Supplementary material for:

Subnational variation in sustainable nitrogen management across Indian croplands and its linkage with state-level governance

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Supplementary Methods

* Mixed-effects model for the Madhya Pradesh–Maharashtra comparison

To provide a quantitative assessment of the association between regional policy–management context and nitrogen-management performance, we fitted a district–year mixed-effects model for the selected districts in Madhya Pradesh and Maharashtra located within the Western Plateau and Hills agro-climatic region. The outcome variable was the Sustainable Nitrogen Management Index (SNMI), where lower values indicate improved composite nitrogen-management performance.

Mixed-effects models are widely used for repeated-measures and hierarchical environmental data because they allow observations to be grouped within spatial or temporal units while accounting for non-independence among repeated observations [1,2]. Before model fitting, variables were checked for missing values, outliers, collinearity and distributional issues following standard data-exploration guidance for ecological and environmental regression analyses [3].

The model was specified as:

$$\mathrm{SNMI}_{d,t} = \beta_0 + \beta_1 \mathrm{PolicyPhase}_{d,t} + \mathbf{X}_{d,t}\boldsymbol{\beta} + u_d + v_t + \epsilon_{d,t}, \tag{1}$$

where $\mathrm{SNMI}_{d,t}$ is the SNMI value for district d in year t, $\mathrm{PolicyPhase}_{d,t}$ is a regional

policy–management phase indicator for the selected Madhya Pradesh districts, and $\mathbf{X}_{d,t}$ is a vector of agricultural-management covariates. These covariates included irrigation share, fertiliser input, manure input, biological nitrogen fixation, atmospheric nitrogen deposition and cropping intensity. The terms u_d and v_t represent district- and year-level random intercepts, respectively, and $\epsilon_{d,t}$ is the residual error term.

Continuous covariates were standardised to zero mean and unit standard deviation before model fitting, allowing coefficients to be compared on a common scale. The policy–management phase indicator was retained as a binary contextual variable. The inclusion of district-level random intercepts accounts for persistent spatial heterogeneity among districts, while year-level random intercepts account for common temporal shocks affecting all districts in a given year. This structure is appropriate because district-level SNMI values may be influenced by unobserved time-invariant district characteristics, such as soil properties, infrastructure, agro-economic conditions and historical cropping patterns, as well as by common year-specific variation.

The policy–management phase variable was used to represent a broad regional transition in Madhya Pradesh involving procurement support, irrigation development, rural-road connectivity, market access and crop-composition shifts. It was not interpreted as the causal effect of any single policy intervention. Instead, the coefficient β_1 was interpreted as a conditional association between this broader regional policy–management environment and district-level SNMI after accounting for measured agricultural-management vari-

ables. This cautious interpretation is consistent with methodological guidance that longitudinal or panel models can adjust for some forms of unobserved heterogeneity, but do not by themselves establish causal effects without stronger identification assumptions [4,5].

Model results are shown in Supplementary Fig. S22. Negative coefficients indicate lower SNMI values and therefore improved composite nitrogen-management performance, whereas positive coefficients indicate higher SNMI values and poorer performance. The Madhya Pradesh policy–management phase indicator was negatively associated with SNMI after controlling for irrigation share, fertiliser input, manure input, biological nitrogen fixation, atmospheric nitrogen deposition and cropping intensity. This result supports the interpretation that the observed Madhya Pradesh–Maharashtra divergence reflects broader differences in regional agricultural-management trajectories, but it should not be interpreted as proof of direct causality.

* Sensitivity and interpretation

Because the analysis is based on observational district-level data, causal attribution to individual interventions is not possible without more detailed information on policy implementation, adoption intensity, farmer-level behaviour and local enforcement. We therefore used the mixed-effects model as a supplementary diagnostic analysis rather than as a causal identification strategy. The estimated coefficients describe conditional associations after accounting for observed covariates and grouped district–year data structure.

We also evaluated alternative model specifications, including models with district and year fixed effects and sensitivity tests using alternative transition-period definitions. These additional checks produced qualitatively similar interpretations for the main agricultural-management drivers, although more granular policy encodings were less stable. This supports our revised framing that regional nitrogen-management trajectories are shaped by interacting changes in input use, irrigation, crop composition, market access and policy environment, rather than by any single intervention alone.

Supplementary Tables

[p]

Supplementary Table S1. Main variables used in the SNMI analysis. The table defines the principal variables used to calculate and interpret SNMI trajectories.

Variable	Unit	Definition
Nitrogen input	kg N ha^{-1} yr^{-1}	Total nitrogen input from synthetic fertiliser, manure, biological nitrogen fixation and atmospheric nitrogen deposition.
Harvested nitrogen	kg N ha^{-1} yr^{-1}	Nitrogen removed in harvested crop products.
Nitrogen surplus	kg N ha^{-1} yr^{-1}	Difference between total nitrogen input and harvested nitrogen.
NUE	Dimensionless	Nitrogen-use efficiency, calculated as harvested nitrogen divided by total nitrogen input.
$NYield^*$	Dimensionless	Normalised nitrogen yield, benchmarked against the agro-climatic-zone-specific 90th percentile of district maximum harvested nitrogen.
NUE^*	Dimensionless	Normalised NUE component used in SNMI.
SNMI	Dimensionless	Euclidean distance from the ideal point in $NYield^*$–NUE^* space; lower values indicate improved nitrogen-management performance.

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Supplementary Table S2. Agro-climatic-zone numbers and names used in the analysis. Zone names follow the agro-climatic regional classification used to aggregate district-level SNMI trajectories.

Zone number	Agro-climatic-zone name
1	Western Himalayan Region
2	Eastern Himalayan Region
3	Lower Gangetic Plains Region
4	Middle Gangetic Plains Region
5	Upper Gangetic Plains Region
6	Trans-Gangetic Plains Region
7	Eastern Plateau and Hills Region
8	Central Plateau and Hills Region
9	Western Plateau and Hills Region
10	Southern Plateau and Hills Region
11	East Coast Plains and Hills Region
12	West Coast Plains and Ghat Region
13	Gujarat Plains and Hills Region
14	Western Dry Region
15	The Islands Region

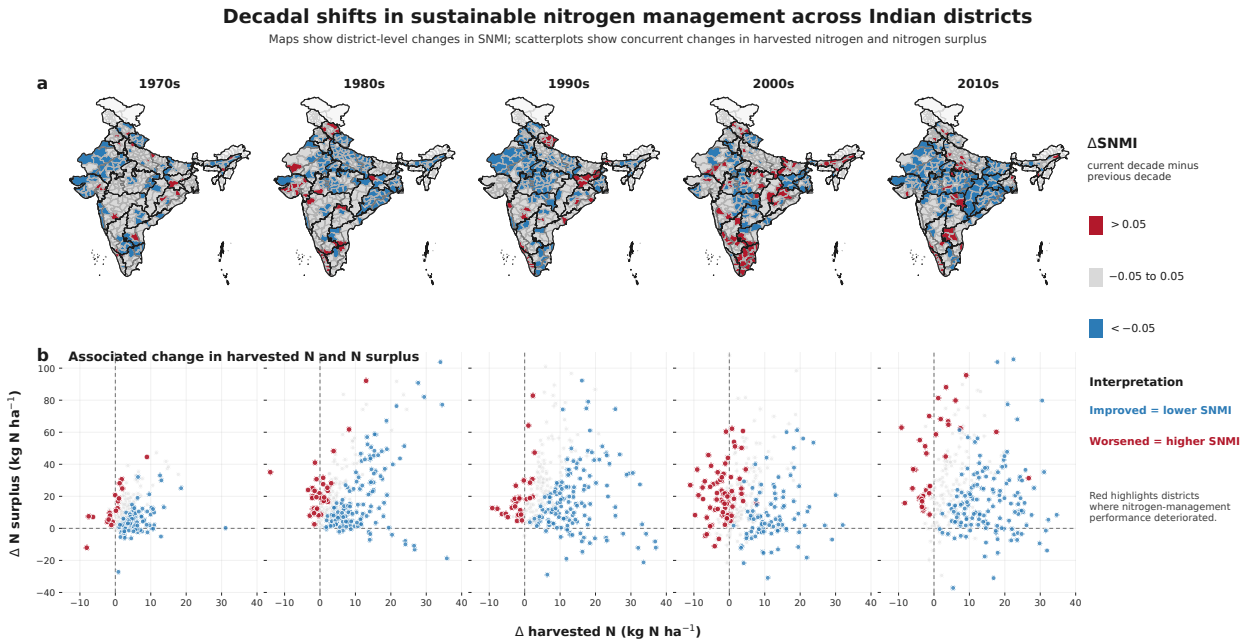
Supplementary Table S3. Definitions of variables and parameters used in the nitrogen-budget calculations. The table summarizes the main indices, variables and statistical terms used to estimate district-level nitrogen surplus, nitrogen-use efficiency and spatial variability in nitrogen-management indicators.

Symbol / term	Definition	Unit / note
i	District index used as the spatial unit of analysis.	District-level analysis unit.
y	Year index used for annual nitrogen-budget calculations.	Annual values from 1966 to 2016.
$NS_{i,y}$	Nitrogen surplus in district i and year y, calculated as total nitrogen input minus harvested crop nitrogen output.	kg N yr^{-1}; expressed as kg N ha^{-1} yr^{-1} after area normalization.
$N_{\mathrm{FERT},i,y}$	Synthetic fertilizer nitrogen input in district i and year y.	kg N yr^{-1}.
$N_{\mathrm{BNF},i,y}$	Nitrogen input from biological nitrogen fixation in district i and year y.	kg N yr^{-1}.
$N_{\mathrm{MAN},i,y}$	Animal manure nitrogen input in district i and year y.	kg N yr^{-1}.

