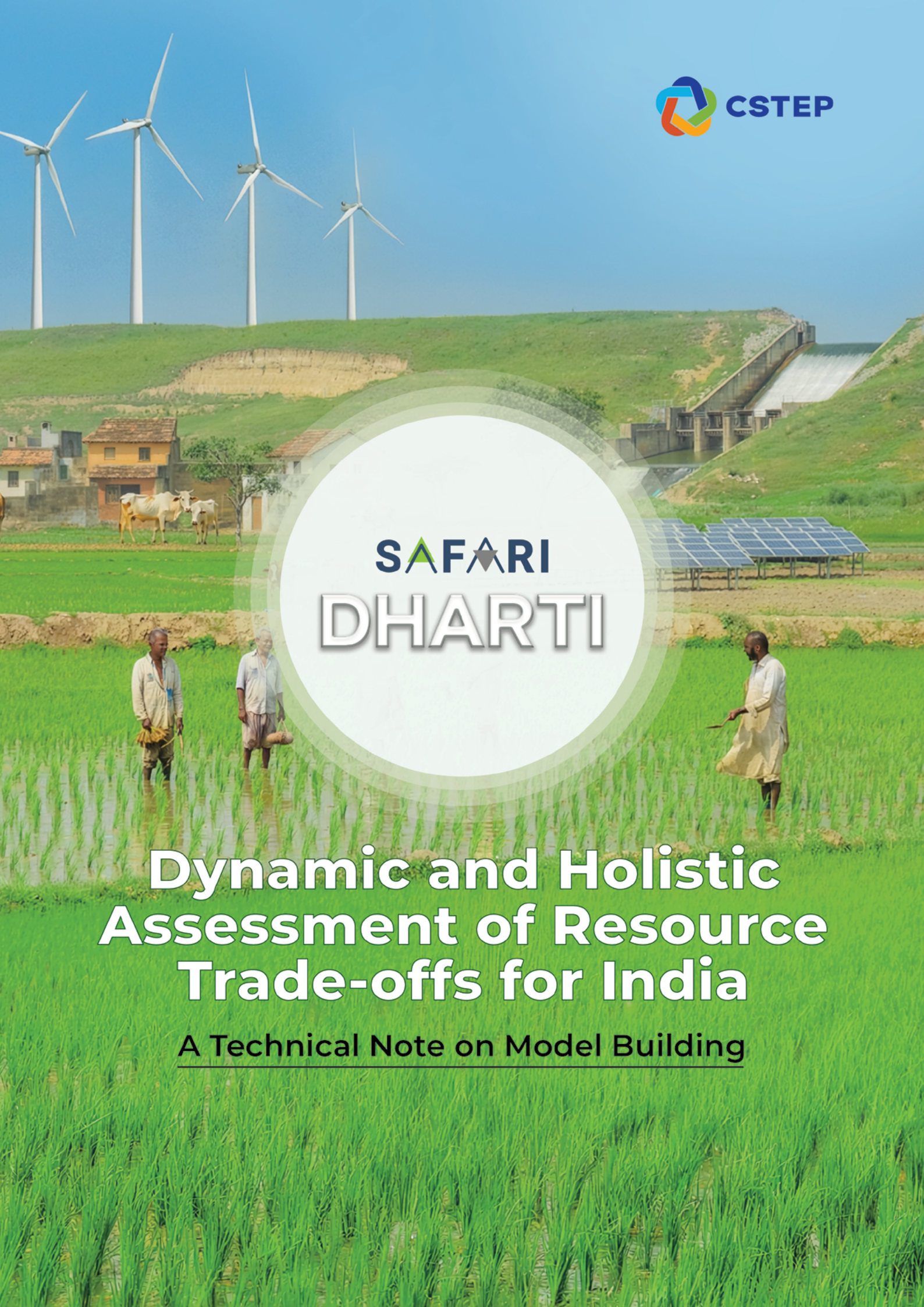



# Dynamic and Holistic Assessment of Resource Trade-offs for India

## A Technical Note on Model Building

# SAFARI-DHARTI
# Dynamic and Holistic Assessment of Resource Trade-offs for India

A Technical Note on Model Building


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# Executive Summary

Land, a critical and limited resource, is shaped by the relationship between human and natural ecosystems globally. In a country like India, with a large, growing population and ambitious decarbonisation goals, land becomes a particularly valued resource. India's Land Use, Land-Use Change, and Forestry (LULUCF) sector is a net sink of emissions, offsetting the country's total greenhouse gas emissions by 17% in 2022 (Ministry of Environment, Forest and Climate Change, Government of India, 2025), highlighting the sector's immense mitigation potential.

Land use and land-use change are dynamic, evolving processes shaped by environmental, economic, and policy drivers. Alongside the need to ensure food security, housing, and other Sustainable Development Goals, decarbonisation efforts such as forestry and renewable energy (RE) expansion also demand land, leading multiple sectors to compete for a limited resource. Moreover, while national goals are set at the central level, states and local governments largely determine land governance, implementation priorities, and the ecological impacts of land-use change. With this in mind, we endeavour to capture regional variations in land-use dynamics in this study.

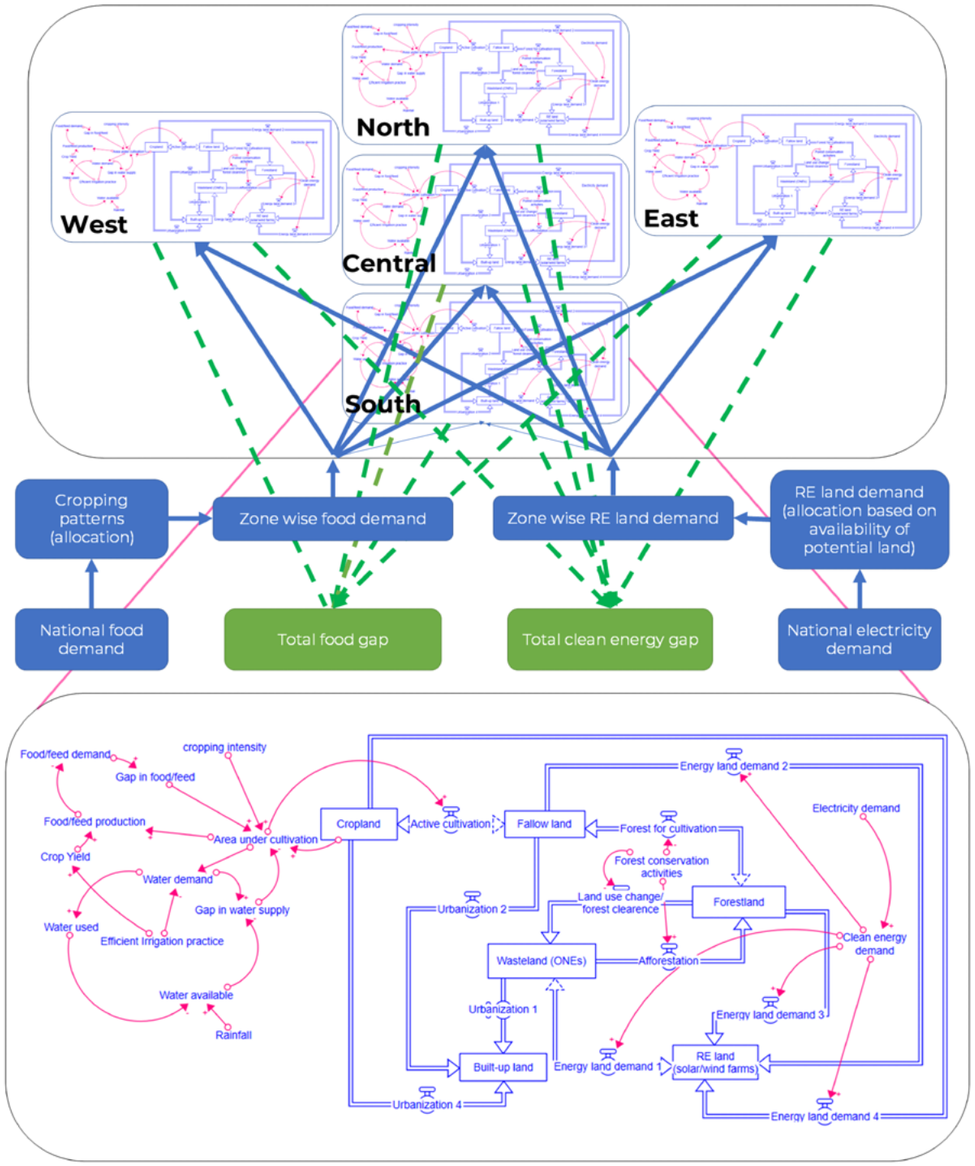
**Building SAFARI-DHARTI**

At CSTEP, we have developed two novel system dynamics models: SAFARI (Sustainable Alternative Futures for India) and its regional extension, SAFARI-R (Ashok et al., 2021; CSTEP, 2020; Kumar et al., 2021). SAFARI simulates cross-sectoral interlinkages and feedback processes across sectors, including agriculture, buildings, industry, transport, and the power sector.

SAFARI-R extends this framework by disaggregating the agricultural module across India's five hydrometeorological zones, namely, North, South, East, West, and Central, to explore the regional implications of national decisions (Ashok et al., 2021; Figure ES1).

Building on this framework, we disaggregate SAFARI's land-use module using the same zonal approach and integrate it with SAFARI-R to develop SAFARI-DHARTI (Dynamic and Holistic Assessment of Resource Trade-offs for India). Figure ES1 shows the complete model structure.

***Figure ES1:*** *Schematic diagram, zonal causal loop diagram, and stock-and-flow diagram for SAFARI-DHARTI.*




*Note: The zonal sub-models for agriculture are driven by food demand in each zone, based on the zonal allocation of national demand according to each zone's productivity capacity and cropping patterns. Similarly, the zonal sub-model for RE land is driven by RE land demand for each zone, based on the zonal allocation of national electricity demand according to the potential RE land available each year. It also accounts for land demand from other sectors in each zone, such as forest management activities, urbanisation, and available wasteland for conversion. The reported total food gap and total clean energy gap are the sum of the individual zonal dynamic gaps.*



To formulate the model, we use data from the National Remote Sensing Centre (NRSC), land-use statistics reports, and the Forest Survey of India to analyse historical land-use change patterns. We compare zonal land-use transitions with aggregated national trends and complement this analysis with qualitative reviews of representative states and expert consultations to understand local nuances.

Table ES1 summarises the national-level land-use change 'rules' and compares them with the zonal patterns. Although regional variations exist in land-use patterns (as seen in Table ES1) and policy priorities across states and zones, the dominant land conversion pathways remain broadly consistent with those observed at the national level. Accordingly, we adopted a common set of rules that apply in the national context when building SAFARI-DHARTI. We validated the model using a back-casting approach and reproduced aggregate land-use trends with accuracy of ±3% (mean absolute percentage error [MAPE]) at the national level. We initialised the model with 2011 data and back-cast for 2012 to 2021.

***Table ES1:*** *Summary of the national land-use rules and how they vary across zones, based on patterns observed in the NRSC dataset.*

| Land classes | National rule | North | East | South | West | Central |
|---|---|---|---|---|---|---|
| Fallow and net sown | Net sown expands into fallow land | Yes | Yes | Yes | Yes | Yes |
| Fallow and forest | Parts of deforested land fall under the category of 'fallow' | No | Yes | Yes | No | No |
| Forest and wasteland | Parts of deforested land fall under the category of 'wasteland' | No | Yes | Yes | Yes | No |
| Wasteland and built-up | Built-up expands into wasteland | Yes | Yes | Yes | Yes | Yes |
| Grassland and wasteland | Grassland expands into wasteland | Yes | No | No | No | No |
| Built-up and fallow | Additional built-up expansion occurs in fallow land | Yes | Yes | Yes | Yes | Yes |
| Wasteland and net sown | Net sown area can expand into wasteland when additional agricultural land is required. | Yes | Yes | Yes | Yes | Yes |

*Note: Green denotes a strong relationship similar to national rules, yellow denotes a weaker relationship similar to the national rules, grey denotes no relationship at the regional level, and orange denotes a strong opposite relationship compared to national rules.*

**What SAFARI-DHARTI can do**

SAFARI-DHARTI provides a decision-support framework for assessing how India's land resources can be allocated under different low-carbon development pathways. It is particularly useful for exploring food-first, RE-first, and balanced growth scenarios, assessing implications for land availability, emissions reduction, and development priorities in a consistent, dynamic way. Listed below are questions that can be explored using this tool:

- What are the biophysical constraints (land) of the low-carbon transition at the regional level? For instance, is there enough land to meet India's RE targets, and where will that land come from?
- How do land-use dynamics vary across regions and states, and what drives these changes? For example, do forest-related land-use changes differ drastically between the forest-rich and agriculture-dominant regions?
- What trade-offs arise when biophysical constraints and state or regional priorities do not align? For instance, is land identified for RE deployment ('wasteland') already used for grazing, or is it considered ecologically important enough to warrant conservation?
- How do regional land-use dynamics influence national outcomes? For example, does land-use pressure in one region make it harder to achieve national targets without shifting the burden elsewhere? If burden sharing is a possibility, how can it be achieved given each region's context?

