

Sustainability Assessment of Farming in Northeast India Using PSR Model

Nandita Debnath ¹, Giribabu. M ², Bondita Saikia ^{3,*} and James Riffat ⁴

¹ Department of Economics, Management and Information Science, Mizoram University, Tanhril, Aizawl 796004, Mizoram, India; nanditadebnath12@gmail.com; +91 7005074475

² Department of Economics, Management and Information Science, Mizoram University, Tanhril, Aizawl 796004, Mizoram, India; girihcu@gmail.com; +91 9862195552

³ Center for Economic Studies and Policy, Institute for Social and Economic Change, Bengaluru 560072, Karnataka, India

⁴ World Society of Sustainable Energy Technologies, Hill Side, Clifton Lane, Nottingham NG116AA, UK; drjamesriffat@gmail.com; +86 19366885574

* Corresponding author: saikiabondita432@gmail.com; Tel.: +91 7636944551

Abstract: Agricultural sustainability in India's North Eastern Region (NER) is challenging due to mounting environmental degradation, socio-economic inequalities, and institutional gaps. The region faces challenges such as land degradation, limited irrigation, and inadequate rural infrastructure despite its rich agroecological diversity and traditional practices. This study assesses the sustainability of agriculture in the eight Northeastern states using the Pressure-State-Response (PSR) model to generate a composite Agricultural Sustainability Index (ASI). A total of 16 indicators across environmental, economic, and social dimensions are selected. These indicators are normalized using the Min-Max method, and objective weights are assigned using the entropy method. The PSR framework was applied to analyze human-induced pressures, the current state of resources, and institutional responses across the states. Findings show significant spatial disparities. Tripura ranks highest in sustainability (ASI = 0.543), owing to better productivity, irrigation, and strong social indicators. Assam (ASI = 0.481) and Meghalaya (ASI = 0.430) follow, while Nagaland (ASI = 0.278) and Sikkim (ASI = 0.313) perform poorly due to ecological stress, low economic security, and weak institutional support. There is a trade-off between environmental conservation and increasing agricultural output. This requires socially inclusive and flexible policies without affecting the local realities of NER. **Originality/Value:** This study advances a standard PSR application through implementation-level rigor and decision relevance. First, the study provides a fully auditable indicator pipeline—explicit selection rules, polarity checks, and PSR tagging—so readers can reproduce each step. Second, the study report formal robustness of the composite to common researcher degrees of freedom (normalization, outlier handling, imputation, and weighting choices), described transparently in Methods, with qualitative results summarized in the text. Third, the study benchmarks entropy-weighted results against a simple equal-weights baseline to demonstrate that headline findings are not an artifact of a single weighting scheme. Finally, the study translates the composite into policy guidance by identifying the most influential indicators behind each state's position and explaining why those levers matter in context. These elements yield context-sensitive insights without introducing new data or exotic methods.

Keywords: agricultural sustainability; composite sustainability index; northeast region; pressure-state-response framework; sustainable farming

Code: Q01, Q15, Q18, Q56, R11

1. Introduction

Food security and environmental protection are two key areas where sustainable agriculture contributes to advancing global sustainable development (Singh, 2020a). The North Eastern Region (NER)



has long been neglected in the context of national agricultural policy despite its socio-ecological importance (Saikia et al., 2024). During the Green Revolution of the 1960s and 70s, while regions such as Punjab, Haryana, and Western Uttar Pradesh witnessed massive transformations through state-backed intensification, public irrigation, and credit infrastructure, the NER remained peripheral to this movement (Veluguri et al., 2019; Patra et al., 2024). The ecological unsuitability of High-Yielding Varieties (HYVs), the absence of canal-based irrigation, and logistical isolation excluded the region from the high-investment path that defined India's food security strategy. Even recent policy frameworks such as the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), Rashtriya Krishi Vikas Yojana (RKVY), and the National Mission on Sustainable Agriculture (NMSA) have failed to adapt their approaches to the region's ecological and cultural specificities (Jain et al., 2022).

As a result, the NER continues to experience lower agricultural productivity, inadequate market linkages, limited institutional support, and a lack of climate-resilient infrastructure. Ironically, this marginalization has also allowed the NER to maintain relatively sustainable agricultural practices. Fertilizer use, for instance, remains the lowest in the country, well below 60 kg/ha in most NER states compared to over 250 kg/ha in Punjab and Haryana (Sigh et al., 2021; Roy et al., 2015). Similarly, mechanization and pesticide use are minimal, preserving soil health and biodiversity but also limiting scalability and yield optimization. The low-carbon footprint, organic farming culture (especially in Sikkim), and traditional seed sovereignty are increasingly being recognized as assets in global sustainability conversations (Babu et al., 2020). However, these benefits coexist with high rural poverty, poor market access, and inadequate infrastructure, which hinder long-term resilience and economic viability. Analogous evidence from the green-technology literature shows that passive and low-impact design/retrofit strategies can deliver resource efficiency without ecological harm, supporting the case for context-specific, low-input solutions in sensitive regions like the NER (Suman et al., 2025; Tapia-Brito & Riffat, 2025; Zhang et al., 2025).

The region also faces unique environmental vulnerabilities due to its geographical terrain. The Eastern Himalayas are identified by the IPCC as one of the most climate-sensitive zones globally, with increasing frequency of landslides, flash floods, erratic rainfall, and rising temperatures threatening agricultural livelihoods (Malik et al., 2025). Cropping calendars are disrupted, pest incidences are rising, and extreme weather events are becoming more common, severely impacting small and marginal farmers who constitute over 85 per cent of the agricultural workforce in the NER. There has been a persistent gap between development visions and realities. The North Eastern Council's *Vision 2035* identifies agricultural diversification, climate-resilient cropping systems, and value chain development as key priorities. Without strong monitoring mechanisms, sustainability indicators, and state-wise benchmarks, these goals remain aspirational. The need to localize the Sustainable Development Goals (SDGs) through a region-sensitive approach is particularly important given India's national and global climate commitments under the Paris Agreement and the SDG target.

However, progress remains hampered by data scarcity, limited institutional capacity, and insufficient integration between environmental and agricultural planning in the region. At the same time, NER gives an important opportunity to reimagine sustainability pathways that are based on ecological integrity, cultural resilience, and decentralized governance (Patra et al., 2024). The region's relatively low chemical usage, rich traditional knowledge systems, and growing interest in organic farming, particularly in states like Sikkim, position it favorably within national and global sustainability discourses (Babu et al., 2020). Another key issue is the absence of an integrated framework to assess the dynamic interplay between environmental degradation, socio-economic stress, and institutional responses in the NER. Studies have examined land-use change, climate vulnerability, and poverty metrics; few have attempted to integrate these into a composite sustainability evaluation.

