenhouse gases like nitrous oxide (N_2O).
- **Phosphorous and Sulphur Cycles:** Excessive fertiliser use and fossil fuel combustion disrupt these cycles, contributing to water quality degradation and acid rain, respectively.

These cycles are also influenced by climatic feedbacks—e.g., warming-induced soil respiration further increases atmospheric CO_2, while increased drought frequency limits the nitrogen uptake capacity of vegetation. Such feedbacks create a reinforcing loop, where climate change accelerates biogeochemical fluxes that, in turn, intensify atmospheric GHG concentrations. Additionally, altered precipitation patterns and higher temperatures can disrupt microbial activity and nutrient mineralisation, reducing ecosystem productivity and resilience over time.

3.4 Land Use Change and Environmental Impact

Over decades, land use change has become the primary driver of biodiversity loss, soil degradation and water system disruption (Roy et al., 2015b; Meiyappan et al., 2017).

- **Soil Degradation:** Removal of vegetation exposes topsoil, increases erosion and reduces fertility. Agricultural intensification, while boosting yields, has led to compaction, salinisation and nutrient depletion.
- **Deforestation:** Conversion of forests for agriculture or infrastructure has fragmented habitats, reduced carbon sequestration capacity, and increased fire vulnerability.

- **Urbanisation**: Impervious surface growth has impaired infiltration, increased surface runoff, and led to wetland shrinkage. Urban heat islands and water scarcity are direct outcomes.

These cascading impacts affect not only natural ecosystems but also human health, food security and disaster risk.

Agricultural Transitions and Land Use in India

India's agriculture-dominated landscape has seen a complex evolution in land use from 1965 to 2024. With approximately 46 per cent of the country under net sown area, agriculture remains the backbone of rural livelihoods. However, the performance across subsectors varies widely. Horticulture, livestock and fisheries have demonstrated higher growth rates than traditional cereal cultivation, reflecting both economic opportunity and the limitations of climate-vulnerable cropping systems. The regions focussing solely on rainfed crops like pulses and oilseeds have experienced stagnation or decline in productivity, exacerbated by climate anomalies such as temperature extremes and erratic rainfall. Technological interventions—such as precision agriculture, climate-resilient varieties, and micro-irrigation—are needed to bridge this gap. Meanwhile, smallholder farmers must be incentivised to diversify income sources via allied activities like poultry farming and dairying.

Agricultural Monitoring

Agriculture remains the largest land user in India, covering over 140 million hectares of the net sown area. Satellite-based LULC maps support agricultural planning through:

- **Cropping pattern assessment**: Multispectral data from satellites like Resourcesat (LISS-III, AWiFS) and Sentinel-2 allows classification of crop types (e.g., rice, wheat, sugarcane) and monitoring seasonal changes in sown area.

- **Fallow land tracking:** Remote sensing helps identify regions with chronic fallow land, enabling state governments to implement schemes for crop diversification or soil health restoration.
- **Precision agriculture and advisories**: LULC data, coupled with Normalised Difference Vegetation Index (NDVI), various satellite-derived indices and weather inputs, supports real-time advisories for farmers through platforms like Forecasting Agricultural output using Space, Agro-meteorology and Land based observations (FASAL), Kisan Vigyan Kendra (KVK), and supported by the Mahalanobis National Crop Forecast Centre (MNCFC).
- **Assessing impact of droughts or floods:** Remote sensing-based LULC maps provide baseline information to evaluate damage to cropped areas and inform relevant parties regarding compensation and insurance, e.g., Pradhan Mantri Fasal Bima Yojana (PMFBY).

Water Resource Management

Water is intimately linked with land use, and LULC maps inform both quantity and quality aspects of surface and groundwater resources (Das et al., 2018):

- **Watershed prioritisation and planning:** Programmes like the Integrated Watershed Management Programme (IWMP) and Pradhan Mantri Krishi Sinchai Yojana (PMKSY) use LULC maps along with other thematic layers to delineate micro-watersheds and plan soil and water conservation structures.

- **Monitoring wetlands and reservoirs:** LULC classification supports the inventory and seasonal mapping of water bodies, including Ramsar wetlands and man-made reservoirs, providing insights into shrinkage trends or encroachments.
- **Groundwater recharge zones:** Combined with hydrogeological layers and rainfall data, LULC maps help identify potential recharge zones and areas vulnerable to over-extraction.
- **Irrigation potential mapping:** Remote sensing assists in evaluating command areas of irrigation projects and estimating the efficiency of surface irrigation schemes.

Urbanisation and Climate Resilience

India is undergoing a rapid urban transformation, with its urban population projected to exceed 600 million by 2036, accounting for nearly 40 per cent of the total population (MoHUA, 2021). This growth is marked by increasing spatial sprawl, land conversion and resource-intensive development. Unplanned and poorly regulated urban expansion has significantly heightened environmental and social vulnerabilities. Key impacts include the intensification of Urban Heat Islands (UHIs), depletion of groundwater resources, inadequate solid waste and wastewater management and disruption of local hydrological cycles due to the loss of wetlands, lakes, and vegetated surfaces. The UHI effect where urban areas become significantly warmer than surrounding rural areas due to heat-absorbing materials and lack of vegetation—has been directly linked to increased morbidity and mortality during extreme heat events. The 2024 Delhi heatwave, with record-breaking temperatures exceeding 47°C, and the 2015 Chennai floods, caused by extreme rainfall overwhelming the city's drainage and encroached floodplains, demonstrate the compounded risks of climate change and poor urban planning. To enhance urban climate resilience, a multipronged strategy is essential:

- **Green Infrastructure Development**: Integrating urban forests, tree-lined streets, green roofs, vertical gardens and open parks helps moderate microclimates, reduce runoff, and improve air quality. Green infrastructures also serve as carbon sinks and buffers against extreme events.
- **Water-Sensitive Urban Design (WSUD)**: Restoration and protection of wetlands, tanks, bioswales, urban lakes and natural drainage channels (e.g., the *nallahs*) can mitigate flood risks and support groundwater recharge. Adoption of permeable pavements and rainwater harvesting further augments water security.
- **Climate-Responsive Zoning and Building Codes**: Urban master plans must include climate risk mapping, restrict construction in ecologically sensitive areas, and mandate energy-efficient building norms. Redevelopment of informal settlements must integrate thermal comfort, risk reduction and equitable access to services.
- **Integration with National Missions**: Urban resilience needs to be mainstreamed within AMRUT 2.0 (Atal Mission for Rejuvenation and Urban Transformation), the Smart Cities Mission and State Urban Development Policies. These frameworks should mandate climate vulnerability assessments, urban ecosystem valuation and community-based resilience planning.
- **Geospatial and Real-Time Monitoring**: High-resolution remote sensing, AI-enabled heat and flood risk analytics, and urban

climate observatories can support dynamic planning and early warning systems.

Building climate-resilient cities requires interdisciplinary planning, institutional coordination, and sustained investment in nature-based solutions. It also demands community engagement, especially in vulnerable urban peripheries where climate impacts are disproportionately felt.

3.5 LULC Satellite Monitoring and Remote Sensing

Modern LULC monitoring has transitioned from conventional field surveys and aerial photos to high-resolution satellite-based observation systems. Remote sensing platforms like Landsat, Sentinel, MODIS and Indian satellites (CartoSat, Resourcesat) now provide frequent and detailed data for national LULC mapping. Forest Survey of India (FSI) under Ministry of Environment, Forest and Climate Change (MoEFCC) has developed decadal and annual LULC datasets since 1985, classifying land into 12 major classes. These datasets are also used by ISRO and are vital for understanding trends like seasonal cropping, cropland intensification, urban sprawl, forest loss and wetland shrinkage in different granularity.

National Resource Planning

Satellite-based LULC maps have become foundational tools for national-level resource planning and land management in India. Institutions such as NRSC and ISRO, use these spatial datasets to evaluate land productivity, infrastructure expansion and ecological sustainability.

Status of Land Use and Land Cover (LULC) Reporting System

India's LULC reporting system has evolved from traditional, survey-based approaches to advanced satellite-based geospatial monitoring. This dual-track system plays a vital role in policy planning across sectors such as agriculture, forestry, biodiversity and urban development. Historically, conventional LULC reporting has been carried out by institutions such as the Directorate of Economics and Statistics (DES) under the Ministry of Agriculture and State Revenue Departments. These agencies rely on field surveys, cadastral records and agricultural land statistics to compile LULC data. The classification includes nine primary categories such as forests, non-agricultural lands, pastures, fallows, and net sown area, with annual reporting in the 'Land Use Statistics at a Glance'. While intensive, this system is constrained by time lags, manual processing and inconsistencies across states, particularly in un-surveyed or disputed lands. Its major limitation lies in the lack of spatial granularity and dynamic change detection.

In contrast, India has made notable progress in developing a satellite-based LULC reporting system, primarily driven by NRSC and the Space Applications Centre (SAC) under the Department of Space. Using multi-spectral imagery from IRS satellites like LISS-III, LISS-IV, and CartoSAT, periodic LULC maps are generated at scales from 1:2,50,000 to 1:10,000. The National LULC Mapping Programme by NRSC offers a consistent synoptic view of India's land surface, capturing both annual and decadal changes (Roy et al., 2015b). Forest cover mapping by FSI, published biennially, is a key reference for afforestation and degradation policy. Additionally, Bhuvan, ISRO's geoportal, provides LULC layers on agriculture, water bodies, wetlands and wastelands for national and district-level planning. These satellite-based approaches offer broad spatial coverage, objectivity, and repeatability, overcoming many of the limitations of conventional methods.

Despite their strengths, satellite systems also face challenges. Classification accuracy is affected by cloud cover, sensor resolution and terrain effects, especially in hilly or forested areas. Furthermore, limited integration with administrative boundaries and legal land records restricts their application in property rights and land tenure disputes. Recognising this, India is moving towards an integrated LULC framework. Programmes like the Digital India Land Records Modernisation Programme (DILRMP) aim to digitise land ownership data and overlay it with spatial maps. The Survey of Villages Abadi and Mapping with Improvised Technology in Village Areas (SVAMITVA) scheme, led by the Ministry of Panchayati Raj, uses drone-based surveys to map rural habitation and link spatial data with property entitlements. Complementing these are Gram Manchitra and the national Geographic Information Systems (GIS), which serve as platforms for integrating LULC data with socio-economic and planning indicators. Additionally, the 2021 Geospatial Data Guidelines have liberalised access to high-resolution data, opening opportunities for private, academic and civil society participation in LULC monitoring and analysis.

In summary, India's LULC reporting landscape is in a phase of dynamic transformation. While conventional methods provide long-term consistency and administrative legitimacy, satellite-based systems offer spatial accuracy, real-time monitoring, and environmental relevance. *The future lies in harmonising these approaches to develop a unified, transparent and accessible LULC information system that supports climate-resilient planning, sustainable land governance, and informed policy-making across scales.*

Land Use Optimisation

High-resolution land use and land cover (LULC) maps play a pivotal role in the rational, sustainable allocation of land resources across sectors. These maps enable planners and policymakers to assess, with spatial precision, the current status and potential availability of land for competing uses—such as agriculture, forestry, urban housing, industrial development, transportation and ecological conservation. Integrating these assessments with data on land capability, ecological sensitivity and slope stability helps prevent land use conflicts and ensures alignment between developmental priorities and ecosystem sustainability.

Infrastructure and Development Zoning

Satellite-derived land use maps, when coupled with digital terrain models, hazard zoning and ecological vulnerability assessments, are instrumental in delineating areas suitable for infrastructure development. These include roads, economic corridors, industrial hubs, urban expansion zones and smart cities. High-resolution spatial data from missions like CartoSAT-3 and Sentinel-2 helps avoid development in ecologically sensitive or disaster-prone zones—such as floodplains, landslide-prone slopes or biodiversity hotspots. This approach ensures infrastructure planning minimises environmental degradation and is resilient to climate risks. Geospatial zonation also enables targeted implementation of land acquisition and compensation frameworks in line with social and environmental safeguards.