At the national level, SAFARI-DHARTI can support resource-aware planning by evaluating land availability constraints and their implications for climate targets in RE, forestry, and land-based mitigation. At the state and regional levels, it enables comparisons of alternative land allocation strategies while accounting for local RE-rich, agrarian, and biodiversity-sensitive conditions, as well as land degradation risks, agri-photovoltaic opportunities, and crop diversification. Overall, the model provides a structured approach for balancing low-carbon transitions with food security, water sustainability, ecosystem protection, and state-specific development priorities.

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# Abbreviations

| Abbreviation | Definition |
|---|---|
| AFOLU | Agriculture, Forestry and Other Land Use |
| AgriPV | Agri-photovoltaics |
| CLD | Causal loop diagram |
| CSTEP | Center for Study of Science, Technology and Policy |
| DHARTI | Dynamic and Holistic Assessment of Resource Trade-offs for India |
| EV | Electric Vehicle |
| GDP | Gross domestic product |
| GHG | Greenhouse gas |
| GIS | Geographic Information System |
| GW | Gigawatt |
| IPCC | Intergovernmental Panel on Climate Change |
| ISRO | Indian Space Research Organisation |
| LULC | Land use and land cover |
| LULUCF | Land use, land-use change and forestry |
| LUS | Land Use Statistic |
| MAPE | Mean absolute percentage error |
| MDF | Moderately dense forests |
| MSME | Micro, small and medium enterprises |
| NDC | Nationally Determined Contribution |
| NRSC | National Remote Sensing Centre |
| OF | Open Forest |
| PV | Photovoltaics |
| RE | Renewable energy |
| SAFARI | Sustainable Alternative Futures for India |
| SAFARI-R | Sustainable Alternative Futures for India - Regional |
| SAPCC | State Action Plan on Climate Change |
| SDG | Sustainable Development Goals |
| VDF | Very Dense Forest |



# 1. Introduction

Land use and land-use change are critical processes that shape the relationship between human activities and natural ecosystems. A complex interplay of topographical, climatic, environmental, and socio-economic factors, including land management practices and allocation priorities, influences them.

India's land use is primarily dominated by agriculture, followed by forests, built-up areas, grasslands, and other categories, including wasteland. According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, the Agriculture, Forestry and Other Land Use (AFOLU) sector accounts for 13%–21% of global greenhouse gas (GHG) emissions (IPCC, 2023). At the same time, the Land Use, Land-Use Change and Forestry (LULUCF) sector acts as a carbon sink, offering significant mitigation potential through carbon sequestration in forest biomass and forest and agricultural soils. These mitigation measures also provide multiple co-benefits aligned with the Sustainable Development Goals (SDGs), including biodiversity conservation, water and food security, and livelihood opportunities. However, if local contexts and existing land-use patterns are not adequately considered, they may increase climate risks or create unintended trade-offs. Therefore, it is essential to incorporate local priorities and stakeholder perspectives alongside mitigation objectives to minimise trade-offs and maximise co-benefits with other economic sectors.

India's LULUCF sector is a net sink of emissions, offsetting 17% of the total greenhouse gas emissions in 2022 (Ministry of Environment, Forest and Climate Change, Government of India, 2025). This sink is largely driven by carbon stored in forests and agricultural soils, which together occupy a substantial share of India's land area. Beyond climate mitigation, land is a critical resource for economic development. As a developing nation with a rapidly growing population, India faces increasing demand for land, both for agricultural expansion to ensure food security and for urbanisation to accommodate economic growth. Additionally, India's ambitious forestry commitments, such as achieving 33% forest and tree cover and enhancing carbon sequestration potential, necessitate large-scale afforestation and reforestation efforts, further increasing land demand. The transition to a low-carbon economy adds another layer of complexity to land competition, particularly as solar and wind deployment expands.

With multiple sectors competing for limited land resources, it is crucial to assess how land allocation decisions influence trade-offs between development priorities and climate goals. A strategic, data-driven approach is needed to balance competing demands while ensuring sustainable and equitable land use planning.

## 1.1. Land use policy in India

India is a topographically diverse country, comprising 20 agroecological zones and 10 biogeographical zones (NBBSS & LUP, 2015; Rodgers et al., 2000). Administratively, it comprises 28 states and 8 union territories (Ministry of Environment, Forest and Climate Change, Government of India, 2024). Each has distinct environmental conditions, land governance systems, land feasibility, and land availability. Cultural differences also shape how communities and individuals relate to land and use it.

Land classification, tenure, and revenue administration fall primarily under state jurisdiction, resulting in regional variations in how land use is regulated across the country. At the same time, Parliament shares legislative authority over subjects such as land acquisition, forests, and property transfer and registration. Central statutes therefore overlay state-level governance, adding complexity to India's land governance dynamics.

In contrast, many developmental and climate commitments, including the SDGs, Nationally Determined Contributions (NDCs), and India's net-zero targets, are established at the national level. States must therefore reconcile national objectives with local ecological

conditions and development priorities when making land-use decisions. The complexity of national decisions and regional allocations often goes unaddressed. Furthermore, planning processes are often sector-specific, resulting in fragmented decision-making because sectors work in silos. This is increasingly visible in rising land conflicts and competing claims over the same land. These factors add a layer of social complexity to an already complex land-use sector.

## 1.2. Land–water–food–energy nexus

Land-use decisions are closely linked with water, food, and energy systems. Declining aquifer levels, erratic monsoons, stagnating crop yields, and increasing GHG emissions all interact with land dynamics to influence food and water security. Likewise, expanding renewable energy (RE) infrastructure requires land and, in some cases, water resources, further entangling sectoral priorities (Ashok et al., 2021).

Meeting net-zero goals demands that we embrace the complexity of these interlinked systems. For example, food systems are deeply interconnected with water, energy, forestry, and biodiversity (Adamovic et al., 2019). These systems are not only ecologically entwined but also vital to rural livelihoods, nutrition, and social inclusion. Climate change further intensifies these interactions. India is among the regions that are most vulnerable to climate impacts, with declining precipitation and increasing droughts leading to the drying up of wetlands and severe degradation of ecosystems (Chakraborty et al., 2023; Karmakar et al., 2023; Subramanian et al., 2023).

Despite the importance of these interdependencies, systems-level assessments of the land–water–food–energy nexus remain limited. While numerous long-term energy forecasting models exist, ranging from top-down models driven by the gross domestic product (GDP) to bottom-up development-oriented models, few explicitly represent intersectoral linkages or incorporate feedback from water and natural resource constraints (Ashok et al., 2021).

## 1.3. SAFARI and its regional extensions

At CSTEP, we have developed two novel system dynamics models: SAFARI (Sustainable Alternative Futures for India) and its regional extension, SAFARI-R (Ashok et al., 2021; CSTEP, 2020; Kumar et al., 2021). SAFARI simulates cross-sectoral interlinkages and feedback processes across the agriculture, buildings, industry, transport, and power sectors. SAFARI-R extends this framework by disaggregating the agricultural module across India's five hydrometeorological zones, namely, North, South, East, West, and Central, to examine the regional implications of national decisions (Ashok et al., 2021; Figure 1).

Building on this framework, we disaggregate SAFARI's land-use module using the same zonal approach to develop SAFARI-DHARTI (Dynamic and Holistic Assessment of Resource Trade-offs for India).

By incorporating regional land-use dynamics and state-level nuances, the model captures how land governance shapes trade-offs among competing development and climate objectives. For example, allocating more agricultural land for RE deployment may reduce land available for food production. These trade-offs arise from differences in legal and policy interactions, land classification systems, and ecological characteristics across states, as discussed in Table 1. Crucially, modelling regional land use can help identify where competition for land is greatest and support integrated land-use planning that balances RE deployment, ecological conservation, agricultural productivity, and community needs.



***Table 1:*** *Differences in land-use laws and policies across selected Indian states.*

| States/Themes | Haryana | Karnataka | Gujarat | Rajasthan | Odisha | Nagaland | Madhya Pradesh |
|---|---|---|---|---|---|---|---|
| Agricultural tenancy | Permitted. Tenants have purchase rights; sub-tenants also acquire purchase rights where land is sublet. | Near-complete prohibition on agricultural tenancy | Permitted. Tenants acquire purchase and deemed ownership rights after a specified period | Leasing permitted for fixed periods based on tenant category | Regulated. Tenancy rights of tribal communities are protected in Scheduled Areas | No codified tenancy laws. Governed primarily by customary practices | Permitted. Occupancy tenants are conferred Bhumiswami ownership rights. |
| Purchase of agricultural land | Non-agriculturists may purchase agricultural land subject to ceiling limits. | Non-agriculturists may purchase agricultural land subject to income limit criteria. | Purchase by non-agriculturists is generally restricted, except for specific purposes such as bona fide industrial purposes. | Non-agriculturists may purchase agricultural land subject to ceiling limits. | Purchase is subject to restrictions and prior approval; land transfers in Scheduled Areas are restricted for non-tribal persons. | Land ownership, transfer, and leasing are restricted to indigenous inhabitants of Nagaland. | Non-agriculturists may purchase agricultural land subject to ceiling limits. |
| Agricultural tenancy | Permitted. Tenants have purchase rights; sub-tenants also acquire purchase rights where land is sublet. | Near-complete prohibition on agricultural tenancy | Permitted. Tenants acquire purchase and deemed ownership rights after a specified period. | Leasing permitted for fixed periods based on tenant category | Regulated. Tenancy rights of tribal communities are protected in Scheduled Areas | No codified tenancy laws. Governed primarily by customary practices | Permitted. Occupancy tenants are conferred Bhumiswami ownership rights. |

| States/Themes | Haryana | Karnataka | Gujarat | Rajasthan | Odisha | Nagaland | Madhya Pradesh |
|---|---|---|---|---|---|---|---|
| Rights, conservation, and commons | Shamilat deh (village common land) is legally protected, although encroachment disputes persist. Recent amendments have permitted conversion of specific categories of common lands into private ownership. | Scheduled Caste and Scheduled Tribe land is protected. Grassland ecosystems, including Hessarghatta, receive legal protection, although implementation remains contested. | Community grazing lands and forest rights are legally recognised but remain contested in practice. | Orans and common grazing lands receive customary protection, although implementation remains contested. | Community forest rights are protected in Scheduled Areas, with Gram Sabha consent required for land diversion. Conflicts are prevalent. | A strong customary land tenure system, with Gram Sabhas managing land and consent-based decision-making. | Tribal and community forest rights are protected; Gram Sabha consent is required for land diversion in Scheduled Areas. Contested in practice. |
| Agricultural tenancy | Permitted. Tenants have purchase rights; sub-tenants also acquire purchase rights where land is sublet. | Near-complete prohibition on agricultural tenancy | Permitted. Tenants acquire purchase and deemed ownership rights after a specified period. | Leasing permitted for fixed periods based on tenant category | Regulated. Tenancy rights of tribal communities are protected in Scheduled Areas. | No codified tenancy laws. Governed primarily by customary practices. | Permitted. Occupancy tenants are conferred Bhumiswami ownership rights. |