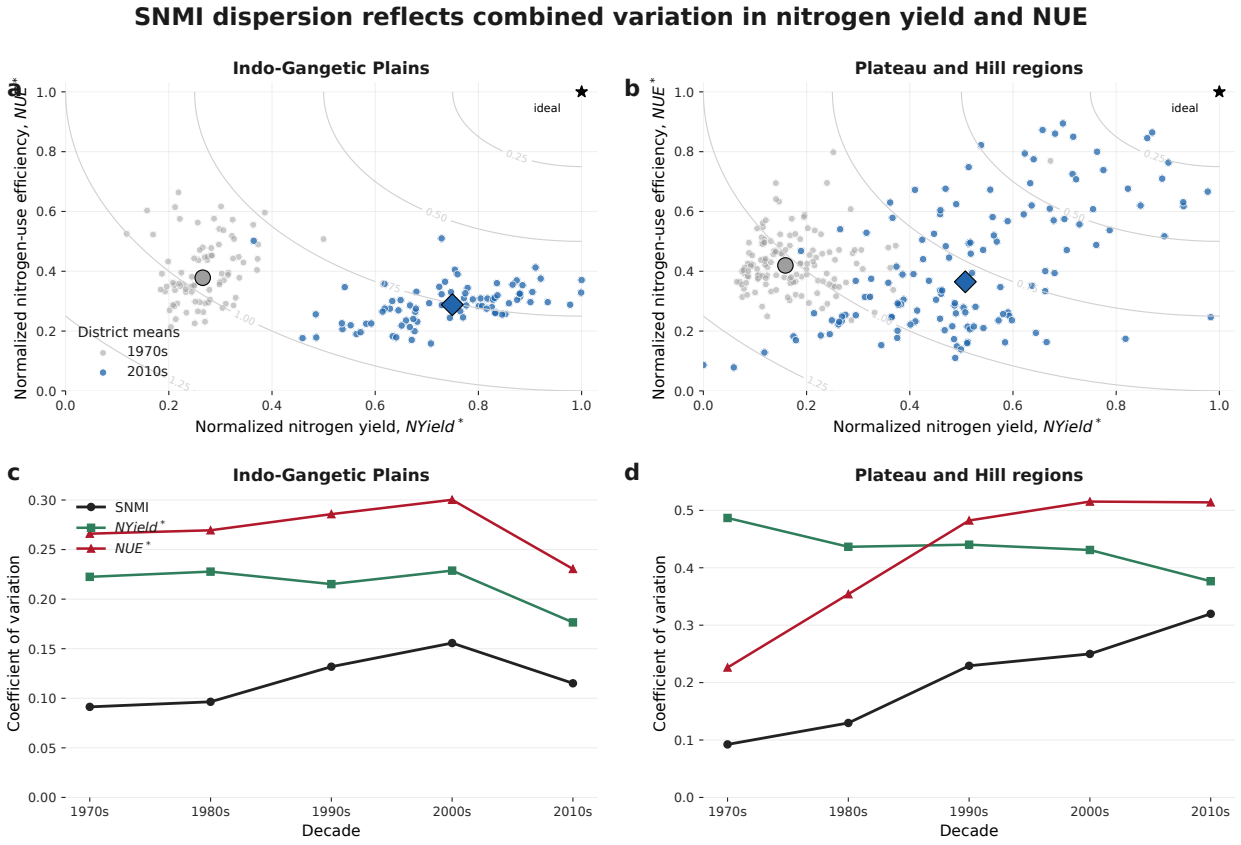
Symbol / term	Definition	Unit / note
$N_{\mathrm{DEP},i,y}$	Atmospheric nitrogen deposition in district i and year y.	kg N yr^{-1}.
$N_{\mathrm{output},i,y}$	Harvested crop nitrogen output in district i and year y.	kg N yr^{-1}.
$N_{\mathrm{input},i,y}$	Total nitrogen input in district i and year y, calculated as the sum of fertilizer nitrogen, biological nitrogen fixation, manure nitrogen and atmospheric nitrogen deposition.	kg N yr^{-1}.
$A_{i,y}$	Harvested crop area.	ha.
ACZ	Agroclimatic zone used to define region-specific nitrogen-yield reference values and summarize spatial patterns.	Indian agroclimatic-zone classification.
σ	Standard deviation of SNMI or its components across districts within a given year or agroclimatic zone.	Same unit as the variable being summarized.
μ	Mean value of SNMI or its components across districts within a given year or agroclimatic zone.	Same unit as the variable being summarized.

CV	Coefficient of variation, calculated as σ/μ, used to describe relative dispersion across districts.	Dimensionless.

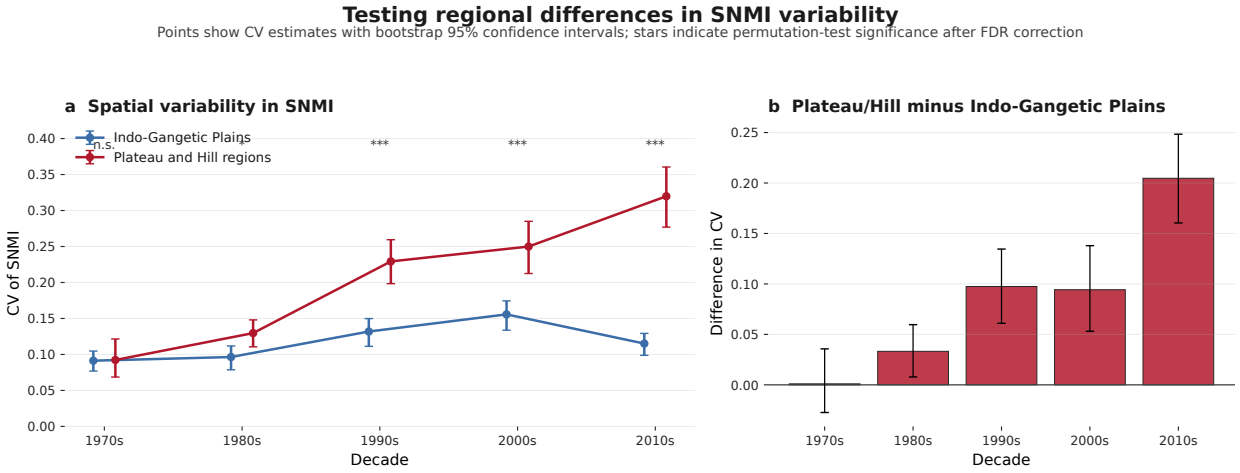
Supplementary Figures



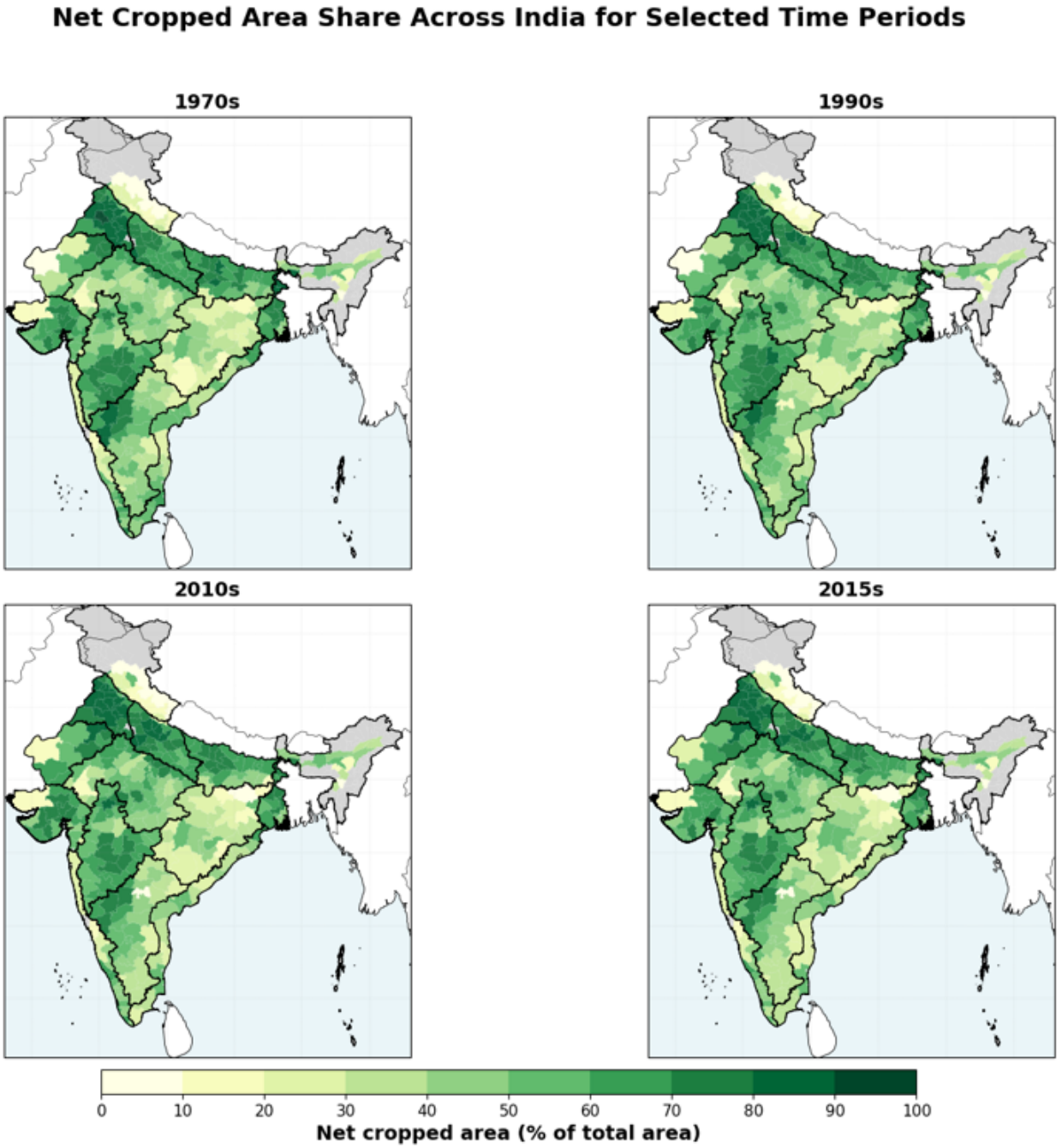
Supplementary Figure S1. Decadal shifts in sustainable nitrogen management across Indian districts. **a,** District-level changes in SNMI between consecutive decades. Blue indicates improvement, defined as a decline in SNMI of more than 0.05; grey indicates relative stability; and red indicates worsening, defined as an increase in SNMI of more than 0.05. **b,** Corresponding district-level changes in harvested nitrogen and nitrogen surplus. Point colours match the SNMI-change classes shown in panel a. Lower SNMI values indicate improved nitrogen-management performance; therefore, negative ΔSNMI values represent improvement.