Thus, the present study sets out to address this important gap in the literature and policy discourse by examining the agricultural sustainability of the NER using an integrated and regionally sensitive framework. Specifically, the focus is to construct a Composite Agricultural Sustainability Index (ASI) accounting for the environmental pressures, current agricultural conditions, and institutional responses characterizing each state. By doing so, the study shows interstate disparities within the region, highlights critical sustainability gaps, and provides policy-relevant recommendations aligned with the NEC Vision 2035 and the national SDG commitments. The study aspires to support a more inclusive and ecologically rooted vision of agricultural development that moves beyond productivity-centric paradigms and centers the socio-ecological realities of India's Northeastern frontier.

2. Methodology

2.1. Study Area

This study area includes the eight Northeastern states of India, namely Arunachal Pradesh, Assam,

Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura. These states collectively form the Eastern Himalayan Region, characterized by mountainous terrain, rich agrobiodiversity, traditional knowledge systems, and unique ecological challenges. This region is geographically located between 21.57°N to 29.45°N latitude and 88.10°E to 97.30°E longitude, sharing international borders with China, Bhutan, Myanmar, Bangladesh, and Nepal. Covering about 262,230 sq km, the NER accounts for nearly 8% of India's land area, but only around 3.8% of the national population. The region is known for its rich biodiversity, tribal population, and ethnolinguistic diversity. However, it faces challenges related to economic underdevelopment, infrastructure gaps, and climate vulnerability. Some states like Mizoram and Tripura report high literacy rates, but many areas still lack adequate access to education, healthcare, and livelihood opportunities. The population density, literacy, and development indicators vary widely across states, making the region both strategically important and developmentally sensitive.

2.2. Data Sources

The study is based on secondary data. The sources of the secondary data include the North Eastern Council, Databank, Census of India (2011), Indian Meteorological Department (IMD), Rural Development Statistics, and the MNREGA portal. They assembled a state-year panel for the eight NER states using five established sources, selected to span the PSR construct. NEC Databank supplies land-use, production, and income measures (AFC, LUNSA, ANAU, CI, FGP, PCDP, LSO), offering policy-relevant coverage but with the usual caveats of administrative compilations (periodic revisions, inter-state definitional heterogeneity). IMD gridded datasets provide objective climate observables (AAR, AAT); their strengths are consistency and full spatial coverage, while interpolation from stations can smooth local extremes. Rural Development Statistics contribute sectoral inputs and infrastructure (CFert, II), though the series may reflect evolving program definitions. MNREGA MIS yields transaction-based employment intensity (EMP MNREGA), rich but subject to administrative reporting practices. Census 2011 underpins social structure (SR, LR, PWA; IMR where available) as a point-in-time baseline; later years rely on our imputation protocol when annual updates are unavailable.

2.3. Analytical Framework

The data are analysed using the Pressure–State–Response (PSR) framework, originally developed by the Organisation for Economic Co-operation and Development (OECD, 1993). Recent applications in the Indian agricultural context include Suresh et al. (2022).

The PSR framework classifies indicators into three:

- A. **Pressure:** Anthropogenic and environmental stressors (e.g., land-use change, input intensification, climate variability)
- B. **State:** The current condition of agricultural resources and outputs (e.g., cropping intensity, productivity)
- C. **Response:** Policy, institutional, and community actions to address sustainability challenges (e.g., public investment, social infrastructure)

Agricultural sustainability can also be assessed through the Drivers-Pressures-State-Impact-Response (DPSIR) or the Triple Bottom Line (TBL). However, PSR is the most suitable tool in a region that is ecologically sensitive, like NER. DPSIR requires detailed causal linkages and impact tracking, which is impractical due to the unavailability of data in many cases. Similarly, the TBL model focuses on economic, environmental, and social outcomes and does not explicitly account for causality or institutional responses. The PSR model is suitable because it allows for a focused analysis of systemic challenges by linking human-induced pressures, ecological conditions, and governance responses.

Selection of Indicators

Indicator screening via multi-criteria decision analysis (MCDA).

To make indicator selection auditable rather than judgmental, the study screened all using a five-criterion MCDA on a 0–5 scale: (C1) theoretical relevance to sustainability in the North-Eastern Region (NER); (C2) policy/actionability; (C3) data quality (authoritativeness, measurement error, frequency); (C4) spatial completeness across NER states; (C5) temporal coverage for the study period. Each indicator received a score for C1–C5 based on published definitions and data documentation. The study used equal criterion weights and retained indicators with a total score $\geq 15/25$. The study also mapped each retained indicator to the PSR framework to ensure conceptual balance (See Table 1).

Table 1. Indicators, Units, Polarity, PSR Tags, and Rationale.

Component	Code	Indicator (full name)	Unit	Polarity (+/-)	PSR	Rationale
Environmental	AFC	Area under Forest Cover	% of geographic area	+	S	Ecosystem integrity/land cover
	LUNSA	Land Use: Net Sown Area	% of area	+	S	Agricultural land availability
	ANAU	Area under Non-Agricultural Uses	% of area	–	P	Land-conversion/urbanisation pressure
	CFert	Fertilizer Consumption (N+P+K)	kg/ha	–	P	Chemical input intensity/stress
	LSO	Livestock Ownership	per 1,000 persons	–	P	Grazing/land pressure
	AAR	Average Annual Rainfall	mm/year	+	S	Water availability
	AAT	Average Annual Temperature	°C	–	P	Thermal/heat stress
	CI	Cropping Intensity	%	+	S	Land-use efficiency
Economic	FGP	Foodgrain Yield per Hectare	kg/ha	+	S	Crop productivity
	II	Irrigation Intensity	% of GCA	+	R	Irrigation access/adaptive capacity
	PCDP	Per-Capita Domestic Product	₹ per capita (constant)	+	S	Income/prosperity
	EMP_MNREGA	MNREGA Employment	person-days per 1,000 pop.	+	R	Public employment support
Social	SR	Sex Ratio	females per 1,000 males	+	S	Gender equity
	LR	Literacy Rate	%	+	S	Human capital
	IMR	Infant Mortality Rate	per 1,000 live births	–	S	Health burden
	PWA	Population in Working Age (15–49)	%	+	S	Demographic potential

Source: Author's Own; Note: P = Pressure, S = State, R = Response (per your PSR definitions). Polarity ('+' benefit; '–' cost) determines normalization direction; "+" means higher values improve sustainability; "–" means higher values worsen sustainability.

Empirical validation:

Beyond qualitative rationale, the study validates design choices by (i) leave-one-indicator-out re-estimation and (ii) cross-validated weighting: the study choose λ in a hybrid prior–entropy weight $w_j(\lambda) = (1 - \lambda)\pi_j + \lambda\bar{w}_j$ (normalised) to maximise Kendall's τ between ASI ranks and an external proxy (e.g., SDG progress/poverty reduction). Robustness is summarised via Spearman/Kendall correlations and the share of states with rank shifts >2 positions under equal-weights, PCA-weights, and $\pm 10\%$ weight jitter.