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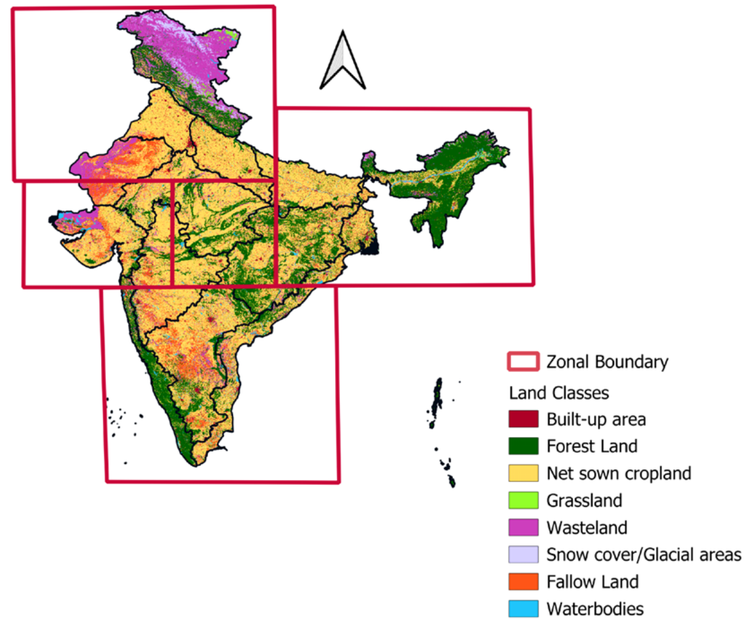
| States/Themes | Haryana | Karnataka | Gujarat | Rajasthan | Odisha | Nagaland | Madhya Pradesh |
|---|---|---|---|---|---|---|---|
| RE expansion | Panchayat land may be leased for government solar projects. Exemptions apply to land ceiling limits, land-use conversion approvals, and associated fees and charges. | Online auto-conversion of land and exemptions from land-use conversion approvals, supported by additional incentives and fee waivers through the online portal. No prior approval required from Deputy Commissioner for land-use conversion. | RE projects permitted on government wasteland and private land; land is deemed non-agricultural under policy. | Government land allocated on lease within notified RE zones. | Government land earmarked for RE projects with exemptions from ceiling limits, stamp duty, and land conversion charges; community consent retained. | RE projects require negotiation with village councils and landowners under customary land ownership. Floating solar is promoted to reduce land demand. | Government land available at concessional rates; 50% reimbursement of stamp duty on private land. |

*Note: Colours indicate the regions to which the states belong: orange for northern, blue for southern, yellow for western, green for eastern, and purple for central India.*



In this study, we integrate the disaggregated land-use and agriculture modules within SAFARI to develop SAFARI-DHARTI, providing a more granular and dynamic representation of the land–water–food–energy nexus. The framework supports more informed planning for India's low-carbon transition by enabling the assessment of land-use trade-offs while recognising ecological sustainability, food security, and equitable development as interconnected priorities rather than competing objectives. This document describes the methodology used to develop the disaggregated land-use model, SAFARI-DHARTI.

***Figure 1:*** *Hydrometeorological zones of India considered in the study.*




*Note: The zones are adopted from Bhanja et al. (2017). The land classes are derived from reclassifying the 2023–24 land use and land cover (LULC) map provided by the National Remote Sensing Centre (NRSC,).*

This report is organised into four methodological steps. The first step is to collect data from three primary land-use datasets—the NRSC LULC maps, Land Use Statistics (LUS) reports, and Forest Survey of India data—and harmonise them by reconciling their classification systems into six common land classes (Chapter 2). Second, we conducted a GIS-based spatial analysis to estimate land areas within India's five hydrometeorological zones—North, South, East, West, and Central—by overlaying the NRSC LULC maps with the zonal boundaries and reclassifying the resulting 18 land-use categories to align with the national model (Section 2.4). Third, regional analyses were conducted to formulate the model's land-use transition rules, including correlation analyses of historical land-use trends and comparisons with national-level patterns; state-level case studies interrogating anomalies; and incorporation of the policy and governance context (Chapter 3). The fourth is integrating these zonal rules and land-area estimates into the SAFARI-DHARTI model—extending the national land use and agriculture modules into five regional sub-models—and back-casting and validating the resulting model structure (Sections 3.2 and 3.3). Chapter 4 concludes the report and outlines the way forward.



# 2. Data and Methodology

In India, three major datasets are used to characterise land use: 1) the annual LULC 250K maps produced by the NRSC, Hyderabad; 2) Land Use Statistics, published by the Department of Agriculture and Farmers Welfare, Government of India; and 3) the India State of Forest Report published by the Forest Survey of India.

## 2.1. NRSC's LULC maps

The NRSC, under the Indian Space Research Organisation (ISRO), has published LULC maps since 2005–06.

The NRSC produces LULC maps at two spatial resolutions: 1:50,000 and 1:250,000 (NRSC, 2024). Owing to the greater processing requirements, the finer 1:50,000-scale maps are released every five years, whereas the 1:250,000-scale maps are released annually. This annual dataset comprises 18 land-use classes, which were reclassified into the 6 land categories aligned with IPCC categories for this study (CSTEP, 2024). In this study, due to a lack of data, we included the Wetland category; the 'Other land' category is named 'Wasteland'; and the 'Cropland' category is disaggregated into 'Net sown cropland' and 'Fallow land'.

## 2.2. Land Use Statistics

The Land Use Statistics reports (Ministry of Agriculture and Farmers Welfare, 2023) classify land into nine categories, with agricultural land further disaggregated by crop type. The dataset provides land-use statistics from 1980 onwards, enabling analysis of long-term land-use trends. However, data for 2015–16 to 2023–24 remain provisional and may be revised.

The Land Use Statistics reports compile information from the Agricultural Census, the State Directorates of Economics and Statistics, and the Forest Survey of India. To enable comparison with the NRSC dataset, the nine Land Use Statistics land classes were mapped to the six IPCC land categories (CSTEP, 2024). Within SAFARI-DHARTI, however, only the crop-wise disaggregation of net sown area provides greater detail for the agriculture module.

## 2.3. Forest Survey of India

The Forest Survey of India defines forest cover as land of at least one hectare with a tree canopy density of 10% or more. Forest cover is classified into three different density classes:

- very dense forest (VDF): canopy density greater than 70%;
- moderately dense forest (MDF): canopy density between 40% and 70%; and
- open forest (OF): canopy density between 10% and 40%.

The Forest Survey of India also reports tree cover, which includes tree-covered areas smaller than one hectare outside recorded forest area, such as parks, highways, roadside plantations, and railway corridors. Because India's NDCs include targets to expand both forest and tree cover, SAFARI-DHARTI includes both categories. Further details of the national forestry module in SAFARI are available in CSTEP's (2024, 2023) reports.

## 2.4. GIS-based regional land quantification

This study uses India's five hydrometeorological zones, defined by river basins and water availability (Figure 1). The Northern region comprises both the Himalayan and the Indo-Gangetic Plain states. The Eastern region includes the eastern and northeastern states. The Southern region comprises Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, and Telangana. The Western region includes Gujarat, southern Rajasthan, and western Maharashtra. The Central region covers Madhya Pradesh, parts of Chhattisgarh, Maharashtra's Vidarbha region, and south-eastern parts of Rajasthan (Hadoti plateau).

Because several states span more than one hydrometeorological zone, we first mapped state areas across the five regions. We then used GIS-based spatial analysis to quantify the area under each land-use class within each zone. The workflow comprised the following steps:

1. Annual LULC 250K maps (1:250,000 scale) for 2005-06 to 2024–25 were obtained from the Bhuvan Geoportal. The datasets have a spatial resolution of 56 m (NRSC, n.d.).

2. The LULC maps were overlaid with the hydrometeorological zonal boundary layer (Figure 1) to estimate the area under each of the 18 NRSC land-use classes within each region.

3. These 18 NRSC land-use classes were subsequently reclassified into the six land-use categories used in the national SAFARI model—net sown area, current fallow, forest, wasteland, built-up area, and grassland area—to ensure consistency with both the national model and the IPCC land-use classification. As in the national model, the analysis excluded water bodies and snow/glacier classes.



# 3. Model Building

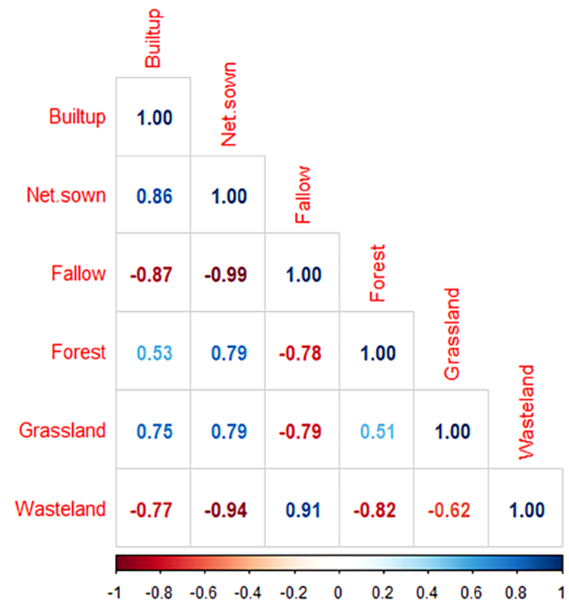
## 3.1. Regional assessments and establishment of logical flows

Although each hydrometeorological region encompasses a range of climatic zones and landscapes, it was important to understand how the regions differ. As part of the intuition-building process, we selected one representative state from each region as a case study to understand state priorities and land allocation across sectors. In the Eastern region, however, we selected two states to account for the distinct land governance systems in the northeastern states.

The selection of the states was based on two criteria: (i) the complete state should be within the zone's boundary to attribute the state-level findings to a single zone and (ii) the state contributes significantly towards a national goal or target. Using the state-level analysis as a benchmark, we assessed the land-use change patterns for the corresponding region. This helped explain regional land-use patterns in the context of state-level priorities and governance.

For each region, we performed a Pearson correlation analysis and compared the results with the national correlation matrix (Figure 2). However, correlation between land class-area time series does not establish that one class is converting into another. Because all the land classes sum to a near-fixed total, negative correlations are partly forced, and any two trending series will correlate regardless of cause. This is a limitation of correlation estimation. In this study, we contextualise the observed correlations through a structured review of the land-use literature and expert elicitation following the ecosystem knowledge sharing approach. The following sections present the findings from the regional analyses and the corresponding state case studies.

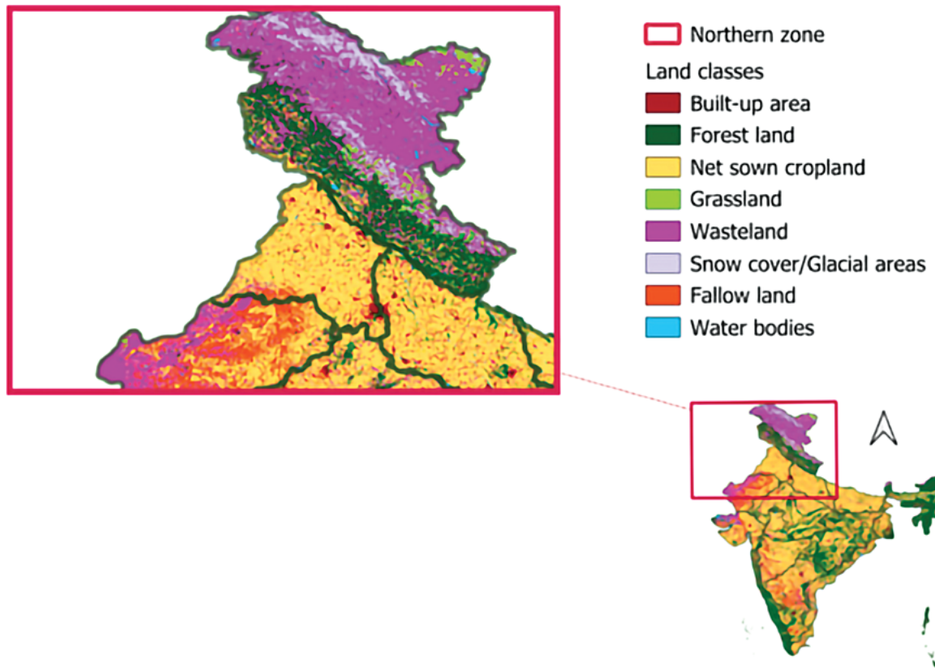
***Figure 2:*** *National-level Pearson correlation matrix based on NRSC LULC 250K data for 2005-06 to 2023-24.*



### 3.1.1. Northern region

The Northern region comprises two broad categories of states. The plains states, such as Haryana, Punjab, and northern Rajasthan, are predominantly agricultural, whereas the Himalayan states, including Uttarakhand, Himachal Pradesh, and Jammu and Kashmir, are characterised by extensive forest cover (Figure 3). Given this diversity, land-use priorities and the resulting conflicts vary considerably across the region. For example, in the plains, where agriculture is the dominant land use, conflicts often arise from converting agricultural land for industrial development and infrastructure such as roads and housing. In contrast, in the Himalayan states, converting forest land for orchard plantations and hydropower projects raises important ecological concerns.

