Policy Paper 42

A Spatial Assessment of Sustainability in Indian Agriculture

Prem Chand
Kiran Kumara TM
Suresh Pal
Kalu Naik

भाकृअनुप
ICAR

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ICAR – National Institute of Agricultural Economics and Policy Research
New Delhi - 110 012

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Prem Chand and Kiran Kumara TM are Senior Scientist and Scientist, respectively at ICAR-NIAP, New Delhi. Suresh Pal is former Director, ICAR-NIAP, New Delhi. Kalu Naik is Research Associate, ICAR-NIAP, New Delhi.

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Preface

Sustainable development of agriculture is essential to achieve the multiple goals of improving food and nutrition security, improving farmers' income, and reducing poverty, especially in developing countries like India where agriculture is the main source of livelihood for millions of small-scale producers. Hence, understanding the dimensions and indicators of sustainability is important for targeting technologies and policies for ensuring inter-general equity in agriculture. Considering several dimensions and indicators related to soil health, water management, ecology, and socioeconomic conditions this study has constructed composite indices of agricultural sustainability for major states of India. These indices will aid policymakers to identify weak linkages in agricultural development at a spatial scale, and accordingly take corrective actions.

Pratap Singh Birthal
Director, ICAR-NIAP

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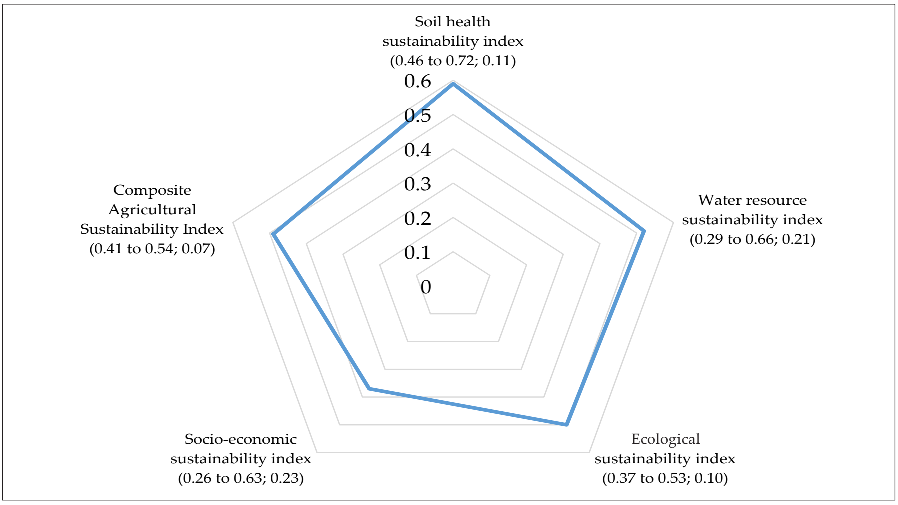
Authors

Executive Summary

Striving for sustainable development of agriculture means achieving multiple goals of ensuring food and nutrition security, enhancing farmers' income, alleviating poverty, and improving human and animal health through responsible production and consumption unharmful to natural resources, environment and inter-generational equity. It is, therefore, imperative to objectively assess the status of agricultural sustainability along the social, economic, and ecological dimensions that govern agricultural production systems and their outcomes. Such an assessment can provide useful feedback to researchers and policymakers to make informed decisions to achieve sustainable development goals.

Sustainability is multi-dimensional. Thus, this paper has developed a Composite Index of Agricultural Sustainability (CIAS) using 51 indicators related to ecology, soil and water health, and socio-economic development. The mean value of CIAS is 0.50, suggesting a moderate level of sustainability of Indian agriculture. Water sustainability and socio-economic dimensions are more important concerns than ecological sustainability (Figure E1).

Figure E1. Composite Index of Agricultural Sustainability and its dimensional indices



Note: Figures in parentheses indicate the range of respective index and the coefficient of variation

There is considerable spatial heterogeneity in agricultural sustainability (Figure E2). Agriculture is the least sustainable in Rajasthan because of the low and erratic rainfall, frequent dry spells, high temperatures, and the poor endowment of soil and water resources. Sustainability is also threatened in Punjab and Haryana due to the fast-depleting groundwater resources, increasing mono-cropping of rice and wheat, intensive use of agro-chemicals, and limited yet disappearing forest cover. Madhya Pradesh, Kerala, Mizoram, West Bengal, Andhra Pradesh, and Uttarakhand rank better on the sustainability index. Spatial heterogeneity highlights the need for regionally differentiated strategies and interventions to promote sustainability in agriculture and reduced trade-offs among its different dimensions. Therefore, the state-specific priorities for sustainable development of agriculture are outlined in Table E1.

Figure E2. Spatial mapping of agricultural sustainability

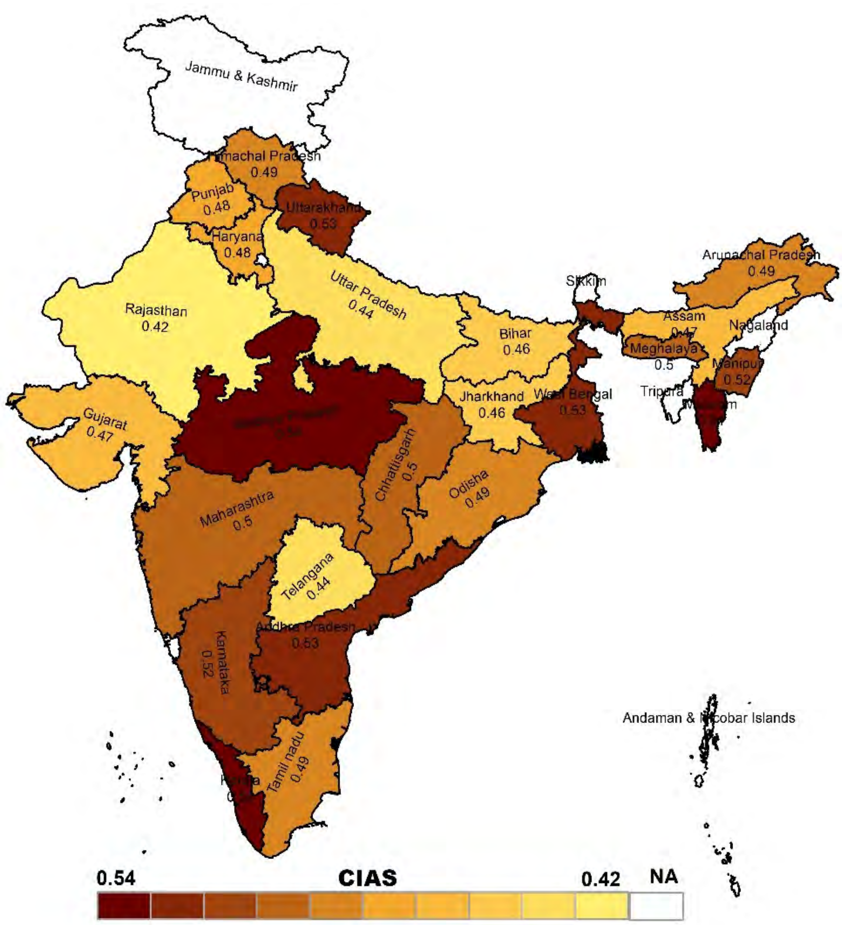


Table E1. State-specific priorities for sustainable agricultural development

States	1st	2nd	3rd	4th	5th
Andhra Pradesh	Fodder availability	Chemical-free farming	Biodiversity conservation	R&D investment	Pasture and grazing land development
Arunachal Pradesh	Improving irrigation water quality	Soil reclamation	Wasteland development	Increasing pollinators diversity	Fodder availability
Assam	Crop diversification	Micro-irrigation	Cereals self-sufficiency	Fodder availability	Improving livestock productivity
Bihar	Cereals self-sufficiency	Increasing soil secondary and micro-nutrient availability	Increasing labour productivity	Off-farm and non-farm employment	Pasture and grazing land development
Chhattisgarh	Increasing water productivity	Fodder availability	Increasing land productivity	Organic farming	Investment in soil and water conservation
Gujarat	Adaption against rainfall anomalies	Cereals self-sufficiency	Irrigation availability	Biodiversity conservation	Increasing fish productivity
Haryana	Checking groundwater depletion	Improving soil organic carbon	Increasing green cover	Reducing use of agro-chemical	Organic farming
Himachal Pradesh	Wasteland development	Frost resistant varieties	Land consolidation	Investment in soil and water conservation	Increasing fish productivity
Jharkhand	Fodder availability	Cereals self-sufficiency	Minimizing land degradation	investment in soil and water conservation	Minimizing GHG emission
Karnataka	Biodiversity conservation	Cereals self-sufficiency	Increasing fish productivity	R&D investment	Increasing land productivity
Kerala	Cereals self-sufficiency	Protein self-sufficiency	Pasture and grazing land development	Increasing area under legume crops	Increasing varietal diversity

Madhya Pradesh	Biodiversity conservation	R&D investment	Increasing water productivity	Increasing fish productivity	Micro-irrigation
Maharashtra	Biodiversity conservation	Increasing fish productivity	Cereals self-sufficiency	Improving bargaining power	R&D investment
Manipur	Wasteland development	Cereals self-sufficiency	Fodder availability	Pasture and grazing land development	Improving bargaining power
Meghalaya	Wasteland development	Cereals self-sufficiency	Improving irrigation water quality	Conservation agriculture	Fodder availability
Mizoram	Wasteland development	Cereals self-sufficiency	Fodder availability	Protein self-sufficiency	Increasing soil primary nutrient availability
Odisha	Fodder availability	Cereals self-sufficiency	Increasing labour productivity	Increasing fish productivity	Investment in soil and water conservation
Punjab	Checking groundwater depletion	Crop residue management	Reducing use of agro-chemical	Micro-irrigation	Increasing green cover
Rajasthan	Checking groundwater depletion	Wasteland development	Improving irrigation water quality	Combating desertification	Irrigation availability
Tamil Nadu	Reorienting subsidies	Food self sufficiency	Increasing fish productivity	Organic farming	Biodiversity conservation
Telangana	Checking groundwater depletion	Balanced fertilizer use	Increasing fertilizer productivity	Organic farming	Investment in soil and water conservation
Uttar Pradesh	Improving bargaining power	Micro-irrigation	Improving soil organic carbon	Pasture and grazing land development	Organic farming
Uttarakhand	Wasteland development	Improving fish diversity	Increasing fish productivity	Micro-irrigation	Cereals self-sufficiency
West Bengal	Fodder availability	Cereals self-sufficiency	Organic farming	Pasture and grazing land development	Biodiversity conservation

The low soil organic carbon, soil salinity, declining water table, micronutrient deficiency, excess use of chemical fertilizers, and loss of agrobiodiversity are common concerns across states and have arisen primarily due to input subsidization, and limited adoption of sustainable agricultural practices. This indicates the need for repurposing input subsidies to encourage technologies and practices that generate ecosystem services and mitigate climate impacts.

Despite better scores on the sustainability of water resources, the eastern and north-eastern states, particularly West Bengal, Manipur, Assam, Mizoram, Chhattisgarh, and Jharkhand, are unable to fully exploit their irrigation potential, adversely affecting their socio-economic development. These states also face significant challenges of problematic soils. A comprehensive strategy to improve resource use efficiency is needed to enhance agricultural sustainability in these states. The policy should focus on crop diversification, exploitation of irrigation potential, and promotion of sustainable land management practices. Besides, the development of rural non-farm sector can reduce employment pressure on agriculture.

Crop and enterprise diversification is necessary for building resilience of agriculture and agriculture-based livelihoods in arid and semi-arid regions, particularly in Rajasthan, Gujarat, Karnataka, Maharashtra, and Tamil Nadu. These states have better indicators related to livestock productivity and crop diversification. Investing in animal husbandry and high-value crops is crucial to enhance the sustainability of diversified production systems and improve farmers' livelihoods. Additionally, the revival of the traditional management system of common property resources should be a priority. Further, agro-forestry can strengthen crop-livestock interactions and enhance economic and ecosystem services.

1 Introduction

The concept of agricultural sustainability is rooted in the history of agriculture itself, as evident from the ancient texts on human civilization (King 1911; Li Wenhua 2001; Pretty 2003; Pretty and Bharucha 2014). Agriculture was considered inseparable from nature. However, with the growing demand for food and non-food commodities, the balance between agriculture and nature has dwindled, especially during the past seven decades. Between 1950 and 2022, the global population increased more than three-fold, from 2.5 to 8 billion. Rapid growth occurred in Asia, contributing more than 60% to the incremental population (UN 2022). However, the agricultural land did not expand with the rising population. This led to agricultural intensification to produce more from the limited resources to meet the growing food and non-food demand.

Whether the intensification-led growth in agriculture has damaged or saved natural resources is debatable. The proponents of the Borlaug Hypothesis[1] argue that the Green Revolution technologies helped in saving natural ecosystems from being converted into agricultural systems. The Green Revolution could save somewhere between 18 to 27 million hectares of land from being brought under cultivation, which helped arrest the quantitative and qualitative deterioration of the natural resources (Borlaug 2007; Burney et al. 2010; Green et al. 2005; Phalan et al. 2011; Stevenson et al. 2013; Villoria et al. 2014). The critics, however, argue that the technology-driven improvements in agricultural productivity have created incentives to clear forests, rendering the intensification counterproductive to sustainable development (Rudel et al. 2009; Lambin and Meyfroidt 2011; Ewers et al. 2009). The crux of these arguments lies in distinguishing the technology-driven intensification from the market-driven intensification. According to the Borlaug Hypothesis, adopting

[1] The "Borlaug Hypothesis", due to the Nobel Prize Laureate Norman Borlaug, states that 'increasing crop yields prevents cropland expansion and deforestation, thus contributes to alleviation of hunger and poverty, and without any significant negative impact on the environment'.

advanced agricultural technologies has caused a significant increase in crop yields while sparing the natural ecosystems. Conversely, market-driven intensification, as argued by Byerlee et al. (2014), could inadvertently lead to cropland expansion and deforestation. Nevertheless, technology-driven intensification alone is insufficient to arrest the degradation of natural resources, and appropriate mechanisms for the governance of natural resources should accompany it.

