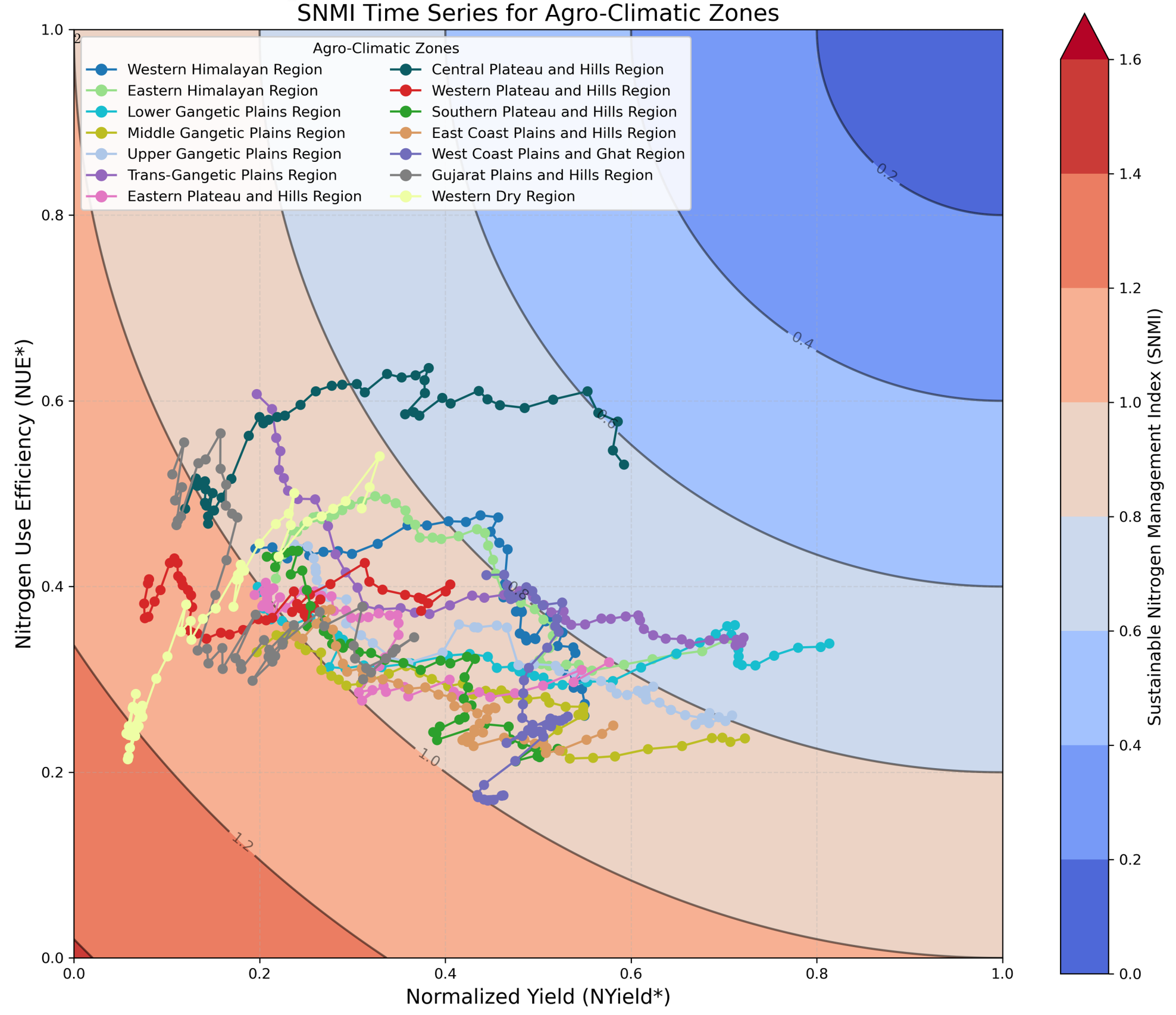
Supplementary Information

Rising Disparity in Nitrogen Management across Indian Croplands

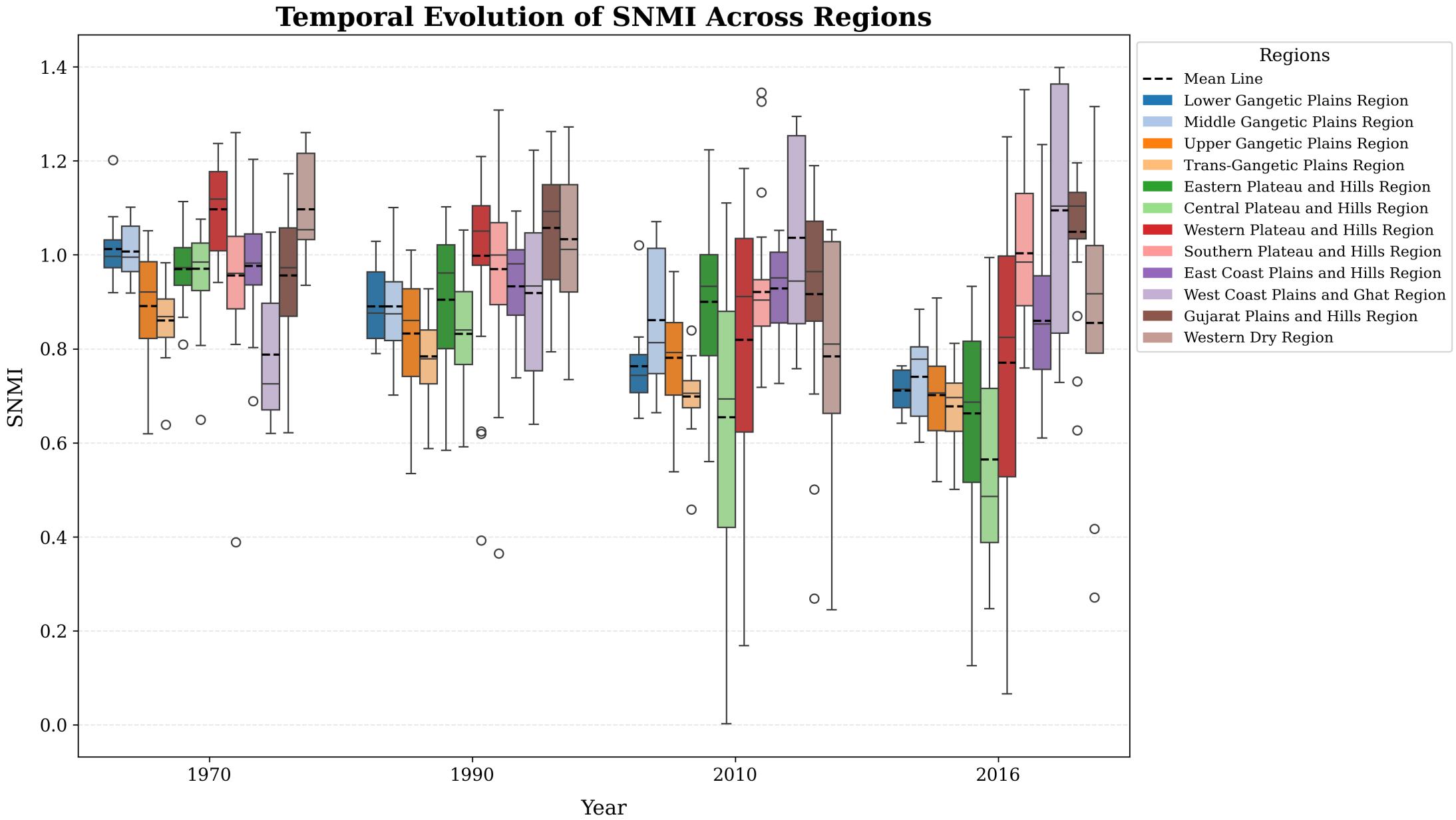
Shekhar Sharan Goyal[1,*], Udit Bhatia[2], Wim de Vries[3], Rohini Kumar[1,*]

[1] Computational Hydrosystems, Helmholtz Centre for Environmental Research – UFZ, Leipzig, Germany.
[2] Discipline of Civil Engineering, Indian Institute of Technology Gandhinagar, Palaj, Gandhinagar 382055, Gujarat, India.
[3] Environmental Systems Analysis Group, Wageningen University, Wageningen, The Netherlands.