***Figure 3:*** *Landforms in the Northern region.*

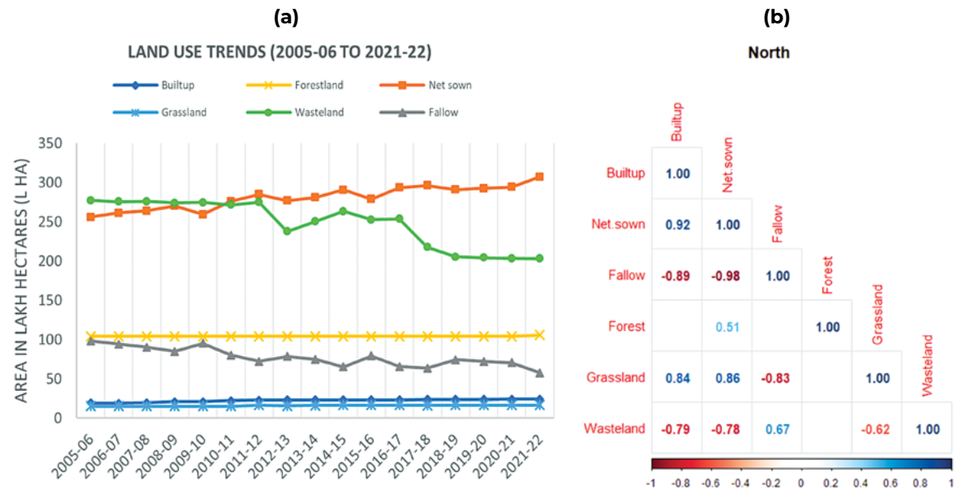



Across the Northern region, agricultural land and built-up area have increased slightly over time, while wasteland has continued to decline (Figure 4a). The regional correlation matrix suggests that this trend may be driven by the conversion of wasteland into built-up and agricultural land (Figure 4b). Fallow land and net sown area continue to interact dynamically in response to annual cropping patterns.





***Figure 4:*** *Northern region: (a) land-use trends and (b) correlation matrix.*



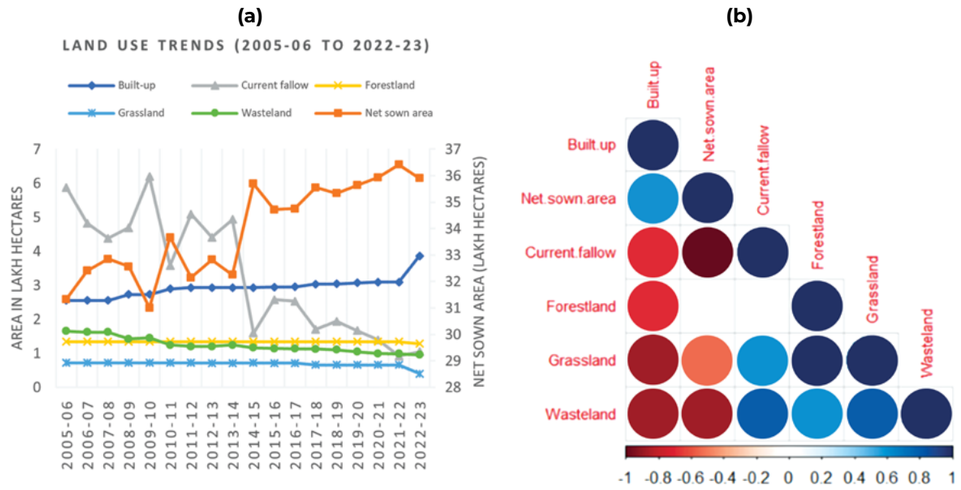

**Case study: Haryana**

In terms of land use, Haryana is predominantly agricultural, with nearly 80% of its land under cultivation (Figure 5a). Haryana plays a key role in India's food security, contributing 4.33% of rice, 9.87% of wheat, and more than 5% of total food production nationwide (Ministry of Food Processing Industries, 2025). Notably, land use intensity (cropping intensity) is very high. This implies that meeting additional agricultural demand will require converting new land, as opportunities to further intensify agricultural production on existing farmland are increasingly limited. Combined with competing demands from urban expansion, infrastructure development, and RE deployment, this places considerable pressure on the state's remaining land resources. The state also has limited notified forest cover, which accounts for just 3.9% of its geographical area.

Over the years, forest, grassland, and wasteland areas have shown a declining trend, while built-up area has increased considerably (Figure 5a). In contrast, the area under agriculture (net sown area and current fallow) has remained relatively stable over time. However, similar to regional and national trends, fallow land and net sown area interact dynamically in response to annual cropping patterns.

A historical correlation matrix (Figure 5b) indicates that built-up area is negatively correlated with all other land-use categories, except net sown area. The positive correlation between net sown area and built-up area may seem counterintuitive from a land-conversion perspective but likely reflects their shared response to underlying drivers, particularly population growth and economic development (i.e. GDP), rather than a direct conversion relationship.

***Figure 5:*** *Haryana: (a) land-use trends and (b) correlation matrix.*




Haryana's State Action Plan on Climate Change (SAPCC) identifies actions related to agriculture, land restoration, forestry, and water management that are closely linked to land-use change and directly affect RE deployment. By promoting crop diversification, agroforestry, soil restoration, and efficient water use, the SAPCC supports a gradual transition from intensive monocropping towards more flexible and multifunctional land-use systems. These measures could also create opportunities for co-located RE solutions, including agri-photovoltaics (agriPV), canal-top solar, and rooftop solar PV, while prioritising degraded lands for utility-scale projects. Such approaches can help reduce land conflicts among food production, carbon sequestration, and RE expansion.

Against this backdrop, it is important to examine how land-use patterns and climate action policies in Haryana influence the scope, siting, and configuration of RE deployment. This can help identify pathways that minimise land-use conflicts while supporting both climate and development objectives.

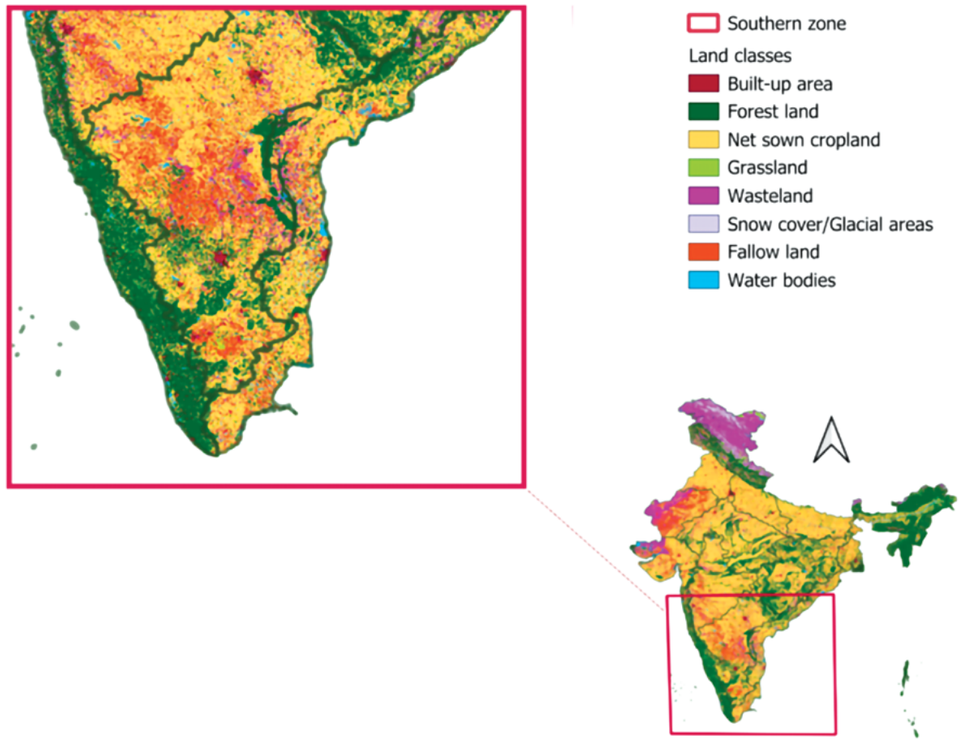




## 3.1.2. Southern region

Southern India consists of Karnataka, Andhra Pradesh, Telangana, Tamil Nadu, and Kerala (Figure 6). Most of the Western Ghats and some parts of the Eastern Ghats fall in this region. Across southern India, land-use dynamics are driven less by land availability and more by intense competition among agriculture, forests, and built-up areas. The key challenge is not the quantity of land available but its quality, which makes land-use decisions difficult and often irreversible.

***Figure 6:*** *Landforms in the Southern region.*



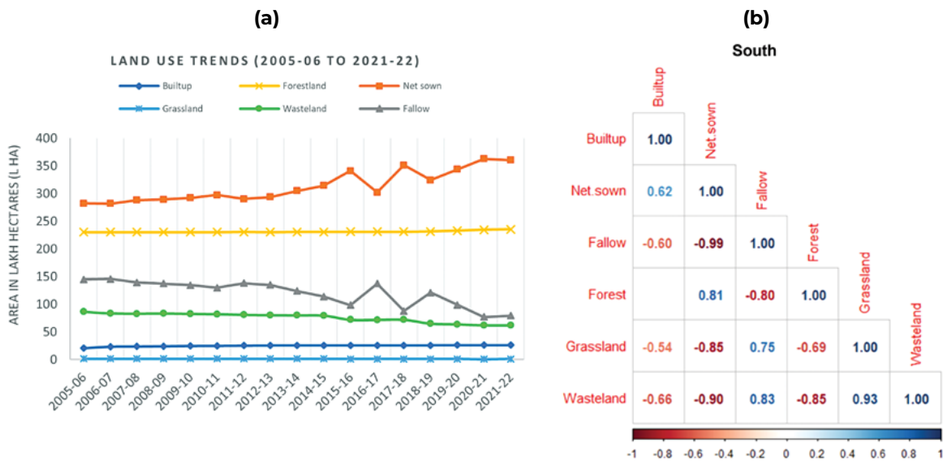

Beyond forests and agriculture, wetlands and peri-urban areas are emerging as some of the most stressed and contested landscapes. Land-use pressures also vary across states. Kerala and Tamil Nadu are increasingly constrained by ecological sensitivity and water stress, whereas Karnataka, Andhra Pradesh, and Telangana face greater pressure from infrastructure development and economic diversification. Evidence also demonstrates how these broader trends translate into on-the-ground conflicts over land ownership, livelihoods, and access to natural resources (Land Conflict Watch, n.d.).

Southern India is entering a phase of intensified competition for scarce, high-value land, making early intervention, integrated planning, and conflict-sensitive governance increasingly important. Although state-level trajectories differ, the regional trend highlights the need to explicitly manage land-use trade-offs rather than rely on economic growth alone to resolve them.

At the regional level, net sown area and built-up land have gradually increased, while fallow land and wasteland have steadily declined (Figure 7a). Forest areas have remained relatively stable, suggesting limited scope for further conversion. The regional correlation matrix indicates that the expansion of agriculture and built-up areas is likely occurring at the expense of wasteland, grassland, and fallow land, reflecting increasing pressure on

available land resources (Figure 7b). The strong inverse relationship between net sown area and fallow land also suggests shifts in cropping patterns and cultivation intensity over time. In addition, the close relationship between grassland and wasteland indicates that these ecologically sensitive land types are undergoing similar land-use transitions under increasing development pressure.

***Figure 7:*** *Southern region: (a) land-use trends and (b) correlation matrix*



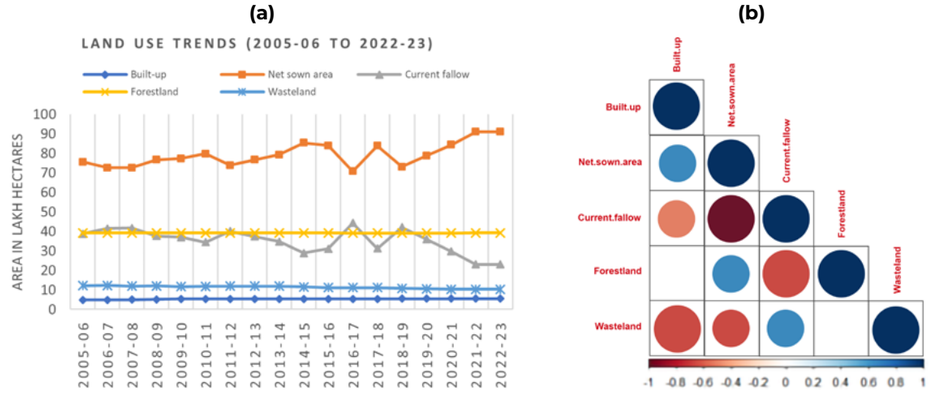

**Case study: Karnataka**

Karnataka plays a pivotal role in national economic growth through proactive policies that support RE deployment and industrialisation. At the same time, NRSC data shows the state had nearly 114 lakh hectares of net agricultural land in 2022–23, including both cropland and fallow land. Diverse agro-climatic zones support agriculture and enable the cultivation of a wide range of crops, including rice, pulses, sugarcane, oilseeds, and cotton. Karnataka also has an extensive forest cover spanning nearly one-fifth of its geographical area, ranging from the evergreen forests of the Western Ghats to the dry deciduous forests of the Deccan Plateau, underscoring the ecological importance of conserving and restoring these diverse ecosystems.