Despite its historical significance, sustainability only started assuming importance in the academic and policy debates recently. The multi-faceted nature of sustainable agriculture is apparent if one tries to understand sustainability over temporal and spatial scales. The most important milestone in sustainable agriculture was the UN Conference on Human Development in 1972, which emphasized reducing agriculture's reliance on external inputs while maintaining productivity. This shift in approach led to an understanding of sustainability in agriculture as an optimization of agricultural practices while minimizing their negative externalities to natural resources and the environment.

However, as time progressed, a paradigm shift occurred towards eco-agriculture, reflecting its different connotations such as the 'organic agriculture', 'permanent agriculture', and 'indigenous agriculture'. This emphasizes the integration of natural resources with traditional indigenous knowledge and practices and is termed the 'sustainable agriculture' or 'agro-ecological intensification'. This approach accepts the likely trade-offs between agricultural productivity and the environment with a reduction in external inputs.

A nuanced concept of sustainable development of agriculture that centred around its intensification with judicious use of resources and technologies evolved in 1987 when the Brundtland Commission (World Commission on Environment and Development) suggested a comprehensive and holistic definition of sustainability. This definition runs as 'the development is sustainable only if it meets the needs of the present without compromising the ability of future generations to meet their own needs' (UN 1987). Subsequently, the Food and Agriculture Organization (FAO) defined sustainable agriculture as 'the management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs of the present and future generations. Such development conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable, and socially acceptable' (FAO 1988).

The concept of agricultural sustainability became more prominent with a call from the World Commission on Environment and Development for a global sustainability agenda (UN 1987). The initial efforts to measure sustainability lacked a unified and comprehensive framework that could capture the intricate interplay between environmental, social, and economic dimensions of agricultural practices. As sustainability gained recognition, the need for a more integrated and comprehensive approach, which could consider the long-term impacts of agricultural activities on ecosystems, communities, and future generations, became evident. Consequently, the emphasis shifted towards evolving robust methodologies for a holistic and accurate agricultural sustainability assessment to guide policy decisions, agricultural research, and on-the-ground practices (Devuyst 2001).

Notwithstanding, the progress toward sustainability measurement was not commensurate with its conceptualization. Concerns remain about the relevance of sustainability frameworks and indicators (OECD 2003; Binder et al. 2010; Magrini and Giambona 2022). The current methodological approaches suit developed countries having comprehensive data on sustainability indicators. Developing countries like India, however, lack such data. In a conference convened by the World Bank and the United Nations University recommended for constructing a very simple index yet covering complex aspect for the purposes measuring sustainability for better communication and informed decision making (Munasinghe and Shearer 1995). To address these challenges, improvements are needed in (i) identifying sustainability indicators for smallholder production systems dominating agriculture in developing countries, (ii) evolving a holistic approach for their integration, and (iii) measuring trade-offs between natural and man-made capitals.

This paper aims to evolve a framework to quantify the sustainability in Indian agriculture over a spatial scale, that is, the states. The paper contributes to the literature in three specific ways. First, by identifying and introducing relevant indicators, it constructs a composite index of agricultural sustainability, which guides the path to sustainable intensification of agriculture. Second, it contributes towards better targeting of policies and programs for sustainable agricultural development. Third, it provides directions for future research on the refinement of indicators and methodologies.

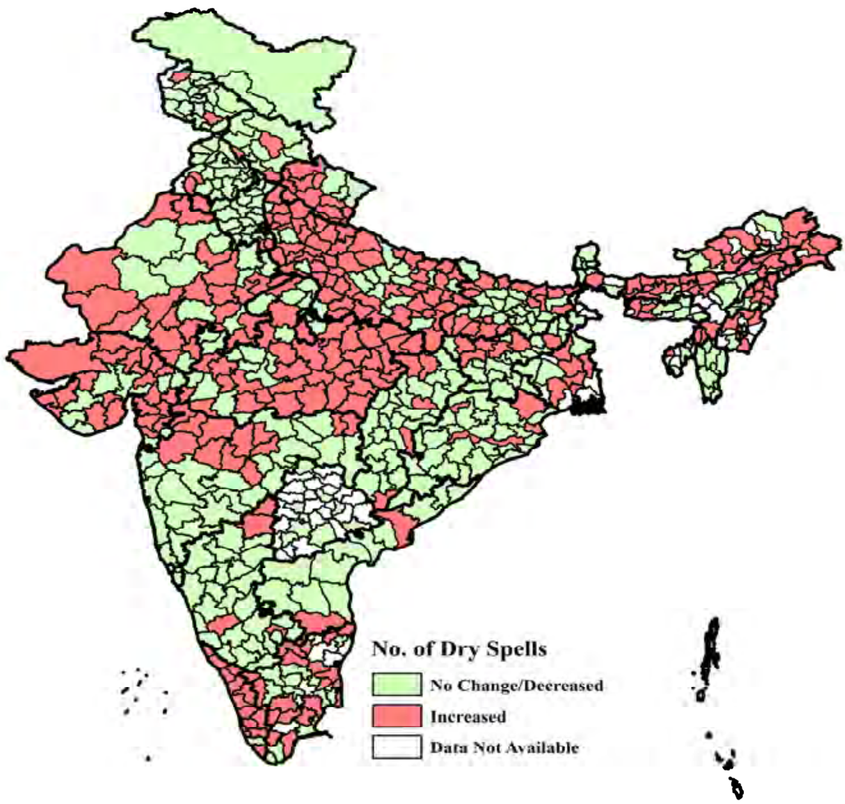
The structure of this paper is as follows. Chapter 2 sheds light on key issues related to the sustainability of agriculture in India and provides a context for its assessment. Chapter 3 elaborates on the process of the construction of a composite index of sustainability. The results on the sustainability of agriculture at the national and sub-national level are discussed in Chapter 4. Conclusions and policy implications are provided in the last chapter.

2 Sustainability Issues in Indian Agriculture

The technology-centric input-intensive approach to agricultural development has profoundly impacted socio-economic development, but its environmental consequences became increasingly evident. The quantitative and qualitative degradation of soils, water and biodiversity are now apparent, particularly in the intensively-cultivated states of Punjab, Haryana and western Uttar Pradesh. Groundwater depletion has become a serious concern in Punjab, Rajasthan, and Haryana, where the extraction rate has exceeded the recharge rate by 66, 51, and 34%, respectively. As per the latest assessment report, the groundwater in 76% of the assessed blocks in Punjab, 72% in Rajasthan, and 61% in Haryana has been overexploited (GoI 2022). Further, more than 16% of water bodies in the country are not in use due to one or the other reasons (GoI 2023). Common property resources (CPRs) that help reduce economic and social inequalities arising from property rights have degraded both qualitatively and quantitatively. Increasing water salinity and grey water footprints, too, have become a significant threat to the sustainability of agriculture — 2.23% of the aquifers are now saline, a significant increase from 0.52% in 2004. This problem is severe in West Bengal (17.39%), Andhra Pradesh (5.86%), and Gujarat (5.16%). If the current trends in groundwater depletion continue, the cropping intensity may decline by 20% at all-India but by more than two-thirds in the groundwater-depleted regions (Jain et al. 2021).

India receives 80% of its rainfall in four months (June to September). The rainfall is erratic, often leading to floods and droughts. The number of dry spells – a continuous period of two or more weeks during the monsoon season with a daily precipitation less than 2.5mm—has increased significantly, especially in the rainfed regions (Figure 1). The prolonged dry spells cause crop failures, leading to economic hardships for farmers and rural-urban migration. Migration hotspots include Bundelkhand, Marathwada, Vidarbha, Ladakh, and western Rajasthan. Despite an extensive network of canals, their maintenance and management remain poor, resulting in sedimentation and water

Figure 1. Changes in incidences of dry-spells in India during 1965-2016



Source: Computed based on data from Indian Meteorological Department

losses. The water-use efficiency of surface irrigation is low, ranging between 30 to 65% (GoI 2014a).

The indiscriminate and unbalanced use of chemical fertilizers has resulted in the deterioration of soil fertility and loss of micro- and macro-nutrients. Most Indian soils have low organic carbon (<0.5%) and micronutrients. As much as 70% of the soil samples from Tamil Nadu, Uttar Pradesh, Haryana, Punjab, Rajasthan, Kerala, Karnataka, Odisha, Andhra Pradesh, Telangana, Chhattisgarh, and Madhya Pradesh are deficit in organic carbon or nitrogen or both (https://soilhealth.dac.gov.in). Studies also report that more than 70% of land suffers from acidity or alkalinity (Das et al. 2022). Unbalanced use of chemical fertilizers also causes deterioration in soil and water quality, reduces nutrient-use efficiency, and increases production costs.

Besides, the rising demand for land for housing, urbanization, and industrialization has also led to quantitative degradation of natural resources, i.e., land and water, jeopardizing socio-economic sustainability. Encroachment of common property resources (CPRs) by rich and powerful people has increased the vulnerability of the landless and marginal farmers who depend on these for animal grazing, domestic fuel, and non-timber products. It has also affected the biodiversity. Arnold (1990) has reported that the panchayat revenue and forest lands have been illegally encroached upon for agricultural purposes. The Water Bodies Census (2023) shows that more than 38 thousand water bodies, mainly ponds, have been encroached upon (Table 1). In Punjab, Haryana, and Uttar Pradesh, more than 6% of the total water bodies have been encroached.

Table 1. Region-wise water bodies encroached in India

Regions	No. of water bodies encroached
Northern hills (Jammu & Kashmir, Himachal and Uttarakhand)	150 (0.15)
Northern plains (Haryana, Punjab and Uttar Pradesh)	16929 (6.13)
South plateau and coastal region	16377 (3.68)
Central region	1890 (1.62)
Eastern plains and coastal region	2492 (0.20)
Western dry region	320 (0.19)
North eastern hills	21 (0.04)
All India	**38496 (1.59)**

Source: GoI (2023)

Note: Figures in parentheses indicate % of total water bodies in the respective region

Another critical agricultural sustainability concern revolves around the alarming loss of biodiversity. The issue is of particular worry in smallholder-dominated agrarian economies like India, where 86% of farm households possess two hectares or less. In such vulnerable systems, biodiversity holds special significance for food and nutrition security, dietary diversity, building resilient production system and livelihood, and human and animal health. Estimates show that agricultural expansion is responsible for depleting 45% of the temperate forests, 50% of the savannas, and 70% of the grasslands worldwide (Balmford et al. 2012; Power et al. 2010). India is not an exception to this. In the Indo-Gangetic plains, the agroeco system has become highly cereal-centric, causing damage to the natural resources and agrobiodiversity (Roul et al. 2021). The traditional knowledge and culture associated with agriculture have also disappeared to a great extent.

3 Framework for Quantifying Sustainability

Several methodological frameworks have been developed to assess the sustainability of agriculture. These include the RISE - Response-Induced Sustainability Evaluation (Grenz et al. 2009), the IDEA-Indicateurs de Durabilité des Exploitations Agricoles (Zahm et al. 2008), the SEAMLESS- European Union's Component-based Sustainability Assessment Framework (Van Ittersum et al. 2008), the MESMIS- Spanish Indicator-based Sustainability Assessment Framework (Astier et al. 2012), the SAFA-Sustainability Assessment of Food and Agriculture Guidelines (FAO 2014), the SDFI-Sustainable Dairy Farming Index (Chand et al. 2015) and SMART-Sustainability Monitoring and Assessment RouTine Farm Tool (Schader et al. 2016). Although most of these have followed a holistic approach, limitations remain regarding the appropriateness of data and indicators. Pal et al. (2023) have developed a composite index of agricultural sustainability for the Indo-Gangetic plains of India using several ecological, economic, and social indicators. However, their study is limited in its spatial coverage.

This paper develops a Composite Index of Agricultural Sustainability (CIAS) using well-established sustainability indexing principles. The construction of the sustainability index typically involves several logical and coherent steps, including a theoretical basis, selection of indicators, data normalization, and indicators aggregation into a composite index (OECD 2008). A detailed description of these steps, viz., selection of indicators, normalization of data, and aggregation of indicators into a composite index, is provided below.

3.1 Selection and clustering of indicators

There are three universally accepted dimensions of sustainability, viz., economic, social, and environmental (Mensah 2019). However, a few approaches also include governance (e.g., Schader et al. 2016) and food and nutrition (e.g., Béné et al. 2019) as separate dimensions, while others combine the economic and social dimensions (e.g., Galdeano-Gómez et al. 2013) depending on the synergy and trade-offs between the two. Daly (1991) argues that natural capital stock must be treated independently of the total capital. Since agriculture is the primary user of natural resources, our analysis strongly emphasizes natural capital, including soil, water, and ecology. However, we combine the economic and social dimensions, often showing strong interdependence and co-movements (Chand et al. 2011).