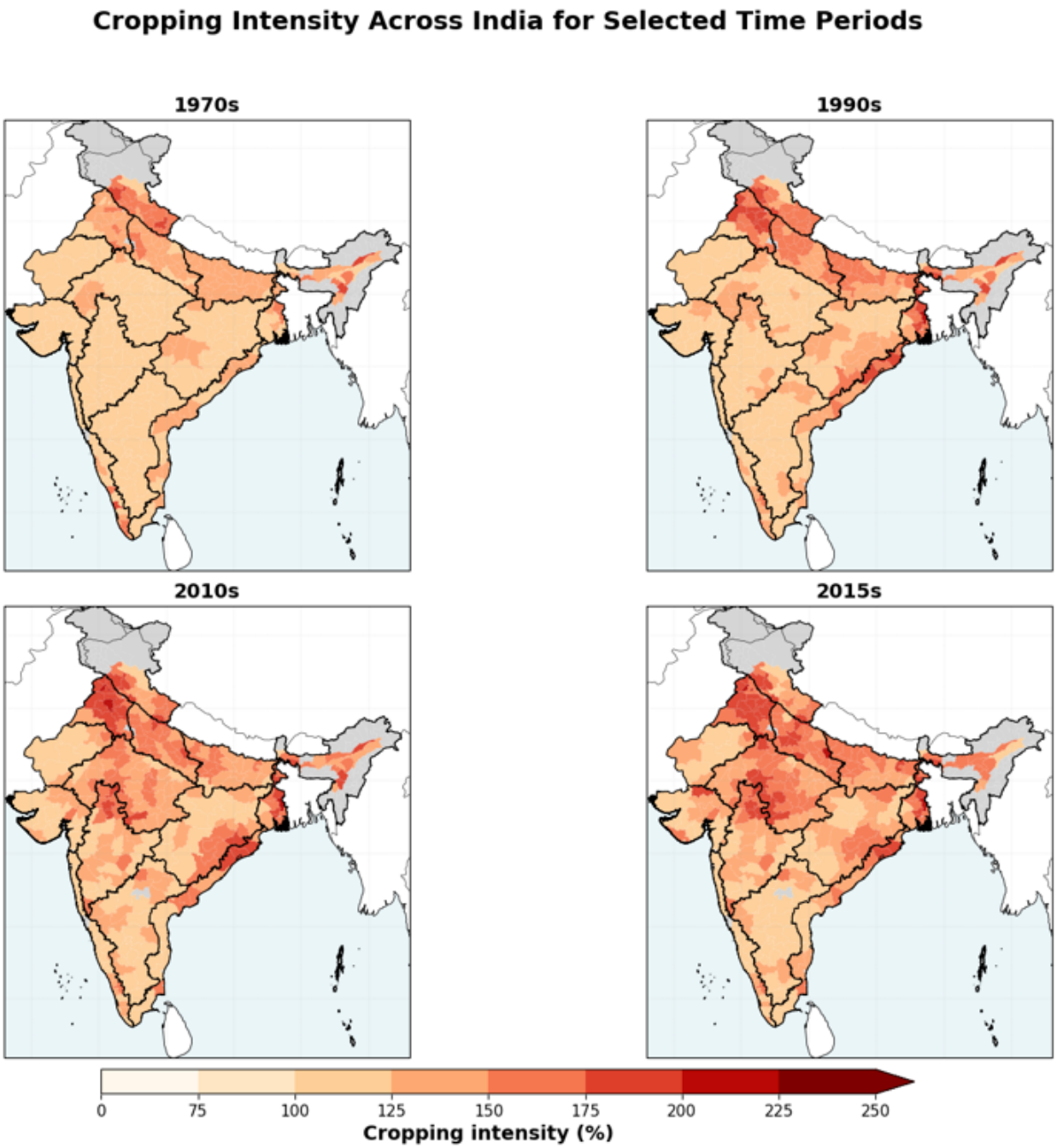
Supplementary Figure S2. Component-level interpretation of SNMI variability across major agro-climatic regions. a,b, District-level distributions in normalised nitrogen-yield–NUE space for the Indo-Gangetic Plains and the Plateau and Hill regions. Grey points represent district means for the 1970s and blue points represent district means for the 2010s. Background contours show constant SNMI values, with the ideal point located at $NYield^* = 1$ and $NUE^* = 1$. **c,d,** Decadal coefficient of variation for SNMI, normalised nitrogen yield ($NYield^*$) and normalised NUE (NUE^*).



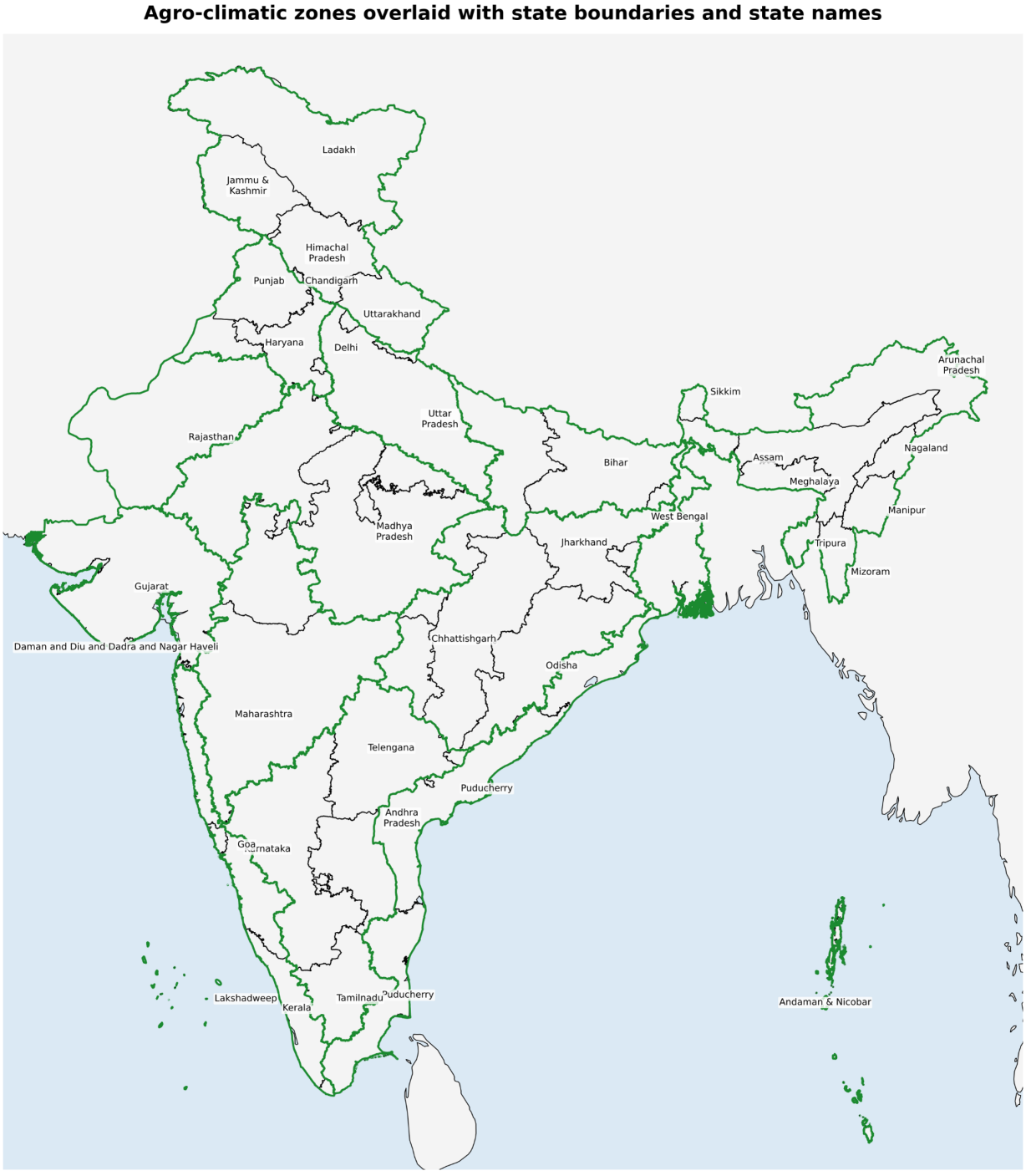
Supplementary Figure S3. Statistical comparison of regional SNMI variability. **a,** Decadal coefficient of variation (CV) of SNMI for the Indo-Gangetic Plains and the Plateau and Hill regions. Points show CV estimates and error bars show bootstrap 95% confidence intervals. **b,** Difference in CV between the Plateau and Hill regions and the Indo-Gangetic Plains. Positive values indicate higher SNMI variability in the Plateau and Hill regions. Significance markers are based on permutation tests after false-discovery-rate correction.