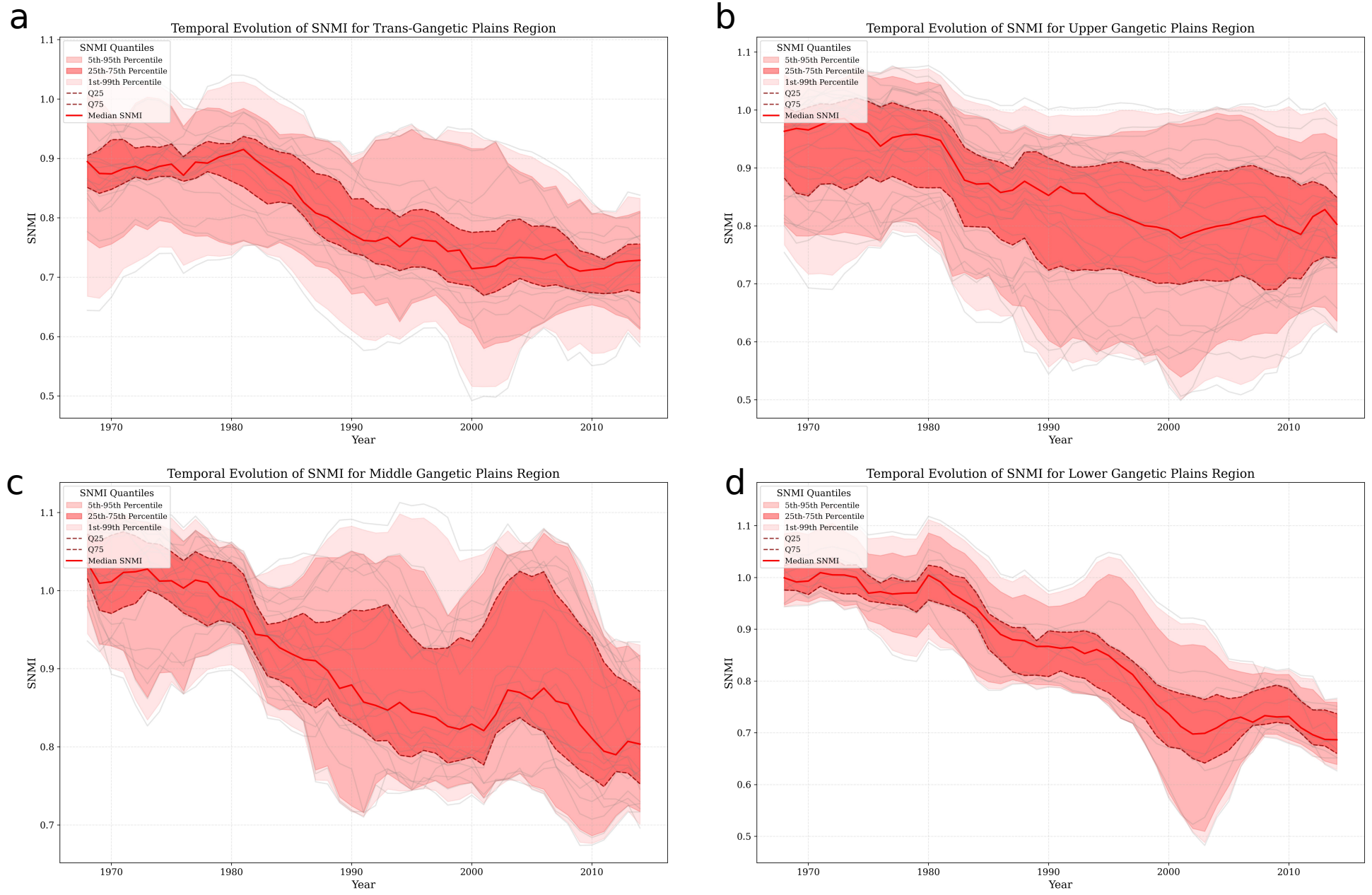
*Corresponding authors: shekhar-sharan.goyal@ufz.de, rohini.kumar@ufz.de


SNMI Time Series for Agro-Climatic Zones
Agro-Climatic Zones
Western Himalayan Region
Eastern Himalayan Region
Lower Gangetic Plains Region
Middle Gangetic Plains Region
Upper Gangetic Plains Region
Trans-Gangetic Plains Region
Eastern Plateau and Hills Region
Central Plateau and Hills Region
Western Plateau and Hills Region
Southern Plateau and Hills Region
East Coast Plains and Hills Region
West Coast Plains and Ghat Region
Gujarat Plains and Hills Region
Western Dry Region
0.2
0.4
0.6
0.8
1.0
1.2
Nitrogen Use Efficiency (NUE*)
Normalized Yield (NYield*)
0.0
0.2
0.4
0.6
0.8
1.0
Sustainable Nitrogen Management Index (SNMI)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

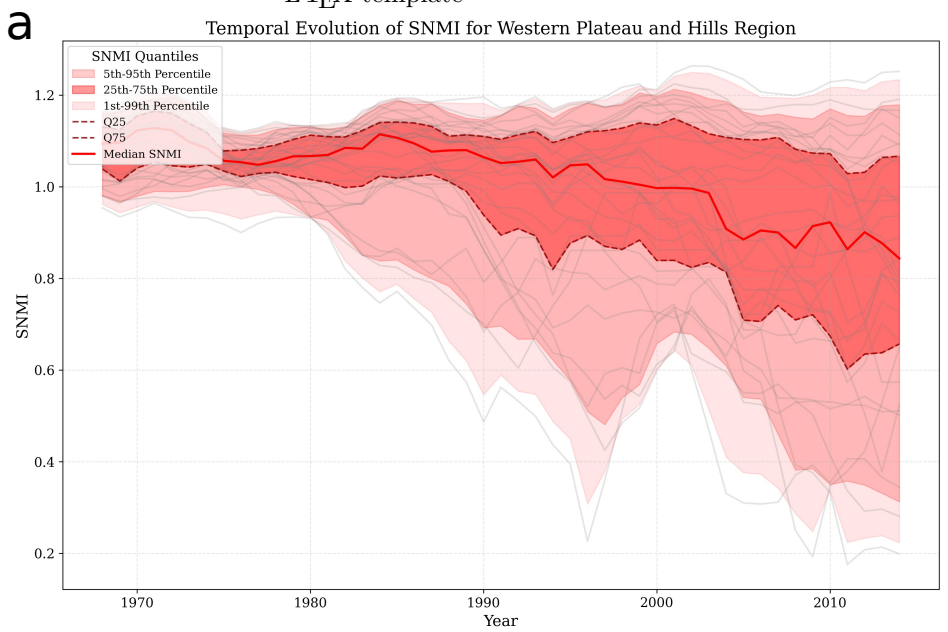
Supplementary Figure 1 – **Trajectories of nitrogen use efficiency (NUE*) and normalized yield (NYield*) across Indian agro-climatic regions.** The plot shows temporal trajectories (1966–2015) for each agro-climatic region in NUE*–NYield* space, with background contours and color shading representing the Sustainable Nitrogen Management Index (SNMI). SNMI is computed as the Euclidean distance from optimal nitrogen management, with lower values (blue) indicating higher sustainability. Normalized yield values are benchmarked to the 90th percentile of region-specific maximum yield to capture food security potential. Divergent regional pathways illustrate heterogeneous progress toward sustainable nitrogen use.