We define 18 broad principles of sustainability that guide the selection of indicators. Our process of selection of indicators is based on the review of related literature, expert elicitation, and statistical treatment. Initially, an exhaustive list of 144 indicators was prepared. Based on the nature and reliability of data and expert advice, 79 indicators were retained and validated (Pal et al. 2023). This exercise suggested further optimization of the indicators, as some lacked precision. It is also necessary due to the larger geographical coverage in this study. Béné et al. (2019) have shown that the availability of data (or lack thereof) results in an unavoidable trade-off between indicators and geographical coverage. Thus, a rigorous inclusion/exclusion protocol was followed, and finally, we selected 51 indicators. Then, an aggregate sustainability score was computed on four dimensions, viz., soil health, water resource, ecology, and socio-economics. Dimensional details of the sustainability principles, the definitions of the associated indicators, and the rationale for their selection are discussed below.

3.1.1. Soil health indicators

We identified eleven indicators of soil health aligning with four sustainability principles: (i) minimum soil degradation, (ii) soil fertility, (iii) soil biodiversity, and (iv) minimum use of agrochemicals. The indicators and their definitions are given in Table 2.

***Minimum soil degradation*:** Three indicators have been identified to assess the soil degradation aspects of agricultural sustainability: (a) area of degraded land (ADL), (b) land area with poor water holding capacity (SPWHC), and (c) area with unfavourable soil pH (USPH).

Improving soil fertility: Soil fertility is captured through: (a) deficiency of primary soil nutrients (SNPRIMARY), and (b) deficiency of secondary and micro soil nutrients (SNSECONDARY).

Enhancing soil biodiversity: The indicators chosen to evaluate the soil biodiversity are: (a) deficiency of soil organic carbon (SOC), which directly impacts the biodiversity, and (b) crop residue burning (CRB), which negatively affects the soil biodiversity.

Minimum use of agrochemicals and soil pollutants: Reducing the use of agrochemicals and other soil pollutants is crucial to ensure sustainability. Here the indicators used are: (a) chemical pesticide use intensity (CPUI), and (b) fertilizer use deviation (FUD) to know whether the fertilizer use is in the optimal range or not.

The definitions of soil health indicators and the data sources to capture these are given in Table 2.

Table 2. Definitions of soil health indicators

Indicator	Definition	Data source	Year
ADL^{-}	Area under degraded lands as % of geographical area (GA)	GoI (2016a)	2013
SPWHC^{-}	Area under poor water holding soils as % GA	GoI (2020a)	2011
USPH^{-}	% of soil samples with pH >=8.5 & <5.5	Soil health portal (https://soilhealth.dac.gov.in/)	2019-20
SNPRIMARY^{-}	Soil samples deficit (low and very low) in primary nutrients (P & K) (% of total samples)		
SNSECONDARY^{-}	Soil samples deficit in secondary (Sulphur) and micro nutrients (boron and zinc (% of total samples)		
SOC^{-}	Soil samples deficit in organic carbon (% of total samples)		
CPUI^{-}	Use of chemical pesticides (kg) per ha of net sown area (NSA)	Directorate of Plant Protection, Quarantine & Storage, Government of India (http://ppqs.gov.in/statistical-database)	2019-20
FUD^{-}	$FUD = \left(\frac{NU}{GCA}\right) - \left[\frac{\sum RDN_i * A_i}{\sum A_i}\right]$; Where NU = nitrogen use in kg in the state, RDNi = is the recommended dose of N for ith crop (kg/ha), Ai = area under ith crop	NU and crop-wise area: Directorate of Economics and Statistics, Government of India. (https://eands.dacnet.nic.in/); RDN: GoI (Undated)	TE 2018-19
CRB^{-}	Crop residue burnt as % of total residue generated	GoI (2014b)	2008-09
RCT^{+}	% of farmers using any one of the resource conservation machinery and equipment (Power operated planter, leveller, raised-bed planter/ BBF planter, zero-till seed-cum-fertilizer drill, straw combines, laser land leveller, straw baler, happy seeder, sprinkler Irrigation set, solar pump set and drip irrigation set)	GoI (2021a)	2016-17
OM^{+}	Use of farm yard manures (tons) per ha of NSA		

Notes: '+' or '-' sign as superscript on an indicator implies "more is better" or "less is better. ADL – area under land degradation; SPWHC – area under soils with poor water holding capacity; USPH – area under unfavourable soil pH; SNPRIMARY – deficiency of primary soil nutrients; SNSECONDARY – deficiency of secondary and micro soil nutrients; SOC – deficiency of soil organic carbon; CRB – crop residue burning; CPUI – chemical pesticides use intensity; FUD – fertilizer use deviation; RCT – adoption of resource conservation technology; OM – organic manuring; Data on GA (geographical area) and NSA (net sown area) were taken from DES, Government of India.

3.1.2 Water resource indicators

To understand agricultural sustainability through the lens of water, we have relied on three of its principles: (i) climate resilience, (ii) water availability, productivity and quality, and (iii) effective management and governance of water use. Applying these principles, we assess environmentally sound and economically viable agricultural practices that save water resources for future generations. The definitions of indicators associated with these principles are given in Table 3.

Climate resilience: Minimizing climate-related risks is crucial for the sustainable development of agriculture. To measure climate resilience, three indicators have been identified: (a) rainfall anomalies (RAI), (b) incidences of dry spells (DOI), and (c) temperature extremes (TEI).

Water availability, productivity and quality: Sufficient availability of water and its efficient use are essential for sustaining agricultural productivity. Based on this principle, we identified four indicators: (a) groundwater extraction versus recharge ratio (GE), (b) rate of groundwater depletion (RGD), (c) water productivity index (WPI), and (d) water quality index (WQI).

Effective management, policies, and governance: Effective management, policies, and institutions are essential for ensuring optimal water use for irrigation. Towards this, we have included three indicators: (a) percentage of irrigation potential utilized (IPU), (b) investments in soil and water conservation measures (ISWC), and (c) area under micro-irrigation (MI).

Table 3. Definitions of water resource indicators

Indicator	Definition	Data source	Year
RAI^{-}	Frequency of rainfall deviations > ± 25% from long-term average (50 years' average) during the period 1965-2016 converted into % of maximum possible events (51 years).	High spatial resolution (0.25X0.25 degree for rainfall and 1.0X1.0 degree for temperature) daily gridded data on rainfall and temperature (minimum and maximum) collected from Indian Meteorological Department. (https://www.imdpune.gov.in/lrfindex.php)	1965-2016
DOI^{-}	Frequency of dry spells of consecutive 14 days during monsoon season (June to September) (numbers converted into % of maximum possible in a year).		
TEI^{-}	Frequency of cold waves (temperature <4°C) and heat waves (number of days/year converted into % of maximum possible)		

Indicator	Definition	Data source	Year
WPI⁺	Area weighted average water productivity of major crops expressed in index terms using min-max approach	Water productivity (kg/m^3) estimated using the approach used by Chand et al. (2020)	2020
WQI⁺	Irrigation water quality index computed using methodology suggested by Yıldız and Karakuş (2020).	Data on water quality parameters (chloride, electrical conductivity, sodium, bicarbonate & sodium absorption ratio) taken from groundwater year books of the states: http://cgwb.gov.in/GW-Year-Book-State.html	2019-20
GE⁻	Annual groundwater extraction as % of recharge	GoI (2019a)	2017
RGD⁻	Rate of groundwater depletion (meters/annum) during last one decade	Dynamic Groundwater Resources of India (Various issues) https://cgwb.gov.in/Dynamic-GW-Resources.html	2008 to 2018
IPU⁺	Area actually irrigated as % of total irrigation potential created	GoI (2017)	2013-14
ISWC⁺	Investment on soil and water conservation (Rs./ha of degraded lands)	Department of Land Resources, Government of India (http://iwmpmis.nic.in/mainPage.jsp?requestAction=finProgresRptStateDistrict)	As on 31st March, 2020
MI⁺	Area under drip and sprinkler as % of GIA	GoI (2021b)	As on 31st March, 2020

Notes: '+' or '-' sign as superscripts on an indicator implies "more is better" or "less is better. RAI – rainfall anomalies; DOI-dry spell incidences; TEI – temperature extremes; GE – groundwater extraction vis-à-vis recharge; RGD – rate of groundwater depletion; WPI – water productivity index; WQI – water quality index; Irrigation potential utilized; ISWC – investment in soil and water conservation; MI – area under micro-irrigation. Data on GIA (gross irrigated area) was taken from DES, Government of India.

3.1.3 Ecological indicators

Ecology is a crucial dimension of agricultural sustainability in countries like India, where most farmers are smallholders who often practice intensive agriculture to meet their food requirements. We identified 13 indicators based on three biodiversity principles: (i) maintaining ecosystem diversity, (ii) preserving genetic and species diversity, and (iii) management and conservation of agrobiodiversity (Table 4).

Table 4. Definitions of ecological indicators

Indicator	Definition	Data source	Year
AGF^+	Area under agroforestry as % of NSA	Rizvi et al. (2019)	2014
$FOREST^+$	Area under forest (by dictionary meaning) as % of GA	Land use and area under crops: Directorate of Economics and Statistics, Government of India (https://eands.dacnet.nic.in/LUS_1999_2004.htm)	2016-17
PGL^+	Areas under pasture and grazing lands as % of NSA		
CDI^+	Crop Diversity Index$^\$$		
VDI^+	Varietal Diversity Index$^\$$	Variety-wise area under crops estimated based on data of seed sale collected from Seed India Portal: https://seednet.gov.in/NotificationDetails.aspx?type=dk%2bkYls9NygT22yT2DR3Mw%3d%3d	TE 2019-20
LDI^+	Livestock Diversity Index$^\$$	GoI (2021c) for species-wise and GoI (2015) for breed-wise livestock population	2019; 2012
FDI^+	Fish Diversity Index$^\$$	Species-wise fish production: GoI (2020b)	2017
NF^+	Area under certified organic farming (cultivated + wild harvest) as % of NSA	Agricultural and Processed Food Products Export Development Authority of India (https://apeda.gov.in/apedawebsite/organic/data.htm#Summary_Statistics)	2019-20
LC^+	Area under legume crops (pulses, groundnut and soybean) as % of gross cropped area (GCA)	Directorate of Economics and Statistics, Government of India (https://eands.dacnet.nic.in/LUS_1999_2004.htm)	TE 2016-17
HP^+	Honey production (kg per 1000 ha of GA)	Department of Agriculture and Farmers Welfare, Government of India: (https://agricoop.nic.in/en/StatHortEst)	TE 2018-19
EGC^+	Ex-situ collection of plant genetic material (number of accessions of indigenous plant species in seed gene banks) per 1000 ha of NSA	ICAR-National Bureau of Plant Genetic Resources, Government of India : (http://genebank.nbpgr.ernet.in/SeedBank/StateWiseDtls.aspx)	Up to December 2020
WL^-	Wastelands as % of GA	GoI (2019b)	2015-16
$GHGE^-$	Estimated using formula ; $GHGE = \frac{\sum EF_i * A_i/N_i}{NSA}$ Where GHGE = Green House Gas Emission (kg/ha), EF_i = Emission factor of i^{th} crop or livestock species/breed, A_i/N_i = area under i^{th} crop/number of i^{th} livestock species/breed	Crop-wise area: Directorate of Economics and Statistics, Government of India (https://aps.dac.gov.in/LUS/Public/Reports.aspx) Livestock population: GoI (2021c); GoI (2015) Emission factors: Pathak et al. (2014); Sapkota et al. (2019); Vettera et al. (2016)	2019

Notes: '+' or '-' sign in superscript on an indicator implies "more is better" or "less is better. FOREST – area under forest; AGF – area under agroforestry; PGL – pastures and grazing lands; CDI – crop diversification index; VDI – varietal diversification index; LDI – livestock diversity index; FDI – fish diversity index; NF – area under natural/organic farming; LC – area under legume crops; HP – honey production; EGC – ex-situ germplasm conservation; WL – wastelands; GHGE –greenhouse gas emissions. Data on GA (geographical area), NSA (net sown area) and GCA (gross cropped area were taken from DES, Government of India. $^\$$Index computed using Simpson's formula (Simpson 1976).

Maintaining ecosystem diversity: We emphasize the preservation of ecosystems associated with agriculture. The ecosystems impact agriculture and are impacted by agriculture. The indicators considered here are: (a) area under forest cover (FOREST), (b) area under agroforestry (AGF), and (c) area under pastures and grazing lands.

Preserving genetic and species diversity: Genetic and species diversity in agriculture (crops, livestock, and fisheries) is essential for its resilience. The following indicators are used to measure the diversity: (a) crop diversification index, (b) varietal diversification index, (c) livestock diversity index, and (d) fish diversity index.

Management and conservation of agrobiodiversity: Management and conservation of agrobiodiversity is pivotal to the sustainable development of agriculture. Six indicators have been identified to assess the management and conservation aspects: (a) area under natural/ organic farming practices, (b) area under legume crops, (c) honey production, (d) ex-situ germplasm conservation, (e) wastelands, and (f) greenhouse gas emission from agriculture.

3.1.4 ***Socio-economic indicators***

To ascertain the socio-economic sustainability of agriculture, we have relied on several principles of sustainability: (i) efficient resource utilization, (ii) meeting food, feed, and fibre needs, (iii) scale of operation, viability, and employment generation, (iv) minimizing dependence on subsidies, (v) empowerment of farmers, and (vi) support for sustainable practices. The indicators associated with these are listed in Table 5.

Efficient resource utilization**:** Sustainable agriculture should emphasize the efficient use of resources. To quantify this, we have included partial productivity of land, labour, and fertilizers.

Meeting food, feed, and fibre needs**:** An essential aspect of sustainable agriculture is its ability to meet the current and future demands for food, feed, and fibre. To capture this, we have selected three indicators: (a) availability of nutritional energy, (b) protein for human consumption, and (c) cultivated fodder for animals.