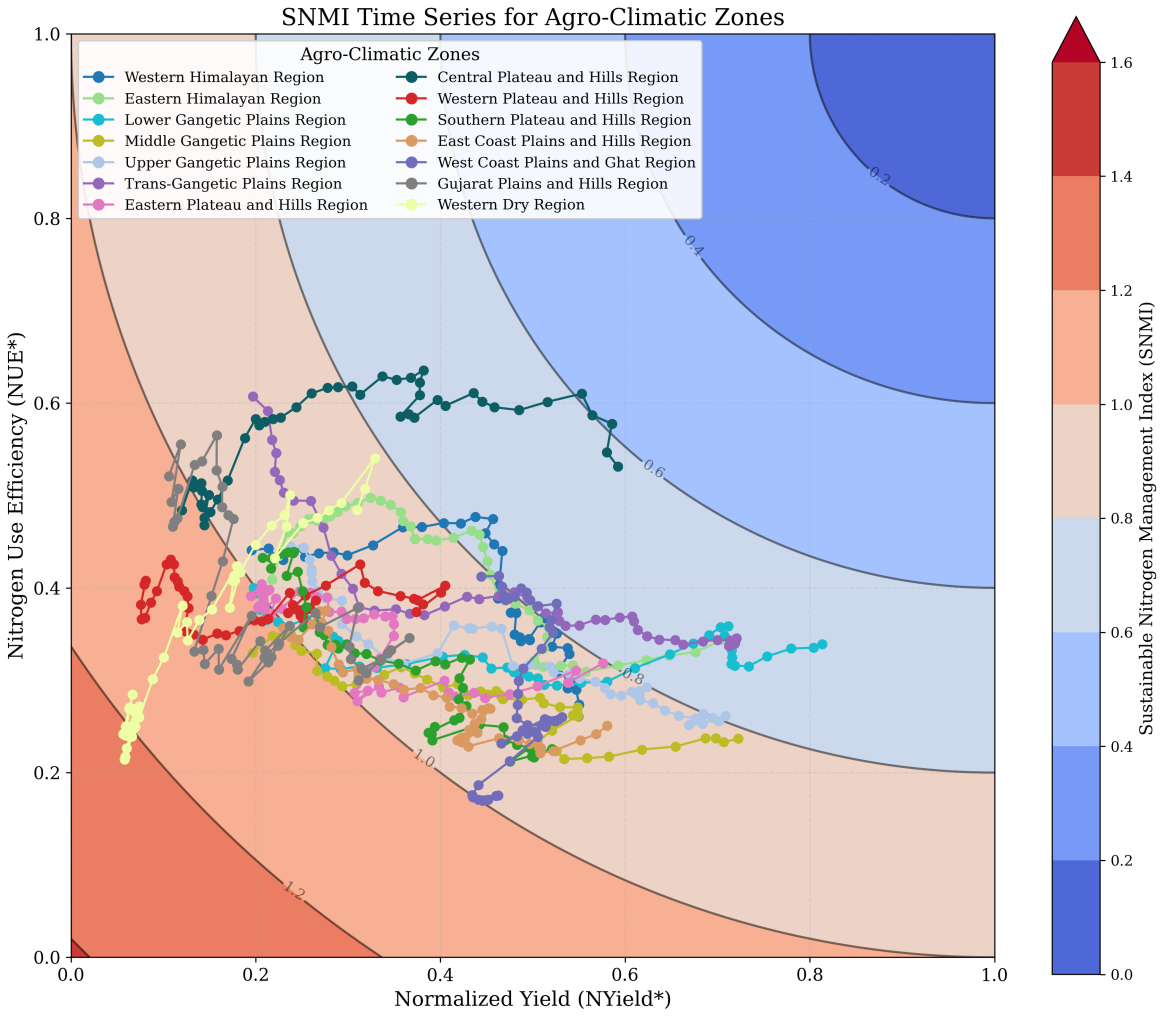
Supplementary Figure S4. Spatial distribution of net cropped area share across India. Maps show district-level net cropped area as a percentage of total district area for selected time periods. Higher values indicate districts where agricultural land occupies a larger share of the landscape.



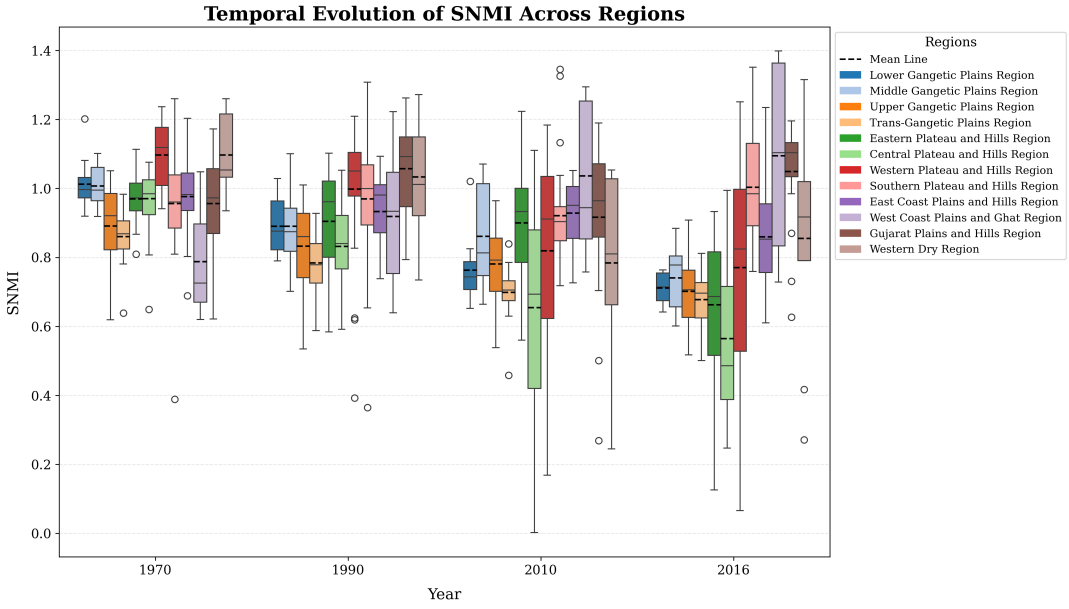
Supplementary Figure S5. Spatial distribution of cropping intensity across India. Maps show district-level cropping intensity for selected time periods. Cropping intensity represents the ratio of gross cropped area to net cropped area, expressed as a percentage, and indicates the extent of multiple cropping within a district.



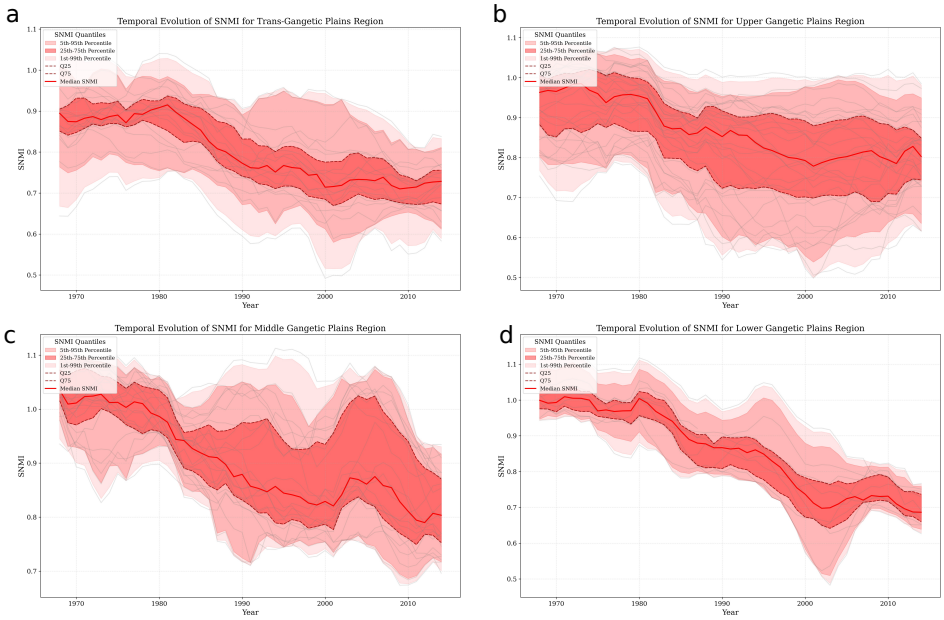
Supplementary Figure S6. Spatial context for agro-climatic zones and Indian states. The map shows agro-climatic-zone boundaries overlaid with Indian state boundaries and state names.



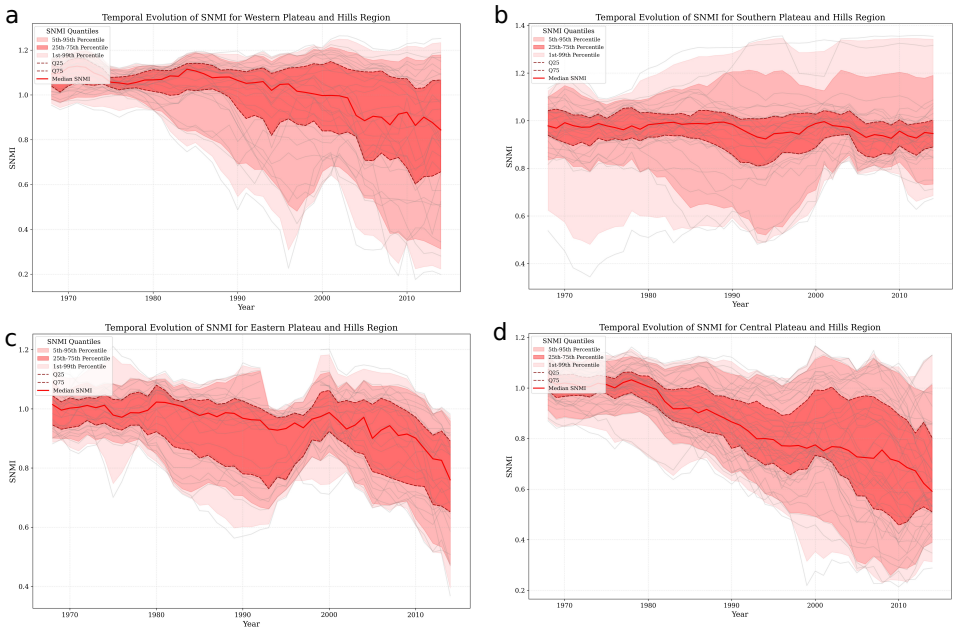
Supplementary Figure S7. Trajectories of normalised yield and nitrogen-use efficiency across Indian agro-climatic regions. The plot shows trajectories in NUE^*–$NYield^*$ space with SNMI background contours. Lower SNMI values indicate improved nitrogen-management performance. Nitrogen yield is benchmarked against the agro-climatic-zone-specific 90th percentile of district maximum harvested nitrogen.