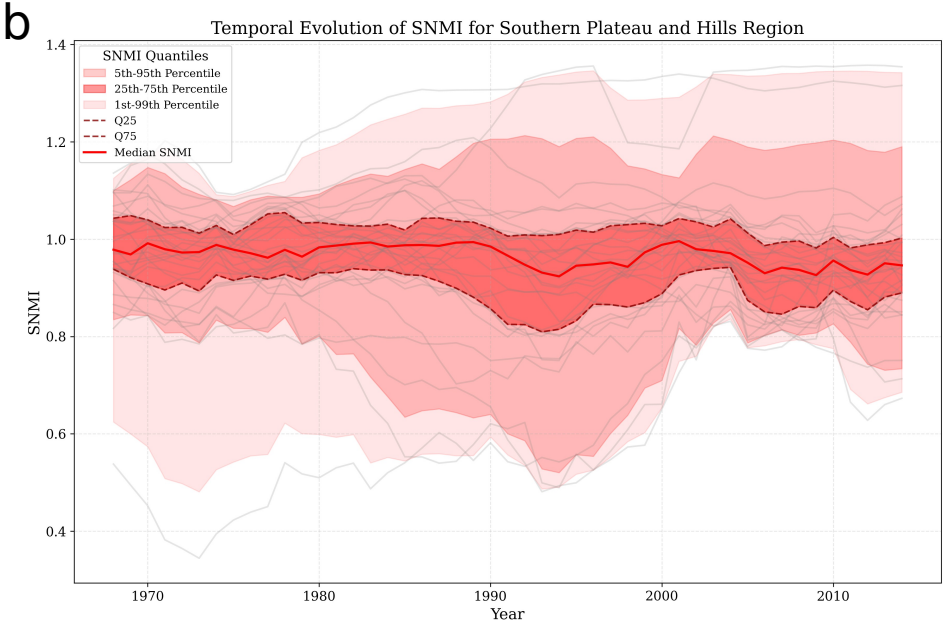

Temporal Evolution of SNMI Across Regions
SNMI
Year
1970
1990
2010
2016
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Regions
Mean Line
Lower Gangetic Plains Region
Middle Gangetic Plains Region
Upper Gangetic Plains Region
Trans-Gangetic Plains Region
Eastern Plateau and Hills Region
Central Plateau and Hills Region
Western Plateau and Hills Region
Southern Plateau and Hills Region
East Coast Plains and Hills Region
West Coast Plains and Ghat Region
Gujarat Plains and Hills Region
Western Dry Region

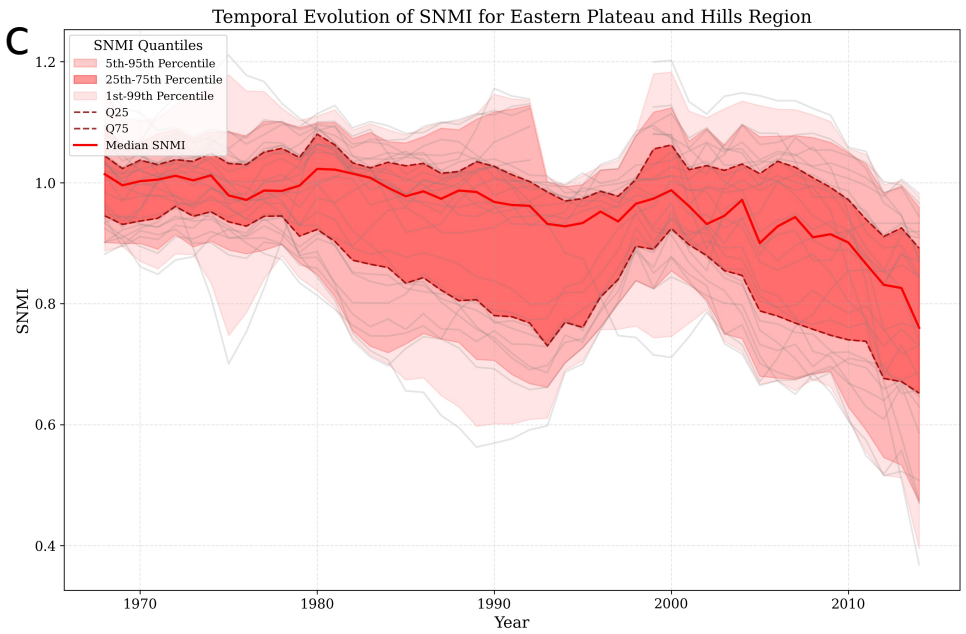
Supplementary Figure 2 – **Temporal trends in inter- and intra-regional variability of the Sustainable Nitrogen Management Index (SNMI).** The figure tracks the mean SNMI across India's agroclimatic regions, referencing region-specific maximum achievable yields.

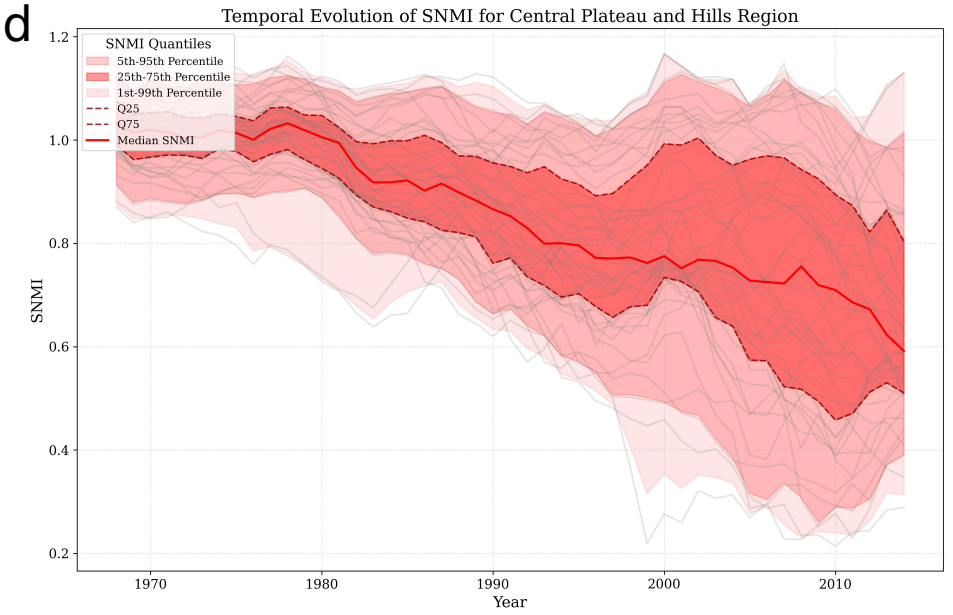

a
Temporal Evolution of SNMI for Trans-Gangetic Plains Region
b
Temporal Evolution of SNMI for Upper Gangetic Plains Region
c
Temporal Evolution of SNMI for Middle Gangetic Plains Region
d
Temporal Evolution of SNMI for Lower Gangetic Plains Region
SNMI Quantiles
5th-95th Percentile
25th-75th Percentile
1st-99th Percentile
Q25
Q75
Median SNMI
SNMI
Year

Supplementary Figure 3 – **Rising temporal variability in SNMI across the Indo-Gangetic plains.** Panels (a–b) represent the Trans- and Upper Gangetic plains, whereas panels (c–d) correspond to the Middle and Lower Gangetic regions. The dark red line denotes mean SNMI, with shaded areas indicating variability across different percentiles.