Scale of operation, viability, and employment generation: The scale of agriculture should be adequate, viable, and capable of generating gainful employment. Three indicators used to capture this include: (a) land-man ratio, (b) land fragmentation, and (c) terms of trade (agriculture to non-agriculture).

Table 5. Definitions of socio-economic indicators

Indicator	Definition	Data source	Year
LP^{+}	Value of output from crops and inland fisheries (Rs. lakh) per ha of NSA	Value of output: GoI (2020a); Number of cultivators and agricultural labourers: 2011 Population Census; Nutrient consumption: GoI (2021b); SAUs: Converted based on number of livestock (GoI 2021c) and SAU conversion coefficients from Sirohi et al. (2015)	TE 2017-18
LABP^{+}	Value of output from agriculture (Rs. lakh) per worker (cultivators and agricultural labourers)		
FP^{+}	Value of output from crops (Rs. lakh) per ton of nutrient use through fertilizers		
LSP^{+}	Value of output from livestock (Rs. lakh) per Standard Animal Unit (SAUs)		
FI^{+}	Fish production (tons) per ha of catchment area	GoI (2019c); GoI (2020b)	2018-19
CALORIES^{+}	Per capita per day availability of energy (kcal) from food estimated based on production of food (cereals, pulses, fruits, vegetables, oilseeds, egg, milk and meat) & calorific values of foods.	Food production: Directorate of Economics and Statistics, Government of India; Calorific and protein values of various foods: Gopalan and Sastri (2017); Population: 2011 Census	TE 2017-18
PROTEIN^{+}	Per capita per day availability of proteins (g) from food		
FODDER^{+}	Area under cultivated fodder as % to NSA	Directorate of Economics and Statistics, Government of India (https://eands.dacnet.nic.in/LUS_1999_2004.htm)	TE 2016-17
LMR^{+}	Availability of arable lands (ha/capita)	Arable lands: Directorate of Economics and Statistics, Government of India (https://eands.dacnet.nic.in/LUS_1999_2004.htm); Population: 2011 Census	TE 2018-19
AGINVEST^{+}	Investment in agriculture (Rs./ ha of NSA)	State Finances (Various issues): https://www.rbi.org.in/Scripts/AnnualPublications.aspx?head=State+Finances+%3a+A+Study+of+Budgets	TE 2018-19
PPH^{-}	Number of parcels per holding	GoI (2021a)	2016-17

Indicator	Definition	Data source	Year
TOT^{+}	Ratio of price received by farmers (GDP deflator of agriculture) and price paid by farmers (GDP deflator of non-agriculture).	National Statistical Office, Government of India (https://mospi.gov.in/GSVA-NSVA)	TE 2018-19
ISA^{-}	Subsidies on fertilizer and electricity used in agriculture (Rs./ha of NSA) estimated by multiplying fertilizer (N, P, K) and electricity used in agriculture by per unit subsidies on fertilizer and electricity, respectively	Fertilizer consumption: Directorate of Economics and Statistics, Government of India; Per unit subsidy: Department of Fertilizer, Government of India; Electricity used in agriculture and per unit subsidies: Central Electricity Authority	TE 2018-19
R&DINVEST^{+}	Investment on agricultural research and education (at current prices)(Rs./ha of NSA)	GoI (2019d)	TE 2018-19
FPO^{+}	Members of Farmers Producer Organizations/1000 holdings	NABARD (https://nabfpo.in/#)	2018-19
SHG^{+}	Members of Self-Help Groups/ 1000 holdings	Ministry of Rural Development, Government of India (https://nrlm.gov.in/shgReport.do?methodName=showPage)	2019-20
COOP^{+}	Members of cooperative (credit, dairy, poultry, fishery, livestock cooperatives, agro-processing and sugar)/1000 holdings	NFSCOD (2019); NCUI (2018); GoI (2020c)	2018-19

Note: '+' or '-' sign as superscripts on an indicator implies "more is better" or "less is better. LP –land productivity; LABP – labour productivity; FP – fertilizers productivity; LSP – livestock productivity; FI – fish productivity; CALORIES – calories availability; PROTEIN – protein availability; FODDER – area under cultivated fodder; LMR – land-man ratio; PPH – land fragmentation; TOT – terms of trade (agriculture to non-agricultural); ISA – input subsidies in agriculture; FPO – farmers producer organisations; SHG – self-help groups; COOP – co-operatives; AGINVEST – investment in agriculture; R&DINVEST – investment in agricultural research and development. Data on GA (geographical area), GIA (gross irrigated area), NSA (net sown area) and GCA (gross cropped area were taken from DES, Government of India.

Minimizing dependence on subsidies: One of the key objectives of sustainable agriculture is to minimize reliance on the input subsidies that harm the environment. There is evidence of an adverse effect of input subsidies on land and water resources (Rasul 2016). We have captured this aspect by including the intensity of input subsidies (i.e., electricity and fertilizers) in our sustainability framework.

Empowerment of farmers: Farmers' empowerment is vital for socio-economic sustainability. We measured this through the farmers' membership in the Farmer Producer Organizations, Self-Help Groups, and cooperatives, reflecting collective actions, bargaining power, and inclusiveness.

Support for sustainable practices: Adequate support for the adoption of sustainable practices by farmers is essential. To assess this, we have considered investment in agriculture and agricultural research and development.

3.2 Normalization of data

Expressing complex indicators in a simple and unified way is essential for their comparability across spatial scales for informed decision-making. This can be achieved through the normalization of the actual values of the indicators. There are many normalization methods, and their choice depends on several factors, including the strong or weak concept of sustainability (Gan et al. 2017).

The min-max or unitary normalization method is the most commonly used. However, the evaluation of performance through this approach is based on internal comparisons among assessment units, and hence, it produces relative rather than absolute values of sustainability. Such indices may be misleading and are not amenable to comparability across spatial and temporal scales. We normalize the indicators as follows:

Let X_i be the actual value of an indicator for i^{th} unit (a state in our case), and X_{SA} and X_{LD} are its highest and the least desired values, respectively. Then, the normalized value can be expressed as: $\frac{X_i - X_{LD}}{X_{SA} - X_{LD}}$ for an indicator having a positive association with sustainability, and $\frac{X_{LD} - X_i}{X_{SA} - X_{LD}}$ for a negatively associated indicator.

The direction of the association of the indicators is indicated through the superscripts as in column 1 of Tables 2 to 5. A +(-) superscript on an indicator signifies its direct positive (negative) relationship. The normalized value of an indicator may exceed one or be negative as the comparison was made against external benchmark rather comparing within assessment units (e.g. states). Hence, we have restricted it to lie between one and zero to make the index robust and comparable. The desired values of sustainability indicators are based on scientific logic, expert opinion, and targets set by the governments. For example, for calorie and protein intake indicators, the desired values are the norms suggested by the Indian Council of Medical Research. For other indicators (mainly expressed as % or index), these thresholds are applied at the definitional or compilation stage of the indicator. For instance, unfavourable soil is defined as an area with soil pH <5.5 and >8.5, which affects agricultural productivity. Likewise, the indicators on the soil nutrient deficiencies are available as default threshold limits. The desired benchmarks for all the indicators are given in Table 6.

3.3 Aggregation of indicators into a composite index

The final step is to combine all the indicators through a weighting scheme to arrive at a comprehensive Composite Index of Agricultural Sustainability (CIAS). The CIAS for ith state is computed as: $\sum_{ji} W_j X_{ji,}$ where W_j is the weight, and X_{ji} is the normalized value of the jth indicator. We did a sensitivity analysis of the CIAS to the weights, i.e., equal weights, statistical weights, and experts' weights. We find that weighting methods do not make any difference to the estimated values of the indices when the number of indicators is sufficiently large. In such a situation, equal weights are as good as the endogenous weights (Roul et al. 2020). Therefore, the indicators were aggregated by assigning equal weights.

Table 6. Targets/ambitions of 51 indicators of agricultural sustainability

	Indicator	**Benchmarks**	**Rationale**
Soil health	RCT	35%	Average of the top three states
	OM	10t/ha	10t of FYM per ha in soil gives 50 kg N, 20 kg P_2O5, and 50 kg of K_2O (generally adequate for most of the crops).
	Remaining nine indicators	0	Best possible case
Water management	RAI, DOI & TEI	0	Best possible case
	WPI	1	Best possible case
	WQI	40 to 85	Standards defined by Yıldız and Karakuş (2018): Index value <40 is considered unsuitable for irrigation, and >85 is regarded excellent.

	Indicator	**Benchmarks**	**Rationale**
	GE	70 to 100%	Standards defined by CGWB (2019): ≤ 70% categorised as safe and > 100% considered as overexploitation.
	RGD	-0.22 m/year	Minimum among the states
	IPU	100%	Best possible case
	ISWC	15000/ha	Government norms for reclamation of problematic soils (GoI 2016b)
	MI	48.62%	Potential area for micro-irrigation.
Ecology	FOREST	33%	Forest norms set by the Government of India
	WL	16.61%	Targets corresponding to land Degradation Neutrality Targets of India
	PGL	12.87%	Average of top three states
	AGF	25.34	Average of top three states
	CDI, VDI, LDI, & FDI	1.00	Indicating perfect diversification
	EGC	16.35	Average of top three states
	HP	0.35 kg	Double the production level of 2015 as Government targeted bee keeping as one of thrust area for doubling farm income
	GHGE	0	Best possible case
	LC	30	Optimum area to meet the need of nutrients organically (Babu et al. 2015)
	NF	10	Target set by Government of India (GoI 2016c)
Socio-economic	LP, LABP, FP, LSP & FI	Rs.2.54 lakh, Rs.2.28 lakh, Rs.13.37 lakh, Rs.0.30 lakh & 7.64t, respectively	Average of top three states
	CALORIES	2140 to 6055 KCal	Minimum calorie requirement of an adult and average of top three states
	PROTEIN	45.84 to 261 g	Minimum protein requirement of an adult and average of top three states
	FODDER	5.63	Average of top three states
	LMR	0.35	Average of top three states
	AGINVEST	Rs.36883	Average of top three states
	PPH	1	Best possible case
	TOT	1.57	Average of top three states
	ISA	0	Best possible case
	R&DINVEST	Rs.3306	2% of the value of output from agriculture & allied (Rs./ha)
	FPO, SHG & COOP	25, 1178 & 3000 respectively	Average of top three states

Note: For full names of indicators, please refer to notes below Table 2 to 5.

There is a consensus that the multiplicative aggregation rule outperforms the additive aggregation rule (Ebert and Welsch 2004; Munda 2005, Saisana et al. 2005; OECD 2008). However, multiplicative aggregation is not possible if any of the normalized values of indicators is zero. Therefore, we applied the additive method to aggregate indicators into component indices. However, to combine the component indices, we applied the multiplicative method. For this, we used geometric mean, the most widely used multiplicative aggregation function (Gan et al. 2017). The index can range from zero to one, with zero signifying unsustainability and one denoting perfect sustainability.

3.4 Analysis of trade-offs and synergies

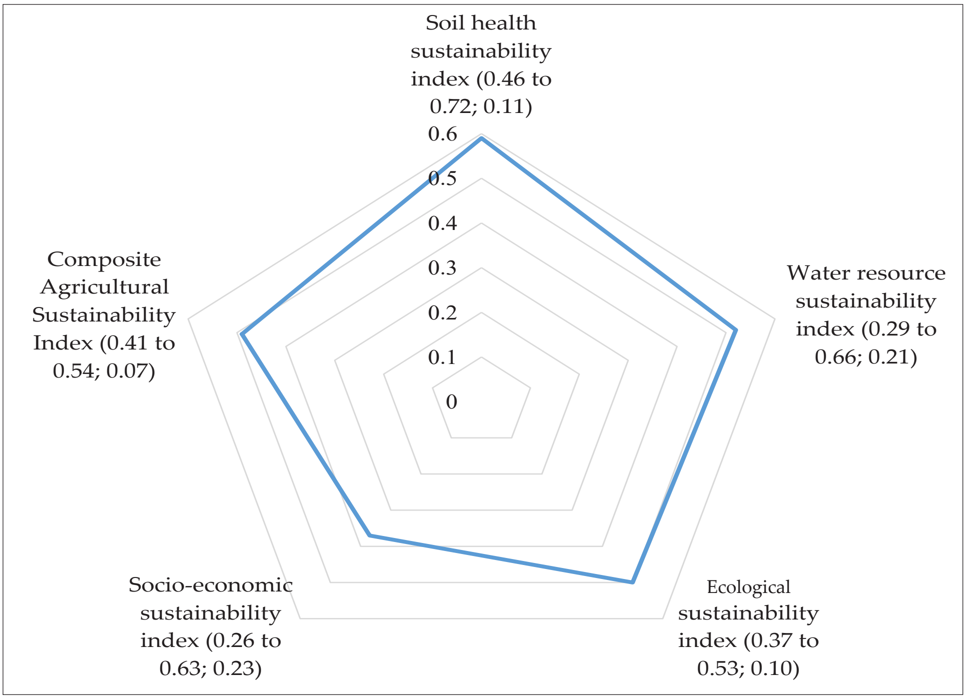
There could be trade-offs and synergies among different dimensions and indicators. Several approaches are used to know the trade-offs and synergies. The Spearman's rank correlation is the most straightforward and widely used tool to provide insights into the synergies and trade-offs. A negative coefficient indicates trade-offs, while a positive one indicates synergy (German et al. 2017, Sylla et al. 2020). Spearman's correlation coefficient is less sensitive to outliers than Pearson's correlation coefficient (Shevlyakov and Oja 2016; Schober et al. 2018). Hence, we calculated Spearman's rank correlation using the original values of the indicators.