Similar to the broader regional trends, land-use change in Karnataka (Figure 8a) is driven largely by transitions within open and underutilised land categories rather than by the direct conversion of forests or productive agricultural land. Urban expansion is increasingly occurring on fallow land and wasteland, while changes in net sown area largely reflect cyclical shifts in agriculture driven by climatic conditions (Figure 8b). Overall, these patterns indicate increasing pressure on open landscapes and highlight the need for strategic land-use planning and management.



***Figure 8:*** *Karnataka: (a) land-use trends and (b) correlation matrix.*




Karnataka is already a leading state in RE deployment, with about 19.42 GW installed as of June 2026 (KREDL, 2026). The Karnataka Renewable Energy Policy 2022–27 targets a further 10 GW, including at least 1 GW of rooftop solar, by 2027 (Energy Department, 2021). The policy leaves land acquisition to developers, who either acquire or lease the land they need. It also reimburses land conversion fees in full. However, the state's high solar and wind corridors (Chitradurga, Koppal, Gadag, Vijayapura, Ballari, and Raichur) overlap with rainfed and irrigated agricultural belts, commons, and forest-fringe areas. This raises concerns about future conflicts over food security, livelihoods, and ecology. Linking land planning directly to RE target-setting would let the state move from reactive remedy to proactive, system-level planning.

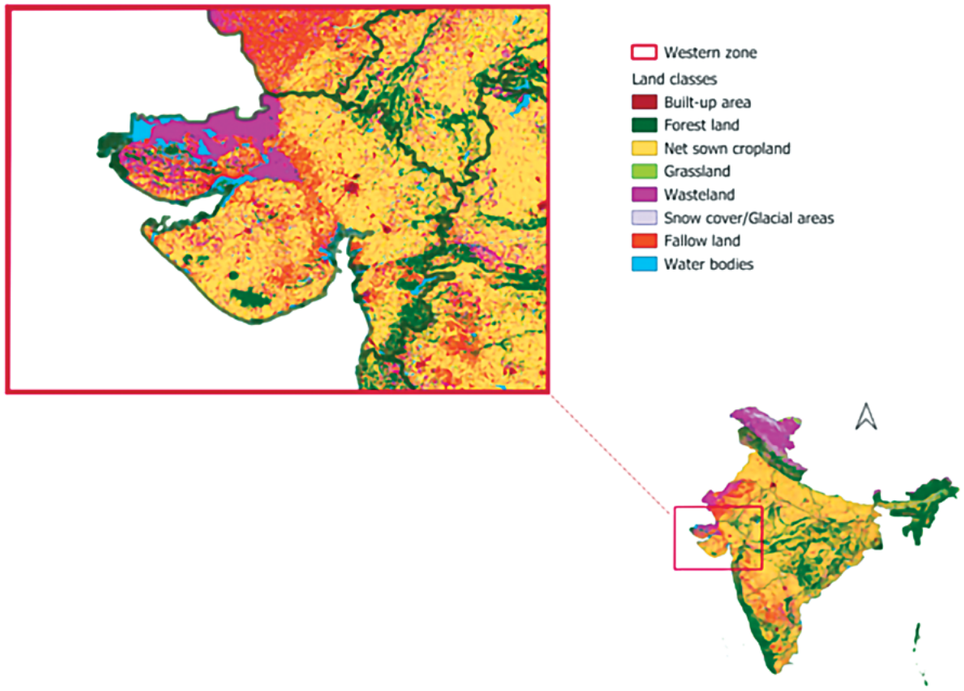


### 3.1.3. Western region

The Western region comprises the arid states of Gujarat, southern Rajasthan, and parts of Maharashtra, including some coastal areas and the northern Western Ghats (Figure 9). Interestingly, much of this region shares common characteristics of aridity and dry landscapes, irrespective of state boundaries. However, seasonal rainfall in the Western Ghats supports moderately dense forests in parts of Maharashtra.

Across the broader Western region, particularly in southern Rajasthan and northern Maharashtra, areas of forest cover, such as thorny forests and dry deciduous forests, overlap with areas of high RE potential, especially for solar and wind projects. This suggests that land-use conflicts may intensify as RE expansion increasingly overlaps with ecologically sensitive landscapes and commons-dependent areas.

***Figure 9:*** *Landforms in the Western region.*

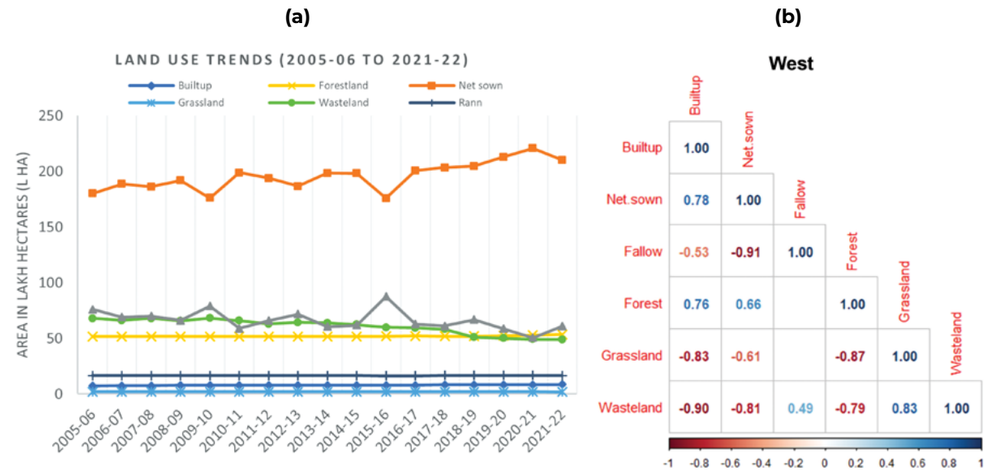



The Western region has a relatively large net sown area, which has increased over the past two decades (Figure 10a). A clear inverse relationship is observed between net sown area and fallow land, with both exhibiting closely mirroring trends over time. The regional correlation matrix indicates associations between declines in fallow land and wasteland and increases in built-up areas and net sown area (Figure 10b). In addition, grasslands and wastelands show a tendency to increase alongside forest cover, while wasteland also shows a positive association with grassland.





***Figure 10:*** *Western region: (a) land-use trends and (b) correlation matrix.*




**Case study: Gujarat**

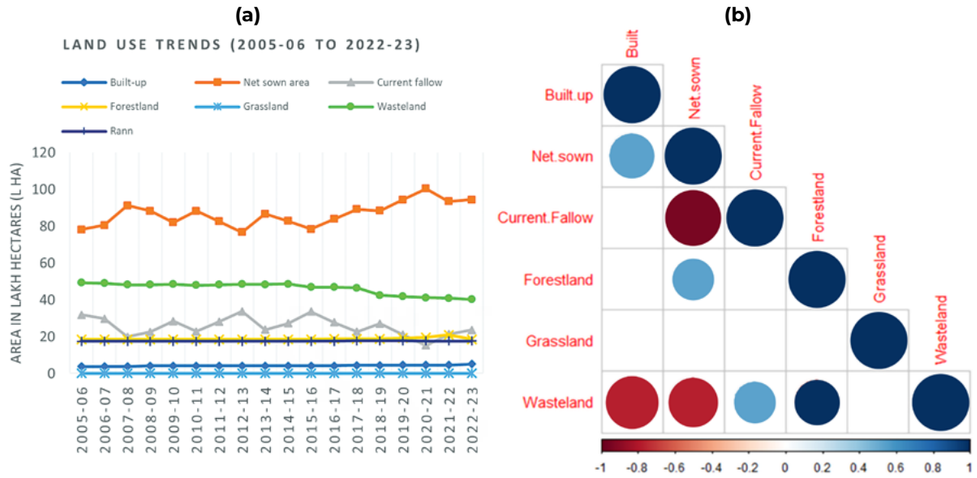
Gujarat is one of India's most industrially advanced states and a major contributor to national economic growth. The state has a highly urbanised, industry-led economy driven by manufacturing, petrochemicals, services, trade, logistics, agriculture, and construction. Rapid industrialisation and infrastructure development have strengthened Gujarat's position as an economic hub while simultaneously increasing pressure on land and natural resources.

Agriculture in Gujarat operates under semi-arid, water-scarce conditions where irrigation is critical for productivity. The state is a leading producer of cotton, groundnut, bajra, wheat, rice, sugarcane, and horticultural crops such as mango, banana, and date palm, supported by a strong dairy cooperative network. However, climate variability, erratic rainfall, and groundwater stress are driving a gradual shift towards drought-resilient crops and increasing reliance on irrigation infrastructure, including canals and check dams, while maintaining agricultural productivity and food security remains a key challenge.

Despite its relatively low forest cover, Gujarat contains ecologically sensitive forests in the eastern tribal belt and mangrove ecosystems along the Gulf of Kutch and the Gulf of Khambhat. These ecosystems provide important services, including biodiversity conservation, coastal protection, and climate resilience, but continue to face pressure from industrial expansion, mining, and infrastructure development, leading to habitat fragmentation and localised ecological stress.

Land-use trends indicate a continued shift towards industrialisation and infrastructure development, with increases in built-up area (Figure 11a), RE infrastructure, and net sown area over time. Wasteland is increasingly being repurposed for agriculture, industry, and RE (Figure 11b), while the extent of fallow land has declined. These trends reflect a broader transition in which development is reshaping agricultural and ecological buffers, even as afforestation and tree cover show localised gains.

***Figure 11:*** *Gujarat: (a) land-use trends and (b) correlation matrix.*



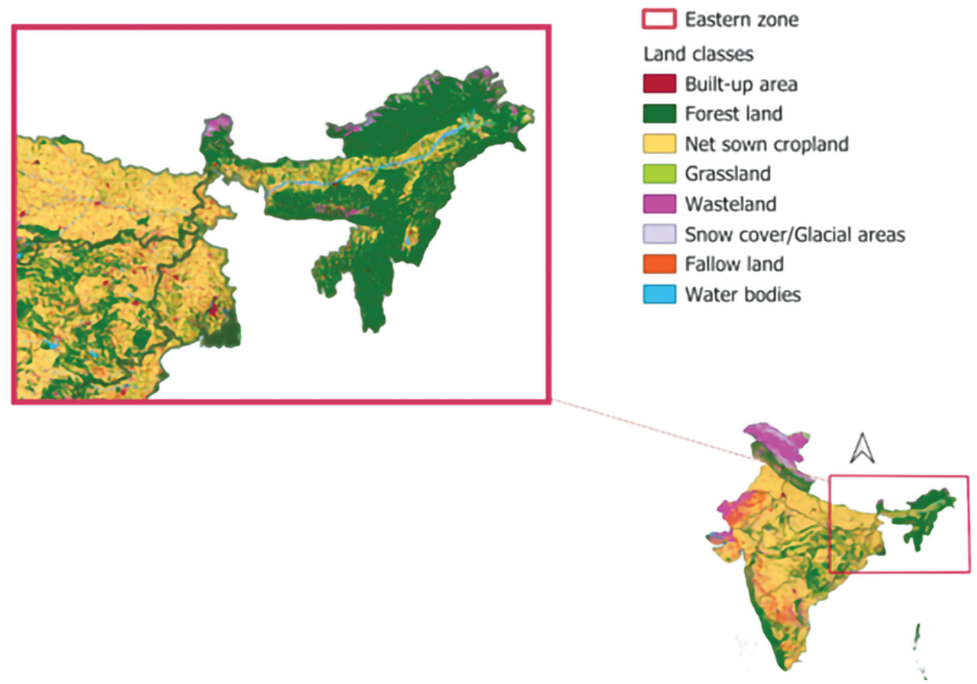

The state has adopted ambitious long-term targets, including achieving net-zero emissions by 2047 and expanding RE capacity to 100 GW by 2030 and 300 GW by 2047, with 50% of installed power capacity expected to come from wind, solar, and hydropower by 2030. Policy measures include allocating fallow and non-fertile land for RE parks while improving agricultural productivity to ensure food and nutritional security for a growing population. Gujarat also seeks to strengthen biodiversity conservation through afforestation, restoration of degraded lands, protection of grasslands, and conservation of migratory species' habitats. Overall, the state's development pathway is shaped by the dual objective of becoming a global industrial hub while expanding urban and rural infrastructure within a resource-constrained environment.