Integration with Census and Socio-Economic Data

When LULC data is combined with granular socio-economic datasets—such as village-level census information, agricultural statistics, and deprivation indices—it will provide a robust framework for integrated rural and spatial development. Platforms such as Bhuvan Panchayat and Gram Manchitra have the potential to demonstrate the use of spatial analytics in linking land use data with asset mapping, demographic indicators and welfare programme outcomes. Such integration can support the identification of underutilised lands, land degradation hotspots and priority areas for rural infrastructure development, agroecological restoration, or livelihood diversification. It also strengthens decentralised planning under schemes like Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), Shyama Prasad Mukherji Rurban (Rural-Urban) Mission (SPMRM), and PMKSY by aligning spatial data with ground-level socio-economic needs.

Forest/Vegetation Monitoring: Scope to Improve Reporting

India's forest and vegetation cover reporting is primarily led by the FSI, which publishes the biennial India State of Forest Report (ISFR). Using moderate-resolution satellite data (23.5 m, such as IRS LISS-III), the FSI assesses forest cover in three categories—Very Dense Forest, Moderately Dense Forest and Open Forest—based on canopy density thresholds. These reports are supplemented by thematic assessments (e.g., bamboo, mangroves) and district-level analyses, making it one of the most comprehensive national forest monitoring systems globally. However, the system has drawn criticism on several fronts. It conflates forest cover (based on spectral greenness) with forest type and quality, including plantations, orchards, and urban green areas as forests, which can distort ecological assessments. The static canopy-based classification overlooks degradation, biodiversity loss or species changes—e.g., monoculture plantations with high canopy cover may be listed as 'Very Dense Forest' despite limited ecological value. Moreover, the reports lack transparency in methodology, error margins and field validation, and are sometimes inconsistent with ISRO or global datasets like Global Forest Watch. They also inadequately reflect shifting cultivation (jhum), forest fires, degradation of grasslands and small-scale fragmentation in forested tribal regions, especially in northeast and central India. Recognition of grasslands as critical ecosystems—not merely as ecological voids—calls for integrated monitoring, restoration, and community-based management. Their reclassification in land use inventories, incorporation in biodiversity policies, and alignment with agro-pastoral sustainability goals are imperative for reversing the ecological neglect of these vital landscapes. Additionally, the biennial frequency restricts timely responses to deforestation or afforestation. Integration with ecological indicators like biomass, biodiversity and forest health remains limited.

To improve scientific credibility and policy relevance, several reforms are needed:

- First, forest assessments must distinguish natural forests from plantations using ecological integrity and land use layers alongside canopy density.
- Adoption of multi-resolution and high-resolution satellite data, such as CartoSAT, Sentinel-2, PlanetScope, and space-based LiDAR (e.g., GEDI) should be mainstreamed to capture fine-scale forest structure and biomass.
- Annual or seasonal monitoring is essential, especially in areas at risk from mining, fires and encroachments. A degradation index combining canopy loss with understory and human pressure indicators should be developed.
- Forest cover data should link to biodiversity databases (e.g., Bhuvan, Botanical Survey of India, Zoological Survey of India), and carbon stock estimates to enable data-driven conservation and climate action.

- Transparency should be enhanced by making raw satellite data and classification methods publicly available.
- Lastly, an institutional framework involving FSI, NRSC, State Forest Departments, and research bodies is essential for methodological coherence, cross-validation, and greater trust in national reporting.

Biodiversity and Forest Conservation: Spatial Characterisation

India's LULC maps play a central role in biodiversity conservation by providing spatial insights into forest cover dynamics, species habitats, and ecosystem health:

- **Forest Type Mapping**: Satellite imagery supports classification of dense, open, scrub, and degraded forests, aiding in forest policy decisions and forest working plans under the Forest Survey of India (FSI, 2023) and Roy et al. (2015a).
- **Biodiversity Hotspot Identification:** Landscape-level biodiversity characterisation (as happens in ISRO-DOS and DBT projects) uses LULC and Vegetation type maps to locate critical wildlife habitats and conservation priority zones in all the biogeographic regions of India.
- **Monitoring Forest Encroachment and Fragmentation:** Time-series LULC datasets detect illegal logging, mining and encroachments inside reserved forests and protected areas, supporting enforcement under the Forest Conservation Act, 1980.
- **REDD+ and Carbon Accounting:** India's LULC maps contribute to quantifying forest carbon stocks and changes under international climate frameworks like REDD+

and the UNFCCC Biennial Update Reports. These high-resolution spatial datasets enable the monitoring of deforestation, degradation and forest enhancement activities critical to REDD+ implementation. Accurate carbon accounting also supports the development of national reference emission levels, facilitates performance-based payments, and strengthens transparency in reporting climate mitigation actions aligned with India's Nationally Determined Contributions (NDCs).

3.6 Disaster Response and Climate Resilience

Land use and land cover (LULC) maps are vital for disaster preparedness and long-term climate adaptation. As climate-induced floods, cyclones, droughts and heatwaves intensify, high-resolution LULC data (10 m–5 m) becomes essential for identifying vulnerable zones, modelling hazards, and planning relief. LULC layers help map floodplains, track forest and wetland changes, and monitor urban sprawl into risk-prone areas. Fine-scale data supports local interventions like embankments, rainwater harvesting, and urban slum upgrades. Integrating citizen science through mobile apps and participatory mapping improves data accuracy and community engagement, making disaster response more inclusive and effective.

- **Flood Forecasting, Risk Zoning and Urban Vulnerability:** Integration of LULC data with elevation through Digital Elevation Models, rainfall and hydrological models supports flood mapping, especially in urban and riverine regions like Bihar, Assam and coastal Odisha. Ghosh et al. (2019) presented India's first integrated expert urban flood forecasting system for Chennai, combining real-time weather, hydrological, tidal and drainage models. It delivers high-resolution flood forecasts to support early warnings and urban disaster management.

- **Post-disaster Damage Assessment:** During events such as cyclones, forest fires or droughts, near real-time satellite data helps quantify affected land classes (croplands, forests, settlements and infrastructures) for effective relief allocation.
- **Drought Vulnerability Analysis:** By combining LULC with soil moisture and rainfall anomaly data, regions susceptible to agricultural droughts can be identified, enabling early warning systems.
- **Climate Adaptation Planning:** District-level climate vulnerability assessments (e.g., by MoEFCC, ISRO-NRSC and National Institution for Transforming India [NITI Aayog]) rely on LULC inputs to target interventions in agriculture, forestry and water sectors.
- **Smart City and Resilient Urban Planning:** Urban LULC maps aid in designing green infrastructure, open spaces, and drainage systems to enhance resilience to climate extremes.

Despite this progress, gaps remain in spatial resolution (e.g., for wetland microhabitats), real-time availability and integration with socio-economic data.

3.7 Emissions and Emerging Sustainable Land Practices in India

India's land-based GHG emissions stem from agriculture, deforestation, urban expansion and wetland degradation. The agriculture sector alone accounts for about 13.7 per cent of India's total emissions, with rice cultivation and livestock as major sources of methane. However, India has made efforts to reverse some trends:

- **Afforestation:** Through the Green India Mission and Bonn Challenge commitments, India is restoring degraded landscapes. Yet, critiques remain about the ecological quality of such plantations.
- **Sustainable Farming:** Practices like zero-tillage, alternate wetting-drying, and organic farming are being promoted to reduce emissions and improve resilience.
- **Climate-Smart Agriculture:** Integrated approaches using Artificial Intelligence (AI), GIS, drones and weather advisories aim to reduce input waste and maximise yield sustainably.
- **Community-based Restoration:** Efforts in Pachgaon (Maharashtra) or Aravalli Biodiversity Park show the promise of locally-driven afforestation and ecosystem restoration.

3.8 Climate Change Feedbacks from LULC

LULC modifications influence climate directly and indirectly (Roy et al., 2022):

- **Surface Albedo:** Forests have lower albedo than croplands or bare land, thus absorbing more solar energy. Their removal increases reflectivity but disrupts atmospheric circulation and moisture recycling.
- **Greenhouse Gas Emissions:** Land conversion emits CO_2, CH_4 (from rice and livestock), and N_2O (from fertilisers). These emissions are key contributors to global warming, alongside fossil fuels.
- **Hydrological Alterations:** Changes in evapotranspiration due to forest loss or irrigation schemes affect local and regional precipitation. Urbanisation alters runoff and may intensify flooding or droughts.

- **Vegetation-Biodiversity Shifts:** Deforestation reduces evapotranspiration, weakening rainfall patterns. Biodiversity loss reduces ecological resilience and the capacity to adapt to climate shifts.

India's climate anomalies over the last five decades have shown pronounced spatial variability in temperature and rainfall, with significant effects on cropping seasons and net sown areas. The Northeastern and Himalayan states, for example, are warming faster, impacting perennial horticulture and biodiversity. Central India's declining monsoon patterns pose risks to major kharif crops, requiring urgent adaptation strategies.

3.9 LULC Policies and Sustainable Development Goals (SDGs)

LULC policies in India are key to achieving climate mitigation, biodiversity conservation and sustainable agriculture. Initiatives like Reducing Emissions from Deforestation and Forest Degradation (REDD+), conservation reserves, eco-sensitive zones and land reforms support this vision. Policies must address:

- Zoning for conservation and agriculture
- Regulations on forest diversion
- Urban planning guidelines to manage sprawl
- Wetland and mangrove protection laws

Further, LULC-based emissions mitigation strategies—such as forest conservation, agroforestry and rewilding—must align with national SDGs and global treaties like the Paris Agreement. India's LULC reporting landscape is undergoing a significant transformation, shifting from legacy systems based on manual surveys and revenue records to advanced satellite-based geospatial monitoring platforms. The conventional system, led by the Directorate of Economics and Statistics, Forest

Survey of India (FSI), and State Revenue Departments, remains valuable for long-term statistical continuity, but is hindered by time lags, inconsistent land classification, and limited spatial precision. In contrast, satellite-based systems—spearheaded by ISRO's NRSC, FSI, and the Bhuvan portal—provide synoptic, near-real-time, high-resolution maps at national and district levels. These are critical for monitoring agriculture, forest health, urban sprawl, wetlands and climate-sensitive land transitions. Despite advances, the lack of legal integration between spatial data and land governance frameworks continues to impede the mainstreaming of LULC data into planning, regulation and judicial processes.

To address this, a comprehensive National Land Use Policy must be formulated and operationalised with strong legal and institutional backing. It should elevate land use as a national priority, central to food security, climate resilience, biodiversity conservation and sustainable urban development. The policy must mandate periodic high-resolution mapping using remote sensing technologies (e.g., CartoSAT and future Resourcesat satellites) and make such data legally binding for use in planning, infrastructure, watershed management, and forest conservation. Integration with digital land records (under DILRMP and SVAMITVA) should be mandatory, making geospatially referenced land ownership legally enforceable. This would reduce land disputes, clarify tenurial rights, and streamline compensation and acquisition processes. The policy should also establish legal land zoning frameworks at national, state, district and panchayat levels, clearly designating zones for agriculture, forests, wetlands, peri-urban areas, ecological hotspots, and climate-vulnerable regions. Land conversion—especially in floodplains, forest margins, and tribal areas—must be strictly regulated.

A Land Use Regulatory Authority, with representation from the Ministries of Environment, Agriculture, Urban Development, and Tribal Affairs, should oversee coordination and dispute resolution. Local governments (panchayats and municipalities) must be empowered through decentralised GIS-based platforms like Gram Manchitra to enable participatory land planning with scientific support. The framework should also mandate open access to LULC data for researchers, civil society and startups working on land governance.

In essence, a legally-backed National Land Use Policy is vital to transform LULC data into actionable governance tools. It must bridge the gap between scientific data and regulatory processes, ensuring that satellite-derived LULC assessments inform planning, regulation and legal adjudication. Such a policy would align India's land governance with national Sustainable Development Goals (SDGs), NDCs, and international obligations under the UNFCCC, the CBD, as well as the United Nations Convention to Combat Desertification (UNCCD).