Handling missing data:

For indicators with gaps, the study implemented a two-stage imputation: Stage 1 (spatial) uses inverse-distance weighting from neighboring states within the same agro-climatic zone and a ± 2 -year

window; Stage 2 (temporal) fits a Theil–Sen trend on each state series to fill any remaining gaps. Hyperparameters (neighbor radius and temporal window) were selected via leave-one-out cross-validation (LOOCV), minimizing MAE. The study report, for every indicator, % Missing, % Imputed (Stage 1), % Imputed (Stage 2), MAE, RMSE, and affected states/years in [Appendix B](#).

Fertilizer consumption (CFert, kg/ha) is missing for several states. The study retains CFert by imputing its missing values using **multiple imputation by chained equations (MICE)** with **predictive mean matching (PMM)**. The imputation model includes agronomic and structural predictors plausibly related to CFert (cropping intensity, irrigated-area share, HYV share, foodgrain yield, rainfall, road density, rural population share; all measured contemporaneously). The study generates $m=20$ imputed datasets with **10 iterations** each, constraining draws to a plausible range (e.g., 0–300 kg/ha). Imputation is performed on **raw CFert**; afterward, CFert is normalized to [0,1] using **fixed anchors** (external or robust sample bounds) to avoid circularity.

Data Normalization and Index Construction

As summarised in Table 1, each indicator's polarity ('+' benefit, '-' cost) governs the direction of normalization; cost indicators are reverse-scaled. The study normalizes each indicator to [0,1] using min–max scaling, with explicit treatment of indicator direction and edge cases.

Normalization: For benefit indicators (higher is better):

$$z_{ij} = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}}$$

For cost indicators (lower is better):

$$z_{ij} = \frac{\max_i x_{ij} - x_{ij}}{\max_i x_{ij} - \min_i x_{ij}}$$

The study index states by $i=1\dots n$, indicators by $j=1\dots m$, and years by $t=t_0\dots t_T$. To ensure temporal comparability, all min–max anchors are computed on the pooled panel (i^*t) rather than year-by-year; year-wise anchors are reported as a robustness check.

When $\max_{ij} x_{ij} = \min_{ij} x_{ij}$ (zero variance), the study sets $z_{ij} = 0$ and flags the indicated year as non-informative.

Outliers and skew: Before scaling, the study applies light winsorization (e.g., 1–99th percentile) and, where distributions are highly skewed, a monotone transform (e.g., $\log^{(1+x)}$) to stabilize ranges. The transform choice is documented per indicator.

Temporal anchoring: For comparability over time, min and max are computed on the pooled panel (all states $\times$ years) rather than year-by-year. As a robustness check, the study replicates results using year-wise anchors.

Index aggregation: The composite index for state i is:

$$ASI_i = \sum_{j=1}^m w_j z_{ij}, \quad w_j \geq 0, \sum_{j=1}^m w_j = 1$$

Baseline weights w_j are estimated via entropy weighting; equal-weight and alternative schemes are reported as robustness checks.

In addition to state-level indices, we construct a composite for the entire NER. The NER composite score is derived by pooling raw indicator values across all eight states before normalization and weighting, thereby treating the region as a single aggregate unit. This approach ensures that the NER composite is directly comparable with state-level indices

Entropy weights: From $Z = [z_{ij}]$, define $p_{ij} = \frac{z_{ij}}{\sum_{i=1}^n z_{ij}}$ (adding ϵ only if a column sum is zero). The Shannon entropy of indicator j is

$$e_j = -k \sum_{i=1}^n p_{ij} \ln p_{ij}$$

$$k = \frac{1}{\ln n}$$

With dispersion $d_j = 1 - e_j$ and weights $w_j = \frac{d_j}{\sum_{i=1}^n d_i}$ (See [Appendix A](#)).

To ensure robustness, the entropy-weighted ASI was benchmarked against an equal-weight baseline and a PCA-based scheme. Concordance tests showed moderate-to-strong alignment: Kendall's $\tau = 0.50$ and Spearman's $\rho = 0.69$ for entropy versus equal weights, with only 25% of states shifting more than two ranks. PCA-based weights reproduced the equal-weight ranking exactly ($\tau = 1.0$; $\rho = 1.0$). These diagnostics confirm that headline rankings are not artifacts of a single weighting choice.

The final entropy weights emphasize land-use pressures and economic security variables. Livestock Ownership ($w = 0.154$), Non-agricultural Land Use ($w = 0.147$), and Net Sown Area ($w = 0.133$) received the highest weights, while demographic and social indicators such as Sex Ratio and Working-age

Population carried lower weights ($w = 0.022\text{--}0.023$). This distribution reflects the strong discriminating power of land-use and structural pressures relative to demographic variables across the North Eastern states (full weight vector in [Appendix A](#)).

Directionality and redundancy checks: Indicator polarity (benefit vs cost) is pre-specified from theory/policy. Highly collinear indicators ($|\rho| > 0.9$) are reviewed to avoid overweighting a single construct.

Uncertainty and sensitivity: The study quantifies uncertainty via a 2,000-draw Monte-Carlo that perturbs (i) imputed cells using LOOCV-based error distributions and (ii) weights using a Dirichlet prior centred on the entropy vector w . The study reports 95% CIs for ASI_i and rank stability under equal weights, $\pm 10\%$ weight jitter, PCA-weights, and z-score normalisation.

External benchmarking

Construct validity is assessed by correlating ASI ranks with an external sustainability composite relevant to the Indian context (PSR/SLSI-type). The study describes agreement qualitatively (e.g., “high”/“moderate”) and discusses systematic divergences by domain.

The final ASI scores are used to compare the performance of the eight Northeastern states and the NER as a whole. Inter-state disparities are analyzed to identify leading and lagging states in terms of sustainability, while domain-wise scores (Pressure, State, Response) revealed specific areas requiring policy attention. These results aim to guide evidence-based, spatially sensitive interventions for inclusive and resilient agricultural development in Northeast India.

Ethical approval:

There is no direct involvement of human or animal subjects.

3. Results

3.1. Environmental Dimension

Assam ranks highest in environmental sustainability ($ESI = 0.555$) in the NER. This is due to its balanced mix of moderate forest cover, relatively high cropping intensity ($CI = 0.701$), and adequate rainfall, which together enhance agricultural resilience without exerting excessive pressure on forest ecosystems. Although the state registers the highest fertilizer use ($CFert = 1.000$), the effects appear moderated by sufficient rainfall ($AAR = 0.413$) and optimal temperature suitability ($AAT = 1.000$), reducing risks of soil and water degradation. At the lower end, Nagaland and Sikkim record the lowest sustainability scores ($ESI = 0.256$ and 0.268 , respectively). This is primarily attributed to their small net sown areas, relatively low cropping intensity, and greater exposure to climatic vulnerabilities. The disaggregated index further reveals that Assam’s leading performance curbs from its relatively expansive net sown area ($LUNSA = 0.603$), efficient cropping cycles, and rational livestock footprint ($LSO = 0.740$). These factors collectively ensure both food security and ecological stability. Tripura emerges as the second-best performer ($ESI = 0.462$). Despite having a smaller net sown area, it validates the highest cropping intensity ($CI = 1.000$) while maintaining minimal environmental trade-offs. Its controlled livestock pressure and moderate climatic risks underline efficient land utilization and adaptive management strategies (See [Table 2](#)).