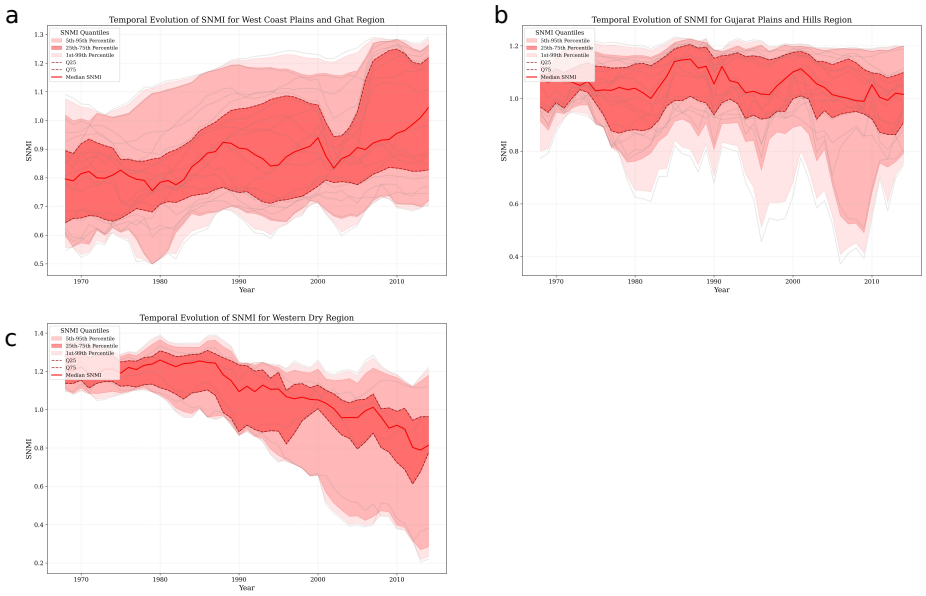
Supplementary Figure S8. Temporal trends in inter- and intra-regional variability of SNMI. The figure shows temporal trajectories of mean SNMI across agro-climatic regions, using region-specific reference yields.



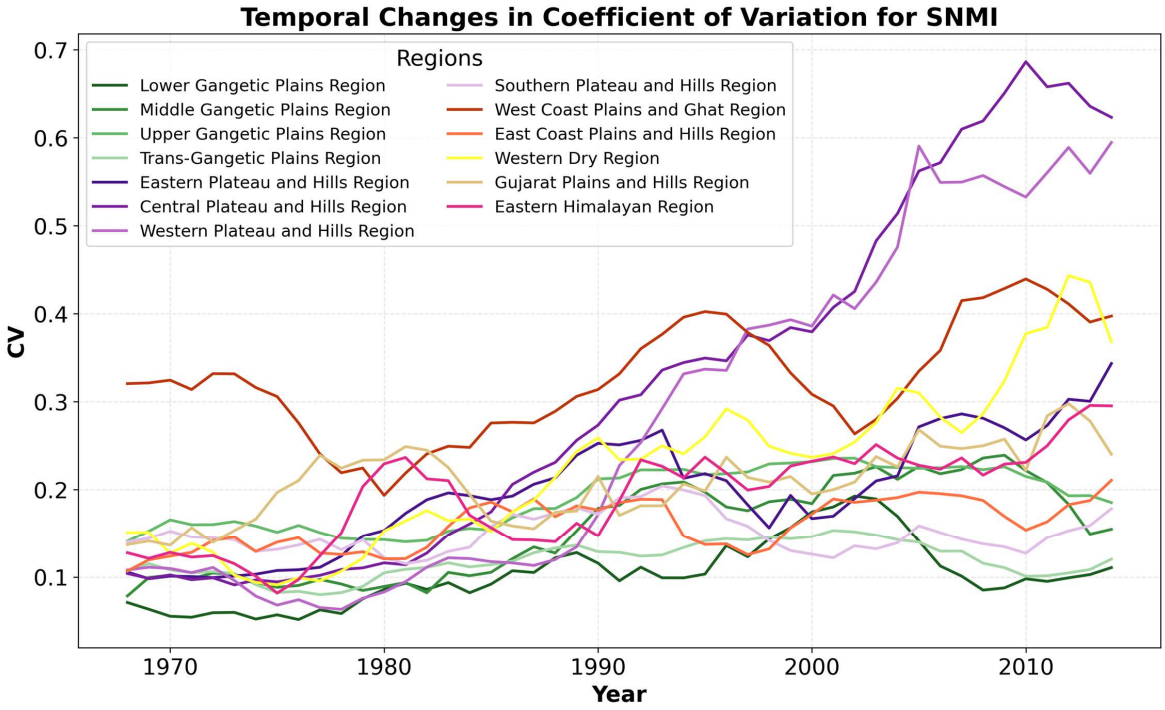
Supplementary Figure S9. Temporal variability in SNMI across the Indo-Gangetic Plains. Panels show SNMI trajectories for the Trans-Gangetic, Upper Gangetic, Middle Gangetic and Lower Gangetic Plains. Dark lines represent central tendencies and shaded bands indicate percentile ranges across districts.



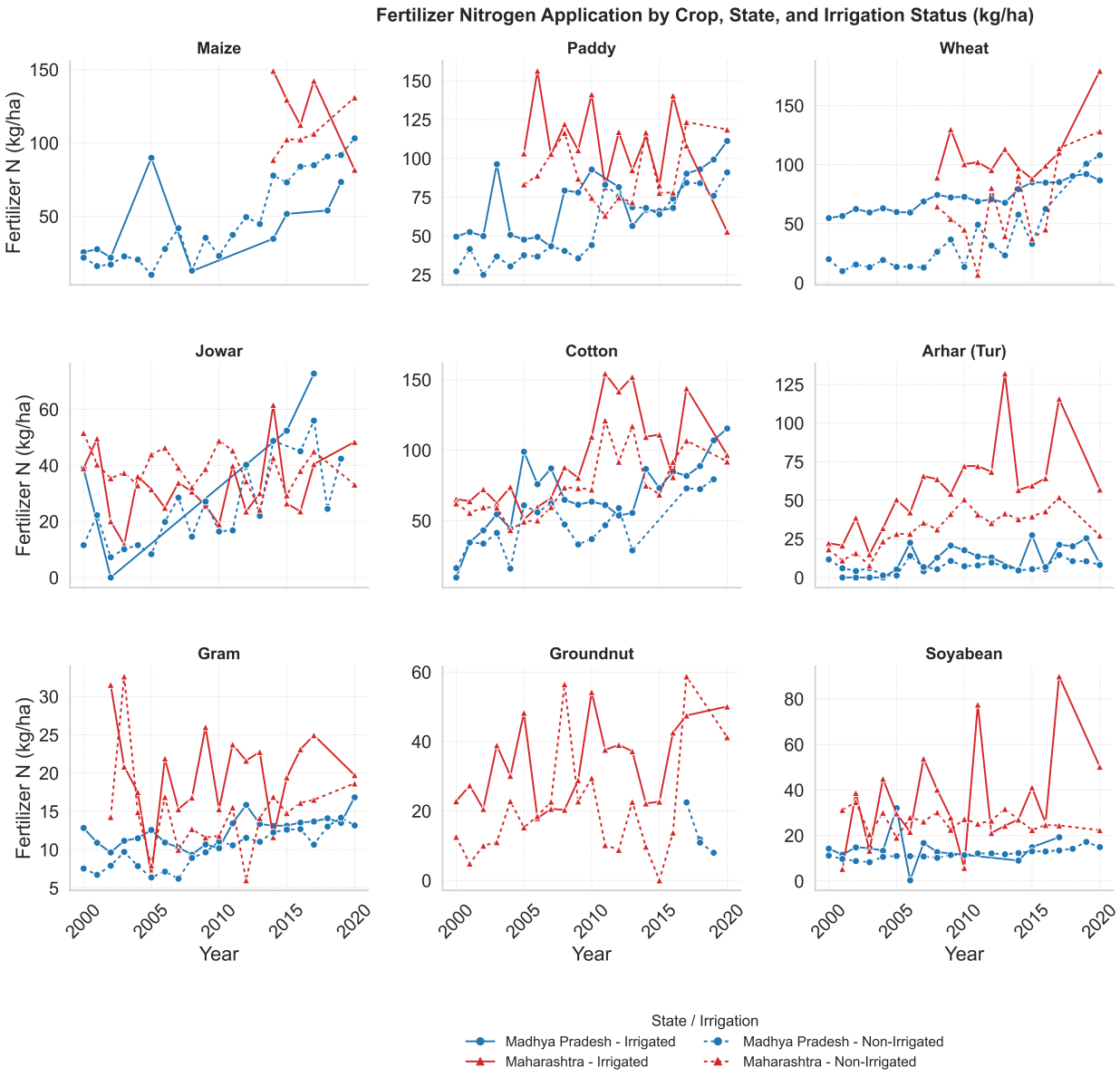
Supplementary Figure S10. Temporal variability of SNMI across India's plateau regions. Panels show SNMI trajectories for the Western, Southern, Eastern and Central Plateau and Hills regions.