## 3.1.4. Eastern region

The Eastern region in this model includes the eastern rice belt states of Odisha, West Bengal, Bihar, and Jharkhand, as well as the northeastern states with extensive forest cover (Figure 12). Despite their apparent differences, these states share a rich endowment of natural resources that have historically contributed to India's development. Around 55% of India's rice production comes from these states (Mohanty & Yamano, 2017). Further, nearly 65% of the country's coal reserves are located in this region (Ministry of Statistics and Programme Implementation, 2024). In addition, despite their relatively small geographical area, the northeastern states make significant contributions to the national economy through tea production, timber and bamboo, limestone and coal reserves, and hydrocarbon resources (Press Information Bureau, 2026).

***Figure 12:*** *Landforms in the Eastern region.*

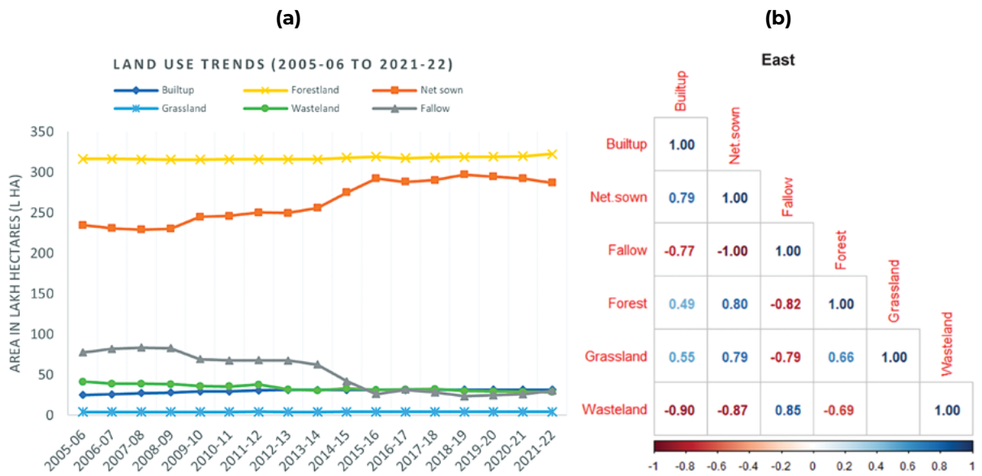



Across the region, growing pressures from RE expansion, urbanisation, conservation priorities, and large infrastructure projects are intensifying competition for land and natural resources. Large-scale solar, green hydrogen, hydropower, and urban infrastructure projects increasingly overlap with ecologically sensitive areas, commons, peri-urban landscapes, and community-owned land. At the same time, conservation initiatives—including afforestation, wetland restoration, and forest protection—often intersect with customary land rights and traditional land-use systems, particularly in states such as Mizoram, Arunachal Pradesh, and Assam. These overlapping demands create complex governance and implementation challenges, making integrated and sustainable land-use planning increasingly important.

Land-use trends indicate that forests remain the dominant land-use category across the region (Figure 13a). Net sown area and current fallow land exhibit closely mirrored trends, suggesting an inverse relationship between the two, driven by both the dominance of agriculture across the eastern rice belt states and the prevalence of shifting cultivation in the Northeast. In the northeastern states, cyclical cultivation practices result in periodic transitions between cultivated land and fallow, while variations in agricultural land use across the eastern states further shape these trends.

The regional correlation matrix suggests that wasteland and fallow land are being converted into built-up areas (Figure 13b). Grasslands appear relatively stable, with limited evidence of significant change over time. In addition, the conversion of wasteland to forest is observed, indicating localised afforestation or natural regeneration.

***Figure 13:*** *Eastern region: (a) land-use trends and (b) correlation matrix.*




Given the distinct land governance systems in the northeastern states, two case studies—Odisha and Nagaland—were selected to illustrate the diversity of land-use dynamics within the Eastern region.

**Case study: Odisha**

Odisha is a mineral-rich coastal state that plays a major role in India's mining and heavy industry sectors. It is a leading producer of iron ore, coal, and bauxite, supporting the steel, aluminium, and energy industries while also having a large tribal population that depends heavily on forests and natural resources for livelihoods. As a result, land governance in the state is closely linked to both economic development and social equity, with persistent trade-offs between resource extraction and conservation.

Agriculture is predominantly rainfed and highly dependent on monsoon variability. Paddy is the principal crop, along with pulses, oilseeds, and horticultural crops such as cashew and coconut. While net sown area has gradually increased, productivity remains constrained by fragmented landholdings, uneven irrigation access, and other structural limitations. The fertile Mahanadi delta supports intensive cultivation, whereas upland and tribal regions remain less productive, raising concerns that agricultural expansion may become increasingly land- and energy-intensive under climate stress.

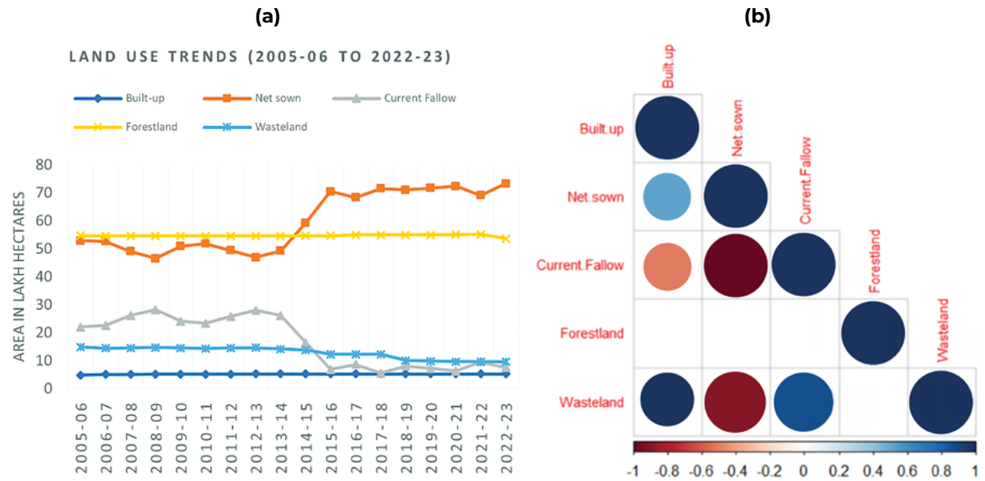
Odisha also has one of the highest forest covers in eastern India, particularly in tribal-dominated districts. These forests, including those in the ecologically sensitive Eastern Ghats, provide critical ecosystem services such as water regulation, carbon storage, and livelihood support. However, they face increasing pressure from mining, industrial expansion, infrastructure development, and competing land demands, increasing the risk of forest degradation, fragmentation, and displacement.

Land-use change in Odisha reflects the structural tension between mineral-driven industrialisation and ecological and agricultural systems (Figure 14a). Over the past two decades, forest cover has remained relatively stable, while built-up areas have expanded steadily due to urbanisation and industrial growth. Net sown area has increased gradually, alongside cyclical shifts in fallow land associated with traditional and transitional cultivation



systems (Figure 14b). These trends highlight the complexity of balancing economic growth with ecological sustainability and community rights in a resource-dependent landscape.

***Figure 14:*** *Odisha: (a) land-use trends and (b) correlation matrix.*




Recent policy reforms introduced during 2024–25 aim to accelerate industrial development by simplifying land conversion processes for micro, small, and medium enterprises (MSMEs) and expanding land access for landless households, thereby supporting mining and industrial expansion in districts such as Keonjhar, Sundargarh, and Angul. At the same time, RE and green hydrogen initiatives are increasing demand for large-scale land allocation, adding a new dimension to competition over commons and marginal lands. Rapid urbanisation—targeted to become 60% by 2047—along with infrastructure expansion is further increasing pressure on peri-urban land, particularly around Paradip, Bhubaneswar, and Rourkela, where agricultural and forest land is increasingly being converted to built-up areas (Government of Odisha, 2025). Ecological priorities continue to compete with industrial and infrastructure expansion, making integrated land-use planning a central challenge for the state.

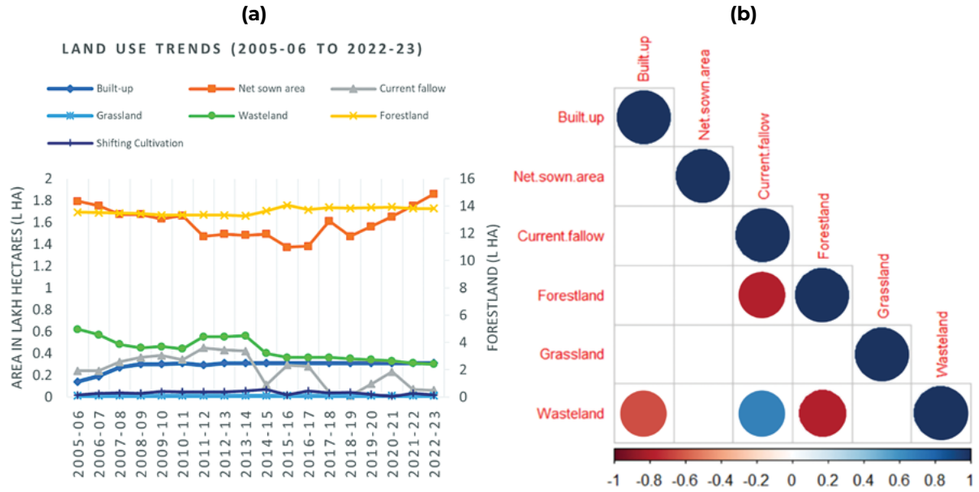
**Case study: Nagaland**

Nagaland is a predominantly hilly, forested, tribal-majority state where community ownership, customary governance, and protections under Article 371A shape land use. Unlike industrial or mining-intensive states, its land-use dynamics are driven mainly by forests, shifting cultivation systems, and limited urban expansion, resulting in relatively low industrialisation but high ecological and cultural sensitivity. Agriculture is dominated by jhum (shifting cultivation) and terrace farming systems, which support tribal livelihoods, biodiversity conservation, and cultural continuity. These practices are closely integrated with forest cycles and community land governance. The agricultural system also includes upland and wet-rice cultivation, along with horticultural crops such as pineapple, orange, banana, and spices. This farming system remains central to rural livelihoods and the state's ecological balance.

Forests cover more than 80% of Nagaland's geographical area and form the backbone of its environment and economy. Largely managed by communities, they provide essential ecosystem services, including watershed protection, biodiversity conservation, carbon storage, and livelihood support. However, forests face growing pressures from shorter jhum cycles, settlement expansion, infrastructure development, and timber extraction, increasing the importance of afforestation and community-based forest management.

Land-use change in Nagaland is shaped primarily by transitions in shifting cultivation systems, forest regeneration cycles, and gradual settlement expansion rather than industrialisation (Figure 15). One notable trend is the transition from long-fallow jhum systems to shorter fallow cycles or more permanent agricultural systems, including plantations and orchards. Although forests remain the dominant land-use category, built-up areas are gradually increasing while wasteland is declining, reflecting the gradual transformation of traditional land-use systems under demographic and policy pressures.

***Figure 15:*** *Nagaland: (a) land-use trends and (b) correlation matrix.*




Emerging resource discoveries are adding new complexities to land management. The identification of crude oil, nickel-cobalt-chromium, and coal deposits has created prospects for future industrial development while also raising concerns about ecological impacts, land tenure security, and resource governance. Existing issues such as illegal coal mining have already contributed to localised land conflicts, highlighting the challenges of balancing resource extraction with community rights.