a
Temporal Evolution of SNMI for Western Plateau and Hills Region
SNMI Quantiles
5th-95th Percentile
25th-75th Percentile
1st-99th Percentile
Q25
Q75
Median SNMI
SNMI
Year

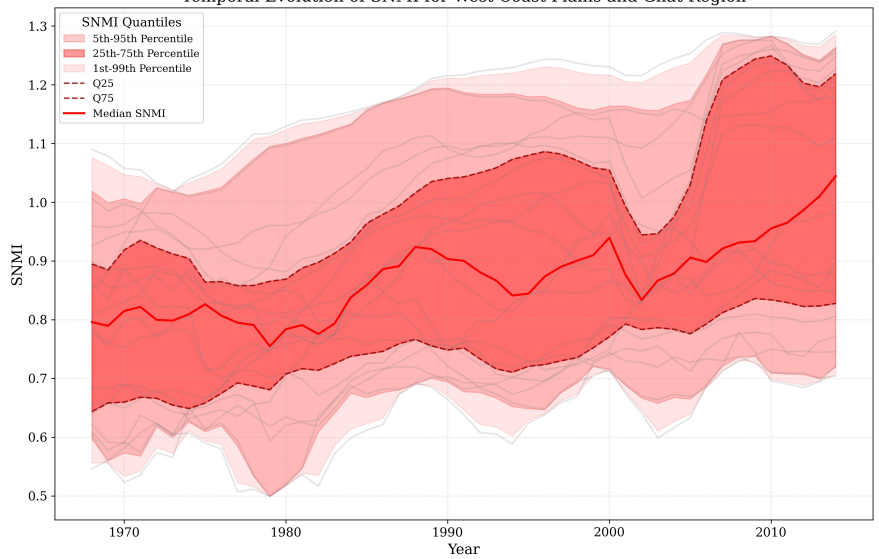

b
Temporal Evolution of SNMI for Southern Plateau and Hills Region
SNMI Quantiles
5th-95th Percentile
25th-75th Percentile
1st-99th Percentile
Q25
Q75
Median SNMI
SNMI
Year


c
Temporal Evolution of SNMI for Eastern Plateau and Hills Region
SNMI Quantiles
5th-95th Percentile
25th-75th Percentile
1st-99th Percentile
Q25
Q75
Median SNMI
SNMI
Year

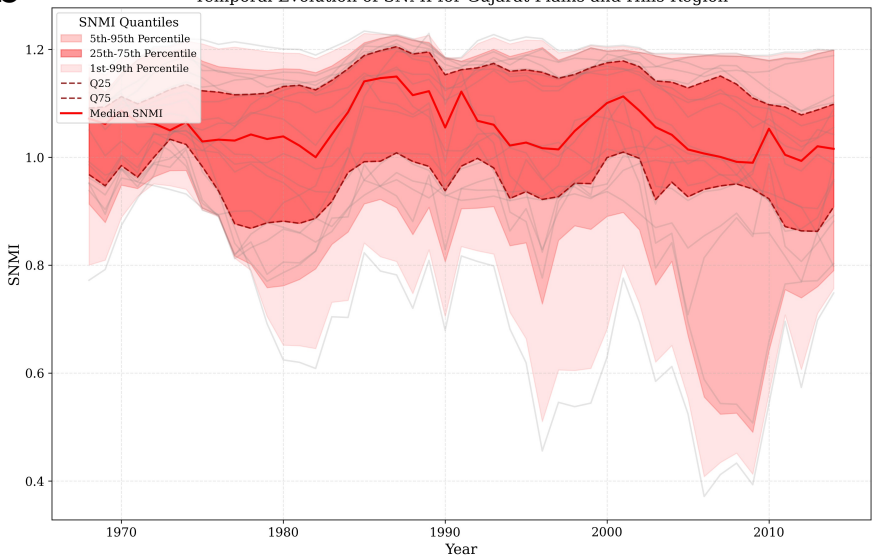

d
Temporal Evolution of SNMI for Central Plateau and Hills Region
SNMI Quantiles
5th-95th Percentile
25th-75th Percentile
1st-99th Percentile
Q25
Q75
Median SNMI
SNMI
Year

Supplementary Figure 4 – **Rising temporal variability of SNMI across India's plateau regions.** Panels (a–b) focus on the Western and Southern plateaus, while panels (c–d) detail trends in the Eastern and Central plateau regions. Mean SNMI is represented by a dark red line, with shaded percentiles highlighting the extent of regional variability.

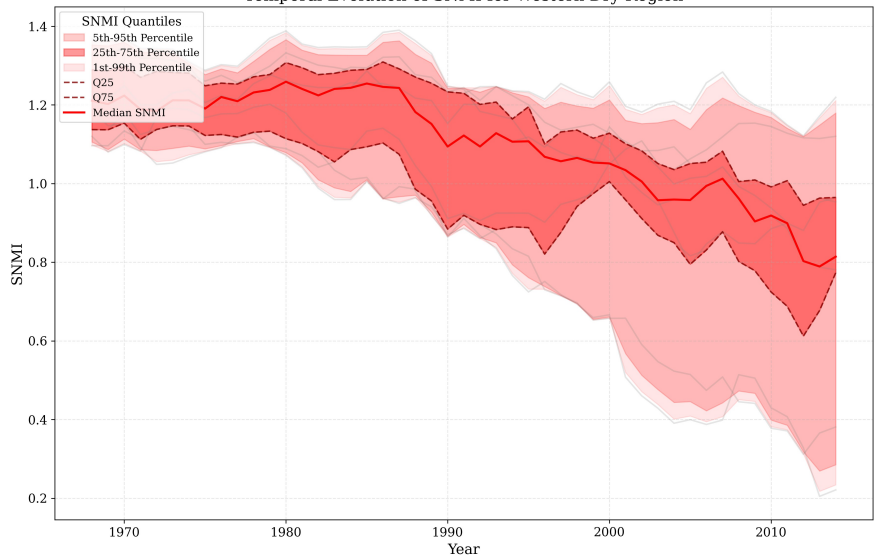
a


Temporal Evolution of SNMI for West Coast Plains and Ghat Region
SNMI Quantiles
5th-95th Percentile
25th-75th Percentile
1st-99th Percentile
Q25
Q75
Median SNMI
SNMI
Year
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
1970
1980
1990
2000
2010