4 Status of Sustainability in Indian Agriculture

4.1. Status of sustainability at all-India level

The average estimated value of the Composite Index of Agricultural Sustainability (CIAS) is 0.49 (Figure 2), indicating that Indian agriculture is moderately sustainable. Of its four dimensions, the sustainability of the socio-economic dimension is the least, while that of the soil health is relatively better. Further, there is considerable spatial heterogeneity in the CIAS — the coefficient of variation is 0.23 for socio-economic sustainability and 0.21 for water resource sustainability.

Figure 2. Composite Index of Agricultural Sustainability and its dimensional indices, all India

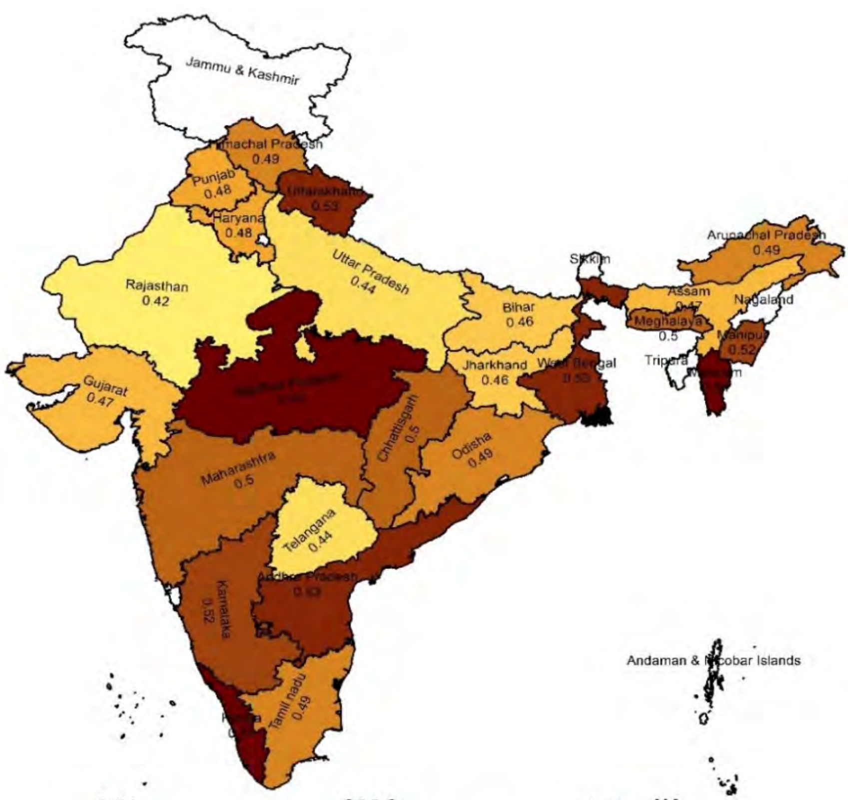


Note: Figures in parentheses indicate the range index and coefficient of variation, respectively

4.2. Spatial mapping of sustainability

The state-level CIAS presented in Figure 3 indicates that agriculture is the least sustainable in Rajasthan (CIAS= 0.42) among the states. It is more sustainable in Madhya Pradesh, Kerala, Mizoram, West Bengal, Uttarakhand, and Andhra Pradesh. Infrastructure, farm credit, inputs, and crop diversification are major drivers of agricultural growth in these states, especially in Madhya Pradesh, which leads in organic farming (Rada and Schimmelpfennig 2015; Gulati et al. 2017). The CIAS score for more than half of the states is half the mark, indicating that one or the other dimension of sustainability is jeopardized in these states. Rajasthan, followed by Uttar Pradesh, Punjab, Bihar, and Haryana, rank lower on the CIAS score. The rice-dominated states of Jharkhand and Assam also perform poorly. Note that most of India's cereal production, particularly wheat and rice, comes from these states, and the poor sustainability of agriculture has severe implications for the nation's food security.

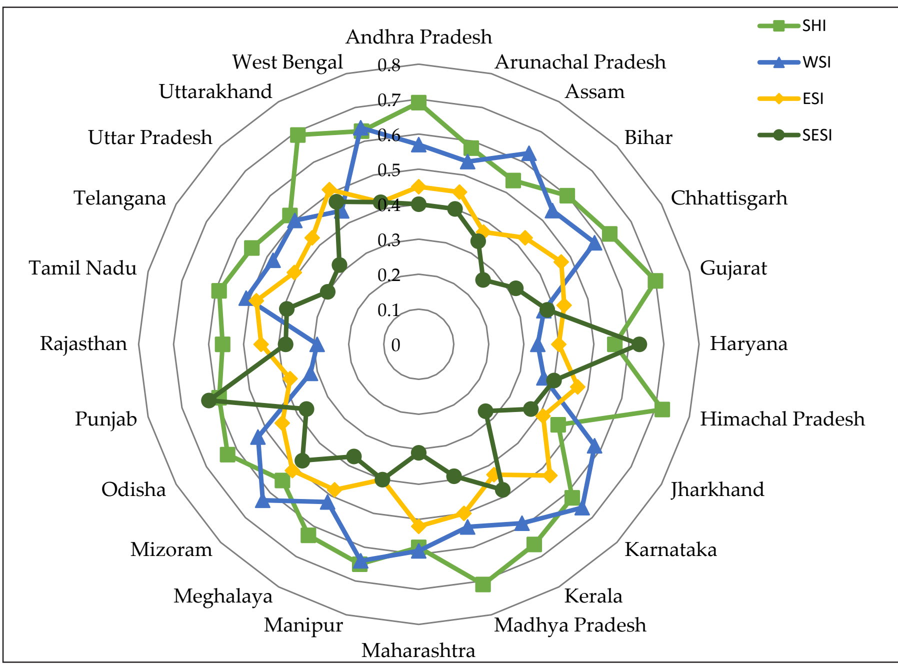
Figure 3. Spatial mapping of agricultural sustainability



4.3. Spatial heterogeneity in the dimensions of sustainability

The aggregate score hides disparities. Therefore, we have explored spatial heterogeneity in the individual dimensions of sustainability. Contrary to the widely prevalent belief that environmental sustainability is at stake, our findings reveal that socio-economic sustainability matters more. The aggregate scores of the remaining three dimensions are also varied very widely across states. The individual dimensions of sustainability are described hereunder.

Figure 4. Agricultural sustainability dimensional indices for states



4.3.1. Soil health sustainability

The soil health sustainability index (SHSI) has been constructed using 11 indicators related to soil degradation, soil fertility, biodiversity, of agrochemicals, and sustainable soil management practices. The average soil health score is estimated at 0.59 (see Figure 2) but varies significantly from 0.46 for Jharkhand to 0.72 for Himachal Pradesh (Figure 4). Madhya Pradesh and Gujarat also score high on the SHSI (0.70). The rice-wheat-dominated states in the Indo-Gangetic plains rank poor on the SHSI. Some studies have also echoed concerns of deteriorating soil health in this region because of increasing deficiency of soil organic carbon, micronutrients, and increasing use of agrochemicals.

The SHSI is the composite score of soil health indicators, masking the heterogeneity in individual indicators. For a better understanding, we examine the performance of states on individual indicators. Based on the normalized value of an indicator, the states are ranked as low (<0.33), medium (0.33-0.66), and high (>0.66) (Table 7). The poor water holding capacity (SPWHC), deficiency of organic carbon (SOC) and secondary and micronutrients, i.e., Sulphur, Boron, and Zinc (SNSECONDARY), high pesticide use (CPUI), and land degradation (ADL) are the leading causes of poor soil health. The performance of some of the states is also equally poor on some of the indicators (Table A1 in the Appendix). For example, despite the average high score at the national level, most states score low on soil salinity, alkalinity, and acidity, RCT (use of sustainable soil management practices), and SNPRIMARY (deficiency of P and K).

Table 7. Performance soil health sustainability indicators

Indicator	Unit of measurement	National mean value	Range	National mean normalized score	No. of states in bottom 1/3rd of range
ADL	% of GA	29.32	1.84 – 68.98 (0.66)	0.57	3
SPWHC	% GA	0.87	0.00 – 7.31 (1.71)	0.88	1
USPH	% of GA	7.23	0.00 – 72.71 (3.01)	0.90	2
SNPRIMARY	% of samples analysed	48.20	12.25 – 97.44 (0.57)	0.51	8
SNSECONDARY		46.16	0.08 – 98.54 (0.54)	0.53	3
SOC		63.93	0.20 – 90.10 (0.42)	0.29	5
CPUI	kg/ha	0.52	0.00 – 1.19 (0.75)	0.56	4
FUD	% of recommendation	-8.38	-100.00 – 90.70 (6.73)	1.00	2
CRB	Residue burnt (% total)	18.50	2.26 – 38.72 (0.57)	0.52	5
RCT	% of adoption	11.74	0.00 – 36.27 (0.98)	0.33	13
OM	t/ha	3.44	0.15 – 8.53 (0.60)	0.41	10

Note: Figures in parentheses are coefficient of variation. For full names of indicators, please refer to notes below Table 2.

The adoption of sustainable soil management practices is relatively low; hardly 12% of the farmers in the country adopt resource conservation technologies (GoI 2021a). The excessive use of chemical fertilizers (FUD) and crop residue burning are sporadic and confined to the rice-wheat cropping systems of Indo-Gangetic plains (Table A1 in the Appendix). Some states are extremely poor on some indicators. For example, the deficiency of secondary and micronutrients is as high as 99 % in Bihar, 94 % in Assam, 67 % in West Bengal, and 64 % in Karnataka. Similarly, the deficiency of organic carbon (>70%), crop residue burning (>30%

of residue generated), and indiscriminate use of pesticides (> 1 kg/ha) are major causes of poor soil health in Haryana and Punjab. Integrated nutrient management (INM) incorporating improved cropping pattern, in-situ residue management and composting are the corner stones for improving the soil health. There are ample evidences showing a very high potential of INM in improving soil health besides increasing crop yield and economic gains (Chander et al. 2013; Sharma et al. 2020; Bahinipati et al. 2023). The participatory trials conducted by International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) in Madhya Pradesh and Rajasthan showed that soil test linked balanced nutrient application using INM decreased the use of chemical fertilizers up to 50% besides increasing crop yield up to 10% compared to the chemical fertilizers (Box B1).

Box B1: Sustainable Soil Health Management through Integrated Nutrient Management

The International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) conducted participatory trials in Madhya Pradesh and Rajasthan in 2010 and 2011 and assessed the impact of different nutrient management strategies on crop yields, cost-effectiveness, and environmental benefits. The key findings from these trials are as follows:

Balanced Nutrition (BN): In the BN approach (inputs in traditional farmer practice plus Sulfur + Boron + Zinc) deficient nutrient fertilizers were added to the soil based on soil tests. The findings revealed an increase in crop yields ranging from 6 to 40% with benefit-cost ratio varying from 0.81 to 4.28, indicating that it was economically beneficial to use this method. The improved crop yield was because of enhanced rainwater use efficiency.

Integrated Nutrient Management (INM): INM involved a more holistic approach to nutrient management. It reduced the reliance on chemical fertilizers by up to 50% by incorporating on-farm produced vermicompost and other organic materials. Despite using fewer chemical fertilizers, the recorded yields were comparable to or even higher than those achieved with BN. The benefit-cost ratios for INM ranged from 2.26 to 10.2, indicating that it was a highly cost-effective approach besides environmentally non-degrading. The use of INM also resulted in improvements in soybean grain sulfur (S) and zinc (Zn) contents, which are essential nutrients for plant growth and development.

Residual Benefits: The study also found that the benefits of applied S, B, Zn, and vermicompost had a lasting impact on soil fertility. These residual benefits continued to increase crop yields in the succeeding three seasons. This shows that INM also leads to resilience building of production systems apparently through improved soil health which is manifested as yield benefits in succeeding seasons.

Source: Chander et al. (2013).

4.3.2. Water resource sustainability

With a mean water sustainability index (WSI) of 0.52, water resources' sustainability is worse than soil health's sustainability. Several notable features have emerged from the analysis of water resource sustainability. First, there is considerable spatial heterogeneity in WSI. It is the least for Rajasthan, followed by Punjab, Haryana, Gujarat, and Himachal Pradesh. Karnataka, West Bengal, Manipur, Assam, and Mizoram have better water sustainability (Figure 4). Higher rate of groundwater depletion, inadequate investment in soil and water conservation, less area under water-efficient micro-irrigation, and low water productivity are responsible for the poor sustainability of water resources (Table 8). Groundwater extraction is 66 % higher than its recharge rate in Punjab, 40 % in Rajasthan, and 37 % in Haryana (GoI 2019a). The trend in groundwater depletion during the past decade is a matter of concern — groundwater level declined at an alarming rate of 0.15 meters per year (Table 8). It has depleted in as many as 18 of the 24 states (representing 77% of the country's total cropped area). The rate of groundwater depletion is higher in Telangana (72cm), Andhra Pradesh (59cm), Punjab (54 cm), Haryana (47cm), and Gujarat (34 cm).

Notwithstanding, the states' response is inadequate to adopt micro-irrigation (except in Andhra Pradesh and to some extent in Gujarat), to invest in water conservation and groundwater recharge structures, and to develop mechanisms for water governance (measured as utilization of the irrigation potential) (Table A2 in the Appendix). This necessitates multi-pronged strategy, both in demand side and supply side management of water. One can find number of success stories of sustainable groundwater management and the states need to learn from each other from such successful interventions. The state of Telangana is often cited as good example. The recent report on Dynamic Groundwater Resources of Telangana for 2023 highlights that the total extractable groundwater resources in the state has increased to 20.93 billion m^3 in 2023 compared to 13.37 billion m^3 in 2013 attributed to multi-pronged strategies and policies of the Government (Box B2).