Table 2. Environmental Sustainability Index (ESI) and Indicator Scores Across Northeastern States.

States	Indicators									
	AFC	LUNSA	ANAU	CFert	LSO	AAR	AAT	CI	ESI	Rank
Arunachal Pradesh	0.865	0.039	0.000	0.292*	0.037	0.652	0.957	0.392	0.420	3
Assam	0.000	0.603	0.682	1.000	0.740	0.413	1.000	0.701	0.555	1
Manipur	0.775	0.068	0.001	0.658	0.011	0.000	0.687	0.000	0.275	6
Meghalaya	0.803	0.043	0.090	0.325*	0.073	1.000	0.174	0.225	0.344	4
Mizoram	1.000	0.014	0.023	0.000	0.004	0.412	0.652	0.471	0.322	5
Nagaland	0.764	0.063	0.051	0.331*	0.012	0.225	0.399	0.337	0.256	8
Sikkim	0.228	0.000	0.002	0.347*	0.000	0.905	0.000	0.704	0.268	7
Tripura	0.736	0.039	0.061	0.452	0.043	0.428	0.939	1.000	0.462	2
NER	0.6466	1.000	1.000	0.291	1.000	0.506	0.593	0.465	0.688	

Source: Author's calculation. Note: AP=Arunachal Pradesh, A=Assam, MN=Manipur, MG=Meghalaya, MZ=Mizoram, NA=Nagaland, SI=Sikkim, T=Tripura; Note: CFert denotes fertilizer consumption (kg/ha). CFert for Arunachal Pradesh, Meghalaya, Nagaland, Sikkim is imputed via MICE (predictive mean matching; m=20; seed = 123) using agronomic predictors, bounded to plausible ranges, then min–max normalized before index construction. Pillar weights are re-estimated within each imputed dataset and tabled scores are pooled means. Cells marked* indicate imputed CFert.

Arunachal Pradesh, ranking third in environmental sustainability (ESI = 0.420), presents a contrasting profile compared to Assam and Tripura. Its sustainability performance is primarily ecological rather than agricultural. The state records extensive forest cover (AFC = 0.865) and almost negligible land degradation (ANAU = 0.000), making it a vital ecological buffer in the North-Eastern region. However, its agricultural base remains underutilized, indicated in low cropping intensity (CI = 0.392) and minimal cultivated land, constrained by difficult topography and weak infrastructure. Despite having high temperature adaptability (AAT = 0.957), these agroecological assets are not fully leveraged due to inadequate agricultural systems. Nagaland and Sikkim represent the lowest-performing states in sustainability, with ESI scores of 0.256 and 0.268, respectively. In Nagaland, high livestock pressure (LSO = 0.012) and continued reliance on shifting cultivation (jhum) impose significant strain on ecosystems. Traditionally aligned with ecological cycles, jhum has become unsustainable under shortened fallow periods and population pressure, leading to soil erosion, forest degradation, and low agricultural returns. Sikkim's performance is similarly constrained. Although high rainfall (AAR = 0.905) contributes positively, severe altitude-related limitations (AAT = 0.000) and the absence of net sown area (LUNSA = 0.000) undermine agricultural sustainability (See Table 2).

Traditional agroecological practices are strongly linked to key indicators such as Cropping Intensity (CI) and Livestock Ownership (LSO). Shifting cultivation remains widespread in Nagaland, Mizoram, Manipur, and parts of Arunachal Pradesh. The reduced fallow period in recent years explains low CI scores in Nagaland (0.337), Manipur (0.000), and Mizoram (0.471). Similarly, livestock ownership practices in states like Nagaland and Arunachal Pradesh, reflected in low LSO scores (Nagaland = 0.012; Arunachal = 0.037), highlight ecological strain from unmanaged grazing. By contrast, Assam and Tripura validate more regulated livestock practices, consistent with their relatively higher LSO scores and overall ESI rankings (See Table 2).

3.2. Economic Dimension

The Economic Security Index (EcSI) reveals significant variation across the Northeastern states in terms of farming output, infrastructure, and job support systems. Tripura ranks the highest (EcSI = 0.458), driven by strong foodgrain productivity, good irrigation access, and relatively high participation in employment programs such as MNREGA. These factors collectively stabilize farm incomes and reduce financial risks. Meghalaya follows with EcSI = 0.420. Despite moderate foodgrain productivity, its exceptionally high irrigation intensity (II = 1.000) buffers production against climatic variability. Assam ranks third (EcSI = 0.291), supported by moderate-to-high foodgrain productivity (FGP = 0.551) and reasonable MNREGA employment coverage (EMP = 0.371). However, its per capita domestic product score (PCDP = 0.018) is very low, highlighting weak linkages between agricultural output and rural prosperity (See Table 3).

Table 3. Economic Security Index (EcSI) and Indicator Scores across Northeastern States.

States	FGP	II	PCDP	EMP-MNREGA	EcSI	Rank
Arunachal Pradesh	0.053	0.361	0.216	0.056	0.1712	6
Assam	0.551	0.225	0.018	0.371	0.2911	3
Manipur	0.239	0.216	0.000	0.053	0.1270	8
Meghalaya	0.524	1.000	0.029	0.128	0.4204	2
Mizoram	0.028	0.183	0.253	0.075	0.1348	7
Nagaland	0.080	0.641	0.082	0.064	0.2168	5
Sikkim	0.000	0.000	1.000	0.000	0.2500	4
Tripura	1.000	0.573	0.111	0.148	0.4580	1
NER	0.485	0.322	0.214	1.000	0.5054	

Source: Author's calculation; Note: 1 = Foodgrain productivity/Yield in Kg per Hectare, 2 = Irrigation

Intensity, 3 = Per capita Net Domestic product at Current Prices (2011-12), 4 = Employment availed (Total persons days) under MNREGA (2023-2024), 5 = EcSI = Economic security Index.

Sikkim occupies a middle position (EcSI = 0.250). While it records zero in most agricultural indicators, it scores the highest in per capita income (PCDP = 1.000), reflecting incomes derived from non-agricultural sectors such as tourism, hydropower, organic farming, and state-supported services. The lowest-performing states are Manipur (EcSI = 0.127) and Mizoram (EcSI = 0.134), constrained by low irrigation coverage, limited productivity, and minimal formal employment opportunities. Nagaland (EcSI = 0.216) and Arunachal Pradesh (EcSI = 0.171) also rank low. Both have moderate irrigation coverage but suffer from weak MNREGA participation and low per capita income, with economic systems still heavily reliant on forest-based and subsistence livelihoods. A common pattern among the lower-ranking states is limited rural employment generation, weak market access, and underdeveloped infrastructure, which collectively heighten economic vulnerability (See [Table 3](#)).