4. BIODIVERSITY: FOUNDATIONS, CHALLENGES AND STRATEGIC RESPONSES

4.1 Introduction and Definitions

The term 'biodiversity', popularised by E. O. Wilson, captures the extraordinary range of life on Earth encompassing genes, species, ecosystems and their intricate interactions. Evolving from earlier signifiers like 'biological diversity' (Harris, 1916), biodiversity signifies not only the variety of organisms but also their ecological roles and evolutionary histories shaped over 4.5 billion years. Definitions of biodiversity vary based on context. Wilson (1992) emphasised hierarchical classification from genes to ecosystems, while the Convention on Biological Diversity (1992) and Millennium Ecosystem Assessment (2005) framed biodiversity in functional and ecological terms. In economic terms, Perrings et al. (1995) highlighted its contributions to human well-being through ecosystem services.

Components and Hierarchy of Biodiversity

Biodiversity operates at three major levels:

- **Genetic Diversity** refers to the variability in DNA within species, allowing for adaptability and resilience.
- **Species Diversity** encompasses species richness and evenness, essential for ecological stability.
- **Ecosystem Diversity** involves variations in habitats, biotic communities and ecological processes.
- **Landscape Diversity**, a broader spatial scale, links environmental heterogeneity with species diversity, especially relevant in agricultural mosaics in South Asia.

India's estimated species count stands at 2.16 million (IUCN, 2022), with global projections of around 8.7 million species (Mora et al., 2011). Despite these high numbers, about 86 per cent of terrestrial and 91 per cent of marine species remain undescribed.

Flora and Fauna: Ecological and Cultural Roles

- **Flora (plants)** are categorised into bryophytes, pteridophytes, gymnosperms and angiosperms. They are central to food webs, oxygen production, climate regulation and economic livelihoods.
- **Fauna (animals)** are classified into invertebrates and vertebrates and further segmented by habitat (terrestrial, aquatic, aerial) and ecological function (herbivores, carnivores, omnivores). Faunal components

regulate ecosystems through pollination, seed dispersal and nutrient cycling.

4.2 Biodiversity Inventory and Monitoring Methods

Inventorying biodiversity is fundamental to conservation. Key methods include:

- **For Flora:** Quadrat sampling, transect surveys, point-centre quarter methods and remote sensing. Remote sensing and GIS tools map vegetation types, monitor conservation efforts, and support species distribution modelling (SDMs). Vegetation phenology studies using satellite data show significant shifts in flowering and greening cycles due to warming.
- **For Fauna:** Visual encounter surveys, camera traps, mist netting (for birds and bats), acoustic monitoring and pitfall traps are employed to monitor populations and behaviours.

Emerging tools like environmental DNA (eDNA) and drones provide non-invasive, high-resolution data for remote and endangered habitats.

Spatial Biodiversity Mapping in India

India's satellite-based LULC and vegetation mapping, particularly through ISRO-DOS and Department of Biotechnology (DBT), have enabled landscape-level biodiversity characterisation. Studies by Roy et al. (2012, 2015a) integrated field data, satellite imagery, and environmental variables to model biodiversity in India, providing landscape characterisation of biodiversity-prioritised areas. The key findings included habitat fragmentation, loss of native species, and urgent conservation gaps in biodiversity-rich zones outside protected areas. Species distribution modelling projected range shifts and extinction risks under future climate scenarios. Hotspots like the Western Ghats, Eastern Himalayas and Northeast India were highlighted for their conservation importance. These outputs inform protected area planning and ecological corridor development.

Ecosystem Services and Biodiversity Linkages

Ecosystem services derived from biodiversity are categorised as:

- **Provisioning:** Food, water, timber and medicinal resources
- **Regulating:** Climate moderation, disease control, water purification
- **Supporting:** Soil formation, primary productivity
- **Cultural:** Recreation, spiritual and educational values

Remote sensing helps quantify and map ecosystem services, thereby aiding in resource management and environmental policy.

4.3 Drivers and Consequences of Biodiversity Loss

Biodiversity is declining rapidly due to a combination of anthropogenic pressures and environmental change. A primary driver is habitat loss and fragmentation, where deforestation, infrastructure, mining and agriculture break large ecosystems into isolated patches. This disrupts ecological connectivity, reduces species viability and increases extinction risk (Fahrig, 2003). Climate change worsens this loss by altering temperature and precipitation patterns, shifting species ranges, and increasing extreme weather events—often outpacing species' adaptive capacities, especially for specialists and poor dispersers (Parmesan, 2006). Pollution from intensive agriculture—particularly chemical fertilisers and pesticides—contaminates soil and water, harming soil biodiversity, aquatic systems, and pollinators (Díaz & Rosenberg, 2008). Overexploitation through unsustainable fishing, hunting and logging depletes populations, disrupts ecosystems, and removes keystone species (Pauly et al., 1998). Invasive alien species, spread by global trade and habitat disturbance, displace native flora and fauna, destabilising ecosystems (Simberloff et al., 2013). Unsustainable land use practices such as monocultures, wetland drainage and poorly planned urbanisation further degrade habitats and reduce landscape-level diversity (Foley et al., 2005). Collectively, these pressures diminish species richness, genetic variability and ecosystem services—threatening food and water security, natural disease regulation and climate resilience. Protecting biodiversity is essential for sustainable development, public health and adaptation to environmental change.

4.4 Biodiversity and Climate Change Interactions

Climate Change intensifying Biodiversity Loss

Climate change is emerging as a dominant driver of biodiversity loss, exacerbating already critical threats such as habitat degradation, invasive species, and overexploitation. Its multifaceted impacts are disrupting ecological balances at genetic, species and ecosystem levels. Among the most concerning consequences are:

Species Range Shifts and Extinctions

As temperature and precipitation regimes shift, many species are being forced to migrate to higher latitudes or elevations to find suitable habitats. However, not all species possess the dispersal ability or habitat connectivity to adapt, leading to localised extinctions, particularly in endemic-rich regions such as mountain tops, islands and tropical forests. This trend is particularly alarming for narrow-ranged and specialised species that cannot compete or migrate fast enough.

Phenological Mismatches

Climate change is altering the timing of biological events—such as flowering, breeding or migration—in ways that disrupt ecological synchrony. For example, pollinators may emerge too early or too late relative to peak flowering times, reducing reproductive success for both plants and animals. These mismatches can cascade through food webs, weakening ecosystem resilience.

Extreme Weather Events

The increasing frequency and intensity of extreme events—such as heatwaves, droughts, floods and wildfires—are causing direct mortality of species and degradation of habitats. Such events disproportionately affect species with limited mobility, narrow thermal tolerance or specific reproductive windows. Coral bleaching due to marine heatwaves, amphibian die-offs from extended droughts, and forest degradation from intense cyclones illustrate this growing threat.

Loss of Carbon Sequestration Capacity

Forests, grasslands, mangroves and marine ecosystems like seagrasses and kelp forests play a crucial role in absorbing atmospheric carbon dioxide. However, climate-driven diebacks, deforestation, intensification of forest fires and ocean warming are reducing their carbon sink function. This not only releases stored carbon back into the atmosphere but also disrupts the biodiversity these systems support.

Decline of Key Biodiversity Areas as Climate Refugia

According to Trew et al. (2024), many Key Biodiversity Areas (KBAs) designated for their irreplaceable ecological value are losing their ability to function as climate refugia due to rapidly changing conditions and inadequate adaptive management. This erosion of resilience in protected landscapes highlights the urgent need to expand and interconnect conservation networks, ensuring dynamic protection that accommodates climate-driven species movement and ecosystem shifts.

In summation, climate change is not just a background stressor but a primary agent accelerating biodiversity loss. Protecting biodiversity under a changing climate will require transformative conservation strategies, climate-smart protected area design and global cooperation to reduce emissions while preserving ecological integrity.

4.5 Conservation Strategies and Policy Frameworks

Protected areas and ecological corridors are foundational to in-situ conservation, safeguarding habitats and enabling species migration in response to climate-induced shifts. To complement these, nature-based solutions such as afforestation using native species, wetland restoration and mangrove rehabilitation enhance ecosystem resilience while delivering co-benefits like carbon sequestration and flood mitigation. Agroecology and sustainable land use practices, including agroforestry, crop diversification and conservation agriculture, further integrate biodiversity into productive landscapes. These approaches are reinforced by global and national frameworks such as the CBD, the post-2020 Global Biodiversity Framework, and India's National Biodiversity Action Plan (NBAP), which emphasise ecosystem integrity, sustainable use, and equity. However, effective implementation demands policy coherence and cross-sectoral synergy, aligning biodiversity goals with climate adaptation and land use planning. Crucially, these strategies are increasingly supported by spatial data from remote sensing, ecological inventories and GIS-based decision tools, enabling targeted interventions, monitoring of conservation outcomes, and adaptive management in a rapidly changing environment.

Mitigation and Adaptive Capacity Building

Building biodiversity resilience amid climate change and human pressures requires an integrated approach involving restoration, awareness and governance. Restoration ecology—through rewilding, native reforestation and ecosystem regeneration—revives ecological processes and strengthens habitat functionality. Public awareness and ecological education are equally crucial, promoting community participation, local stewardship and the integration of traditional knowledge in conservation efforts. Strong legal frameworks and scientific monitoring ensure accountability and adaptive management. India's satellite platforms like Bhuvan and Bhoonidhi support real-time habitat mapping and ecological monitoring, enabling timely policy action. Regular updates of biodiversity indicators—such as species richness, endemism and ecosystem health—further aid evidence-based planning and improve the adaptive capacity of both ecosystems and communities.

Biodiversity is the backbone of ecosystem health and climate stability. Loss of biodiversity and ecosystem degradation threaten not only ecological balance but human survival. *An integrated framework involving science, policy, community and technology—grounded in spatial and temporal data—is imperative. India's experience in landscape-level biodiversity assessment and remote sensing integration serves as a model for emerging economies striving to meet conservation and climate objectives.*

5. AGROBIODIVERSITY AND ITS CRITICAL ROLE IN SUSTAINABLE AGRICULTURE AND CLIMATE RESILIENCE

5.1 Understanding Agrobiodiversity

Agrobiodiversity refers to the vast variety of biological components within agricultural systems, including crops, livestock, aquatic species and associated organisms such as soil microbes and pollinators. It plays a crucial role in food systems by supporting ecosystem services, ensuring food security and enhancing agricultural resilience. The Food and Agriculture Organisation (FAO) classifies agrobiodiversity into four categories: plant genetic resources animal genetic resources, aquatic genetic resources and associated genetic resources. These components interact within ecological and cultural contexts to shape resilient agricultural landscapes. Agrobiodiversity aids in developing improved crop varieties, enhancing soil and water health, managing pests naturally, conserving carbon stocks and supporting bio-based economies. As a pillar of sustainable development, it connects food production with environmental conservation and societal well-being.

Global Origins and the Spatial Patterns of Agrobiodiversity

Agrobiodiversity is deeply rooted in the historical domestication and dissemination of crop species. Globally, many of the 36 biodiversity hotspots house significant agrobiodiversity, including regions that are both centres of origin and centres of diversity for key crops. These areas exhibit complex interactions between natural ecosystems and long-standing human agricultural practices. For instance, wheat originated in the Fertile Crescent (which spans parts of Central and West Asia) yet shows high diversity in the South and East Mediterranean due to environmental adaptation and human selection. Such centres, including the Andean region for potatoes and Mesoamerica for maize, highlight the global cultural and ecological value of agrobiodiversity. Modern agricultural systems depend heavily on the genetic resources found in these hotspots for breeding resilient and productive crop varieties.

Indian Agrobiodiversity: A Global Stronghold

India is recognised as one of the 17 mega-biodiversity countries and is home to over 8 per cent of the world's biodiversity, with more than 15 agroclimatic zones that support a wide range of plant and animal genetic resources. India is the centre of origin for approximately 25 crop species including rice, brinjal, citrus and pigeon pea. The country possesses over 15,600 rice landraces and produces a rich diversity of spices, millets, pulses and indigenous vegetables. Traditional and introduced crops have been diversified over centuries through cultural practices and climatic adaptation. Indigenous livestock breeds like *Tharparkar* cattle and *Kadaknath* poultry demonstrate resilience to local stresses and diseases. Moreover, the interweaving of traditional ecological knowledge with agricultural practices exemplified by Jhum cultivation, *Apatani* rice-fish farming and the Zabo system has sustained biodiversity while supporting livelihoods. India's agrobiodiversity also includes underutilised crops and medicinal plants, many of which are embedded in cultural traditions and are critical for food sovereignty and health.