The water quality index, with a mean score of 0.76, is satisfactory at the national level. Still, the groundwater is not suitable for irrigation in Arunachal Pradesh, Meghalaya, and Rajasthan, and is of very poor quality in Andhra Pradesh, Gujarat, Haryana, Tamil Nadu, and Uttarakhand.

Box B2: A success story of sustainable groundwater management in Telangana

The recent report on Dynamic Groundwater Resources of Telangana for 2023 approved by the State-level committee, highlights that over the past decade, the groundwater situation in Telangana has seen a remarkable upswing, witnessing a staggering 56% increase in available resources. In 2023, the total extractable groundwater resources have surged to 20.92 billion m^3, compared to 13.37 billion m^3 in 2013. The average groundwater table has surged by more than four meters between 2013 and 2023. This remarkable rise has been observed in 83% of the mandals, or revenue administrative units, making it one of the most substantial increases in the country. Not just the recharge, there has also been positive changes in demand side as the groundwater extraction has dropped from 58% in 2013 to 39% in 2023.

This has been possible because of multi-pronged strategies adopted by the State. On the supply side, the State taken interventions like restoration of more than 25000 minor irrigation tanks, rejuvenation of feeder channels through the Mission Kakatiya Program, the ambitious Kaleshwaram Project for water lifting, and the periodic filling of minor irrigation tanks through integration with major and medium irrigation projects. This has been supported with the construction of over 1,000 artificial recharge structures, including check dams, percolation tanks, and recharge shafts.

The demand side interventions include Andhra Pradesh Farmer Managed Groundwater System (APFAMGS) with FAO funding and Andhra Pradesh and Telangana State Community Based Tank Management Programme. Review of results from APFAMGS implemented areas shows improved awareness and behavioural changes, which helped the communities to adapt to droughts because of a shift from monocrop culture to mixed/ multiple crops (Reddy and Reddy 2020).

Source: CGWB(2023); Balakrishna (2023).

Table 8. Performance of water resource sustainability indicators

Indicator	Unit of measurement	National mean value	Range	National mean normalized score	No. of states in bottom 1/3rd of range
RAI	% of maximum possible during last 52 years	29.62	13.26 – 48.83 (0.33)	0.39	7
DOI		14.15	2.99 – 24.52 (0.59)	0.42	7
TEI		2.64	0 – 58.02 (1.87)	0.95	1
WPI	Index	0.41	0.21 – 0.97 (0.65)	0.25	9

Indicator	Unit of measurement	National mean value	Range	National mean normalized score	No. of states in bottom 1/3rd of range
WQI	Index	0.71	0.34 – 0.83 (0.19)	0.69	9
GE	% of recharge	63.33	0.28 – 165.77 (0.68)	1.00	3
RGD	m/year	0.15	-0.22 – 0.72 (1.59)	0.60	4
IPU	%	81.09	60 – 100 (0.13)	0.53	4
ISWC	Rs./ha of degraded lands	1506	205 – 8319 (1.39)	0.09	21
MI	% of GIA	11.74	0.46 – 48.62 (1.16)	0.23	17

Notes: Figures in parentheses are coefficient of variation. For full names of indicators, please refer to notes below Table 3.

4.3.3. Ecological sustainability

Ecological sustainability is captured through the (i) state of agro-biodiversity and associated ecosystems, (ii) threats to agrobiodiversity, and (iii) agro-ecological practices (see Table 4 for details). The ESI has a mean score of 0.50 but is characterized by significant spatial heterogeneity, ranging from 0.37 to 0.53 (see Figure 2). Maharashtra, Karnataka, Madhya Pradesh, Mizoram, and Uttarakhand rank better on ecological dimension compared to other states, especially Assam, Punjab, West Bengal, Haryana, and Manipur (ESI<0.45) (see Figure 4). The later mentioned states are characterized by the cereal-based mono-cropping system (crop diversity index <0.5, except for Haryana), a significant decline in the acreage of legume crops (<10% of the total cropped area), low area under organic farming (<2% of the cropped area), and high greenhouse gas emission from agriculture (>0.2 t CO_2-eq ha^{-1}). The management and conservation of the ecosystem (germplasm conservation and area under organic farming), forest cover, varietal diversification, and diversity of pollinators (proxied by honey production) are poor across states (Table 9). Interestingly, the arid and semi-arid states of Maharashtra, Rajasthan, Karnataka, Gujarat, and Tamil Nadu are more diversified (as indicated by Simpson's index of diversity for crops, crop varieties, livestock, and fish) (Table A3 in the Appendix). This indicates that diversification is a resilience mechanism against climate change. Despite this, the efforts to conserve diversity ex-situ are concentrated mainly on hill states. More than 50% of the collections for *ex-situ* management of plant genetic resources for food crops by the ICAR-National Bureau of Plant Genetic Resources (ICAR-

Table 9. Performance of ecological sustainability indicators

Indicator	**Unit of measurement**	**National mean value**	**Range**	**National mean normalized score**	**No. of states in bottom 1/3rd of range**
FOREST	% of GA	21.67	3.62 – 85.41 (1.18)	0.61	6
WL	% of GA	16.96	0.92 – 41.01 (0.53)	0.00	14
PGL	% of NSA	3.12	0.00 – 27.15 (1.77)	0.24	19
AGF	% of NSA	11.86	4.11 – 42.72 (0.63)	0.35	14
CDI	Index	0.90	0.56 – 0.94 (0.12)	0.78	5
VDI	Index	0.77	0.42 – 1.00 (0.26)	0.60	3
LDI	Index	0.90	0.50 – 0.93 (0.11)	0.80	2
FDI	Index	0.69	0.01 – 0.92 (0.35)	0.68	4
EGC	Accessions/ha of NSA x 10^{-3}	1.81	0.33 – 17.65 (3.15)	0.09	19
HP	kg/thousand ha of GA	0.32	0.001 – 3.10 (2.30)	0.91	11
GHGE	t/ha	0.14	0.04 – 0.39 (0.57)	0.65	1
LC	% of GCA	20.35	0.13 – 45.84 (0.60)	0.67	14
NF	% of NSA	1.65	0.12 – 17.07 (2.23)	0.15	19

Notes: Figures in parentheses are coefficient of variation. For full names of indicators, please refer to notes below Table 4.

NBPGR) are from the north-eastern and northern hill states (http://genebank.nbpgr.ernet.in/SeedBank/StateWiseDtls.aspx). The crop-wild-relatives and landraces containing greater genetic variation than their cultivated relatives represent an important reservoir of genetic resources for breeders (Maxted and Kell, 2009). To preserve their valuable genetic traits that continually adapt and evolve, it is imperative to conserve these genetic treasures within their natural habitats.

Community seed banks play a vital role in conserving agrobiodiversity by preserving traditional and locally adapted crop varieties. These banks are often managed by and for local communities, helping safeguard indigenous knowledge and fostering resilience against environmental and market pressures. For example, Navdanya, a Civil Society Organisation, has set up 150 community seed banks in 22 states. These banks have helped in saving and conserving more than 4000 varieties of rice, millets, nutri-cereals and pulses (See Box B3). However, these community-led initiatives

Box B3: Community Seed Banks for agrobiodiversity conservation

Navdanya, a Civil Society organization set up 150 community seed banks in 22 states which are now self-sustaining and operates independently. The organization has also trained and created awareness amongst about 750,000 farmers in seed sovereignty, food sovereignty and sustainable agriculture and helped setup the largest direct marketing, fair trade organic network in the country. Navdanya's seed bank has successfully preserved a wide range of traditional and heirloom seeds from various regions of India. By collecting and storing these seeds, they have contributed to the conservation of agricultural biodiversity. This is especially crucial in the face of modern monoculture farming practices that threaten genetic diversity. The seed bank serves as a valuable resource for farmers seeking to transition from chemical-based agriculture to sustainable and organic farming methods.

Institutional mechanism of Community Seed Bank

A dedicated locally governed collective of farmers, predominantly women, come together to establish an organized effort for the preservation, propagation, and exchange of traditional seeds along with the wealth of indigenous knowledge associated with them. The community seed bank initiative is entrusted with the vital task of safeguarding native crop varieties, and the individuals responsible for nurturing and safeguarding these seeds are popularly known as "Seed Keepers".

Within this network, farmer members collect seeds that is available within their respective villages. The seed bank receives its initial seed stock from Navdanya, either through the contributions of local farmers in surrounding villages who are already cultivating these traditional varieties or by collaborating with existing seed banks and farmers from similar agro-climatic regions. The farmers who express interest in cultivating indigenous crop varieties receive comprehensive technical guidance including cultivation techniques, seed management, and organic pest control methods. At the culmination of each farming season, the participating farmers return the seeds to the seed bank, along with a modest surplus (typically 25%) as a return on the seeds they had initially borrowed. These replenished seeds then find their way into the hands of other farmers during the next season, enabling a continuous cycle of propagation and expanding the circle of member farmers involved in preserving our rich agricultural heritage.

Source: https://www.navdanya.org/index.php need to be up-scaled and out-scaled by providing resources, technical assistance, legal recognition, and incentives for the conservation and use of traditional seeds and promote sustainable agricultural practices. Concerted efforts are required to strengthen seed exchange networks and encourage the sharing of seeds and knowledge among communities.

4.3.4. Socio-economic sustainability

Socio-economic sustainability is estimated based on 17 indicators related to resource-use efficiency, the ability of the food system to satisfy society's requirements for food and feed, inclusiveness and equity, and subsidies and investment in agriculture. The mean score of SESI is 0.37, ranging from 0.26 to 0.63 (see Figure 2). Except for Haryana and Punjab, none of the states has scored more than 0.5 (Figure 4). Bihar, Karnataka, Telangana, Maharashtra, Chhattisgarh, and Uttar Pradesh also perform poorly in socio-economic sustainability.

Classification of states based on the range score given in Table 10 shows that the normalized score of 10 out of 17 indicators does not cross even 1/3rd of the realizable value. The low partial productivity of land and fertilizers, inadequate investment, and poor bargaining power of farmers are major concerns. For example, the normalized score of land productivity is extremely low (<0.10) for Chhattisgarh, Manipur, Karnataka, and Rajasthan (Table A4 in the Appendix). It is less than the national average for eleven states, mostly from the eastern and north-eastern regions. Improved technologies utilizing solar pumps for irrigation in these regions offer a sustainable solution for increasing agricultural productivity. With abundant aquifers reaching depths of 1000 meters and a climate characterized by heavy summer rains and snowmelt-induced flooding, solar pumps allow farmers to tap into groundwater round the year and could potentially boost the capability of alluvial aquifers to absorb a substantial portion of the floodwater (Amarasinghe et al. 2016; Shah et al. 2018). There are success stories of transforming agriculture through solar irrigation in this region including the Jharkhand Opportunities for Harnessing Rural Growth-Community Led Lift Irrigation Scheme (JCLIS) (See Box B4)

Low agricultural research and development investment has been another constraint in socio-economic sustainability of agriculture. The agricultural R&D investment hardly crosses Rs.1000/ha, except in Assam, Himachal Pradesh, Manipur, Uttarakhand, and West Bengal. There is also

Box B4: Sustainable livelihood through solar irrigation in Eastern India

The Jharkhand Opportunities for Harnessing Rural Growth (JOHAR) project, launched in 2017 supported by World Bank and executed by the Jharkhand State Livelihoods Promotion Society (JSLPS) aimed at elevating and diversifying the incomes of rural households spanning 68 blocks in 17 districts within the state. JOHAR seeks to empower farmers to shift towards cultivating high-value crops with a primary emphasis on improving access to irrigation by introducing community-owned and managed lift irrigation systems (JCLIS). Under the JCLIS project, solar pumps of 5 to 7.5 HP capacity, both fixed and mobile, are installed and interconnected via an underground pipeline network, efficiently delivering water to command areas covering six to eight hectares. The data indicated that these pumps collectively irrigating >10,000 hectares of land owned benefitting >20000 farming families across the state.

An impact assessment study of the project by Kishore et al. (2023) highlighted that this initiative has not only enhanced the affordability and accessibility of irrigation for farmers but also expands and sustains water sources, incorporates low-cost solar pumps, and develops an underground water distribution network. Study further revealed that the project actively fosters the formation and training of water users' groups (WUGs) to operate and maintain the irrigation system effectively. The study highlighted that farmers in the command area of the irrigation systems irrigate more land, have higher cropping intensity, are more likely to grow high-value crops, and had higher gross value of output in the Rabi (winter) season. The beneficiaries also spend less money on irrigation, especially compared with non-beneficiaries who use their own or who rent diesel pumps to irrigate their fields. Study emphasized the needed for incentivizing for system managers to increase utilization, gross irrigated area, and irrigation surplus.

Source: Kishore et al. (2023).

inconsistency in scores across states even for the better-scored indicators at the national level, e.g., the area under cultivated fodder at the all-India level is sufficiently large (6.42% of the area sown), but it is mainly concentrated in the states of Rajasthan, Haryana, Punjab, and Gujarat (>75%). Moreover, a large chunk of fodder area is occupied by cluster bean, which is mainly used for industrial purposes (>95%) rather than as animal feed (Sharma and Gummagolmath 2012).