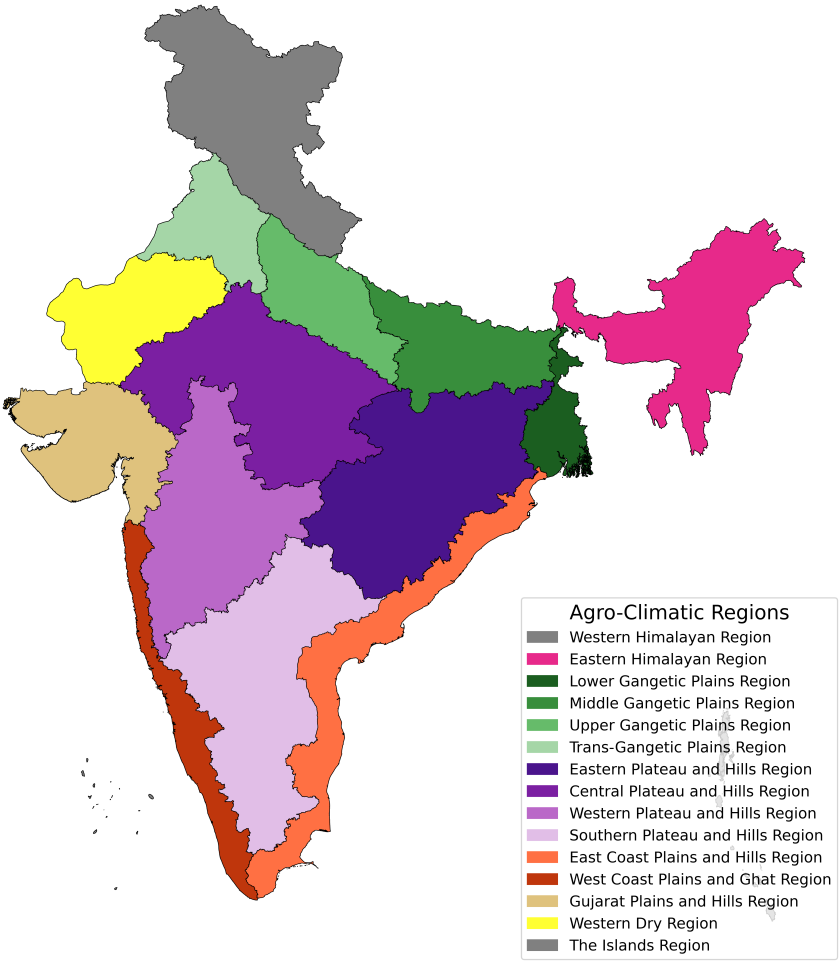
b


Temporal Evolution of SNMI for Gujarat Plains and Hills Region
SNMI Quantiles
5th-95th Percentile
25th-75th Percentile
1st-99th Percentile
Q25
Q75
Median SNMI
SNMI
Year
1.2
1.0
0.8
0.6
0.4
1970
1980
1990
2000
2010

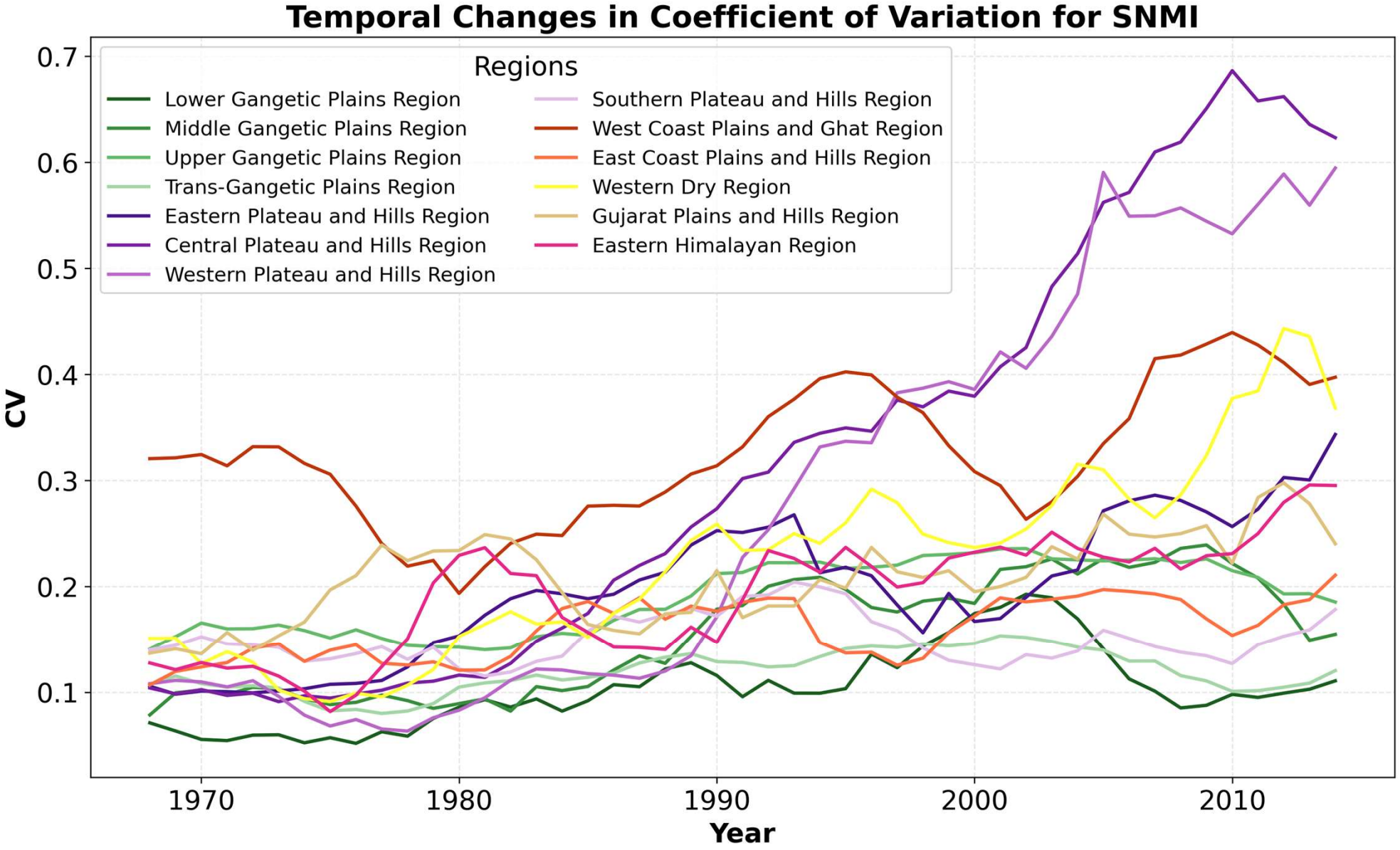
c


Temporal Evolution of SNMI for Western Dry Region
SNMI Quantiles
5th-95th Percentile
25th-75th Percentile
1st-99th Percentile
Q25
Q75
Median SNMI
SNMI
Year
1.4
1.2
1.0
0.8
0.6
0.4
0.2
1970
1980
1990
2000
2010

Supplementary Figure 5 – **Rising SNMI variability across plains and coastal regions of India.** Panels (a–b) illustrate SNMI trends and variability for the Western Ghats and Gujarat plains, with panel (c) representing the Western Dry region. The dark red lines represent mean SNMI trends, and shaded areas denote percentile-based variability ranges.


Agro-Climatic Regions
Agro-Climatic Regions
Western Himalayan Region
Eastern Himalayan Region
Lower Gangetic Plains Region
Middle Gangetic Plains Region
Upper Gangetic Plains Region
Trans-Gangetic Plains Region
Eastern Plateau and Hills Region
Central Plateau and Hills Region
Western Plateau and Hills Region
Southern Plateau and Hills Region
East Coast Plains and Hills Region
West Coast Plains and Ghat Region
Gujarat Plains and Hills Region
Western Dry Region
The Islands Region

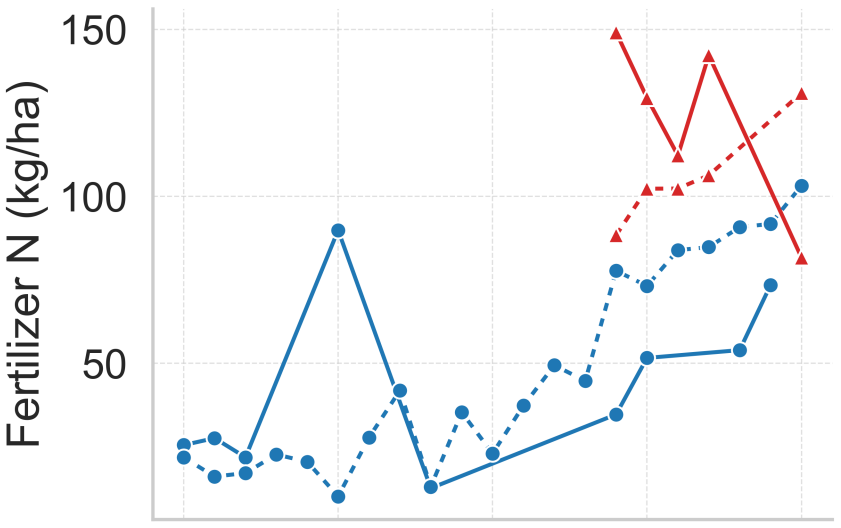
Supplementary Figure 6 – **Agro-climatic zones of India.** Map of India's agro-climatic zones used to define each region throughout the study[1].