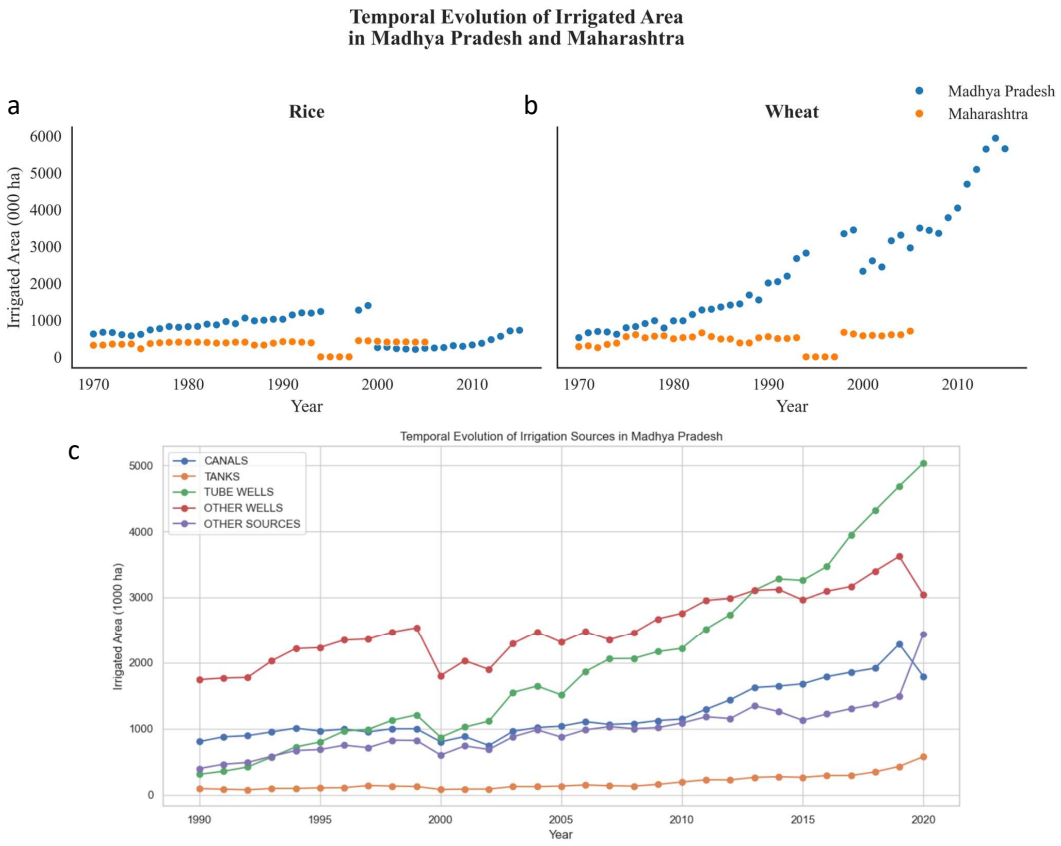
Supplementary Figure S11. SNMI variability across plains, coastal and dry regions. The figure shows temporal SNMI trajectories across additional agro-climatic regions, including the Western Ghats, Gujarat Plains and Hills, and the Western Dry region.



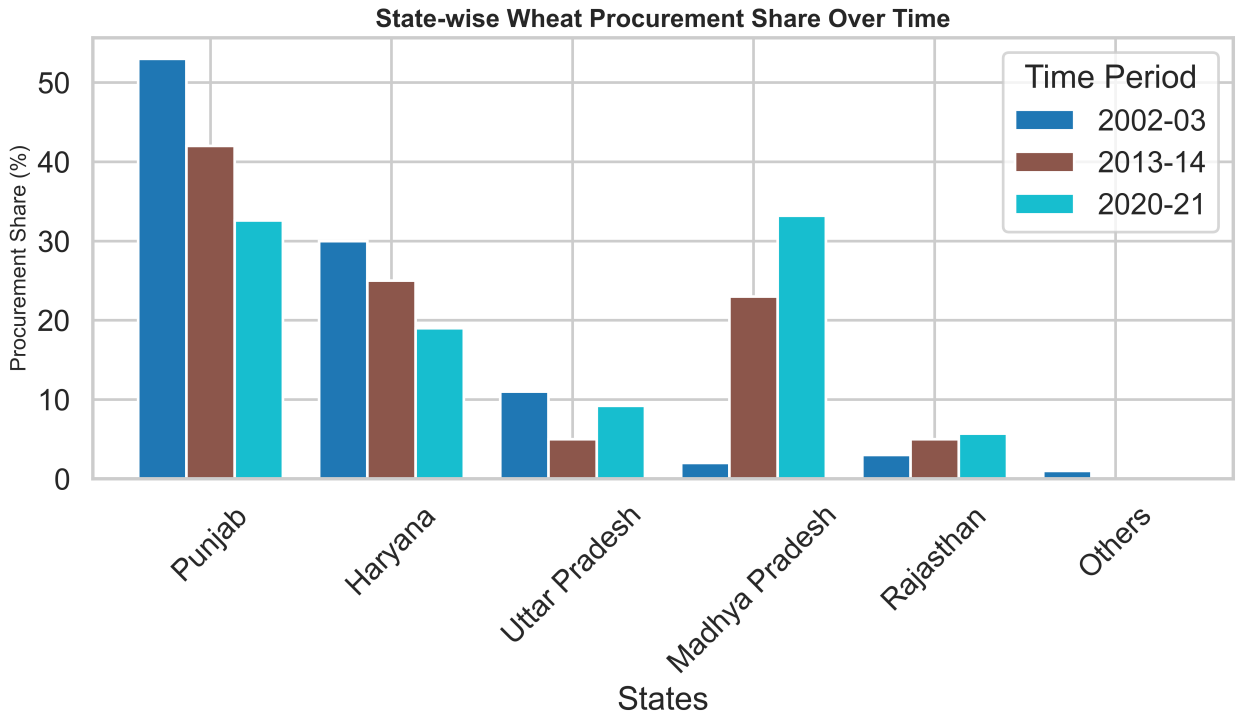
Supplementary Figure S12. Coefficient of variation of SNMI by agro-climatic region. The coefficient of variation was calculated for district-level SNMI within each agro-climatic region through time. Increasing CV indicates widening intra-regional disparity in composite nitrogen-management performance.



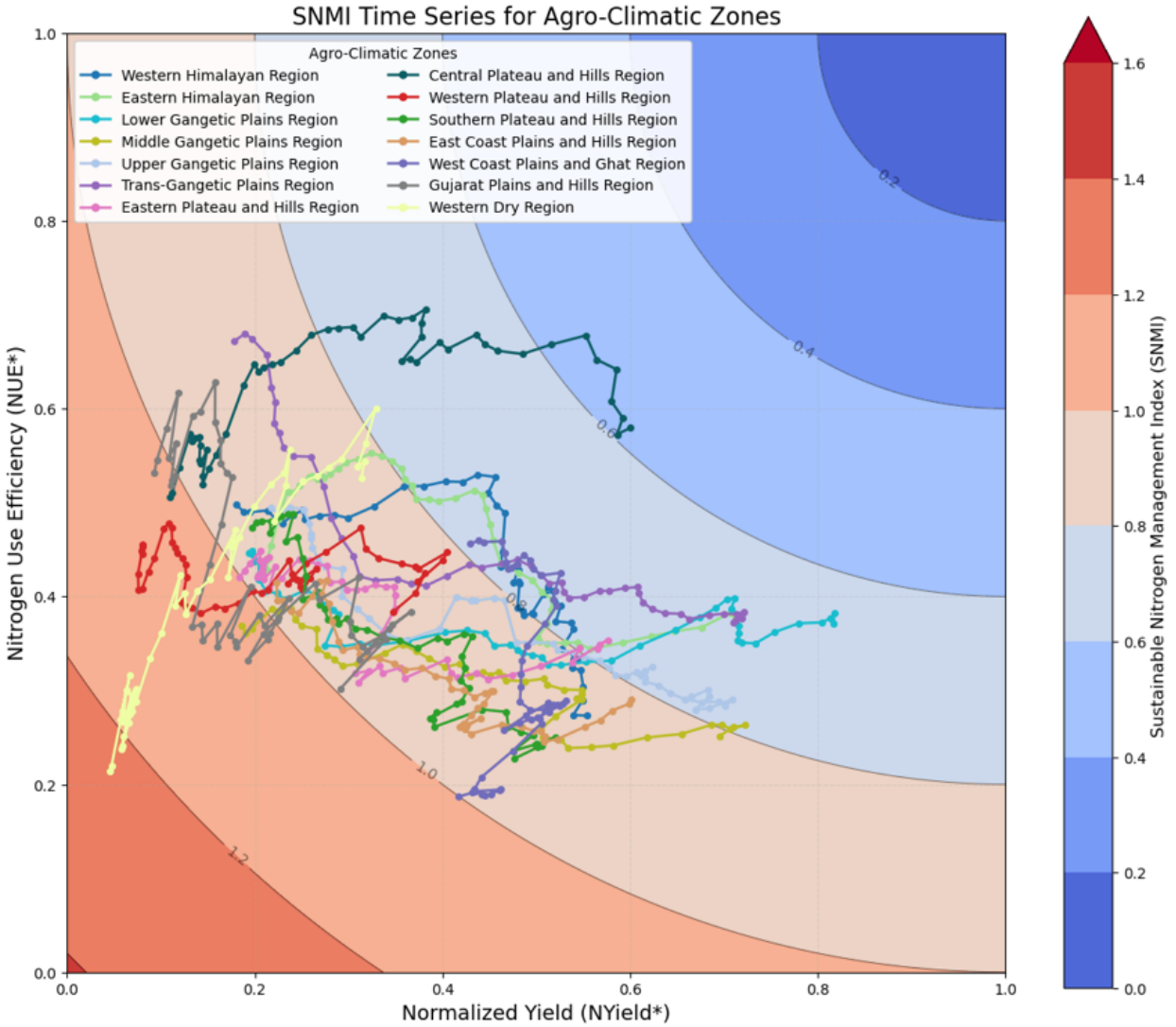
Supplementary Figure S13. Fertiliser nitrogen application by crop, irrigation status and state. Fertiliser nitrogen application is shown for selected crops and irrigation conditions in Madhya Pradesh and Maharashtra using Government of India cost-of-cultivation survey data [6]. Blue and red colours indicate Madhya Pradesh and Maharashtra, respectively; solid and dashed lines distinguish irrigated and non-irrigated conditions.