5.2 The Importance of Agrobiodiversity

Agrobiodiversity is vital for productivity, resilience and ecological health in farming systems. Genetic diversity enables the breeding of climate-resilient crops like flood-tolerant rice and drought-resistant millets. It supports soil fertility, pollination, pest control and water conservation, while reducing reliance on chemical inputs. Traditional Indian practices such as mixed cropping and agroforestry exemplify resilience. Millets, now promoted as 'nutri-cereals', are recognised for their climate and nutritional benefits, supported by initiatives like the National Food Security Mission's coarse cereals programme and other millet-specific initiatives and the International Year of Millets (2023). Diversifying agriculture beyond staple crops also strengthens food security, nutrition and rural livelihoods.

5.3 Conservation Frameworks: Emerging Initiatives

At the international level, CBD promotes the conservation, sustainable use and equitable benefit-sharing of genetic resources. The FAO's Globally Important Agricultural Heritage Systems (GIAHS) initiative recognises traditional farming systems as reservoirs of agrobiodiversity and cultural heritage. GIAHS sites integrate biodiversity with traditional knowledge and community resilience. In India, a robust institutional framework supports agrobiodiversity conservation. The Protection of Plant Varieties and Farmers' Rights Act (PPV&FRA) of 2001 ensures farmers' rights and benefit-sharing. The National Bureau of Plant Genetic Resources (NBPGR) and National Bureau of Animal Genetic Resources (NBAGR) maintain extensive seed and gene banks. Community seed banks and participatory breeding programmes empower farmers and indigenous communities to conserve local varieties. India's schemes such as the National Mission for Sustainable Agriculture (NMSA), Paramparagat Krishi Vikas Yojana (PKVY), and emerging initiatives like Payments for Agrobiodiversity Conservation Services (PACS) encourage on-farm conservation by providing incentives and policy support.

Challenges in Conserving Agrobiodiversity

Despite its richness, agrobiodiversity in India faces significant threats. Modern agricultural practices post-Green Revolution led to monoculture dominance, marginalising traditional varieties and indigenous knowledge systems. Climate change, habitat fragmentation and the erosion of traditional knowledge further aggravate this trend. The decline of saline-tolerant *Pokkali* rice in Kerala, the loss of local cardamom cultivars in Sikkim and shifting apple cultivation zones in Himachal Pradesh are telling examples. Traditional varieties such as *Kavuni* (Tamil Nadu), *Kalajeera* (Odisha) and *Navara* (Kerala) are repositories of adaptive traits and medicinal value. Indigenous cultivation systems like the Apatani and Jhum not only conserve genetic resources but also maintain ecological balance. However, these practices are at risk due to modernisation, policy gaps and socio-economic marginalisation.

5.4 The Future of Agrobiodiversity: Strategies and Policy Directions

Agrobiodiversity is vital for climate-resilient agriculture, food security and ecosystem sustainability. Yet it is increasingly threatened by monocultures, land use change and climate stress. Future strategies must integrate conservation, traditional knowledge and policy support to safeguard and sustainably utilise this critical resource. Securing the future of agrobiodiversity demands integrated strategies that align biodiversity conservation with climate resilience, food security and rural development.

- **Climate Resilience and Agroecology:** Agrobiodiversity enhances adaptability through the cultivation of drought-tolerant, pest-resistant and heat-tolerant crops.

Programmes like NMSA and NICRA must be scaled to promote climate-smart agriculture, water-efficient practices and soil restoration.

- **Conservation Measures:** In-situ conservation through farmer-led initiatives and ex-situ conservation via gene banks must be expanded. Restoration of degraded agroecosystems using native species is essential.
- **Nutritional and Economic Security:** Diet diversification using traditional crops addresses malnutrition and lifestyle diseases. Promotion of millets, pulses and leafy vegetables through Integrated Child Development Services Scheme (ICDS) and Mid-Day Meal schemes can improve public health outcomes.
- **Empowering Communities:** Recognising traditional knowledge, supporting seed networks and implementing PACS will empower indigenous farmers and ensure intergenerational transmission of agrobiodiversity.
- **Science, Technology and Governance:** Emerging biotechnologies, combined with policy instruments like the Nagoya Protocol, can support equitable access to genetic resources. Seed Village Programmes should enhance access to resilient seed varieties. Maini and Basu (2016) elaborated on the benefits of the Agrometeorological Advisory Services (AAS) provided by India’s MoES, detailing how it has helped to provide timely weather-based advisories to improve farm decision-making, reduce input costs, and enhance crop yields—resulting in significant economic gains for farmers.
- **Market Linkages and Value Chains:** Support for traditional crops under schemes like One District One Product (ODOP) and National

Programme for Organic Production (NPOP) can create niche markets. Sustainable branding and value chain development will further incentivise conservation.
- **Education and Awareness:** Curriculum integration, public campaigns like Eat Right India, and citizen science can foster ecological consciousness.
- **Alignment with SDGs:** Agrobiodiversity conservation aligns with SDGs on zero hunger, climate action and life on land. Inclusive development mandates integrating gender and community equity.

Agrobiodiversity stands at the confluence of ecological, economic and cultural sustainability. Its conservation and sustainable use are pivotal in shaping resilient food systems amidst climate uncertainty and global environmental change. India, with its rich biological and cultural heritage, can lead global efforts in agrobiodiversity conservation through a synthesis of traditional wisdom, modern science and progressive policy. A future that protects agrobiodiversity ensures not only food and livelihood security but also a resilient and equitable agricultural landscape for generations to come.

6. INTERPLAY OF CLIMATE CHANGE, LAND USE, BIODIVERSITY AND AGROBIODIVERSITY: POLICY-SCIENCE FRAMEWORK FOR RESILIENCE IN INDIA

6.1 Introduction

The convergence of climate change, land use transformation and biodiversity loss is among the gravest challenges to India's environment, economy and society. As a rapidly developing nation with a growing population and expanding urban-industrial footprint, India faces increasing pressure to balance development with ecological sustainability. Rising temperatures, altered monsoons, frequent extreme events and their interaction with land degradation and biodiversity fragmentation amplify vulnerabilities across sectors. India's biogeographic diversity—from the Himalayan highlands to the Deccan plateau and coastal wetlands—supports unique ecosystems and traditional livelihoods. Yet, climate stress, unsustainable land use and biodiversity decline create a negative feedback loop that reduces agricultural productivity, food and water security, ecosystem services, and climate resilience (Roy et al., 2022).

6.2 Climate Change and Agriculture

Reduced Agricultural Productivity

Agriculture in India is intrinsically linked to climate variability. Rainfed farming accounts for nearly 60 per cent of net sown area, making the sector highly sensitive to monsoon fluctuations. Rising temperatures reduce wheat and rice yields—particularly during critical phenological stages—while heatwaves damage horticultural crops. Droughts reduce soil moisture and evapotranspiration rates, whereas unseasonal floods and cyclones cause waterlogging, erosion, and infrastructure loss. Studies (IARI, 2014; Mall et al., 2006) indicate a projected decline of 3–20 per cent in crop yields per degree Celsius of warming, with smallholders most at risk.

Changes in Land Use

Climate-induced stressors increasingly drive land use transitions. Salinisation of coastal soils due to sea-level rise (notably in the Sundarbans and Gujarat) and glacial retreat in Himalayan valleys force farmers to abandon or shift croplands, often encroaching upon forests or grasslands. Fragmentation of farmland and degradation of commons such as pastures and wetlands compromises landscape-scale productivity and hydrological regulation. These shifts undermine ecosystem integrity and food system sustainability.

Pests, Diseases, and Food Security

Warmer and wetter conditions facilitate the proliferation of pests (e.g., locusts, fall armyworm) and crop diseases, increasing pesticide dependency and reducing biological control. This not only degrades pollinator populations and soil fauna but also leads to bioaccumulation in food chains. The cumulative effect is declining nutritional security, price volatility and farmer indebtedness. Climate-linked food insecurity disproportionately affects women and marginalised communities.

6.3 Climate Change and Biodiversity

Habitat Loss

India is witnessing climate-driven habitat contraction and ecological simplification. Coastal mangroves, alpine forests and wetlands are receding due to sea-level rise, warming, and human encroachment. Forest diebacks are being recorded in the Western Ghats and central India due to shifting rainfall patterns and increasing fire frequency. Such degradation erodes the buffering capacity of ecosystems and reduces carbon sequestration potential.

Species Distribution and Ecosystem Interactions

Shifts in temperature and precipitation patterns cause species to migrate to higher altitudes or latitudes, leading to biotic homogenisation and loss of endemic species. Phenological mismatches, such as altered flowering and pollinator emergence—impact plant reproduction and trophic interactions. Keystone species, including elephants and large carnivores, face shrinking ranges and increased human-wildlife conflicts. These disruptions weaken ecosystem resilience and threaten cultural landscapes.

Invasive Species and Ecosystem Services

Climate change facilitates the spread of invasive alien species such as *Lantana camara*, *Parthenium hysterophorus* and *Neltuma juliflora* (Mesquite), which outcompete native flora and alter fire regimes. Declining biodiversity reduces provisioning, regulating and cultural services, including pollination, water purification, and spiritual values. The net result is reduced adaptive capacity of ecosystems to buffer climate extremes.

6.4 Land Use and Climate Feedbacks

Land use changes—such as deforestation, urbanisation, agriculture expansion and wetland conversion—have significant implications for the Earth's climate system. These alterations affect surface albedo, evapotranspiration, carbon storage and energy fluxes, thereby creating feedback loops that can either amplify or moderate climate change (Das et al., 2018). For example, forest loss not only reduces carbon sequestration but also increases surface temperatures through albedo and moisture changes. Conversely, land restoration and afforestation can enhance cooling effects and carbon uptake. Understanding these complex land–climate feedback mechanisms is essential for developing integrated mitigation and adaptation strategies under a changing climate (Fig. 1).

Deforestation and Emissions

India loses approximately 3,34,000 hectares of forest annually (FAO, 2020), largely due to infrastructure development, agriculture expansion and mining. Deforestation contributes to GHG emissions, disrupts monsoon feedbacks and reduces soil carbon stocks.

Fragmented forests also hinder species movement and resilience under climate stress.

Agricultural Emissions

India's agriculture sector is responsible for 14 per cent of national GHG emissions. Methane from paddy fields and livestock, nitrous oxide from synthetic fertilisers, and emissions from biomass burning collectively make agriculture a major emitter. Livestock intensification and groundwater over-extraction amplify emissions and undermine sustainability.

Land Use as Mitigation Tool

Conversely, land can be a powerful climate ally. Practices like agroforestry, biochar application, no-till cultivation and silvopasture enhance soil carbon

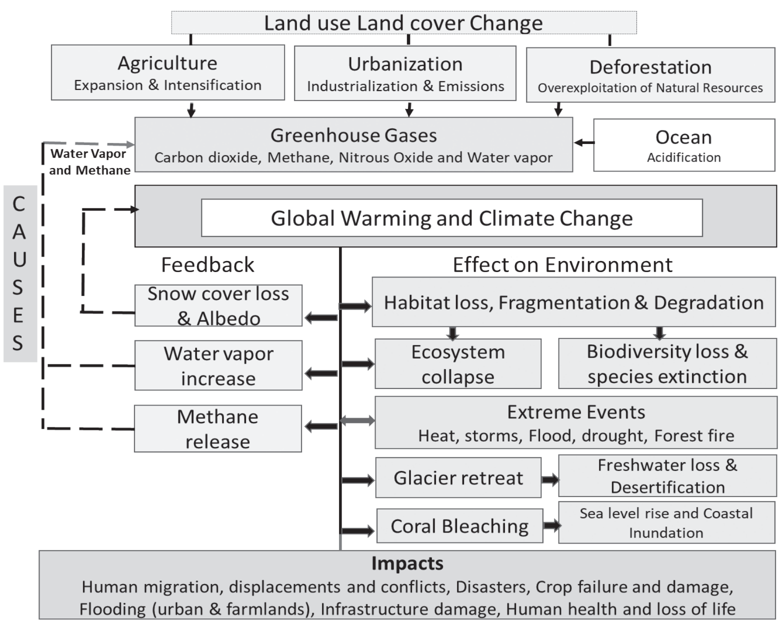

Fig. 1: Drivers and Feedbacks of Land Use and Land Cover Change (LULCC) and their Impacts on Climate and Society

Source: (Roy et al., 2022)

sequestration and biodiversity. Restoring degraded lands (estimated 96.4 million hectares in India) through watershed management and ecological farming can deliver dual mitigation–adaptation benefits.