Temporal Changes in Coefficient of Variation for SNMI
Regions
Lower Gangetic Plains Region
Middle Gangetic Plains Region
Upper Gangetic Plains Region
Trans-Gangetic Plains Region
Eastern Plateau and Hills Region
Central Plateau and Hills Region
Western Plateau and Hills Region
Southern Plateau and Hills Region
West Coast Plains and Ghat Region
East Coast Plains and Hills Region
Western Dry Region
Gujarat Plains and Hills Region
Eastern Himalayan Region
CV
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1970
1980
1990
2000
2010
Year

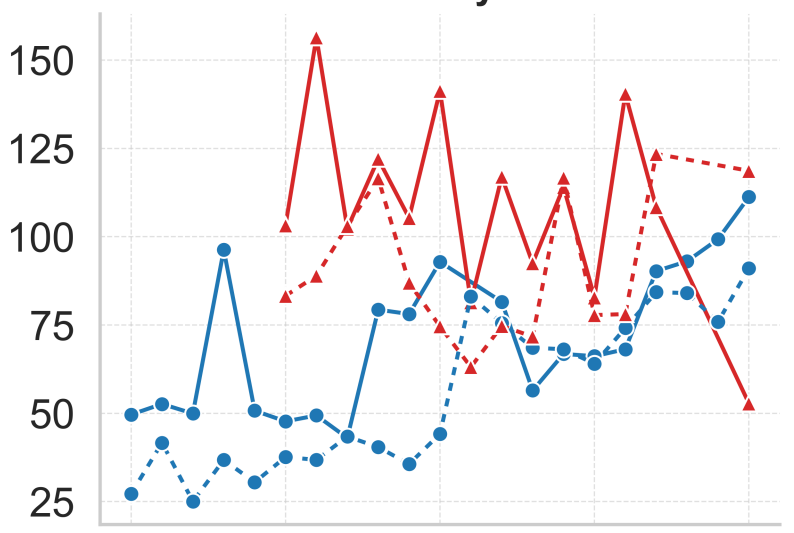
Supplementary Figure 7 – **Temporal trends in the coefficient of variation (CV) for the Sustainable Nitrogen Management Index (SNMI) across Indian agro-climatic regions.** The CV of SNMI is used to evaluate intra-regional variability from 1966 to 2015. An upward trend in CV indicates increasing spatial disparities in sustainable nitrogen use within regions. Notably, the Western and Central Plateau and Hills regions exhibit substantial increases in variability.

Fertilizer Nitrogen Application by Crop, State, and Irrigation Status (kg/ha)