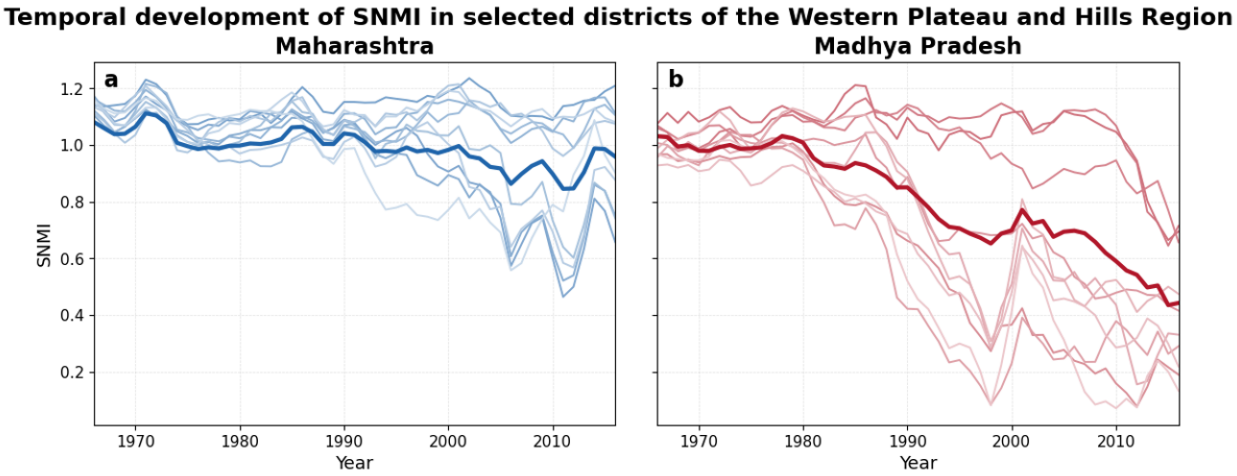
Supplementary Figure S14. Irrigated area and irrigation sources in Madhya Pradesh. The figure shows rice and wheat irrigated area through time and changes in irrigation sources in Madhya Pradesh [7,8].



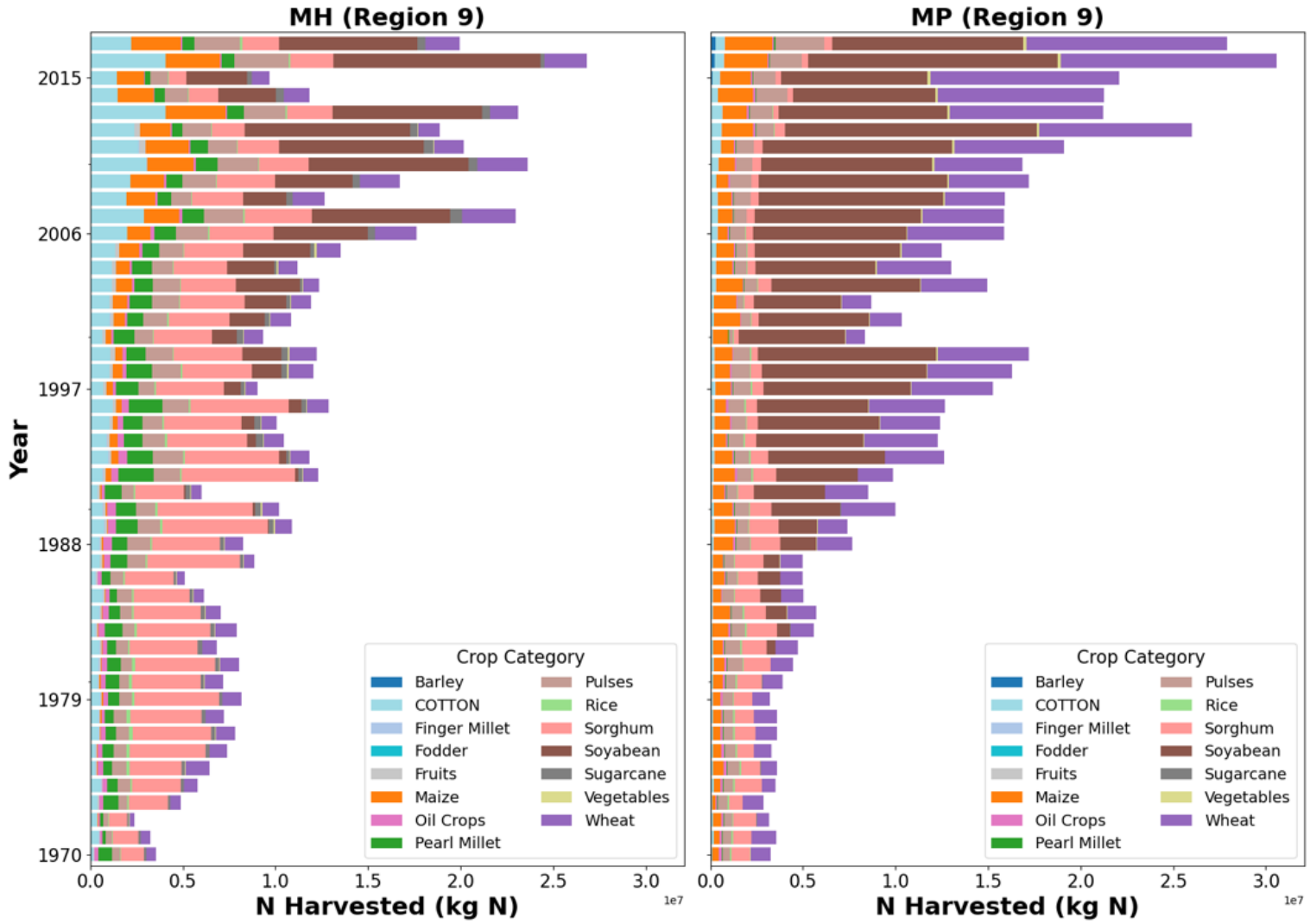
Supplementary Figure S15. State-wise wheat procurement shares. The figure compares wheat procurement shares across Indian states for 2002–03, 2013–14 and 2020–21 [9].



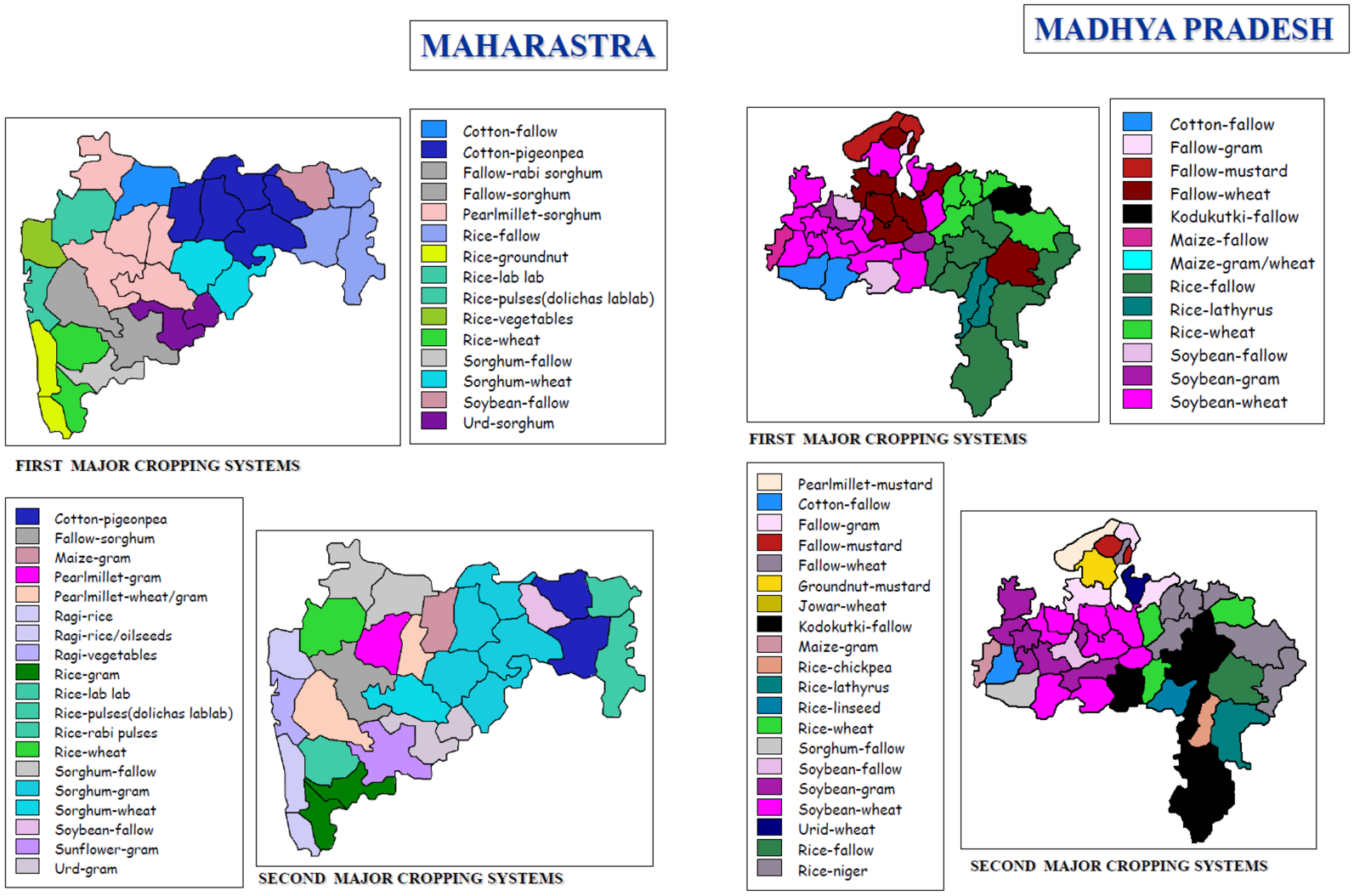
Supplementary Figure S16. Sensitivity of SNMI trajectories to the NUE normalisation boundary. SNMI trajectories across agro-climatic zones were recalculated using an alternative NUE reference value of 0.9 instead of 1.0. The resulting trajectories remain broadly consistent with the main analysis, indicating that the main findings are not sensitive to the chosen NUE normalisation boundary.