6.5 Agriculture, Biodiversity and Agrobiodiversity

Agroecosystem Services and Decline

Industrial agriculture, driven by monoculture cropping and chemical inputs, depletes soil health, reduces water use efficiency, and erodes agrobiodiversity. Loss of traditional varieties, wild relatives and landraces narrows the genetic pool needed for climate adaptation. Pollinator decline, soil biota loss and pesticide runoff degrade ecosystem functions.

Strategies for Resilience

Resilient agriculture requires diversification. Intercropping, agroforestry, crop–livestock integration, and promotion of indigenous millets and legumes (e.g., finger millet, horsegram) support nutritional security and climate robustness. Community seed banks and farmer-managed seed systems enhance adaptive capacity.

Policy Needs

Policy frameworks must move beyond yield maximisation to sustainability metrics. Incentives for ecological farming under schemes like PKVY, integration of climate risk insurance Pradhan Mantri Fasal Bima Yojana (PMFBY) and localised agro-advisories using AI and remote sensing are essential.

6.6 India's Net Zero Challenge (Target 2070)

- **Emission Sectors:** India's carbon-intensive sectors—coal-fired power, steel, cement, transport—pose decarbonisation challenges. Yet, land and agriculture offer near-term mitigation through nature-based solutions.

Addressing fugitive emissions, urban heat island effects and energy inefficiency is vital.

- **Land Use and Agriculture:** Mitigation from land use must be balanced with food security and rural livelihoods. Sustainable intensification, precision irrigation and climate-resilient crops can reduce emissions without compromising outputs. Blue carbon (mangroves, seagrasses) also represents a vital sink.
- **Finance and Governance:** India will require approximately $10–12 trillion to achieve net zero (CEEW, 2021). This demands convergence of the National Action Plan on Climate Change (NAPCC), State Action Plans on Climate Change (SAPCCs), and flagship schemes like MGNREGA, Compensatory Afforestation Fund Management and Planning Authority (CAMPA) and Jal Jeevan Mission. Climate finance must prioritise community-based adaptation, livelihood resilience and gender equity.

6.7 Policy Framework for Climate-Resilient Land, Biodiversity and Agriculture Systems

Achieving sustainability and resilience in the face of climate change requires a robust, integrated policy framework that addresses interlinked challenges across land use, biodiversity conservation and agricultural productivity. This section outlines strategic directions to operationalise science-based planning, ecosystem stewardship and inclusive agricultural transformation in India.

- **Land Use Planning and Governance:** Scientific land use planning is essential to balance development with ecological stability. High-resolution land capability mapping using 10–5 m data from CartoSAT-3, future Resourcesat or open-source SENTINEL-1/2 enables precise zoning for agriculture, forestry, urban growth and conservation, minimising degradation and optimising land use. To manage urbanisation, formal urban growth boundaries (UGBs) must be enforced to contain sprawl, protect farmland, and preserve critical ecosystems like wetlands and buffer forests vital for climate regulation and groundwater recharge. In forestry, CAMPA funds should shift from monoculture plantations to ecologically sound reforestation, prioritising native species and hydrological restoration in degraded uplands and water-scarce areas aligning with biodiversity and watershed goals.

- **Climate, Health and Land Use Changes:** India faces growing public health risks due to climate change, urbanisation and land use shifts. Rising temperatures, erratic rainfall, water stress, air pollution and vector-borne diseases such as dengue and malaria disproportionately affect vulnerable populations, including the elderly, informal workers, and rural communities (Balakrishnan et al., 2019). These risks are compounded by degraded ecosystems, food insecurity and weakened local health infrastructure (WHO, 2021). India's National Action Plan on Climate Change and Human Health (NAPCCHH) offers a strategic foundation but must be localised through climate-resilient health plans at district and panchayat levels (Ray & Shaw, 2022). Measures such as Heat-Health Action Plans (HHAPs), climate-smart agriculture, greening urban spaces and clean energy transitions can deliver co-benefits for public health and environmental sustainability.

- **Biodiversity Conservation and Mainstreaming:** To halt biodiversity loss and enhance ecological resilience, it is essential to expand the spatial network of protected areas and promote connectivity through climate corridors. This is particularly crucial in regions like the Eastern Himalayas and Western Ghats, which host high endemic diversity and act as natural buffers against climate extremes. Establishing biogeographical linkages across fragmented habitats will enable species migration and gene flow in response to shifting climatic zones. Controlling invasive alien species is another urgent challenge. A policy mechanism should be established for Early Detection and Rapid Response (EDRR), and coordinated landscape-level eradication, using remote sensing tools, community participation, and ecological modelling. For example, managing invasive weeds like *Lantana camara* and *Neltuma juliflora* requires integrated strategies at both forest and agroecological scales. Finally, strong convergence between State Biodiversity Action Plans (SBAPs) and SAPCCs must be institutionalised to embed biodiversity within broader climate adaptation strategies. Synergy with national missions such as the National Mission for Sustaining Himalayan Ecosystems (NMSHE) and National Biodiversity Mission will support multi-level governance and financial coherence.
- **Agriculture and Climate-Resilient Rural Livelihoods:** Transforming agriculture into a

climate-resilient, resource-efficient sector is vital to ensure food security, farmer incomes and environmental sustainability. Central to this is enhancing the PMKSY, focussing on micro-irrigation methods like drip and sprinkler systems to improve water efficiency in water-stressed areas. Parallel investments in NMSA, particularly its soil health and organic farming components, will boost long-term land productivity and reduce chemical inputs. India must also promote indigenous crop varieties and livestock breeds naturally suited to local agroclimatic conditions. Genetic resources such as drought-tolerant millets and hardy breeds like *Malnad Gidda* cattle offer resilience to climate variability and require fewer external inputs, thereby supporting agrobiodiversity and rural nutrition. Additionally, risk management and advisory systems for farmers must be upgraded. Strengthening the PMFBY with greater transparency, quicker payouts and climate risk indexing can shield smallholders from climate shocks. ICT-based platforms like Digital Kisan, KVKs and state-level apps should deliver real-time advisories, pest alerts, weather forecasts, and planting guidance tailored to local contexts. This integrated policy framework emphasises the need to shift from fragmented, sectoral planning to systems-based approaches that reflect the interdependence of land, ecosystems and livelihoods. Merging geospatial intelligence, ecological science, traditional knowledge and digital innovation will be key to fostering climate-resilient landscapes and inclusive rural development.

6.8 Capacity, Awareness and International Cooperation

Building climate resilience in India requires more than technological and financial solutions—it demands behavioural change and institutional innovation. This transformation must occur across individual, community, educational and governance levels to foster long-term adaptive capacity and systemic climate integration. Mainstreaming climate education in schools, universities and civil services is essential to create climate-literate citizens and decision-makers capable of embedding climate goals into planning and implementation. Facilitating technology transfer through international partnerships—especially South-South cooperation (SSC)—is also crucial. Shared innovations in renewables, precision agriculture, resilient infrastructure and AI-based early warning systems can accelerate scalable, context-specific solutions. *Finally, to ensure coordinated action, a National Climate Resilience Council within the Office of the Principal Scientific Adviser, through the Prime Minister's Science, Technology and Innovation Advisory Council (PM-STIAC) should be established. This apex body would align adaptation and mitigation efforts across ministries and states, integrate national missions (NAPCC, CAMPA), streamline financing, and track resilience outcomes—embedding climate resilience into India's core development agenda.*

7. INTERNATIONAL PROTOCOLS AND PROGRESS TOWARDS CLIMATE TARGETS AND SDGs

7.1 Role of International Protocols in Climate Mitigation

Global climate governance is structured around a range of international protocols and institutions, each playing a pivotal role in addressing climate change and advancing SDGs. These frameworks such as UNFCCC (Kyoto Protocol, Paris Agreement) and the CBD establish legally binding and voluntary commitments for emission reductions, climate adaptation, technology transfer and climate finance. They also serve as platforms for scientific assessments (e.g., through the IPCC), transparency mechanisms, and international cooperation to align national climate actions with global temperature goals. The success of these protocols depends on robust national implementation, inclusive policy processes and sustained support for developing countries through financial and technical means.

- **Intergovernmental Panel on Climate Change (IPCC):** The IPCC, a collaboration between World Meteorological Organisation (WMO) and United Nations Environment Programme (UNEP) since 1988, produces scientific assessments to inform climate policy. The Sixth Assessment Report (AR6) emphasises limiting warming to 1.5°C and cutting emissions by 45 per cent by 2030 to achieve net zero by 2050. The IPCC highlights the urgent need for decarbonisation across sectors and supports transitions to renewable energy, electrification of transport, and sustainable agriculture practices such as agroforestry and conservation farming.
- **Food and Agriculture Organization (FAO):** FAO promotes Climate-Smart Agriculture (CSA), focussing on increased productivity, resilience and emissions reduction. Strategies include diversified climate-resilient crops, conservation agriculture, efficient water use, improved livestock and manure management and agroforestry. Sustainable forest management, reforestation and silvopastoral

systems are also key to carbon sequestration and ecosystem restoration. FAO supports rural communities with climate literacy and resources for sustainable practices.

- **International Union for Conservation of Nature (IUCN):** International Union for Conservation of Nature (IUCN) champions nature-based solutions and Ecosystem-Based Adaptation (EbA) as climate responses. Restoring forests, wetlands and grasslands not only sequesters carbon but enhances biodiversity and ecosystem services. IUCN promotes community-cantered solutions that integrate conservation with sustainable livelihoods and equitable governance.
- **Convention on Biological Diversity (CBD):** CBD addresses the dual challenges of biodiversity loss and climate change. It advocates Ecosystem-based Approaches (EbA), mainstreamed through National Biodiversity Strategies and Action Plans (NBSAPs) and National Adaptation Plans (NAPs). Key actions include forest conservation, expansion of protected areas and restoration of ecosystems such as wetlands and coral reefs, recognising their roles in carbon storage and climate resilience.
- **Conference of the Parties (COP**): COP, under the UNFCCC, provides the global platform for climate negotiations. Key outcomes include the Kyoto Protocol (1997)[1] and Paris Agreement (2015),[2] the latter aiming to limit global warming to below 2°C. COP decisions encourage countries to adopt NAPs, carbon pricing and climate finance mechanisms to support mitigation and adaptation.

7.2 Aligning with Paris Agreement and SDGs

The Paris Agreement and the Sustainable Development Goals (SDGs) are inherently interlinked, converging on the global imperative for inclusive, equitable and sustainable development. While the Paris Agreement seeks to limit global warming to well below 2°C above pre-industrial levels—with efforts to restrict it to 1.5°C, the SDGs offer a broader framework for eradicating poverty, protecting the planet, and ensuring prosperity for all. The shared objective of climate-resilient development underscores the need for integrated action across sectors. Several key mechanisms form the operational bridge between these global agendas:

- **Renewable Energy Transition:** The shift to renewable energy—solar, wind, hydro and bioenergy—is vital to reduce reliance on fossil fuels, the leading source of GHG emissions. The Paris Agreement's NDCs often prioritise expanding renewables, supporting SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Countries like India, through the International Solar Alliance, and Germany, via its *Energiewende* (energy turnaround) policy, offer scalable models for low-carbon energy transitions that also enhance energy access and security.
- **Carbon Pricing Instruments:** Carbon pricing, through mechanisms such as carbon taxes and emissions trading systems (ETS), incentivises industries and consumers to reduce their carbon footprint by internalising the environmental cost of emissions. Over 70 carbon pricing initiatives are active globally, covering more than 23 per cent of global emissions (World Bank, 2023). These instruments align with SDG 12 (Responsible

Consumption and Production) and SDG 9 (Industry, Innovation and Infrastructure) by encouraging innovation in cleaner technologies and improving resource efficiency. The European Union Emissions Trading Scheme (EU ETS) is a leading example that has significantly driven down emissions in participating sectors.