3.3. Social Dimension

The Social Security Index (SSI) shows wide disparities in demographic, educational, and health-related dimensions across the Northeastern states, reflecting uneven capacity to support inclusive and sustainable agricultural transitions. Tripura ranks the highest (SSI = 0.708), supported by strong performance in literacy (LR = 0.842), sex ratio (SR = 0.686), and working-age population share (PWA = 0.849). Its moderate infant mortality rate (IMR = 0.455) suggests reasonably effective health service delivery, creating a broad social foundation for rural development and agricultural labor mobilization. Assam and Mizoram also perform strongly (SSI = 0.598 each), though with different strengths. Assam excels in infant mortality (IMR = 1.000) and sex ratio (SR = 0.667), while Mizoram leads in literacy (LR = 1.000) but records the weakest infant health outcomes (IMR = 0.000). Manipur scores relatively high (SSI = 0.574), due to an excellent sex ratio (SR = 1.000), moderate literacy (LR = 0.533), and a healthy working-age population share (PWA = 0.670) (See [Table 4](#)).

Table 4. Social Security Index and Indicator Scores Across Northeastern States.

States	SR	LR	IMR	PWA	SSI	Rank
Arunachal Pradesh	0.471	0.000	0.545	0.396	0.353	8
Assam	0.667	0.262	1.000	0.462	0.598	2
Manipur	1.000	0.533	0.091	0.670	0.574	4
Meghalaya	0.971	0.349	0.788	0.000	0.527	5
Mizoram	0.843	1.000	0.000	0.547	0.598	3
Nagaland	0.402	0.546	0.030	0.462	0.360	7
Sikkim	0.000	0.618	0.061	1.000	0.420	6
Tripura	0.686	0.842	0.455	0.849	0.708	1
NER	0.627	0.519	0.758	0.481	0.596	

Source: Authors' calculation. Note: SR= Sex Ratio (2011 census), LR= Literacy Rate (2011 census), IMR= Infant Mortality Rate, PWA= Population in working Age (15-49), SSI= Social Security Index.

However, it performs poorly in infant health outcomes (IMR = 0.091). Sikkim (SSI = 0.445) and Meghalaya (SSI = 0.439) occupy mid-tier positions. Sikkim shows strong demographic potential (PWA = 1.000) and moderate literacy (LR = 0.618), but suffers from a poor sex ratio (SR = 0.000) and weak infant health outcomes (IMR = 0.061). Meghalaya demonstrates a contrasting profile, with a strong sex ratio (SR = 0.971) and good health performance (IMR = 0.788), but a deficit in working-age population share (PWA = 0.000). At the bottom of the rankings, Nagaland (SSI = 0.360) and Arunachal Pradesh (SSI = 0.353) face the weakest social foundations. Arunachal Pradesh records poor literacy (LR = 0.000) and high infant mortality (IMR = 0.545), while Nagaland performs poorly in both education and health indicators. These limitations reduce their adaptive capacity and weaken participatory development processes (See [Table 4](#)).

3.4. Agricultural Sustainability Index

The composite results reveal a clear hierarchy of agricultural sustainability across the Northeastern states. Tripura emerges as the leading state, reflecting a coherent balance across environmental stewardship, economic viability, and social security. Assam and Meghalaya follow, each combining moderate-to-strong environmental and economic conditions with adequate, though improvable, social protection. At the lower end of the distribution, Nagaland and Manipur occupy the weakest positions,

reflecting enduring multidimensional constraints across land use and resource pressures, fragile economic fundamentals, and social vulnerabilities. The uncertainty analysis supports these patterns. Monte-Carlo randomization of sub-index weights produces narrow confidence intervals for the leading states, confirming robust leadership, but wider intervals for mid- and lower-tier performers, reflecting sensitivity to shifts in emphasis across pillars (See [Table 5](#)).

Table 5. Agricultural Sustainability Index among NER States.

State/UT	ESI	EcSI	SSI	ASI (mean)	95% CI (lower)	95% CI (upper)	Rank (median)	Rank stability (IQR)
Arunachal Pradesh	0.420	0.171	0.353	0.315	0.205	0.400	6	3
Assam	0.555	0.291	0.598	0.481	0.336	0.579	2	0
Manipur	0.275	0.127	0.573	0.324	0.168	0.514	6	2
Meghalaya	0.344	0.420	0.527	0.430	0.363	0.504	3	0
Mizoram	0.322	0.135	0.598	0.350	0.181	0.539	4	1
Nagaland	0.256	0.217	0.360	0.277	0.229	0.340	8	1
Sikkim	0.268	0.250	0.420	0.312	0.259	0.393	6	2
Tripura	0.462	0.458	0.708	0.542	0.463	0.667	1	0
NER	0.688	0.505	0.596	0.596	0.526	0.668		

Source: Author's calculation; Notes: ASI (mean) is averaged over Monte-Carlo draws; 95% CI uses 2.5th/97.5th percentiles. Rank (median) and Rank stability (IQR) computed from rank distributions across draws. ESI=Environmental Sustainability Index, EcSI=Economic Security Index, SSI=Social Security Index.

Table 6. Rank concordance across weighting schemes.

Comparison	Kendall's τ	Spearman's ρ	% states with $ \Delta \text{rank} > 2$
Entropy vs Equal	0.5	0.69	25.0
PCA vs Equal	1.0	1.0	0.0

Notes: τ = Kendall's tau; ρ = Spearman's rho; comparisons are between state rank vectors under each weighting scheme.

Robustness checks further confirm the ranking: Principal-Component Analysis reproduces the equal-weight ordering, while entropy weighting alters some middle positions but does not affect the overall identification of winners and laggards (See [Table 6](#)). Together, these diagnostics validate that the rankings are not artifacts of a single weighting approach.

4. Discussion

The sustainability landscape of agriculture in India's Northeastern Region unfolds as an intricate mosaic, where ecological abundance, economic fragility, and institutional asymmetry intersect in ways that both sustain and subvert resilience. The composite results derived through the PSR framework make it unambiguously clear that agricultural sustainability cannot be read as a simple derivative of resource endowment. Instead, it is a dynamic equilibrium, continuously recalibrated through the dialectics of environment, economy, and society. This region, perched at the ecological edge of the Himalayas and at the developmental margins of India, epitomizes the tensions of sustainability under constraint: how to cultivate progress without corroding the very ecological substrate on which life depends. The empirical configuration of the ASI brings forth an essential paradox. States endowed with generous forests, rainfall, and biodiversity—Arunachal Pradesh, Mizoram, Nagaland—do not necessarily perform better in sustainability terms than those with far humbler ecological wealth, such as Tripura and Assam. This contradiction is a foundational truth of sustainability studies: that natural capital, when unaccompanied by institutional capability and human capital, can lapse into inertia. The strength of sustainability lies not in abundance, but in the quality of stewardship. It is this stewardship mediated through governance, knowledge systems, and collective will that differentiates ecological potential from ecological performance ([Jain et al., 2022; Jatav & Naik, 2023](#)).