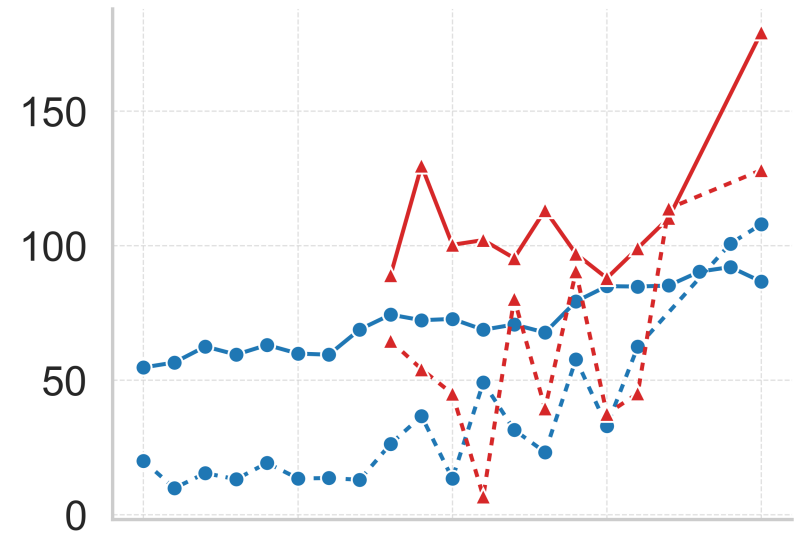
Maize



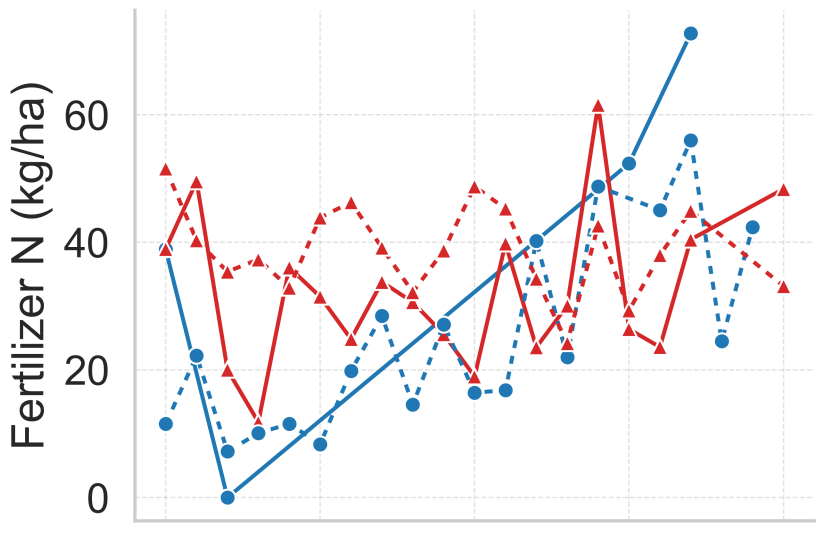
Paddy



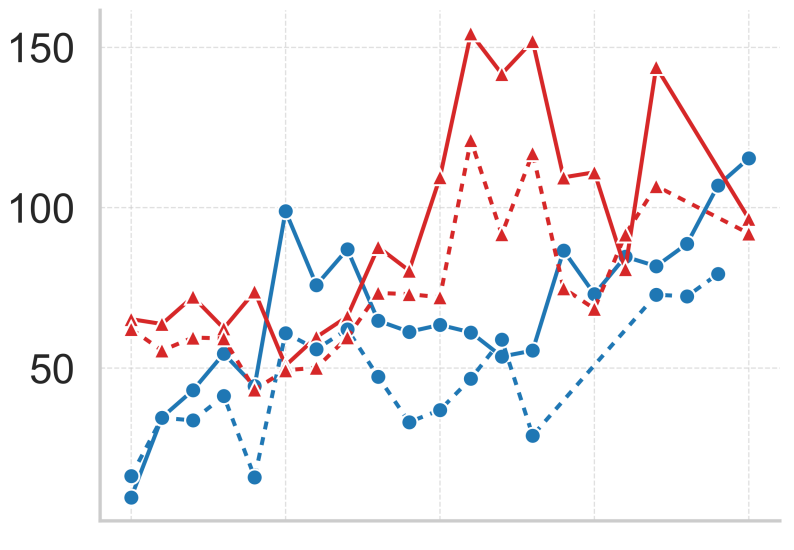
Wheat



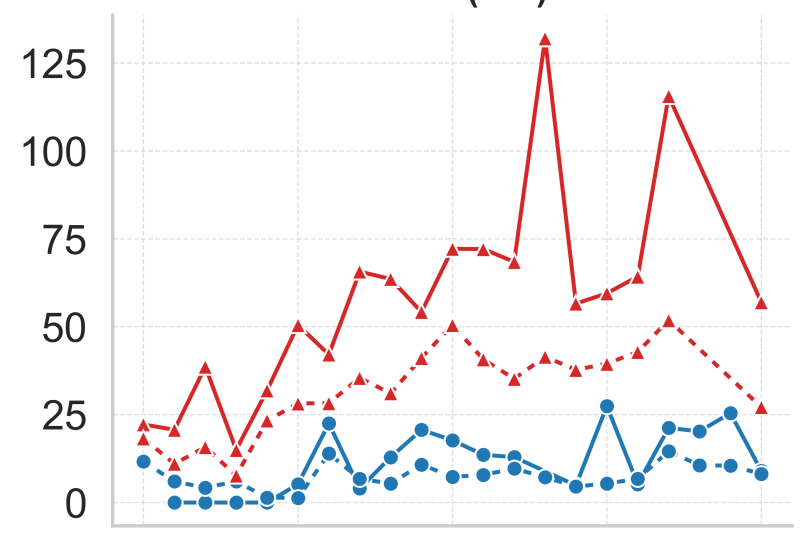
Jowar



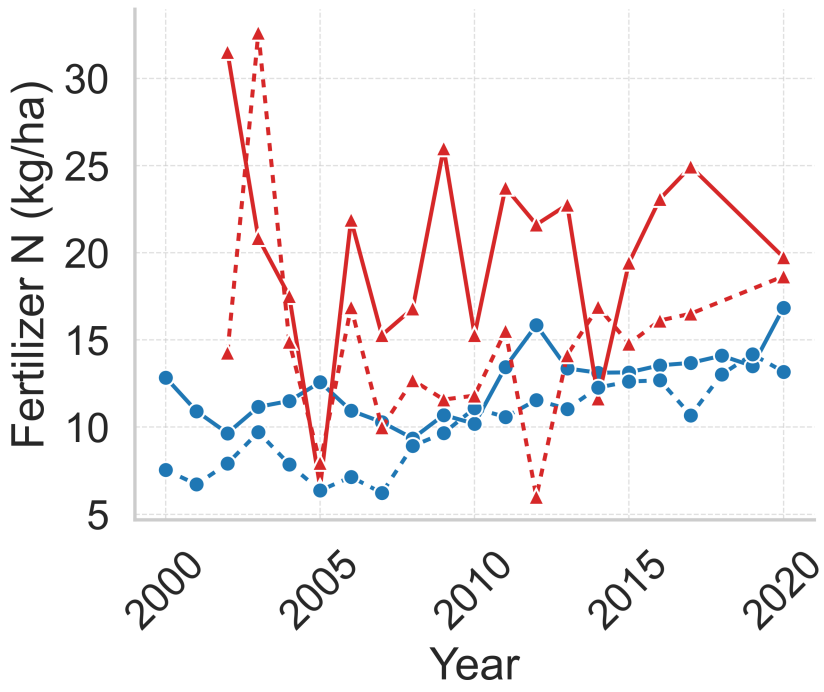
Cotton



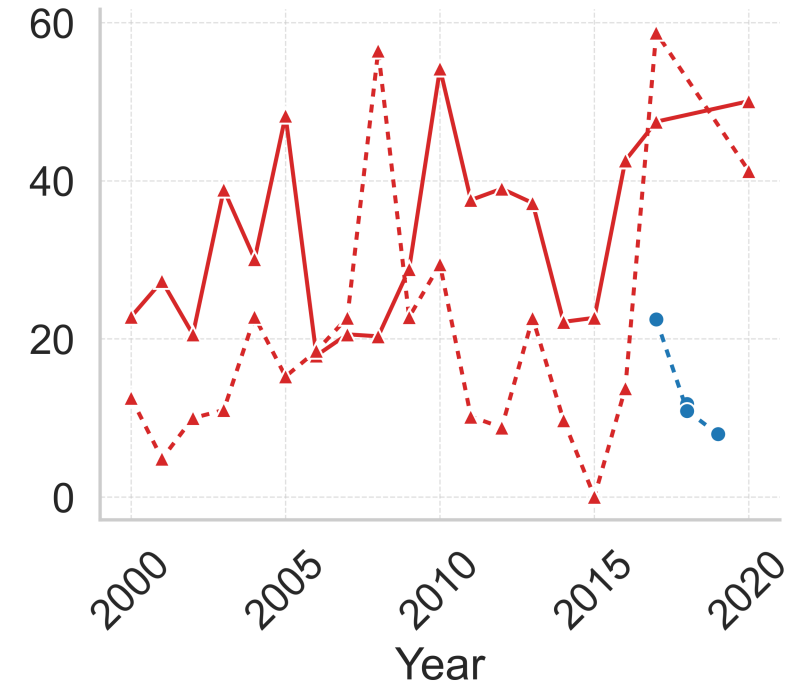
Arhar (Tur)