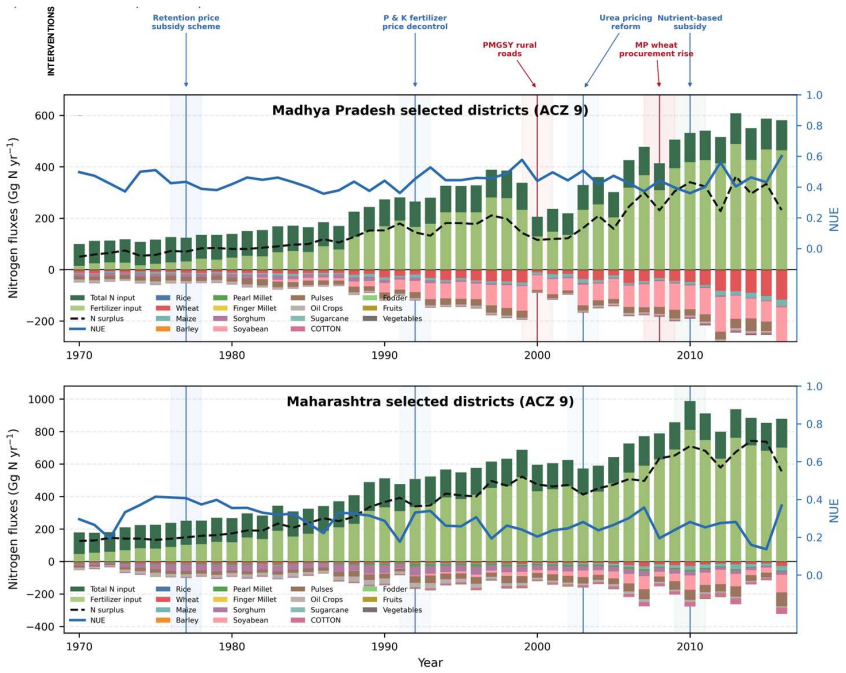
Supplementary Figure S17. Temporal development of SNMI in selected districts of the Western Plateau and Hills region. District-level SNMI trajectories are shown for selected districts in Maharashtra and Madhya Pradesh. Thin lines represent individual district trajectories and thick lines represent state-level means across the selected districts. Lower SNMI values indicate improved composite nitrogen-management performance.



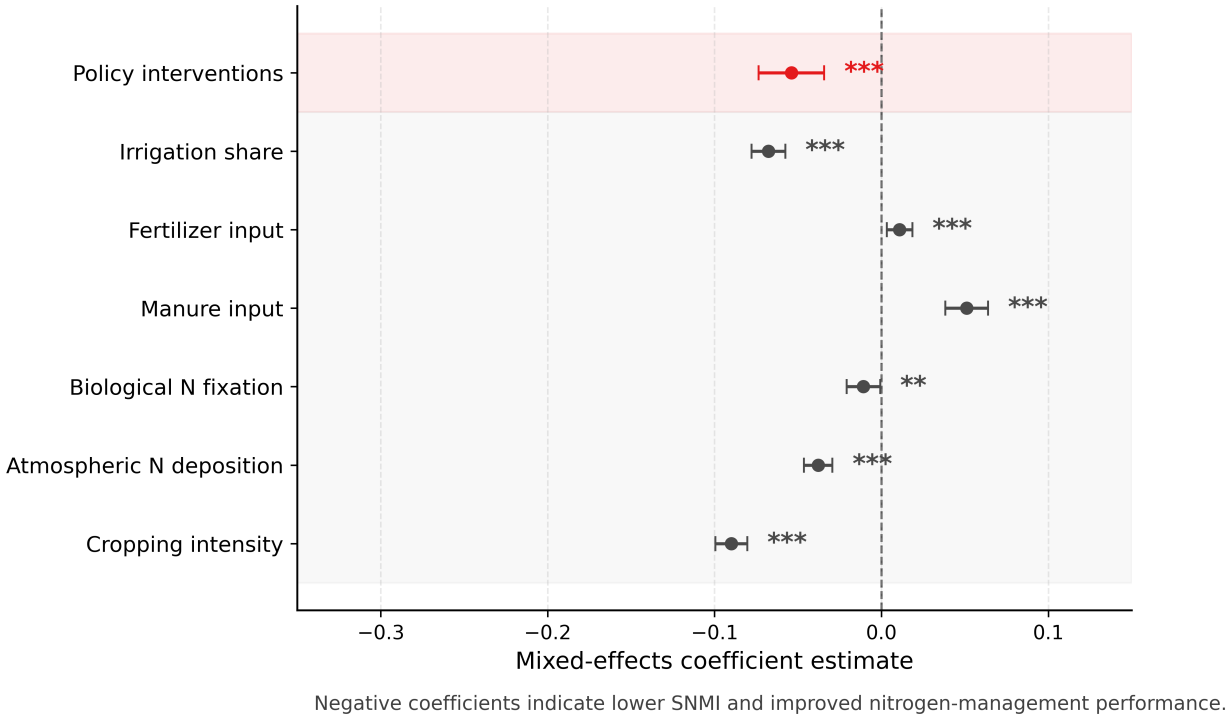
Supplementary Figure S18. Crop-specific harvested nitrogen trajectories in selected districts of Maharashtra and Madhya Pradesh. Annual crop-specific harvested nitrogen is shown for the selected districts in Maharashtra and Madhya Pradesh within the Western Plateau and Hills region. Horizontal stacked bars show the contribution of individual crop groups to total harvested nitrogen through time. The figure clarifies the crop-level composition underlying the aggregated nitrogen-harvest trajectories shown in Fig. 4.



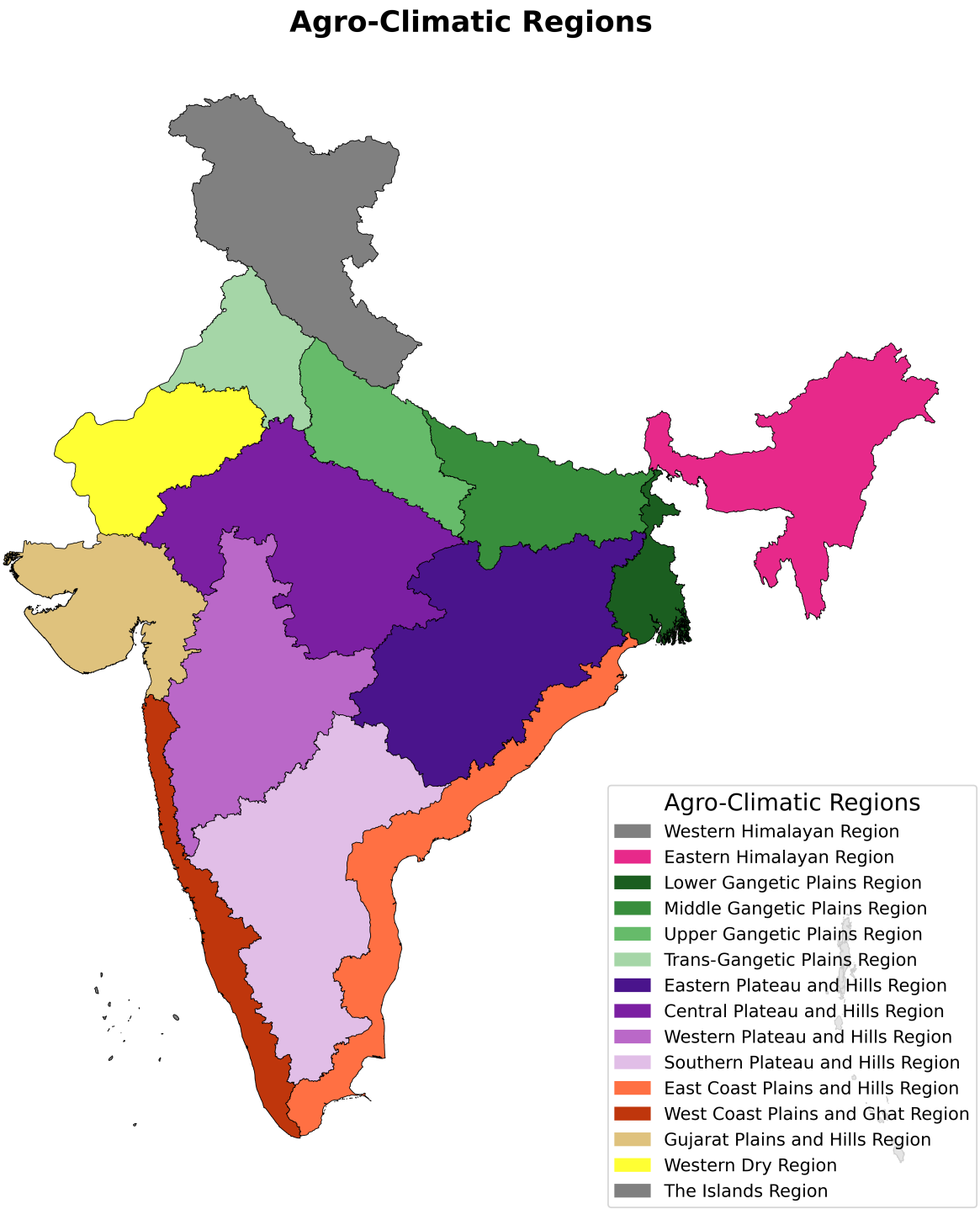
Supplementary Figure S19. Dominant crop combinations in selected districts of Maharashtra and Madhya Pradesh. The figure shows the first and second major cropping systems in the selected districts of Maharashtra and Madhya Pradesh within the Western Plateau and Hills region.



Supplementary Figure S20. Temporal evolution of nitrogen fluxes and nitrogen-use efficiency in selected districts of Madhya Pradesh and Maharashtra. Stacked bars show annual nitrogen inputs and crop nitrogen outputs by source and crop group, while the blue line indicates nitrogen-use efficiency (NUE). Vertical markers denote major fertilizer, procurement and nutrient-management interventions.



Supplementary Figure S21. Mixed-effects coefficient estimates for the Madhya Pradesh–Maharashtra comparison. Coefficient estimates are shown for the supplementary district-year mixed-effects model explaining district-level SNMI in selected Madhya Pradesh and Maharashtra districts. Points show estimated coefficients and horizontal bars show uncertainty intervals. Negative coefficients indicate lower SNMI and therefore improved composite nitrogen-management performance. The regional policy–management phase indicator for Madhya Pradesh is interpreted as a conditional association, not as a causal estimate of any individual policy intervention.



Supplementary Figure S22. Agro-climatic zones of India used throughout the study[10].

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