Tripura's leadership in the composite index exemplifies this distinction. Its success lies not in opulence of resources but in the art of orchestration, coherence between social investment, infrastructural inclusiveness, and adaptive governance. Tripura demonstrates how sustainability, when viewed as a relational property of systems, can be attained through institutional balance even within scarcity. Assam's case, though slightly less consistent, reiterates the same principle: that moderate intensification, managed within ecological limits and underpinned by individual land tenure and infrastructural outreach, can generate a kind of pragmatic resilience that eludes more resource-rich but institutionally brittle states. The frailty of the Himalayan states, Nagaland, Sikkim, and to some extent Arunachal Pradesh, invites a different reading. Here, the weight of topography, climate, and demographic pressure converges to

produce what might be called *structural unsustainability*. The persistence of jhum, once a form of ecological intelligence rooted in long fallow cycles and community reciprocity, has now devolved into a practice of compulsion. Population pressure and land scarcity have shortened fallow periods, transforming jhum from a regenerative rotation into a degenerative necessity (Ramakrishnan, 1992). The very practice that once ensured soil fertility and forest renewal has become, under modern duress, a vector of erosion. This metamorphosis mirrors trends observed across upland Southeast Asia, where traditional ecological knowledge—divorced from its demographic and temporal context—has lost its adaptive efficacy (Mertz et al., 2009; Natori et al., 2023).

Sikkim's story is equally revealing. Despite high rainfall and fertile valleys, the state remains agriculturally constrained by altitude and terrain. Its celebrated organic model functions less as a productivity paradigm than as a post-agricultural identity—an ecological brand rather than an agrarian transformation. This sharpens the distinction between ecological sustainability and agricultural sustainability: the former concerned with maintaining biophysical equilibrium, the latter with sustaining livelihoods. Sikkim's case illustrates that these two may diverge sharply in fragile mountain ecologies (Bhatt, 2023). Ecological virtue does not necessarily translate into agrarian viability. Arunachal Pradesh, in contrast, operates as a regional ecological buffer, a state whose environmental health far exceeds its agrarian dynamism. Vast forest cover and low degradation rates secure its ecological resilience, yet limited sown area and skeletal infrastructure constrain agricultural expansion. This asymmetry exposes the deeper tension between conservation and cultivation, between being an ecological storehouse and a productive economy. Sustainability, in such contexts, demands not the pursuit of intensification but the refinement of coexistence—where ecological preservation and limited agricultural use are woven into a single, adaptive design.

If the environmental dimension reveals the landscape of possibility, the economic dimension discloses the architecture of vulnerability. Across much of the NER, the chronic instability of agricultural incomes, coupled with infrastructural fragility and market isolation, fractures the sustainability edifice. Tripura stands out as a partial exception, where agricultural productivity interlocks with public employment programs and social safety nets, cushioning rural livelihoods from systemic shocks. This synthesis between production and protection validates the proposition that inclusive infrastructure—irrigation, roads, wage guarantees—is as critical to sustainability as natural fertility itself (Jain et al., 2022; Bhatt, 2023). Meghalaya, though less productive, displays infrastructural resilience: its high irrigation density offsets moderate yields, while diversified livelihoods in forestry and horticulture lend flexibility to household economies. Assam's pattern is more paradoxical. Despite leading in output, it suffers from what may be called the productivity–prosperity gap—a disjunction between agricultural growth and distributive welfare. Structural deficiencies in market access, storage, and post-harvest processing obstruct the translation of productivity into prosperity (Jagannath et al., 2025). In short, Assam grows more, but gains less. The deeper insight is that sustainability cannot be equated with production metrics; it resides in the distributional and institutional afterlife of production.

At the social frontier of sustainability, the analysis uncovers the decisive role of human capital. Education, healthcare, and gender equity emerge not as peripheral social variables but as central determinants of adaptive capacity. Tripura's high literacy and balanced demographic profile produce a virtuous cycle: educated populations adopt innovations, diversify livelihoods, and respond resiliently to ecological shocks. Mizoram, with its remarkable literacy rate but fragile health infrastructure, shows how fragmented social progress leads to uneven sustainability outcomes. Manipur's demographic youth bulge, if harnessed through skill formation and employment, could propel agricultural modernization, but without institutional support, it risks translating into underemployment and restlessness. By contrast, the social underdevelopment of Arunachal Pradesh and Nagaland remains a structural impediment. Sparse population, limited schools, and poor healthcare form a triad of vulnerability that neutralizes ecological advantage. These deficits erode the human foundations of resilience and explain the persistence of multidimensional deprivation despite environmental wealth (Cattaneo et al., 2022). The implication is unmistakable: the social architecture of sustainability—education, health, gender parity—determines whether environmental capital can be converted into human capability.

Together, the environmental, economic, and social indices depict a region caught between ecological abundance and institutional scarcity. The interplay among these dimensions reveals both compensations and contradictions. States with weaker natural bases but stronger social infrastructure (Tripura, Meghalaya) achieve balance through governance; those with strong ecology but fragile institutions (Nagaland, Arunachal) remain locked in underdevelopment. This asymmetry explains the region's middling aggregate sustainability level—neither a failure nor a triumph, but a precarious equilibrium. The focus should flow naturally from this diagnosis. First, sustainability interventions must be tiered and asymmetrical—differentiated by the ecological and institutional profile of each state. The Himalayan states require adaptive strategies emphasizing agroforestry, rotational grazing, and community-based

watershed management—policies that reconcile conservation with livelihood security (Datta et al., 2024). The valley and foothill states, with greater agricultural potential, should prioritize irrigation reliability, value-chain infrastructure, and financial risk transfer mechanisms. Second, sustainability demands not merely ecological or economic reform but social reinvestment. Education, health, and gender inclusion are not ancillary—they are the scaffolding without which no sustainability architecture can stand. At a conceptual level, this study reaffirms the value of the PSR framework as a diagnostic grammar of sustainability. By linking anthropogenic pressures, ecological states, and institutional responses, it captures the circular causality of human–environment systems. The entropy-based weighting of indicators enhances objectivity and comparability, though future refinements could incorporate temporal dynamics to trace transitions over time.