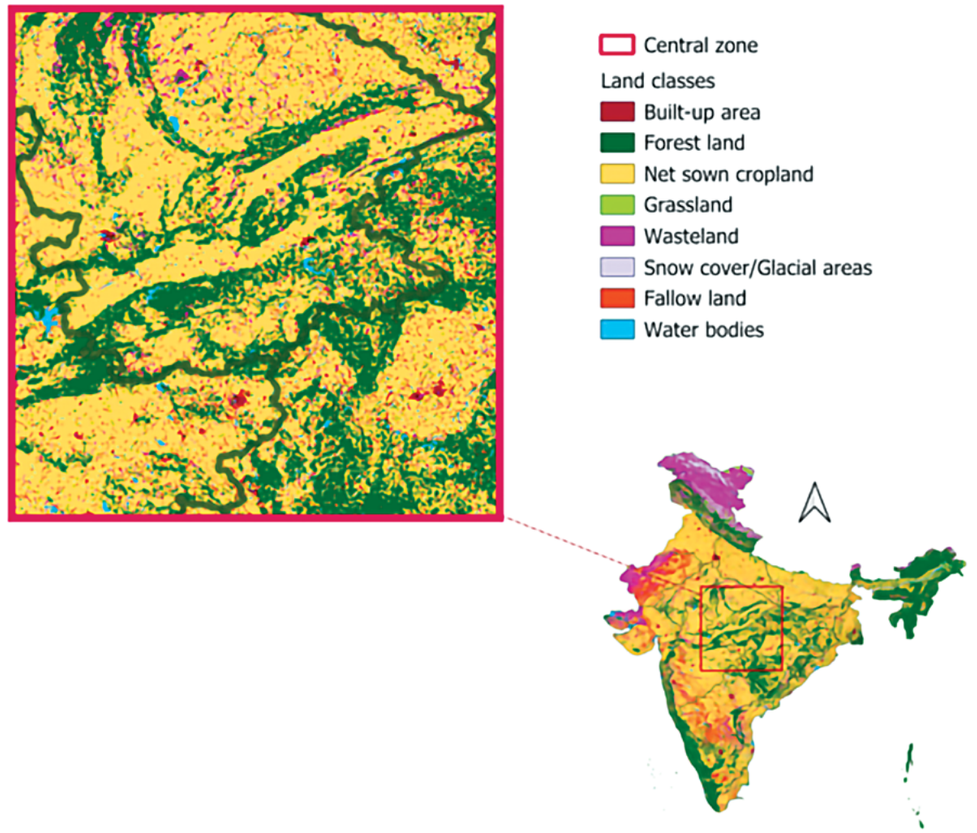
Urbanisation and infrastructure development remain limited but are steadily increasing, particularly around Dimapur and Kohima. Expanding roads, energy systems, and communication networks are improving connectivity and supporting economic development. At the same time, these changes are placing growing pressure on agricultural and forest land, creating localised conflicts among development, conservation, and traditional land uses. In this context, integrated land-use planning is essential to balance economic aspirations with ecological sustainability and cultural heritage.



## 3.1.5. Central region

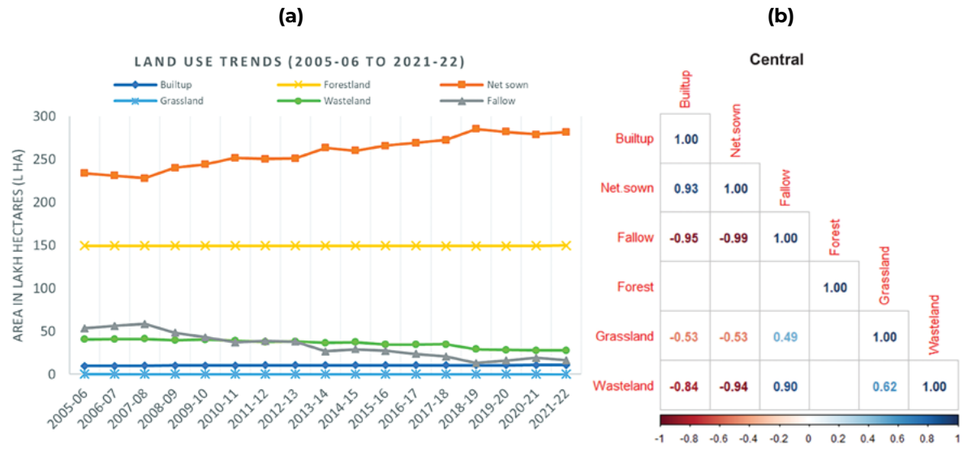
The Central region (Figure 16) consists of south-eastern Rajasthan (comprising major parts of the Hadoti Plateau), Uttar Pradesh, Madhya Pradesh, Chhattisgarh, and Maharashtra. It is a major producer of food grains, including wheat, rice, oilseeds, pulses, and sugarcane, contributing significantly to national food security. The region is also rich in coal, iron ore, limestone, and dolomite reserves. Its proximity to major mineral and energy resources has supported the development of a strong industrial base.

***Figure 16:*** *Landforms in the Central region.*




Agriculture is one of the region's principal economic activities, and the area under cultivation has increased over time to meet growing food demand. Consequently, net sown area has increased (Figure 17a). Forests remain the dominant land-use category across much of the region. However, the expansion of net sown area has largely occurred through the conversion of wasteland and fallow land, resulting in a gradual decline in these land classes over time (Figure 17b).

***Figure 17:*** *Central region: (a) land-use trends and (b) correlation matrix.*




The mix of an agriculture-dependent economy with mining and power development puts competing demands on land across the central region, and land conflicts most often arise at the intersection of farming, forests, and extractive industry.

Many of these conflicts centre on mining and power-sector land acquisition, where tribal and forest-dwelling communities are displaced for coal blocks, thermal and nuclear power plants, or transmission and dam infrastructure, often without adequate consent or rehabilitation. Deforestation and forest-rights disputes are also common, as land diversion for these projects often overlaps with community and individual forest-rights claims under the Forest Rights Act, leading to conflicts over consent, compensation, and the loss of traditional livelihoods tied to forest land.

Compensatory afforestation schemes add another layer of friction because land earmarked for replanting is sometimes taken from village commons or contested forest land rather than degraded land, displacing local use without resolving the original deforestation. Irrigation and river-linking projects are a further source of conflict, submerging agricultural and forest land and triggering long-running disputes over resettlement terms.

**Case study: Madhya Pradesh**

Madhya Pradesh's economy is predominantly agrarian, with agriculture (47%), services (34%), and industry (19%) forming the major sectors (Government of Madhya Pradesh, 2022)

Madhya Pradesh plays a significant role in national food security, producing approximately 32% of India's pulses, 15% of its oilseeds, and 15%–20% of its wheat, earning it the title of the country's 'food basket'. The state also has considerable potential in forestry and wildlife tourism, with forests covering around 28% of its geographical area. National parks, such as Kanha, Bandhavgarh, and Pench, support biodiversity conservation while generating employment and sustaining rural livelihoods.

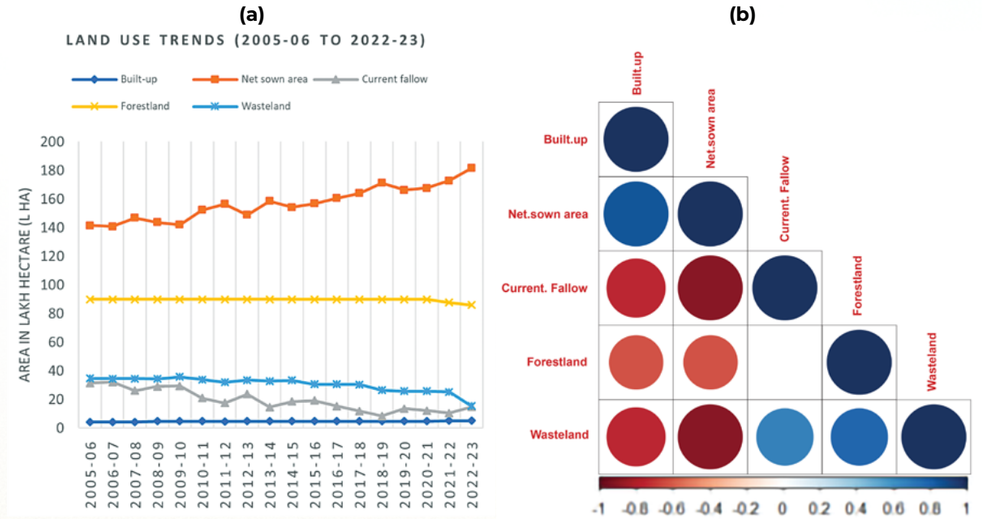
Rich in mineral resources, Madhya Pradesh ranks fourth in India in mineral production and is the country's only diamond producer, accounting for around 90% of national reserves. It is also a major source of copper, manganese, limestone, coal, and rock phosphate, positioning the state for growth in sectors such as electric vehicle (EV) batteries. The availability of these resources, together with the state's proximity to key raw-material sources, is supporting the expansion of industries including cement, agro-processing, automotive manufacturing, and engineering.



Reflecting this diverse economic activity, Madhya Pradesh's land-use patterns have also evolved over time. Analysis of NRSC's LULC data from 2005 to 2023 reveals trends that align closely with the state's development trajectory. During this period, built-up area increased by 17.7%, reflecting growing urbanisation and infrastructure development, while net sown area expanded by 28%, indicating continued agricultural growth (Figure 18a). Much of this expansion appears to have occurred through the conversion of fallow land and wasteland, which declined by 53% and 55%, respectively.

Figure 18b illustrates the extent of these land-use transitions. A small proportion of forest land has also been converted to built-up area and net sown area, contributing to a marginal decline of approximately 4% in forest area. This may partly reflect the classification of mining areas within forest boundaries, as well as infrastructure development.

***Figure 18:*** *Madhya Pradesh: (a) land-use trends and (b) correlation matrix.*






## 3.2. Model design

The state-level analysis showed that land-use priorities are often sector-specific and siloed, a pattern reflected in land-use change trends, policy design, and the regulatory frameworks governing land use. We compared the national land-use change rules with the regional trend analyses to assess whether these relationships were consistently observed across all regions (Table 2).

***Table 2:*** *Comparison of land-use rules with national rules and across zones.*

| Land classes | National rule | North | East | South | West | Central |
|---|---|---|---|---|---|---|
| Fallow and net sown | Net sown area expands into fallow land. | Yes | Yes | Yes | Yes | Yes |
| Fallow and forest | Part of the deforested area transitions to fallow land. | No | Yes | Yes | No | No |
| Forest and wasteland | The remaining deforested area transitions to wasteland. | No | Yes | Yes | Yes | No |
| Wasteland and built-up | Built-up area expands into wasteland. | Yes | Yes | Yes | Yes | Yes |
| Grassland and wasteland | Grassland expands into wasteland. | Yes | No | No | No | No |
| Built-up and fallow | Additional built-up expansion occurs into fallow land. | Yes | Yes | Yes | Yes | Yes |
| Wasteland and net sown | Net sown area can expand into wasteland when additional agricultural land is required.* | Yes | Yes | Yes | Yes | Yes |

*Note: The table shading indicates the following: green = strong significant relationship in the same direction; yellow = weak significant relationship in the same direction; orange = strong significant relationship in the opposite direction; and grey = no significant relationship. *This relationship was observed in the data but was not included in the current model structure. It could be incorporated as an optional switch in future versions of the model.*

As expected, not all the rules emerged uniformly. For example, the regional analysis for the Northern region did not show conversion of forest land to fallow land. However, a closer examination of the constituent states helped explain this anomaly. Analysis of the land-use trends and correlation matrix for Haryana indicated that this relationship does exist at the state level. Based on expert consultations and a review of the literature, we concluded that the absence of this relationship at the regional level likely reflects the influence of forest-rich states such as Himachal Pradesh and Uttarakhand, where agricultural encroachment into forest land is relatively limited, thereby weakening the regional correlation.

The reversal of the national grassland–wasteland relationship in the Southern, Western, and Central regions reflects a data-classification artefact rather than a real difference in land-use dynamics. Under the NRSC classification, grasslands are predominantly classified as alpine, temperate, subtropical, and desert grasslands, which are concentrated in the Northern and Eastern regions and therefore shape the national pattern. In the Southern, Western, and Central regions, tropical grasslands occupy too small an area to establish a statistically meaningful relationship with the wasteland category; consequently, the national pattern does not emerge in these regional datasets.



Comparing state-level land-use trends and correlation analyses with regional data, alongside each state's land-use policy context, showed that the regional analysis alone could not capture all state-specific nuances. Combining insights from these analyses, we concluded that the national land-use change rules can be applied across all regions within the modelling framework. However, the thresholds governing these transitions and their feasibility differ significantly across regions.