- **Nature-based Solutions (NbS):** Nature-based solutions—including reforestation, wetland restoration, conservation agriculture and agroecology—offer synergistic pathways to mitigate emissions while enhancing ecosystem resilience. These strategies simultaneously address multiple SDGs, notably SDG 15 (Life on Land), SDG 2 (Zero Hunger) and SDG 13. For instance, India's Green India Mission focusses on biodiversity conservation and improved rural livelihoods. Agroecological practices further contribute to soil health, crop diversity and food system resilience under changing climate conditions.
- **Climate Finance and Global Equity:** Climate finance mechanisms, particularly the Green Climate Fund (GCF), aim to bridge the equity gap between developed and developing nations. By mobilising resources for mitigation and adaptation projects in vulnerable regions, climate finance reinforces SDG 17 (Partnerships for the Goals) and SDG 1 (No Poverty). As of 2024, the GCF has approved over $12 billion in projects spanning renewable energy, climate-resilient agriculture and infrastructure adaptation in countries across Africa, Asia, and Small Island Developing States (SIDS). Effective financial flows also ensure just transitions,

where no community is left behind in the pursuit of decarbonisation.

- **Earth Observation for Monitoring and Accountability:** Earth observation (EO) systems, including satellite-based remote sensing and geospatial analytics, offer critical data to monitor and evaluate SDG progress and climate pledges. EO contributes to cost-effective, high-resolution and real-time monitoring of land use changes, forest cover, water resources, urban growth, crop health, and disaster risks. For example, satellites from NASA (e.g., MODIS, Landsat), ESA (Sentinel missions) and ISRO (Resourcesat, Cartosat) feed into global platforms like UN SDG Indicators Database, helping nations track indicators across SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), and SDG 2. EO-driven tools like SEPAL (FAO), Global Forest Watch and India's Bhuvan portal exemplify operational support to environmental governance and transparency.

7.3 SDG Implementation and Challenges

Accelerating the Sustainable Development Goals: Challenges, Strategies and the Path Forward

Only 17 per cent of the SDGs are on track for achievement by 2030, according to the 2024 UN progress review. This highlights an urgent need for systemic transformation across governments, global institutions and the private sector. Setbacks arise from overlapping crises—the lingering effects of COVID–19, geopolitical conflicts, mounting debt in the Global South and a major financing gap for climate and development. These challenges have strained fiscal space, weakened political momentum and undermined SDG integration into national policies.

SDG Interactions and Trade-Offs: Navigating Complex Interdependencies

While the SDGs are interconnected, trade-offs can arise when strategies lack holistic alignment. For example, large-scale afforestation or bioenergy projects may compromise food security (SDG 2) and water access (SDG 6) if poorly planned. Similarly, hydroelectric projects, though beneficial for clean energy (SDG 7) and climate action (SDG 13), can harm ecosystems (SDG 15) and displace communities (SDG 10). Resolving such conflicts requires integrated policy design, modelling frameworks and tools like multi-criteria analysis and participatory scenario planning. Cross-sectoral governance and collaboration are essential to balance trade-offs and optimise synergies.

Modelling Tools and Gaps in SDG Assessment

System dynamics models, computable general equilibrium models and network analysis are used to simulate SDG interactions and assess policy scenarios. These tools help reveal feedback loops, bottlenecks and high-impact interventions. However, methodological gaps persist—goals like gender equality (SDG 5), strong institutions (SDG 16) and partnerships (SDG 17) are often underrepresented due to complex social dimensions and limited data. To improve relevance, modelling must become more inclusive, interdisciplinary and context-sensitive. Integrating feminist economics, indigenous knowledge and community metrics can better reflect real-world inequalities. Stronger collaboration between academia, government and civil society is essential to enhance their impact and credibility.

India's Acceleration Strategy: A Multidimensional Approach

India, given its demographic scale and developmental complexity, holds a critical position in shaping global

SDG outcomes. While the country has made notable progress in areas like clean energy and financial inclusion, achievements remain uneven across states and sectors. To accelerate implementation, India must prioritise evidence-based policymaking anchored in disaggregated data to guide development plans and monitor impact. Institutionalising multi-stakeholder partnerships—spanning civil society, academia, industry and state governments—through SDG councils and thematic alliances is essential. Aligning flagship national missions such as Digital India, Jal Jeevan Mission and Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan (PM-KUSUM) with SDG targets requires integration into budgets and performance tracking systems. The use of digital technologies, including GIS, AI and remote sensing, can enhance indicator monitoring, improve service delivery, and support participatory governance. Additionally, science-based corporate sustainability should be encouraged through green taxonomies, Environmental, Social and Governance (ESG) disclosures, and regulatory frameworks that embed SDG principles in business decision-making.

7.4 Private Sector Engagement: Moving Beyond Commitment to Transformation

The private sector has increasingly aligned with the UN Global Compact and SDG frameworks, with many companies publishing sustainability reports and committing to net zero targets. However, corporate engagement often remains selective, focussing largely on SDG 3 (Health), SDG 8 (Decent Work) and SDG 13 (Climate Action), while neglecting broader integration across operations. Fewer than half of large firms have embedded SDGs into core governance, investment or supply chain practices. To maximise their role in sustainable transformation, businesses must adopt holistic strategies that embed SDGs across governance, procurement, Research and development (R&D) and stakeholder engagement; assess both positive and negative externalities to avoid SDG-washing; and use their influence to advocate for ambitious climate action, inclusive labour rights and environmental justice—particularly in emerging economies where their impact on policy and norms can be significant.

7.5 The Decade of Action: From Rhetoric to Systemic Change

The window for achieving the SDGs is rapidly narrowing, making the final stretch to 2030 a period that must be defined by urgency, ambition and innovation. This 'Decade of Action' calls for systemic transformation across key areas. Ensuring gender-balanced leadership and inclusive governance is essential to elevate marginalised voices and make development truly participatory. Accelerating net zero transitions in energy, transport and industry will require both technological innovation and equitable financing. Adopting circular economy models particularly in sectors like construction, textiles and agri-food can help decouple economic growth from resource depletion. *Finally, the SDGs must be mainstreamed into national constitutions, public finance systems and corporate frameworks, transforming them from aspirational targets into enforceable and operational mandates.*

8. POLICY RECOMMENDATIONS

To summarise, it is evident that climate change is a global phenomenon driven by the accumulation of greenhouse gases in the atmosphere, yet its impacts are highly localised and variable. While rising global temperatures, sea level rise and shifting climate patterns are worldwide in scope, the way these changes manifest differs across regions due to variations in geography, land use, socio-economic conditions, and ecological sensitivity. For example, coastal areas may experience more frequent cyclones and saltwater intrusion, while arid regions face intensified droughts and water scarcity. Mountain ecosystems may see rapid glacier melt, whereas urban zones contend with extreme heat and flooding. These uneven and location-specific effects make it essential for climate policies and adaptation strategies to be tailored to regional vulnerabilities, supported by localised climate data, community engagement and place-based resilience planning.

Drawing upon interdisciplinary insights and ground-level experiences, a set of actionable policy recommendations have been developed, which are aimed at strengthening climate resilience, promoting sustainable land governance, conserving biodiversity, and enhancing agrobiodiversity systems. These recommendations serve as a roadmap for aligning national strategies with global environmental commitments while ensuring local relevance and community participation.

8.1 Climate Change and India's Vulnerability

India must place climate change at the core of all development programmes, given its rising exposure to heatwaves, extreme rainfall, cyclones and sea level rise. Region-specific, sectoral adaptation strategies are essential, especially for vulnerable regions like the Indo-Gangetic Plains, Central Indian Plateau and coastal zones facing compounded risks from land use change and biodiversity loss. A parallel focus on public awareness and capacity building is critical. This includes:

- Enhancing local institutions' capacity to use climate data in decision-making,
- Integrating climate education into schools and media,

- Promoting community training on sustainable land use and biodiversity conservation.

Such a holistic approach will strengthen grassroots resilience and support climate-compatible, biodiversity-sensitive land transitions.

8.2 Land Use and Land Cover (LULC) Dynamics

Integrated Urban Planning for Climate-Resilient Peri-Urban Landscapes

India's unregulated urban expansion, particularly in peri-urban areas, threatens agriculture, wetlands and urban climate resilience. Conversion of natural land to built-up areas has intensified heat island effects, reduced flood buffers and fragmented ecosystems. To address this, climate-resilient urbanisation must:

- Incorporate **blue-green infrastructure** and **nature-based solutions** (e.g., green corridors, wetland restoration, permeable surfaces) into Smart City planning.
- Recognise **ecological and hydrological systems**—wetlands, floodplains and recharge zones—within urban design to reduce flooding and ensure water security.
- Recognise **grasslands as a unique ecosystem** which supports livestock use pattern for local communities.
- Institutionalise **peri-urban governance** through multi-level frameworks bridging rural-urban divides.
- Use **geospatial tools** and dynamic zoning to protect high-value farmlands and sensitive ecosystems.
- Regulate **speculative land markets** and strengthen enforcement of environmental safeguards.

- Promote **climate-sensitive infrastructure** with low emissions, water efficiency and enhanced green cover.
- Prioritise proactive planning in **fast-growing urban corridors** like Delhi–NCR, Bengaluru, Hyderabad and Pune to ensure sustainability and resilience to climate shocks.

A shift towards environmentally intelligent urban planning is essential for safeguarding public health, ecosystem services and long-term urban liveability.

Climate-Smart and Agroecologically-Informed Agricultural Transformation

Indian agriculture, crucial for rural livelihoods and food security, faces rising climate stress particularly for smallholders, with 86 per cent farming less than 2 hectares and 52 per cent of land rainfed. To enhance resilience, policies must promote climate-smart, resource-efficient and diversified systems. Key priorities include:

- **Agroecological Zonation:** Tailor cropping strategies to local climates, soils and water using indigenous and scientific knowledge.
- **Climate-Smart Agriculture:** Encourage resilient, low-input crops, diversification and sustainable practices.
- **Water-Efficient Irrigation:** Expand drip, sprinkler and integrated water management to reduce groundwater dependence.
- **Soil Health Management:** Incentivise organic methods, residue use and balanced nutrients via localised soil data.
- **Extension and Innovation:** Strengthen farmer-led platforms, digital advisories and local extension services.

- **Drone Integration:** Promote drones for efficient input use and crop monitoring, especially through Farmer Producer Organisations (FPOs) and service centres, supported by schemes like Sub-Mission on Agricultural Mechanisation (SMAM), training, and subsidies.

This equity-focussed transition is vital for safeguarding agrobiodiversity, farmer incomes and national food sovereignty in the face of climate change.

Ecologically-Sensitive and Transparent Forest Governance for Climate Resilience

India's forests are critical for carbon storage, biodiversity and livelihoods, yet net forest cover gains often mask degradation, fragmentation, and monoculture expansion. With 36 per cent of forests fire-prone and ongoing pressures from development, forest policy must integrate climate adaptation, biodiversity and community rights. Key priorities include:

- **Real-Time Monitoring:** Upgrade forest assessment using AI-enabled satellites, Light Detection and Ranging (LiDAR) and citizen inputs. Expand FIRE-ALERT[3] and develop local dashboards for rapid response.
- **Ecological Classification:** Differentiate natural forests, plantations and agroforestry in cover data, revising definitions to reflect biodiversity and ecosystem function.
- **Community Stewardship:** Strengthen Joint Forest Management (JFM) 2.0, ensure land tenure and enable participatory conservation with equitable benefit-sharing.
- **Transparency and Open Access:** Make forest data publicly available and subject to scientific peer review to enhance trust and governance innovation.

- **Resilient Restoration:** Prioritise native species in degraded areas, introduce predictive fire zoning and implement community fire management in high-risk zones.

India must shift from volume-based to ecological-quality forest governance, driven by transparency, technology, and local participation to meet climate and biodiversity goals.