Table 10. Performance of socio-economic sustainability indicators

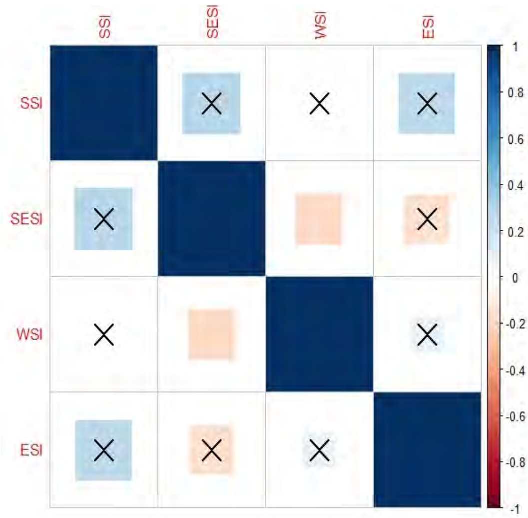
<table>
<tr><th>Indicator</th><th>Unit of measurement</th><th>National mean value</th><th>Range</th><th>National mean normalized score</th><th>No. of states in bottom 1/3rd of range</th></tr>
<tr><td>LP</td><td>Rs. lakh/ ha of NSA</td><td>1.42</td><td>0.81 – 2.72 (0.41)</td><td>0.35</td><td>9</td></tr>
<tr><td>LABP</td><td>Rs. lakh /worker</td><td>0.75</td><td>0.32 – 2.68 (0.78)</td><td>0.22</td><td>20</td></tr>
<tr><td>FP</td><td>Rs. lakh /t of nutrient use</td><td>4.81</td><td>2.49 – 31.27 (1.92)</td><td>0.21</td><td>13</td></tr>
<tr><td>LSP</td><td>Rs. lakh/ Standard Animal Unit</td><td>0.16</td><td>0.04 – 0.33 (0.52)</td><td>0.46</td><td>10</td></tr>
<tr><td>FI</td><td>t/ha</td><td>1.18</td><td>0.001 – 10.88 (2.19)</td><td>0.15</td><td>20</td></tr>
<tr><td>CALORIES</td><td>kcal/capita/day</td><td>2652</td><td>479 – 11238 (0.86)</td><td>0.13</td><td>20</td></tr>
<tr><td>PROTEIN</td><td>g/capita/day</td><td>116</td><td>26 – 485 (0.84)</td><td>0.32</td><td>15</td></tr>
<tr><td>FODDER</td><td>% to NSA</td><td>6.42</td><td>0.00 – 25.50 (0.99)</td><td>1.00</td><td>16</td></tr>
<tr><td>LMR</td><td>Arable land (ha) /capita</td><td>0.15</td><td>0.06 – 0.37 (0.59)</td><td>0.31</td><td>11</td></tr>
<tr><td>AGINVEST</td><td>Rs./ha of NSA</td><td>12668</td><td>3540 – 47653 (0.91)</td><td>0.27</td><td>11</td></tr>
<tr><td>PPH</td><td>Number of parcels/holding</td><td>2</td><td>1 – 5 (0.45)</td><td>0.76</td><td>1</td></tr>
<tr><td>TOT</td><td>Agriculture to non-agriculture GDP deflator ratio</td><td>1.31</td><td>1.05 – 1.68 (0.12)</td><td>0.54</td><td>7</td></tr>
<tr><td>ISA</td><td>Rs./ha of NSA</td><td>5443</td><td>0 – 17984 (0.95)</td><td>0.70</td><td>4</td></tr>
<tr><td>R&DINVEST</td><td>Rs./ha</td><td>351</td><td>41 – 3306 (2.40)</td><td>0.09</td><td>20</td></tr>
<tr><td>FPO</td><td rowspan="3">Members/ holding x 10^{-3}</td><td>6</td><td>2 – 36 (1.22)</td><td>0.17</td><td>15</td></tr>
<tr><td>SHG</td><td>497</td><td>151 – 1245 (0.69)</td><td>0.34</td><td>14</td></tr>
<tr><td>COOP</td><td>902</td><td>6 – 3583 (0.97)</td><td>0.30</td><td>11</td></tr>
</table>

Note: Figures in parentheses are coefficient of variation. For full names of indicators, please refer to notes below Table 5.

4.4. Trade-offs and synergies in sustainability dimensions

Identifying trade-offs and synergies among different dimensions of sustainability is essential for designing policies that minimize trade-offs and foster synergies (UN-ESCAP 2015). We analyse the relationship between different components of the CIAS, viz., SSI, SESI, WSI, and ESI of the CIAS.

Figure 5. Spearman's rank correlation between dimensions of sustainability



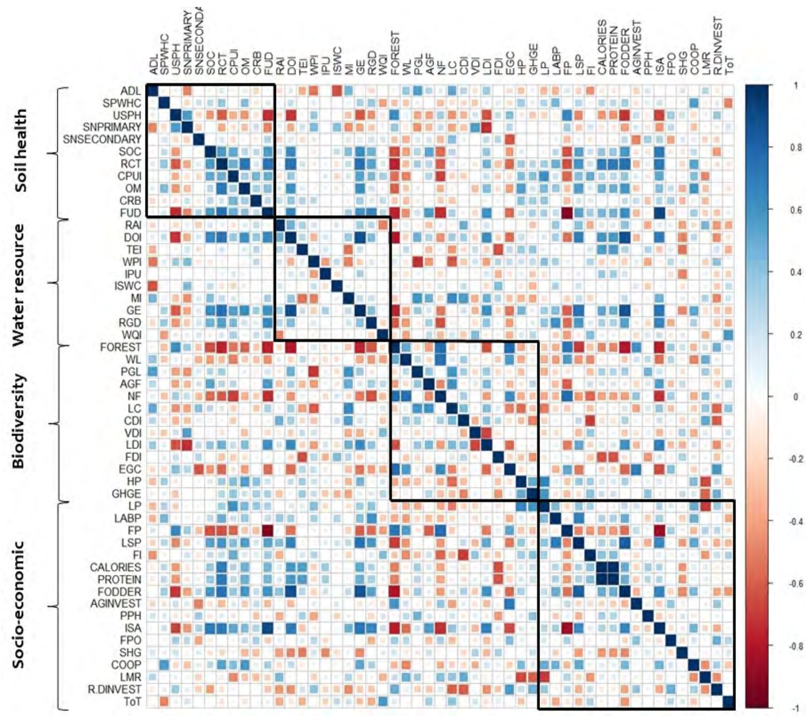
Notes: SSI: Soil Sustainability Index; SESI: Socio-Economic Sustainability Index; WSI: Water Sustainability Index; ESI: Ecological Sustainability Index (ESI). 'x' indicates non-significance; Intensity of color and size of the square is proportional to the correlation coefficient (see color code on the right).

The Spearman's rank correlation coefficients for different dimensions are presented in Figure 5. There is a significant trade-off between the water resources and socio-economic dimensions. These indicate that socio-economic sustainability cannot be achieved without putting the sustainability of water resources at stake. However, there is a synergy between the soil and ecological dimensions. There is also a weak synergy between the soil health and socio-economic dimensions. Overall, these findings suggest balancing economic development and ecological sustainability through appropriate policies and programs for the sustainable intensification of agriculture.

We go ahead and explore the relationships among different indicators. The correlation matrix is presented in Figure 6. For a better understanding, we advise readers to refer to Tables 2 to 6 for the definition of indicators and their expected association with overall sustainability. The FOREST (area under forest), ISA (intensity of agricultural input subsidies), and FODDER (area under cultivated fodder) are critical indicators impacting different indicators or being impacted by other indicators.

Input subsidies are positively associated with the adoption of resource conservation technologies. Nevertheless, input subsidies are also

Figure 6. Spearman-correlation matrix of indicators of agricultural sustainability



Notes: Dark blue squares in the figure represent high positive rank order correlations (rho), while dark red represents high negative rank order correlation. For full names of indicators, please refer to notes below Table 2 to 5.

associated with unfavourable soil pH, deficiency of soil organic carbon, excess use of fertilizer, groundwater overexploitation, and less area under natural and organic farming. The negative relationship of ISA with FP (fertilizer productivity) indicates that fertilizer use, especially nitrogen, is approaching the third stage of the production function in the traditional Green Revolution States. Evidence substantiates this argument, as documented in studies by Chand and Pavithra (2015) and Lu and Tian (2017), which highlight instances of excessive fertilizer utilization. This implies the need to promote their judicious use not only for reducing cost of cultivation with affecting crop yield but also to minimise grey water footprints in these states. The area under forests is negatively associated with dry spells. Further, it is observed that the states with lower land-man-ratio and relatively higher acreage under fodder have better livestock productivity.

5 Conclusions and Policy Implications

Measuring agricultural sustainability at a spatial scale is crucial for identifying the areas of concern and identifying the trade-offs and synergies across dimensions and indicators. This study has assessed the spatial status of sustainability in Indian agriculture along four dimensions, viz., soil health, water resource, ecology, and socio-economic. The results show that Indian agriculture has a moderate level of sustainability. However, the level of sustainability differs across different dimensions. Accordingly, the sustainability of water resources and socio-economic development merit more attention. The main concerns are the low organic carbon and micronutrients, excess use of agrochemicals, depletion of groundwater resources, and loss of agrobiodiversity.

Input subsidies are associated with unfavourable soil pH, overuse of fertilizers, low soil organic carbon, and groundwater overexploitation. Earlier studies have also pointed out the subsidized power supply, cereal-centric procurement system, and poor governance and management of surface irrigation as major reasons for unsustainable trends in natural resource use (Mukherji 2020). Therefore, a paradigm shift in agricultural incentive structure is required in favour of the conservation of natural resources. A typical example could be incentivizing the adoption of agriculture technologies/packages of practices that generate ecosystem services and protect the environment. Practices like laser-aided land levelling, reduced/zero tillage, direct/drill seeding, precise water management, and crop diversification can generate multiple economic and ecosystem services (Kumara et al. 2020; Bhan and Behra 2014; Erenstein 2009).

There is considerable spatial heterogeneity in the pattern of agricultural sustainability, indicating a differential treatment for it in the development policies of states. The eastern and north-eastern states, particularly West Bengal, Manipur, Assam, Mizoram, Chhattisgarh, and Jharkhand, are relatively better in the sustainability of water resources, but their unexplored potential negatively impacts the socio-economic development. However, soil health is poor in these states due to the higher incidence of problematic soils (acidic soils). Hence, a strategy that improves the efficiency of natural resources is the need of the hour. The agricultural development policies should focus on diversifying cropping systems, creating irrigation potential, and enhancing the adoption of biochemical technologies. Besides, there is a need to strengthen agriculture linkages with the rural non-farm sector to de-stress agriculture from excess employment pressure.

Diversification into animal husbandry is one of the main strategies to foster sustainable improvement of agriculture in the arid and semi-arid regions of Rajasthan, Gujarat, Karnataka, Maharashtra, and Tamil Nadu. To accelerate the pace of diversification towards animal husbandry, there is a need to strengthen livestock services and revive the traditional management system of common property resources. The promotion of agroforestry-based production systems will also strengthen the crop-livestock linkages.

The findings of this study can feed into policies for the sustainable development of agriculture, considering the likely trade-offs and synergies among different dimensions of sustainability and indicators of the specific dimension. The trade-offs and synergies in sustainability dimensions vary across states; hence, the strategies for sustainable development will also differ. Table 11 presents the indicators that require immediate attention of the states to improve the sustainability of agricultural production systems.

Table 11. State-specific priorities for sustainable agricultural development

States	**1st**	**2nd**	**3rd**	**4th**	**5th**
Andhra Pradesh	Fodder availability	Chemical-free farming	Biodiversity conservation	R&D investment	Pasture and grazing land development
Arunachal Pradesh	Improving irrigation water quality	Soil reclamation	Wasteland development	Increasing pollinators diversity	Fodder availability
Assam	Crop diversification	Micro-irrigation	Cereals self-sufficiency	Fodder availability	Improving livestock productivity
Bihar	Cereals self-sufficiency	Increasing soil secondary and micro-nutrient availability	Increasing labour productivity	Off-farm and non-farm employment	Pasture and grazing land development

States	1st	2nd	3rd	4th	5th
Chhattisgarh	Increasing water productivity	Fodder availability	Increasing land productivity	Organic farming	Investment in soil and water conservation
Gujarat	Adaption against rainfall anomalies	Cereals self-sufficiency	Irrigation availability	Biodiversity conservation	Increasing fish productivity
Haryana	Checking groundwater depletion	Improving soil organic carbon	Increasing green cover	Reducing use of agro-chemical	Organic farming
Himachal Pradesh	Wasteland development	Frost resistant varieties	Land consolidation	Investment in soil and water conservation	Increasing fish productivity
Jharkhand	Fodder availability	Cereals self-sufficiency	Minimizing land degradation	Investment in soil and water conservation	Minimizing GHG emission
Karnataka	Biodiversity conservation	Cereals self-sufficiency	Increasing fish productivity	R&D investment	Increasing land productivity
Kerala	Cereals self-sufficiency	Protein self-sufficiency	Pasture and grazing land development	Increasing area under legume crops	Increasing varietal diversity
Madhya Pradesh	Biodiversity conservation	R&D investment	Increasing water productivity	Increasing fish productivity	Micro-irrigation
Maharashtra	Biodiversity conservation	Increasing fish productivity	Cereals self-sufficiency	Improving bargaining power	R&D investment
Manipur	Wasteland development	Cereals self-sufficiency	Fodder availability	Pasture and grazing land development	Improving bargaining power
Meghalaya	Wasteland development	Cereals self-sufficiency	Improving irrigation water quality	Conservation agriculture	Fodder availability
Mizoram	Wasteland development	Cereals self-sufficiency	Fodder availability	Protein self-sufficiency	Increasing soil primary nutrient availability
Odisha	Fodder availability	Cereals self-sufficiency	Increasing labour productivity	Increasing fish productivity	Investment in soil and water conservation
Punjab	Checking groundwater depletion	Crop residue management	Reducing use of agro-chemical	Micro-irrigation	Increasing green cover