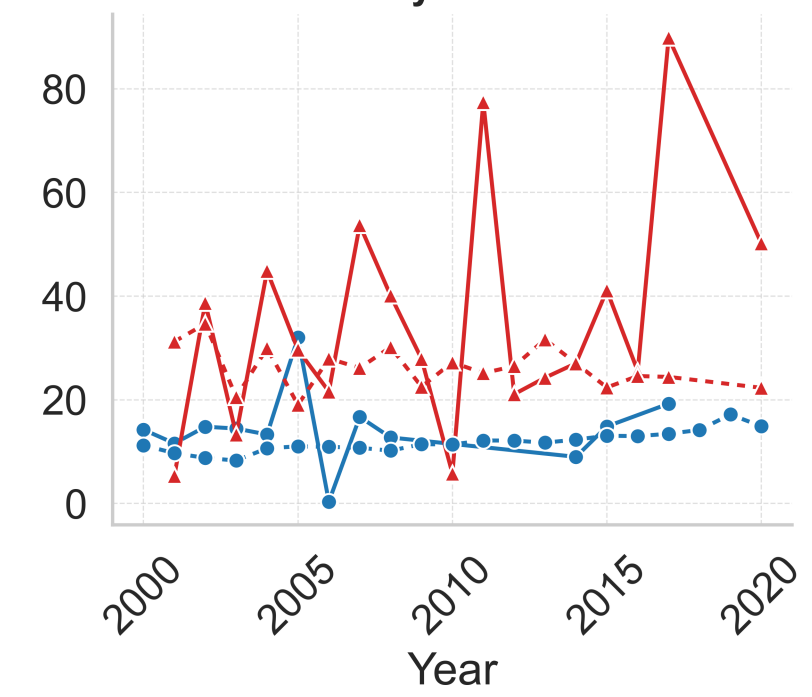
Gram



Groundnut



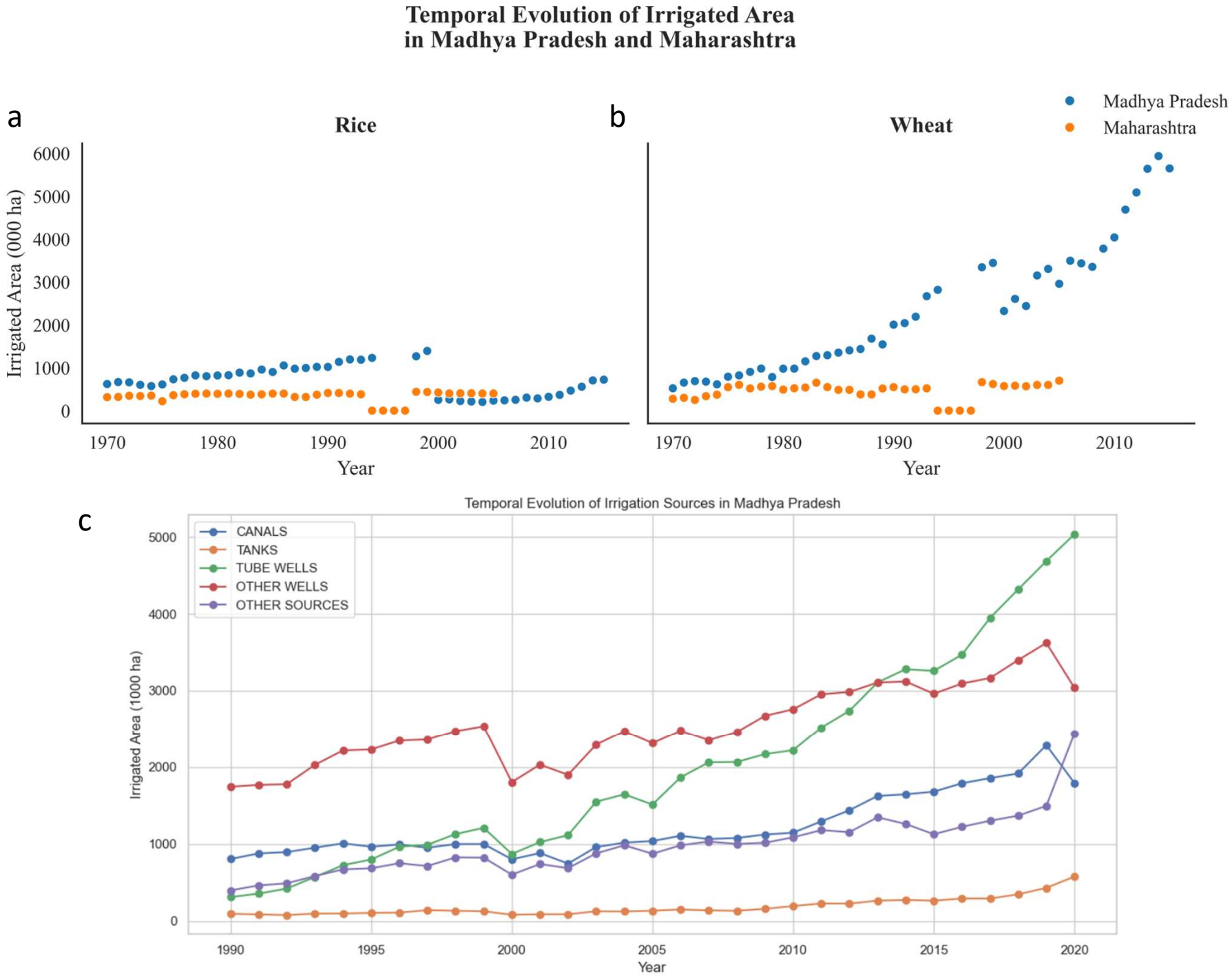
Soyabean



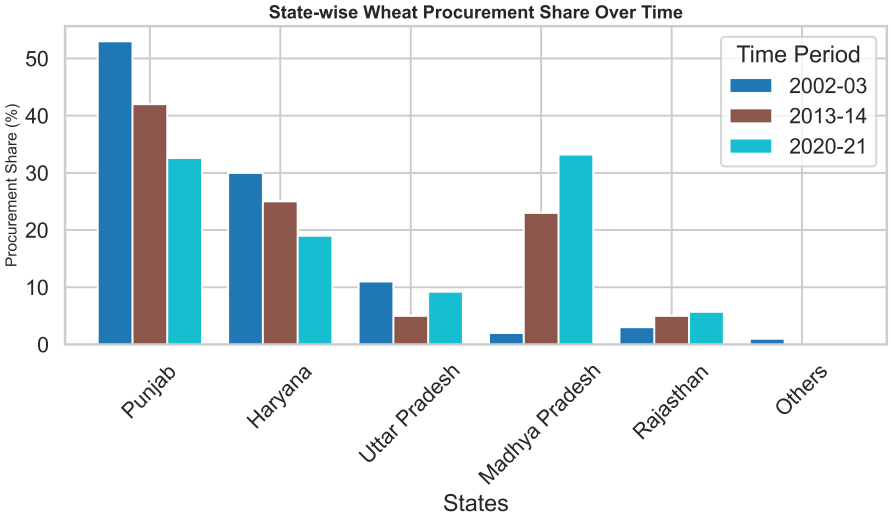
State / Irrigation

- Madhya Pradesh - Irrigated
- Madhya Pradesh - Non-Irrigated
- Maharashtra - Irrigated
- Maharashtra - Non-Irrigated

Supplementary Figure 8 – **Temporal trends in fertilizer nitrogen application by crop, irrigation status, and state.** Application rates (kg N ha^{-1}) from 2000–2019, based on Government of India cost of cultivation surveys[2], are shown for nine major crops in Madhya Pradesh (MP) and Maharashtra (MH). Blue and red lines represent MP and MH, respectively, with solid lines for irrigated and dashed lines for non-irrigated fields.


Temporal Evolution of Irrigated Area
in Madhya Pradesh and Maharashtra
a
Rice
b
Wheat
Madhya Pradesh
Maharashtra
Irrigated Area (000 ha)
6000
5000
4000
3000
2000
1000
0
1970
1980
1990
2000
2010
Year
c
Temporal Evolution of Irrigation Sources in Madhya Pradesh
CANALS
TANKS
TUBE WELLS
OTHER WELLS
OTHER SOURCES
Irrigated Area (1000 ha)
5000
4000
3000
2000
1000
0
1990
1995
2000
2005
2010
2015
2020
Year

Supplementary Figure 9 – **Temporal trends of irrigated area and irrigation sources in Madhya Pradesh and Maharashtra.** Trends in irrigated area under rice and wheat are shown for 1970–2015, alongside the evolution of irrigation sources in Madhya Pradesh for 1990–2020 (data from Agricultural Statistics at a Glance, India[3, 4])


State-wise Wheat Procurement Share Over Time
Procurement Share (%)
0
10
20
30
40
50
Time Period
2002-03
2013-14
2020-21
Punjab
Haryana
Uttar Pradesh
Madhya Pradesh
Rajasthan
Others
States

Supplementary Figure 10 – **Shifts in state-wise wheat procurement share in India over time.** Bar plots show the percentage share of wheat procurement by major states across three periods: 2002–03, 2013–14, and 2020–21.[5]

Supplementary References

[1] Commission, P., et al.: Agro-climatic regional planning: an overview (1989)

[2] Ministry of Agriculture and Farmers Welfare, Government of India: Plot Level Summary Data Under the Cost of Cultivation Scheme. https://desagri.gov.in/document-report-category/selected-zone-tehsil-district-block-year-wise/. [Online; accessed 2022] (2022)

[3] GOI, D.: Agricultural statistics at a glance 2018. Government of India, Ministry of Agriculture & Farmers Welfare, Department of Agriculture, Cooperation & Farmers Welfare, Directorate of Economics and Statistics (2018)

[4] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT): ICRISAT Data: Crops. Accessed: 2024-06-12 (2024). http://data.icrisat.org/dld/src/crops.html

[5] Department of Food and Public Distribution (DFPD), Directorate of Economics & Statistics (DES): Department of Food and Public Distribution, Government of India. https://dfpd.gov.in/en. Accessed: 2025-09-07 (2025)