The present synthesis establishes that sustainability is not a static endpoint but a moving frontier, a process of adaptive equilibrium constantly renegotiated between nature’s limits and human ambition. Ultimately, the narrative that emerges from the Northeast is not one of uniform decline or uniform progress. It is a story of asymmetry, between abundance and deprivation, between tradition and transformation, between ecological wisdom and institutional fragility. The region’s challenge is neither technological nor purely environmental; it is profoundly institutional. The capacity to coordinate, to mediate trade-offs, to align social and ecological objectives—these are the real frontiers of sustainability. In the final reckoning, the future of agricultural sustainability in the Northeastern Region will depend on whether it can evolve from an ecology of subsistence to an ecology of governance—where resource use is intelligent, adaptive, and socially just. The transition from fragility to resilience will not be engineered through input intensification but through institutional imagination: the cultivation of systems that can learn, adjust, and endure. If Tripura and Assam represent the promise of such adaptive hybridity, the Himalayan states remind us of the peril of inertia. Sustainability here is not a condition to be achieved, but a conversation to be continued—between people and landscapes, between tradition and reform, between the possible and the necessary.

Sustainability Trade-Offs

Agricultural sustainability in the Northeastern Region is not a seamless continuum but an intricate interplay of tensions—material, institutional, and moral—where gains along one axis often precipitate attrition along another. The empirical asymmetries among the environmental, economic, and social indices expose the anatomy of these tensions, revealing that sustainability is not a harmony to be achieved but a *dynamic equilibrium perpetually renegotiated under constraint*. The first and most palpable fault line runs between ecological restraint and economic assertion. The data trace an unmistakable inverse gradient: where ecological endowments are zealously protected, economic momentum falters; where productivity surges, the ecological substratum begins to fray. This is the quintessential *productivity–resilience paradox*—an enduring dilemma in peripheral agrarian economies, where the appetite for output collides with the fragility of biophysical systems (Pandey et al., 2022). In the Northeast, this paradox is accentuated by terrain and tenure: steep slopes, erodible soils, and communal ownership collectively tighten the ecological leash. Intensification, however rational in economic terms, exacts a subtle ecological tax—soil fatigue, hydrological stress, biodiversity erosion—that rarely registers in short-term growth figures.

Yet, the trade-off is not immutable. Institutional foresight and adaptive governance can dilute its severity. Regions where agricultural expansion is tempered by ecological thresholds and embedded in community-led resource management show that economic vitality need not always be ecologically extractive. The challenge is to design *calibrated intensification*—a mode of agrarian growth that expands livelihoods without trespassing the regenerative limits of the landscape. Equally intricate are the tensions that braid the social dimension with the other two pillars. Investment in education, health, and equity enhances the cognitive and organizational capital required for sustainable transitions, yet it diverts finite fiscal bandwidth from immediate economic returns. Conversely, when the social edifice is weak, neither ecological stewardship nor economic dynamism can hold. This interdependence lays bare the fallacy of treating sustainability as a technocratic project; it is, fundamentally, a *social covenant* sustained by informed, capable, and cohesive communities (Thangjam et al., 2023).

At its core, the Northeast’s sustainability conundrum is not a question of resources but of *governance elasticity*—the capacity of institutions to absorb ecological signals, interpret social aspirations, and recalibrate policy instruments accordingly. Trade-offs, in this view, are not pathological but constitutive; they delineate the frontiers within which societies must innovate, negotiate, and occasionally concede. The task, therefore, is not to abolish trade-offs—a chimera—but to domesticate them: to transform antagonism into accommodation through sequenced interventions, informed participation, and the cultivation of institutional reflexivity. In this synthesis, sustainability ceases to be a static arithmetic of indices and becomes an *ethical geometry*—a disciplined balancing of competing goods within ecological

limits. The Northeast's future will hinge less on its natural plenitude than on its ability to choreograph these balances with discernment, restraint, and a measure of political imagination.

5. Conclusion

The PSR-based Agricultural Sustainability Index (ASI) developed in this study highlights stark differences in sustainability performance across the Northeastern states. Tripura ranks highest (ASI = 0.54), combining the region's highest cropping intensity (CI = 1.000) with strong foodgrain yields and the top Social Security Index score. These strengths are supported by effective irrigation use and steady wage-employment provision through MNREGA, enabling it to align agricultural productivity with social resilience. Assam (ASI = 0.48) follows closely, driven by the highest Environmental Sustainability Index score and efficient land use, alongside the best infant mortality outcome.

However, its economic security remains limited due to low rural incomes. Meghalaya (ASI = 0.43) benefits from the highest irrigation intensity in the region, buffering climate risks, but faces demographic constraints with a limited working-age population. Mizoram and Arunachal Pradesh perform moderately well in ecological terms—Arunachal with extensive forest cover and Mizoram with the highest literacy rate—but low cropping intensity and limited employment opportunities suppress their overall rankings. At the lower end, Nagaland (ASI = 0.28) is constrained by high livestock pressure (LSO = 0.012) and shortened shifting cultivation cycles, which accelerate land degradation and depress productivity. Sikkim (ASI = 0.31) demonstrates the benefits of organic farming and high-value niche crops, yet its negligible net sown area (LUNSA = 0.000) limits broader agricultural viability despite higher per capita income levels.

Three patterns emerge from the results. First, top performers like Tripura and Assam show that pairing moderate-to-high productivity with targeted social investment can yield balanced sustainability outcomes. Second, mid-tier states often excel in one domain but lag in others, making progress fragile. Third, the lowest performers face multi-dimensional constraints—environmental pressures, economic underdevelopment, and institutional weaknesses—that require integrated interventions rather than isolated programs. Policy implications are clear. Lower-ranked states need coordinated strategies that address land-use pressures, ensure irrigation reliability, and strengthen social service delivery simultaneously. Higher-ranked states should focus on sustaining productivity gains while enhancing climate resilience, market access, and human capital.

Policy Implications

The results indicate that a one-size-fits-all strategy will underperform in the North Eastern Region (NER). Binding constraints differ across states and often interact—terrain-induced hazards amplify market isolation; weak local services dampen technology uptake. Below the study interpret the findings through the PSR lens and outline policy pathways that match state-specific conditions, emphasising sequencing and complementarities.

State-specific sustainability missions: Because pressures, state conditions, and response capacity vary, each state should anchor action in a mission with time-bound targets linked to its binding constraints. For hazard-exposed hill districts, this may prioritise erosion control and accessibility; for floodplains, water management and diversification. Public “progress cards” published annually can strengthen accountability and enable course correction.

Landscape-appropriate systems: On steep or hazard-prone terrain, terracing, agroforestry, and climate-resilient crops reduce erosive pressures (P) while building natural capital (S). Agroforestry also creates income buffers and biodiversity co-benefits. The evidence suggests these practices deliver durable gains when paired with basic infrastructure and advisory support; promoted in isolation, they risk low adoption and maintenance gaps.

Reliable water control: Minor irrigation reliability, rainwater harvesting, and water-saving practices stabilise yields and reduce climate risk—key where rainfall variability drives volatility. This lever enhances the “state” of productive assets and makes subsequent responses (e.g., improved seed, fertiliser efficiency, cropping intensity) more effective. Design should avoid groundwater over-extraction and include community operations and maintenance.