8.3 Mainstream Biodiversity and Agrobiodiversity into Climate Adaptation and Rural Livelihood Strategies

India, home to over 36,150 plant and 1,23,400 animal species, faces growing biodiversity loss due to habitat fragmentation, monocultures, climate change, and neglect of traditional knowledge. Hidden losses—captured in concepts like ‘dark diversity’—weaken ecosystem resilience, even in seemingly intact landscapes. The key priorities for Biodiversity Restoration and Governance include:

- **Restore Landscape Connectivity**: Address ‘dark diversity’ by reconnecting fragmented habitats and reintroducing missing native species to strengthen ecological integrity.
- **Apply a Biodiversity Lens**: Mainstream biodiversity into agriculture, infrastructure, forestry and climate policy by assessing impacts on ecosystems and resilience.
- **Leverage Tier-III Biodiversity Data**: Strengthen People’s Biodiversity Registers (PBRs) at the village level, integrate with geospatial tools and build scientific validation and capacity within Biodiversity Management Committees.
- **Digitise Historical Biodiversity Data**: Publicly host DBT-ISRO biodiversity datasets on platforms like Bhuvan and

India Biodiversity Portal to support local conservation planning and restoration design.
- **Map and Monitor Dark Diversity**: Launch a national programme using species modelling and historical data to identify restoration priorities.
- **Ecological Restoration**: Focus on native species-based rewilding across biodiversity corridors, especially in the Western Ghats, Eastern Himalayas and Central India.
- **Enhance Habitat Connectivity**: Implement green infrastructure (e.g., riparian buffers, agroforestry) in state and district plans.
- **Update Conservation Policies**: Include community completeness and missing species in State Biodiversity Action Plans.
- **Support Traditional Agroecology**: Promote indigenous seeds, intercropping, and Traditional Ecological Knowledge (TEK) through community seed banks and on-farm conservation.
- **Empower Communities**: Incentivise local stewardship via rewilding programmes, biodiversity registers and secure land rights.

Agrobiodiversity for Climate Adaptation

India's traditional crop diversity is a key asset for climate resilience, yet it remains underutilised. Several models exist, like the Odisha Millets Mission, which highlight the value of indigenous varieties in climate-vulnerable regions. It is therefore imperative that we:

- **Integrate Agrobiodiversity into Climate Policy**: Embed agrobiodiversity targets in NDCs and SAPCCs, especially for rainfed and tribal systems.
- **Invest in Crop Conservation**: Scale in-situ and ex-situ conservation through seed banks

and farmer-led initiatives, linking to food and nutrition programmes.

- **Develop Climate-Resilient Corridors**: Strengthen connectivity to reduce genetic isolation and enable species migration.
- **Reward Ecosystem Services**: Launch PES schemes for pollinator protection and medicinal plant conservation, and promote agroecological systems.
- **Create an Agrobiodiversity Risk Index**: Map genetic erosion and climate risks to inform district-level planning and investments.
- **Build Capacity and Awareness**: Promote traditional food heritage, train biodiversity committees and support community-led demonstration models.

India must mainstream biodiversity in its agricultural and climate strategies. From restoring ecosystems to safeguarding seed sovereignty, biodiversity is not just a conservation goal—it is climate insurance for resilient livelihoods and sustainable development.

8.4 Ecologically Coherent and Socially Inclusive Implementation of the Green India Mission

The Green India Mission (GIM) must shift from a tree-centric model to a climate-adaptive, ecosystem-based strategy that respects India's diverse biogeographic regions. Misclassification of grasslands and savannahs as 'wastelands' has led to ecologically inappropriate afforestation. The key priorities for reforming GIM:

- **Ecoregional Zoning:** Implement high-resolution ecological mapping with ICAR-National Bureau of Soil Survey and Land Use Planning, ISRO and State Biodiversity Boards to tailor restoration protocols by region.

- **Grassland-Focussed Restoration:** In arid zones, prioritise grassland regeneration and soil moisture conservation over tree planting.
- **Carbon Accounting Reform:** Include below-ground carbon in national inventories and avoid plantations in high-soil-carbon systems like Banni and Shola grasslands.
- **Community-Led Planning:** Institutionalise Free, Prior and Informed Consent (FPIC), co-create plans with pastoralists and incentivise stewardship through PES.
- **Expanded Outcome Metrics:** Move beyond sapling survival to track biodiversity, soil health and livelihood outcomes using remote sensing, AI, and citizen science.
- **Ecological Literacy and Training:** Promote local awareness, blend traditional knowledge with scientific training and build capacity in gram panchayats and forest departments for participatory restoration.

A reformed GIM, rooted in ecological intelligence and community empowerment, is essential for achieving climate goals and restoring India's natural heritage.

8.5 Enhancing India's Geospatial Data Ecosystem for Climate Resilience

Unlocking Geospatial Potential for Climate Action

India's liberalised geospatial policy offers a foundation for climate-informed planning, but key gaps in resolution, real-time access and cross-sector integration remain. A targeted strategy is needed to fully leverage geospatial tools across agriculture, forestry, wetlands, urban growth and glacier monitoring.

Key Priorities for Geospatial Enablement

- **Open High-Resolution Data**: Ensure free access to 1-metre satellite imagery for public-good applications. Programmes under GIM, PM-KUSUM and Jal Shakti should mandate granular, village-level spatial data sharing.

- **Real-Time Monitoring Dashboards**: Develop sector-specific platforms integrating satellite, weather and socio-economic data with cloud-based processing and near-real-time feeds from Sentinel and Cartosat.
- **Interoperability and Data Standards**: Harmonise platforms like Bhuvan, NSDI, IUDX and ENVIS using standardised metadata and APIs. Institutionalise inter-ministerial data sharing for climate analytics.
- **Citizen Science and Ground Truthing**: Scale protocols for field validation and local ecological knowledge. Link citizen apps for tree cover, wetlands and heat stress to official observatories.
- **Accelerate Adoption of Analysis Ready Data (ARD):** India's evolving space policy has opened access to satellite data, paving the way for widespread use of Analysis Ready Data (ARD)—pre-processed, standardised geospatial datasets (with corrections for geometry, radiometry, clouds and terrain) that enable consistent, time series analysis for climate and environmental applications.
- **Launch Geospatial Hackathons and Innovation Hubs** to foster satellite data interpretation and climate applications.
- **Train Local Governments and Departments** in geospatial tools to ensure climate-smart governance at the grassroots.

A robust, inclusive geospatial ecosystem is vital for evidence-based climate action and resilience across India's diverse landscapes.

8.6 Interplay of Climate Change, Land Use, Biodiversity and Agrobiodiversity

Effective land use planning is central to balancing India's development needs with ecological sustainability. The following strategic priorities outline a roadmap for integrated, climate-resilient land governance bridging agriculture, urbanisation, biodiversity and community stewardship:

- **Integrated Cross-Sectoral Land Use Planning:** Develop spatially informed land use frameworks that align agriculture, urbanisation and biodiversity goals. Protect critical ecosystems (wetlands, forests, peri-urban zones) as no-go zones for unsustainable conversion and dismantle sectoral silos for balanced planning.
- **Reform Subsidies and Incentives:** Redirect harmful subsidies towards agroecology, regenerative farming and nature-based solutions. Penalise wetland encroachment and reward restoration through PES, carbon credits and green bonds.
- **Wetland Protection and Integration:** Eliminate the 'wasteland' label for wetlands and enforce Wetlands Rules (2017).[4] Integrate wetlands into disaster and climate plans with community-led management backed by financial and technical support.
- **Secure Land Tenure and Strengthen Community Governance:** Expand legal recognition of land rights under the Forest Rights Act. Empower local communities to govern landscapes through participatory frameworks and institutional backing.
- **Recognise Ecosystems as Natural Infrastructure:** Include forests, wetlands and agrobiodiversity in development planning

and national accounting for their climate, water and disaster regulation roles. Align budgets and investments accordingly.

- **Establish Inter-Ministerial Coordination:** Create a high-level task force under NITI Aayog or the Prime Minister's Office (PMO) to harmonise land-related policies across ministries and mainstream ecological priorities into national development.
- **Build Public Awareness and Institutional Capacity:** Promote environmental literacy through public access to land data, participatory planning and civic tools. Train Urban Local Bodies (ULBs) and Panchayats in sustainable land governance and ecological urbanism.
- **Mainstream Sustainable Land Management (SLM):** Integrate SLM practices (e.g., agroforestry, soil conservation) into national programmes like MGNREGA and PM-KUSUM, focussing on fragile regions. Leverage digital tools and low-cost innovations for scale.

9. FINAL CONCLUSION AND WAY FORWARD

The interconnected challenges of climate change, land use, agriculture, biodiversity and agrobiodiversity demand a unified, science-driven policy response. Climate change worsens land degradation, disrupts ecosystems and threatens agricultural sustainability, while unsustainable land and farming practices further accelerate emissions and biodiversity loss. This policy paper emphasises the need for integrated strategies combining climate-responsive land use, biodiversity-friendly agriculture, agrobiodiversity promotion and ecosystem-based adaptation.

The impact of climate change—from extreme weather and forest fires to declining crop yields—highlights the urgency of coordinated mitigation and adaptation. Inclusive planning must account for ecological and social vulnerabilities, particularly in coastal and rainfed regions facing climate-induced migration. There is a need for a paradigm shift from fragmented to holistic governance grounded in geospatial technologies, community engagement and fiscal realignment towards ecological priorities.

India faces converging crises of climate change, biodiversity loss and agricultural stress, intensified by erratic weather, land degradation, and declining ecosystem services. A systems-based, spatially informed approach integrating geospatial technology, traditional knowledge and coordinated policy actions is essential:

Unified Science–based Policy Approaches

Climate change intensifies systemic pressures on land resources, ecosystems and agriculture. Warming trends, disrupted rainfall, land degradation and biodiversity loss exacerbate food insecurity and ecological instability. A unified, science-based policy approach is imperative—one that aligns land use, biodiversity and agriculture within a climate-resilient and socially just development paradigm.

Systems-based Resilience Framework

India must operationalise a systems-thinking approach to climate resilience—integrating land, agriculture, biodiversity and socio-economic systems. This requires landscape-scale planning, cross-sectoral coordination and adaptive governance frameworks that are both spatially informed and ecologically grounded.

Urban Growth Boundaries (UGBs)

Legally enforceable Urban Growth Boundaries are vital to prevent unregulated urban sprawl into ecologically and agriculturally productive areas. UGBs help maintain the ecological integrity of wetlands, forests and peri-urban farmlands, which serve as carbon sinks, flood buffers, and biodiversity refuges. Integrating UGBs into state urban planning laws is key for climate-smart urbanisation.

Reorienting Green India Funds

Green India fund allocations must move beyond afforestation metrics towards holistic ecological restoration using native species, especially in degraded watersheds and semi-arid regions. Prioritising biodiversity, ecosystem function and hydrological recovery over monoculture plantations will align Green India objectives with India's global climate commitments and enhance ecological sustainability.

Expanding and Connecting Protected Areas

To address climate-induced habitat fragmentation, India must expand and interlink its protected areas, especially in ecological hotspots such as the Himalayas, the Western Ghats and the Eastern Ghats. Establishing wildlife corridors and climate refugia will support species migration, genetic exchange and ecosystem resilience, particularly under shifting climatic conditions.

Invasive Species Management (EDRR)

The proliferation of invasive species—accelerated by climate change and disturbed land use—necessitates a robust Early Detection and Rapid Response (EDRR) system. Leveraging geospatial technology, ecological modelling and participatory citizen science can enable timely interventions, protecting native species and agricultural productivity from invasive threats.

Integrated Biodiversity and Climate Governance

Integrated governance is essential to harmonise biodiversity and climate strategies. Aligning SBAPs with SAPCCs and national missions (e.g., NMSHE, National Biodiversity Mission) fosters synergy in policy implementation, resource mobilisation and monitoring. This approach strengthens ecosystem-based adaptation and climate resilience at scale.

Climate-Resilient Agriculture

Transforming agriculture to be climate-resilient requires support for micro-irrigation, organic soil amendments, agroforestry and low-emission practices. Programmes like PMKSY and NMSA should promote climate-smart crops such as millets, pulses and native livestock breeds that require fewer resources and can better withstand climatic stress.