For the model, this means the rule structure is common across regions, but the values governing the flows differ, affecting both the direction and amount of conversion. An example of this variation is presented in Box 1, which estimates the feasibility of land available for solar and wind energy in each region based on the distribution of states across the hydrometeorological zones. This data is based on a study done by Negandhi and Kiesecker (2020).

***Box 1:*** *Regional RE land quantification using SiteRight tool.*

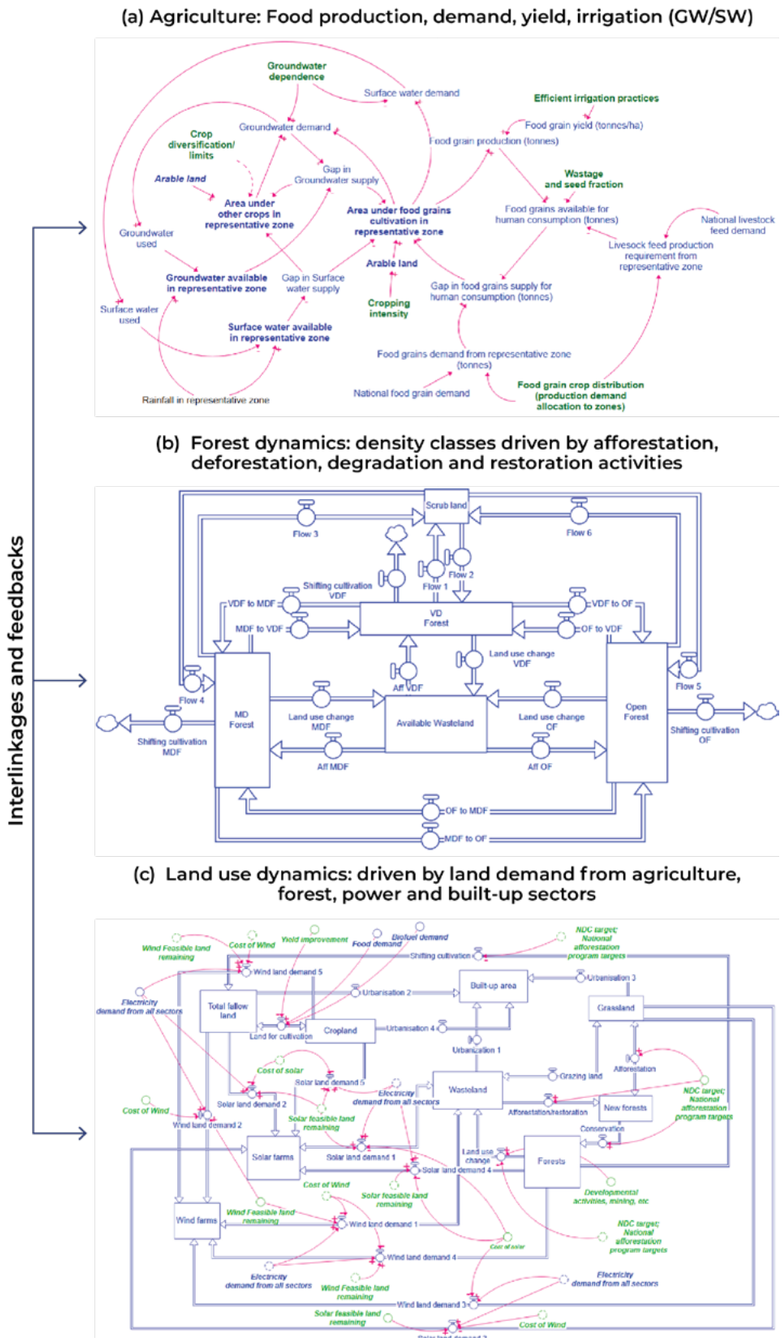
**Regional RE land quantification**

RE potential, particularly for solar and wind, is location-specific and therefore depends on the availability of suitable land. Identifying such land at the regional level is essential for realistic RE deployment planning. The SiteRight tool (Negandhi & Kiesecker, 2020) was used to identify areas with solar and wind resource potential. The *No Silver Bullet* (CSTEP, 2024) report describes the underlying assumptions and methodology.

The SiteRight estimates of RE potential are available at the state level. Using the GIS-based regional allocation of state land, these estimates were disaggregated to the five hydrometeorological regions. For example, if Rajasthan has suitable wasteland and current fallow land distributed across both the Northern and Western regions, the state's total low-conflict RE potential is apportioned between the two regions in proportion to the availability of wasteland and current fallow land within each region. The details of the potential across land uses, states and regions are provided in Annexure Table A1 and A2.

Figure 19 presents the representative model structure for the regional modules. The same overall model structure is applied across all regions, with each regional model driven by its share of national demand estimated within the SAFARI framework. Regional food demand is allocated according to each region's share of national production. This production is determined by both the land available for cultivation and regional foodgrain yields (Ashok et al., 2021). Similarly, land demand for solar and wind energy is driven by national electricity demand and then apportioned across regions based on the availability of feasible land (for details on the land-use module, see CSTEP, 2024).

***Figure 19:*** *Model structure for all regions: (a) causal loop diagram of the agriculture sector; (b) stock-flow diagram of the land-use sector (CSTEP, 2024); and (c) stock-flow diagram of the forestry sector (CSTEP, 2023).*



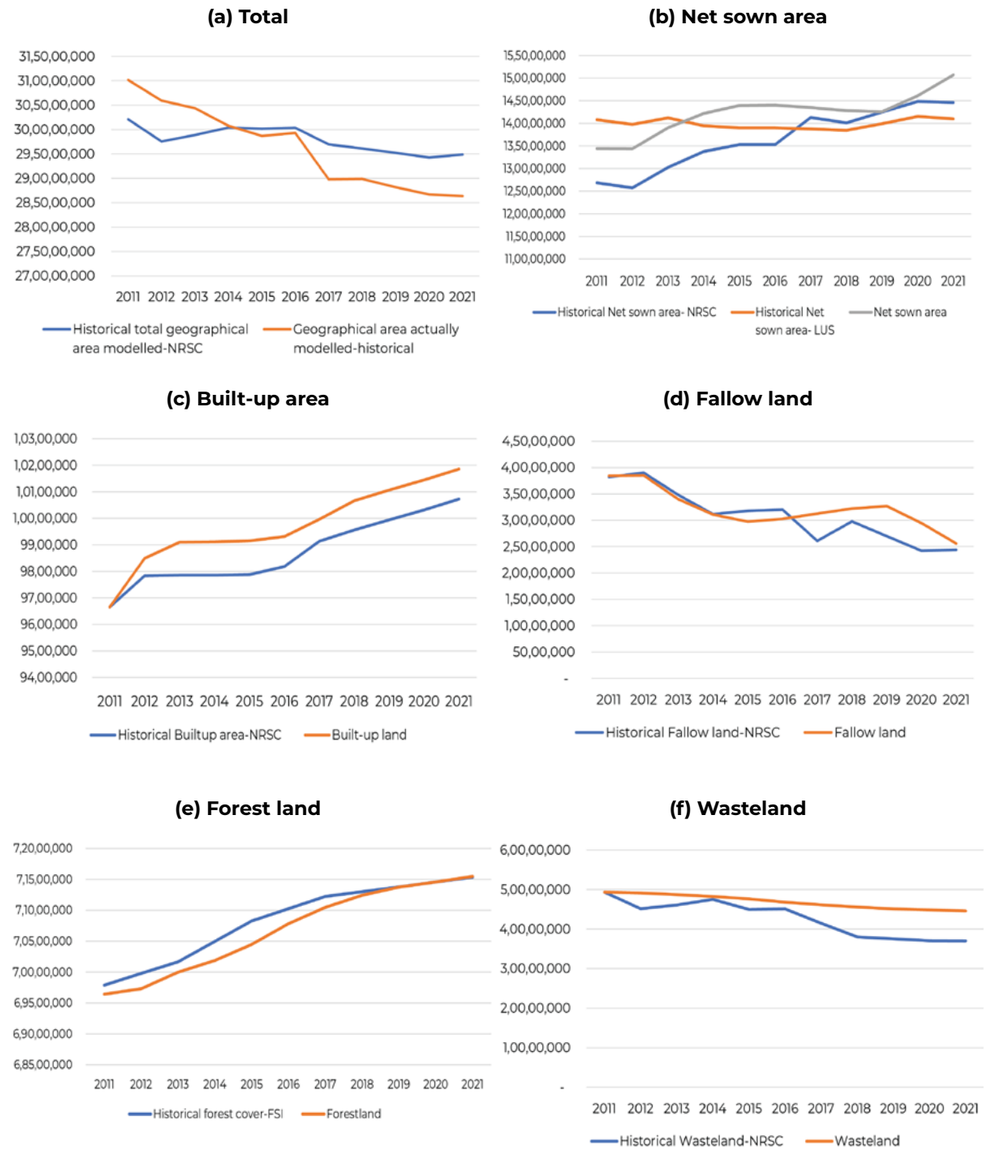

*Note: In (a), plus (+) signs indicate positive relationships, while minus (–) signs indicate negative relationships between variables (see Ashok et al., 2021 for details); the three sectors interact through land demand, as indicated by the red circular arrow at the centre of the figure.*



## 3.3. Model validation

We validated the model using back-casting for the years 2012 to 2021, since the model was initiated in 2011 using the datasets. At the aggregate level, it reproduced historical land-use trends with an accuracy of ±3% (MAPE) at the national level. The comparison between real data and model estimates is presented in Figure 20.

***Figure 20:*** *Validation of modelled land-use trends using back-casting for 2012 to 2021.*



# 4. Conclusion

India faces the challenge of balancing development priorities, climate commitments, and the sustainable use of natural resources. As pressures on land continue to intensify, understanding the long-term implications of land-use decisions becomes increasingly important. The SAFARI tool provides a systems perspective by showing how national decisions shape long-term energy demand and emissions pathways, while revealing the trade-offs and interlinkages across sectors that informed decision-making must consider.

SAFARI-DHARTI builds on this framework by incorporating regional context into national analyses. It treats land as a fundamental constraint rather than an afterthought, enabling an assessment of how resource trade-offs vary across regions and what these differences imply for national goals and targets. By extending the SAFARI framework to estimate the sustainable potential for RE, agriculture, and forestry, the model helps identify where competing land demands may create constraints, trade-offs, and risks across national and state-level development pathways. It is particularly useful for evaluating alternative development scenarios—including food-first, RE-first, and balanced growth—by assessing their implications for land availability, emissions reduction, and development priorities in a consistent, dynamic way.

The tool can also explore crop diversification pathways that improve water-use efficiency and reduce pressure on water-intensive production systems, which is important in India's water–energy–food–land nexus. For instance, it can assess the land, water and energy implications of shifting towards less water-intensive and more diversified crop systems. Such shifts can reduce dependence on groundwater and, indirectly, lower electricity demand for irrigation, thereby reducing additional land requirements associated with power-sector expansion.

## 4.1. Way forward

Although SAFARI-DHARTI incorporates various land-use changes and can be used to explore the implications of allocation priorities at both the regional and national levels, it still misses many nuances in its current form. For instance, some land-use transitions seen in specific case studies are not fully represented in the model. Although these changes may drive land-use dynamics, the model's aggregation may not capture them adequately.

In the next phase, SAFARI-DHARTI will be further enhanced by incorporating additional spatial and sectoral layers. Such enhancements will strengthen the model's ability to represent the constraints, risks, and opportunities that shape land-use decisions on the ground. Planned additions include biodiversity and ecosystem services, administrative and land records, community land systems, transmission infrastructure, and climate layers capturing disaster exposure. Alongside these thematic additions, the model's spatial-resolution classification accuracy can be improved by integrating GIS-based analysis more extensively, enabling finer-scale spatial representation of land-use patterns.

In its current form, the tool can help policymakers and other stakeholders test resource-aware strategies and identify uncertainties related to national-level land availability, informing climate strategies for RE, forestry, and land-based mitigation. At the state level, it can help decision-makers evaluate alternative land-allocation pathways in RE-rich, agrarian, and biodiversity-sensitive landscapes while accounting for land degradation risks, agriPV opportunities, and crop diversification.

Overall, SAFARI-DHARTI provides a structured decision-support framework for balancing low-carbon transitions with food security, water sustainability, ecosystem protection, and region-specific development priorities.



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