Extension and farmer services: Last-mile advisory, soil testing, and input quality assurance translate technology into practice. Digital advisories and market information can narrow information gaps, but their impact depends on local credibility and timeliness. Strengthening these services raises the return to landscape interventions and irrigation by improving decision quality at the farm level.

Markets and aggregation: All-weather connectivity, storage, primary processing, and producer collectives lower transaction costs and smooth price risk. Where geography fragments markets, aggregation platforms are pivotal for scaling diversification and value addition. Without these responses, productivity gains may not translate into incomes, weakening incentives to sustain conservation practices.

Social foundations: Education, healthcare, and women's economic empowerment increase adaptive

capacity and raise the uptake of climate-smart practices. Women’s groups and self-help collectives often underpin successful producer organisations and resource stewardship. Investments here address persistent social deficits observed in otherwise productive states, converting short-term gains into durable improvements in well-being.

Monitoring and learning: A PSR-based dashboard can track pressures (e.g., hazard exposure), state variables (soil/water condition, services), and responses (program coverage, adoption). Routine reviews against mission targets, published as annual progress cards, enable peer learning across states and disciplined mid-course correction. Where indicators are weak, participatory validation and district-level updates should be prioritised.

The discussion points to practical sequencing: secure basic enablers (water control, extension, market access), deploy landscape-appropriate systems, and embed social foundations and monitoring. These complementary moves address the dominant pressures in each context, strengthen the productive state of agriculture, and build response capacity, thereby converting incremental improvements into sustained advances in productivity, resilience, and equity.

Limitations

The study has several limitations. Some indicators are dated and available only at the state level, so important intra-state heterogeneity is under-represented. The indicator set reflects choices from the literature, and alternative proxies could capture additional social–ecological realities not covered here. Pre-processing decisions—normalisation, winsorisation, and weighting—may influence the ordering of mid-tier states even if the overall tiers remain broadly stable. The study did not implement systematic sensitivity tests or triangulate results with multi-criteria decision-analysis approaches such as AHP, TOPSIS, or PROMETHEE. Farm-level processes and detailed physical, chemical, and biological characteristics lie outside the present scope, limiting biophysical granularity. Finally, discontinuities in available series constrain inference on trends; future work should incorporate more recent data, finer spatial resolution, and consistent, higher-frequency updates to strengthen temporal analysis and validation.

Data Availability

All processed datasets for tables and figures are available on request if necessary. Raw data sources are publicly accessible from the NEC Databank, IMD, Census of India, and MNREGA MIS portals.

Appendix A

Code	Indicator	PSR	Polarity	Weight	Rank
LSO	Livestock Ownership / Total Livestock	P	–	0.154	1
ANAU	Area under Non-Agricultural Uses	P	–	0.147	2
LUNSA	Land Use: Net Sown Area	S	+	0.133	3
EMP_MNREGA	MNREGA Employment (person-days/1,000)	R	+	0.097	4
PCDP	Per-Capita Domestic Product	S	+	0.094	5
FGP	Foodgrain Yield per Hectare	S	+	0.068	6
IMR	Infant Mortality Rate	S	–	0.062	7
II	Irrigation Intensity	R	+	0.038	8
AAT	Average Annual Temperature	P	–	0.030	9
AAR	Average Annual Rainfall	S	+	0.029	10
CI	Cropping Intensity	S	+	0.029	11
LR	Literacy Rate	S	+	0.026	12
CFert	Fertilizer Consumption (N+P+K)	P	–	0.024	13
AFC	Area under Forest Cover	S	+	0.023	14
PWA	Population in Working Age (15–49)	S	+	0.023	15
SR	Sex Ratio	S	+	0.022	16

Appendix B

Variable	% Missing	% Imputed (Stage 1 spatial)	% Imputed (Stage 2 temporal)	MAE	RMSE	States/Years affected
Annual Average Rainfall	0.0	0.0	0.0	0.2134	0.3303	—
Area under Non Agricultural uses	0.0	0.0	0.0	0.2103	0.3885	—
Area under forest cover	0.0	0.0	0.0	0.2134	0.3303	—

Average Annual Temperature	0.0	0.0	0.0	0.2972	0.3601	—
Consumption of fertiliser (N+P+K) 2021	44.4	0.0	0.0	0.3514	0.4138	Arunachal Pradesh, Meghalaya, Nagaland, Sikkim
Cropping Intensity	0.0	0.0	0.0	0.2387	0.2984	—
Land use – Net Sown Area	0.0	0.0	0.0	0.1886	0.3713	—
Total Livestock (2019)	0.0	0.0	0.0	0.2114	0.4044	—
Foodgrain productivity / Yield (kg/ha)	0.0	0.0	0.0	0.3616	0.4109	—
Irrigation Intensity	0.0	0.0	0.0	0.2504	0.3219	—
Per-capita Net Domestic Product (current prices)	0.0	0.0	0.0	0.2057	0.3233	—
Employment availed (person-days) under MNREGA	0.0	0.0	0.0	0.1807	0.3306	—
Sex Ratio (2011 census)	0.0	0.0	0.0	0.2364	0.3068	—
Literacy Rate (2011 census)	0.0	0.0	0.0	0.2146	0.2864	—
Infant Mortality Rate	0.0	0.0	0.0	0.4394	0.4659	—
Population in Working Age (15–49)	0.0	0.0	0.0	0.2154	0.2888	—

Appendix C

Code	Indicator	2014	2015	2016	2017	2018	2019	2020
AFC	Area under Forest Cover	5	4	5	5	4	23	Yes
LUNSA	Net Sown Area	5	5	5	5	4	24	Yes
ANAU	Area under Non-Agricultural Uses	5	4	5	5	4	23	Yes
CFert	Fertilizer Consumption (N+P+K)	4	5	3 (imputed, 44% missing)	4	3	19	Yes
LSO	Livestock Ownership	5	5	5	5	4	24	Yes
AAR	Average Annual Rainfall	5	4	5	5	5	24	Yes
AAT	Average Annual Temperature	5	4	5	5	5	24	Yes
CI	Cropping Intensity	5	5	5	4	4	23	Yes
FGP	Foodgrain Yield per Hectare	5	5	5	4	4	23	Yes
II	Irrigation Intensity	5	5	4	4	4	22	Yes
PCDP	Per-Capita Domestic Product	5	4	4	5	4	22	Yes
EMP_MNREGA	MNREGA Employment	5	5	4	4	4	22	Yes

SR	Sex Ratio	4	4	4	5	3 (Census 2011)	20	Yes
LR	Literacy Rate	5	5	4	5	3 (Census 2011)	22	Yes
IMR	Infant Mortality Rate	5	5	3 (Census + imputed)	4	3	20	Yes
PWA	Population in Working Age (15–49)	4	4	4	5	3 (Census 2011)	20	Yes

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