Insurance and Digital Advisory Systems

The PMFBY must become more responsive and data-driven, using satellite-derived indicators for faster claim settlements. Digital platforms, including mobile apps and KVKs, should disseminate timely advisories on climate forecasts, pest outbreaks and best agronomic practices, empowering farmers to adapt locally.

Geointelligence and Open Spatial Data Ecosystem

Geointelligence—derived from Earth observation, GIS, AI and big data analytics—is foundational to modern climate and resource governance. Public agencies must provide **analysis-ready data products** in the open domain, ensuring usability by local governments, researchers and citizens. High-resolution **thematic spatial datasets** (on forests, wetlands, water, soil, biodiversity and land degradation) should be made available at higher granular scales, empowering decentralised planning, accountability and climate-informed decisions. High-resolution satellite imagery (10–5 m) from future Resourcesat satellite series, Sentinel-1 and 2, and similar platforms enables detailed spatial analysis of land use, vegetation cover and human settlements. This allows for precise planning in agriculture, forestry, water management and urban growth. Decision-makers must institutionalise these geospatial inputs for monitoring, zoning and sustainable resource allocation.

Key Actions to Realise the Vision

Decentralised Climate Action

Climate Change Priority: *Localised adaptation and mitigation planning aligned with national climate goals.*

Empowering local governance is vital for tailoring climate strategies to local vulnerabilities. These institutions must be equipped with climate vulnerability mapping tools, early warning systems and the capacity to prepare village-level adaptation and resilience plans. Integration with SAPCCs and the NAPCC ensures alignment with India's overarching climate commitments while allowing flexibility to address region-specific climate risks—such as droughts, floods or heat stress. Climate budgeting and participatory planning will reinforce democratic accountability and social inclusion.

A forward-looking national strategy must prioritise the National Environmental Corridors and Water Resilience Initiative to address growing climate variability. By leveraging citizen science, high-resolution water mapping, and dynamic land use assessments, this initiative will strengthen ecological and hydrological resilience. States must integrate these priorities into spatial planning, aligned with the evolving National Land Use Policy, which mandates legal obligations across governance levels for climate-adaptive development.

Investing in Ecosystem Restoration and Agroecology

Climate Change Priority: *Nature-based mitigation and adaptation through ecological restoration and sustainable agriculture.*

Ecosystem restoration enhances carbon sequestration, regulates hydrological cycles and buffers communities against climate extremes. Prioritising ecologically degraded landscapes for restoration directly supports climate mitigation goals under India's NDCs. Agroecological practices promote soil carbon storage, reduce reliance on fossil-fuel-intensive inputs, and build resilience to climatic shocks in agriculture. These approaches contribute to emission reduction while enhancing food and water security under changing climatic conditions.

Leveraging Traditional Knowledge and Citizen Science

Climate Change Priority: *Culturally rooted, inclusive adaptation and climate literacy.*

Integrating traditional knowledge into climate governance fosters context-sensitive adaptation, especially in vulnerable regions. These practices often reflect centuries of ecological balance and resource conservation, offering valuable insights into adaptive behaviours and risk reduction. Citizen science platforms can strengthen community-based climate monitoring, promote awareness of climate risks and enable real-time responses to events like floods, cyclones, or pest outbreaks. This participatory approach supports climate literacy and enhances the social acceptability of mitigation and adaptation strategies.

Managing Uncontrolled Urban Growth and Solid Waste

Climate Change Priority: *Urban climate resilience and emissions reduction through spatial regulation and circular economy models.*

Uncontrolled urban expansion increases carbon footprints, contributes to UHIs and displaces climate-buffering landscapes. Implementing UGBs, integrating green infrastructure and protecting peri-urban agricultural lands are key climate strategies to reduce urban emissions and increase resilience. Simultaneously, urban waste contributes significantly to methane emissions, a potent greenhouse gas. Effective waste segregation, recycling and treatment can mitigate emissions and reduce landfill pressure. Circular economy principles—such as reuse, composting and energy recovery must be embedded in municipal solid waste systems to support climate goals.

Aligning Fiscal and Policy Instruments

Climate Change Priority: *Realigning development finance to support low-emission, climate-resilient growth.*

Climate-smart public finance is essential to scale up climate action across sectors. Redirecting subsidies and development funds towards carbon-efficient farming, ecosystem regeneration and biodiversity conservation advances India's NDC targets. Programmes like Green India, CAMPA, MGNREGA and PMKSY can be strategically converged to fund climate mitigation (e.g., carbon sinks), adaptation (e.g., drought-proofing), and resilience (e.g., water conservation). Incorporating climate metrics into funding criteria and performance reviews will ensure accountability and climate effectiveness.

India must urgently prioritise the expansion, linkage and effective management of its natural resource assets and ecological hotspots. This is critical not only for protecting natural resources but also for sustaining vital ecosystem services amid accelerating climate change, unsustainable land use and growing resource pressures. An integrated approach must evolve to curb climate-induced land degradation, groundwater depletion, unplanned urban growth and species migration, which continue to destabilise ecological and hydrological systems. Rapid urban encroachment into peri-urban agricultural zones has caused the irreversible loss of fertile farmland and the widespread disappearance of wetlands—natural infrastructures vital for flood control, aquifer recharge and water purification. Groundwater over-extraction, driven by intensive agriculture and unchecked development, further escalates ecological stress and threatens long-term water security.

To counter these converging crises, a landscape-level conservation and land management strategy is essential—one that ensures environmental connectivity across forests, wetlands, grasslands, agricultural mosaics and degraded areas. This intersectoral (in close cooperation of different ministries) approach should foster sustainable land use, prevent fragmentation and enhance both biodiversity and water retention across ecosystems. It calls for creating environmental corridors, enforcing urban growth boundaries and restoring wetlands and catchments, backed by high-resolution satellite data, scientific land classification, geospatial monitoring, and participatory governance.

Legal instruments must be harmonised with land and water governance to secure environmental and hydrological networks. Financial mechanisms—the Green Climate Fund (GCF) and the Adaptation Fund, and domestic funds like the National Adaptation Fund for Climate Change (NAFCC)—should prioritise catchment reforestation, wetland revival, and agroecological transitions in climate change hotspots. Ultimately, this integrated strategy will not only address sustainable development but also revive groundwater tables, reduce flood risks, loss of biodiversity, enhance agricultural diversification and build climate resilience. By aligning conservation and development through spatial intelligence, institutional reform and community engagement, India can secure environmental stability and chart a path towards inclusive, sustainable growth.

India's land is not just a productive asset but a cultural and ecological heritage. By advancing climate-smart agriculture, restoring degraded landscapes and empowering local institutions, India can lead in demonstrating how inclusive, sustainable land use can drive food security, environmental justice, and long-term resilience.

Notes

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ANNEXURE

Seminar on Climate Change: Land Use & Land Cover, Biodiversity and Agrobiodiversity

Interplay, Impact, Policy Framework and Way Forward

Venue: India International Centre
Seminar room II (First Floor), Kamaladevi Complex

9 April 2025

Inauguration (1030 – 1145 hrs.)
Welcome Address: Dr P. S. Roy

Context Setting and About the Monograph: Dr Renu Swarup, Former Secretary, Department of Biotechnology

Address About SPGs: Shri K. N. Shrivastava, Director, IIC

Presentation of Report: Climate Change: Land Use & Land Cover, Biodiversity and Agrobiodiversity: Dr(s) P. S. Roy, Swati Basu, Sanjay Kumar

Special Remarks: Dr P. K. Aggarwal, Regional Programme Leader, Borlaug Institute for South Asia (BISA), CIMMYT India Office.

Panel Discussion I (1145 – 1300 hrs.)

Linkages of Climate Change and its Effects on Land Use, Land Cover, Biodiversity and Agrobiodiversity: Moderators: Dr Sanjay Kumar and Dr P. S. Roy

- **Dr Ch. Srinivasa Rao,** Director, ICAR-Indian Agricultural Research Institute
- **Prof. Sagnik Dey,** Associate Professor, Centre for Atmospheric Science, Indian Institute of Technology, Delhi
- **Dr Joy Rajbansi**, Council on Energy, Environment and Water (CEEW)

- **Dr J. V. Sharma**, Programme Director of Land Resources. The Energy and Resources Institute (TERI)
- **Prof. Pawan K. Joshi,** Professor, School of Environmental Sciences, Jawaharlal Nehru University (JNU)

Panel Discussion II (1400 – 1530 hrs.)
Policy Framework for Addressing the Challenges of Interplay of Land Use and Land Cover, Biodiversity and Agriculture with Climate Change:
Moderators: Dr Renu Swarup and Dr Swati Basu

- **Dr Gyanendra Pratap Singh**, Director, ICAR-National Bureau of Plant Genetic Resources
- **Dr Manish Kumar**, Lead, CSTEP, New Delhi
- **Dr Monalisa Sen,** Associate Director, Biodiversity, International Council for Local Environmental Initiatives (ICLEI)–South Asia, New Delhi
- **Dr Abi Tamim Vanak,** Sr. Fellow & Director, Centre for Policy Design, Ashoka Trust for Research in Ecology and the Environment (ATREE)
- **Dr K. M. Jayahari,** Country Coordinator Food and Land Use Coalition (FOLU), World Resources Institute (WRI) India office
- **Prof. Milap Punia,** Professor, Centre for the Study of Regional Development, School of Social Sciences, Jawaharlal Nehru University (JNU).

Interactive Discussion/Q&A Session and Closing

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ABOUT THE AUTHORS

Dr Renu Swarup has a PhD in Genetics and Plant Breeding. She has been Secretary, Department of Biotechnology (DBT), Government of India, where she served for over 30 years. She has been instrumental in the planning and implementation of some major national programmes, including leading the COVID–19 vaccine, diagnostic and genome sequencing mission. A Fellow of INSA, NASI and Trustee of TAAS, she is currently the Vice Chair of the International Centre for Antimicrobial Resistance Solutions (ICARS), Copenhagen, Denmark and President of the Society and Chairperson of the Governing Board of Indian Association for Cultivation of Science (IACS). She has received many awards, prominent among them being the P. Sheel Memorial Award – NASI, TWAS Regional Science Diplomacy Award and Yashwantrao Chavan National Award 2021 for Public Service.

Dr Parth Sarathi Roy has a PhD in Ecology, with his main contributions being in the Earth Observation Science: Vegetation Science, Land Use and Land Cover Change, Biodiversity and Climate Science. He spent 35 years in ISRO/DOS (1977–2012) in various scientific positions and superannuated as Director IIRS - ISRO. He has been awarded the B. P. Pal National Environmental Fellowship by Government of India and the ISRO Performance Excellence Award and Bhaskara Award by Indian Society of Remote Sensing (ISRS). He has been involved in several national projects and initiatives that aim to promote restoration, conservation, and management of natural resources in India and beyond.

Dr Swati Basu has an MSc in Physics and PhD in Air Pollution from IIT, Delhi. She is Former Scientific Secretary, Office of Principal Scientific Adviser, Government of India. Her previous positions include Director of the National Centre for Medium-Range

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Dr Sanjay Kumar, Chairman of the Agricultural Scientists Recruitment Board, New Delhi, previously served as Director of CSIR-Institute of Himalayan Bioresource Technology (CSIR-IHBT). His scientific achievements include discovering a carbon fixation pathway to boost photosynthetic efficiency, developing an autoclavable superoxide dismutase enzyme, and advancing understanding of secondary metabolism and adaptive mechanisms in plants. Dr Kumar's commitment to the bioeconomy launched startups, spurred a surge in technology transfers and expanded entrepreneurial agreements to bring institute-developed products to market. He is recognised as a distinguished scientist in the field of agricultural innovations.

Dr Reshma M. R. is an accomplished researcher in the field of Ecology, Land Use and Land Cover Change (LULCC), Climate Change and Environmental Sciences. Her field of research has been in the areas of LULCC, Species Distribution Modeling (SDM) and Quantitative Ecosystem Services. She has seamlessly integrated recent and historical LULC maps for predicting future LULC ones in different climate change scenarios in the Eastern Ghats. Her recent work pertains to data-driven solutions including remote sensing and geospatial data for various land use and conservation solutions for policy and decision-makers.

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