States	**1st**	**2nd**	**3rd**	**4th**	**5th**
Rajasthan	Checking groundwater depletion	Wasteland development	Improving irrigation water quality	Combating desertification	Irrigation availability
Tamil Nadu	Reorienting subsidies	Food self sufficiency	Increasing fish productivity	Organic farming	Biodiversity conservation
Telangana	Checking groundwater depletion	Balanced fertilizer use	Increasing fertilizer productivity	Organic farming	Investment in soil and water conservation
Uttar Pradesh	Improving bargaining power	Micro-irrigation	Improving soil organic carbon	Pasture and grazing land development	Organic farming
Uttarakhand	Wasteland development	Improving fish diversity	Increasing fish productivity	Micro-irrigation	Cereals self-sufficiency
West Bengal	Fodder availability	Cereals self-sufficiency	Organic farming	Pasture and grazing land development	Biodiversity conservation

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Appendix Tables

Table A1. Normalized scores of soil health indicators

State	ADL	SPWHC	USPH	SNPRIMARY	SNSECONDARY	SOC	CRB	CPUI	FUD	RCT	OM
Andhra Pradesh	0.79	0.98	1.00	0.86	0.64	0.40	0.84	0.78	0.27	0.60	0.38
Arunachal Pradesh	0.97	1.00	0.00	0.08	0.60	1.00	0.74	0.99	1.00	0.01	0.02
Assam	0.87	0.96	0.38	0.11	0.05	0.56	0.84	0.88	1.00	0.11	0.17
Bihar	0.89	1.00	0.94	0.84	0.00	0.71	0.67	0.84	0.46	0.03	0.22
Chhattisgarh	0.76	0.99	0.78	0.65	0.56	0.44	0.81	0.73	1.00	0.09	0.08
Gujarat	0.24	0.99	0.98	0.85	0.49	0.59	0.66	0.86	0.83	0.40	0.84
Haryana	0.89	0.99	0.91	0.17	0.70	0.00	0.16	0.00	0.47	1.00	0.85
Himachal Pradesh	0.38	0.99	0.96	0.87	0.91	0.88	0.63	0.15	1.00	0.38	0.72
Jharkhand	0.00	1.00	0.39	0.33	0.74	0.62	0.21	0.59	1.00	0.09	0.09
Karnataka	0.47	1.00	0.81	0.63	0.35	0.46	0.57	0.86	0.79	0.48	0.41
Kerala	0.86	0.99	0.38	0.62	0.62	0.78	0.94	0.81	1.00	0.01	0.29
Madhya Pradesh	0.82	1.00	0.98	0.36	0.49	0.60	0.85	0.97	1.00	0.36	0.41
Maharashtra	0.35	1.00	0.95	0.74	0.46	0.43	0.59	0.38	1.00	0.20	0.29
Manipur	0.61	1.00	0.38	0.49	0.81	0.97	0.80	1.00	1.00	0.01	0.05
Meghalaya	0.68	1.00	0.48	0.19	0.81	0.95	0.75	1.00	1.00	0.00	0.08
Mizoram	0.87	1.00	0.26	0.00	1.00	0.48	0.57	0.84	1.00	0.00	0.00
Odisha	0.51	1.00	0.49	0.27	0.96	0.34	0.83	0.82	1.00	0.20	0.46
Punjab	0.96	0.97	0.93	0.44	0.86	0.18	0.00	0.00	0.40	1.00	0.80
Rajasthan	0.09	0.00	0.80	0.73	0.48	0.07	0.84	0.90	1.00	0.96	0.34
Tamil Nadu	0.83	0.98	0.95	0.60	0.45	0.10	0.47	0.66	0.96	0.16	0.33
Telangana	0.55	1.00	0.96	0.74	0.63	0.34	0.84	0.10	0.00	0.55	0.39
Uttar Pradesh	0.91	1.00	0.99	0.11	0.61	0.02	0.06	0.38	1.00	0.30	0.39
Uttarakhand	0.82	1.00	0.99	0.70	0.52	0.57	0.30	0.86	0.86	0.48	0.55
West Bengal	0.72	1.00	0.52	0.48	0.32	0.76	0.64	0.42	1.00	0.69	0.41
All India	0.57	0.88	0.90	0.51	0.53	0.29	0.52	0.56	1.00	0.33	0.41

Note: ADL – area under land degradation; SPWHC – area under soils with poor water holding capacity; USPH – area under unfavourable soil pH; SNPRIMARY – deficiency of primary soil nutrients; SNSECONDARY – deficiency of secondary and micro soil nutrients; SOC – deficiency of soil organic carbon; CRB – crop residue burning; CPUI – chemical pesticides use intensity; FUD – fertilizer use deviation; RCT – adoption of resource conservation technology; OM – organic manuring.

Table A2. Normalized scores of water resource indicators

States	RAI	DOI	TEI	WPI	IPU	ISWC	MI	GE	RGD	WQI
Andhra Pradesh	0.53	0.54	1.00	0.51	0.35	0.32	1.00	1.00	0.14	0.28
Arunachal Pradesh	0.36	0.84	0.65	0.74	0.74	0.42	0.01	1.00	0.61	0.00
Assam	0.72	0.86	0.97	0.96	0.27	0.26	0.00	1.00	0.75	0.52
Bihar	0.48	0.57	0.99	0.54	0.44	0.08	0.04	1.00	0.71	0.55
Chhattisgarh	0.61	0.62	0.99	0.00	0.89	0.05	0.36	1.00	0.74	0.52
Gujarat	0.00	0.01	1.00	0.43	0.25	0.05	0.48	1.00	0.40	0.08
Haryana	0.19	0.04	0.63	0.82	1.00	0.09	0.20	0.00	0.27	0.20
Himachal Pradesh	0.49	0.39	0.00	0.13	0.75	0.03	0.09	0.45	0.94	0.47
Jharkhand	0.60	0.67	0.99	0.26	0.61	0.00	0.29	1.00	0.75	0.66
Karnataka	0.52	0.43	1.00	0.22	0.88	0.15	0.82	1.00	0.76	0.83
Kerala	0.54	0.88	1.00	0.49	0.81	0.12	0.13	1.00	0.73	0.22
Madhya Pradesh	0.37	0.31	0.94	0.05	0.63	0.24	0.10	1.00	0.82	0.89
Maharashtra	0.54	0.49	1.00	0.06	0.72	0.09	0.75	1.00	0.67	0.59
Manipur	0.48	0.84	0.99	0.88	0.62	0.06	0.00	1.00	1.00	0.50
Meghalaya	0.04	0.88	0.99	0.83	0.70	0.05	0.00	1.00	0.73	0.00
Mizoram	0.18	0.78	0.99	0.96	0.00	0.55	0.33	1.00	1.00	0.50
Odisha	0.62	0.76	1.00	0.12	0.11	0.10	0.17	1.00	0.82	0.59
Punjab	0.23	0.11	0.39	0.96	0.55	0.13	0.00	0.00	0.19	0.66
Rajasthan	0.13	0.00	0.84	0.05	0.75	0.06	0.36	0.00	0.68	0.00
Tamil Nadu	0.36	0.26	1.00	0.81	0.44	0.33	0.42	0.64	0.51	0.29
Telangana	0.41	0.52	1.00	0.56	0.55	0.03	0.21	1.00	0.00	0.55
Uttar Pradesh	0.26	0.22	0.88	0.26	0.85	0.21	0.01	0.99	0.68	0.61
Uttarakhand	0.38	0.49	0.53	0.53	0.35	0.07	0.04	1.00	0.71	0.28
West Bengal	0.65	0.72	0.99	0.92	0.49	0.01	0.01	1.00	0.68	0.96
All India	0.39	0.42	0.95	0.25	0.53	0.09	0.23	1.00	0.60	0.69

Note: RAI – rainfall anomalies; DOI-dry spell incidences; TEI – temperature extremes; GE – groundwater extraction vis-à-vis recharge; RGD – rate of groundwater depletion; WPI – water productivity index; WQI – water quality index; Irrigation potential utilized; ISWC – investment in soil and water conservation; MI – area under micro-irrigation.

Table A3. Normalized scores of ecological indicators

States	FOREST	WL	PGL	AGF	NF	LC	CDI	VDI	LDI	FDI	EGC	HP	GHGE
Andhra Pradesh	0.49	0.12	0.10	0.51	0.05	0.97	0.69	0.47	0.77	0.62	0.07	0.31	0.62
Arunachal Pradesh	1.00	0.00	0.02	0.20	0.47	0.12	0.60	0.79	0.41	0.58	0.95	0.00	0.70
Assam	1.00	0.33	0.17	0.25	0.19	0.12	0.00	0.92	0.25	0.72	0.09	0.42	0.37
Bihar	0.14	0.54	0.01	0.50	0.03	0.21	0.47	0.80	0.73	0.67	0.03	1.00	0.48
Chhattisgarh	1.00	0.55	0.51	0.51	0.04	0.56	0.07	0.99	0.49	0.40	0.15	0.15	0.68
Gujarat	0.13	0.35	0.34	0.30	0.08	0.70	0.76	0.43	0.87	0.84	0.01	0.08	0.69
Haryana	0.00	0.82	0.04	0.28	0.01	0.03	0.46	0.88	0.58	0.54	0.08	1.00	0.54
Himachal Pradesh	0.82	0.00	1.00	0.09	0.21	0.09	0.58	0.22	0.72	0.04	0.97	1.00	0.40
Jharkhand	0.88	0.12	0.11	1.00	0.18	0.33	0.45	0.89	0.51	0.25	0.13	0.50	0.00
Karnataka	0.56	0.62	0.37	0.42	0.07	1.00	0.85	0.27	0.84	0.84	0.01	0.30	0.77
Kerala	1.00	0.68	0.00	0.02	0.20	0.00	0.48	0.00	0.62	0.64	0.08	1.00	0.85
Madhya Pradesh	0.73	0.24	0.33	0.22	0.58	1.00	0.69	1.00	0.43	0.41	0.03	0.21	0.70
Maharashtra	0.44	0.31	0.31	0.33	0.15	1.00	0.77	0.89	0.71	0.89	0.02	0.14	0.81
Manipur	1.00	0.00	0.00	0.17	0.31	0.30	0.34	0.85	0.58	0.56	0.26	0.12	0.77
Meghalaya	1.00	0.00	0.00	0.04	1.00	0.10	0.63	0.94	0.43	0.70	0.38	0.33	0.64
Mizoram	1.00	0.00	0.03	0.00	0.69	0.09	0.84	0.96	0.00	0.83	1.00	0.26	0.88
Odisha	1.00	0.30	0.26	0.67	0.20	0.36	0.12	0.82	0.51	0.64	0.10	0.25	0.60
Punjab	0.00	1.00	0.01	0.28	0.01	0.00	0.12	0.90	0.55	0.56	0.04	1.00	0.48
Rajasthan	0.04	0.00	0.38	0.34	0.15	0.78	0.74	0.69	0.85	0.44	0.00	0.69	0.79
Tamil Nadu	0.57	0.66	0.06	0.46	0.04	0.68	0.67	0.46	0.68	0.91	0.04	0.42	0.62
Telangana	0.50	0.25	0.20	0.51	0.01	0.57	0.58	0.83	0.77	0.48	0.05	0.06	0.51
Uttar Pradesh	0.09	0.83	0.02	0.36	0.02	0.28	0.50	0.90	0.78	0.29	0.02	1.00	0.54
Uttarakhand	1.00	0.00	0.28	0.29	0.60	0.20	0.73	0.63	0.64	0.00	0.94	1.00	0.36
West Bengal	0.52	0.94	0.00	0.17	0.00	0.11	0.23	1.00	0.45	0.58	0.00	1.00	0.45
All India	0.61	0.00	0.24	0.36	0.15	0.68	0.78	0.60	0.80	0.68	0.09	0.91	0.65

Note: FOREST – area under forest; AGF – area under agroforestry; PGL – pastures and grazing lands; CDI – crop diversification index; VDI – varietal diversification index; LDI – livestock diversity index; FDI – fish diversity index; NF – area under natural/organic farming; LC – area under legume crops; HP – honey production; EGC – ex-situ germplasm conservation; WL – wastelands; GHGE –greenhouse gas emissions.

Table A4. Normalized scores of socio-economic indicators

States	LP	LABP	FP	LSP	FI	CALORIES	PROTEIN	FODDER	AGINVEST	PPH	ISA	FPO	SHG	COOP	LMR	R&DINVEST	TOT
Andhra Pradesh	0.74	0.26	0.15	0.45	0.70	0.22	0.41	0.16	0.24	0.85	0.39	0.15	0.67	0.34	0.42	0.07	0.62
Arunachal Pradesh	0.34	0.31	1.00	0.13	0.03	0.08	0.31	0.00	0.92	0.75	1.00	0.28	0.08	0.06	0.85	0.14	0.48
Assam	0.37	0.18	0.85	0.02	0.16	0.00	0.14	0.01	0.18	0.56	0.94	0.14	0.96	0.38	0.16	0.43	0.35
Bihar	0.43	0.00	0.04	0.40	0.26	0.00	0.16	0.05	0.06	0.76	0.80	0.02	0.49	0.22	0.00	0.07	0.57
Chhattisgarh	0.00	0.05	0.18	0.08	0.33	0.25	0.41	0.00	0.61	0.57	0.91	0.18	0.35	0.30	0.54	0.21	0.53
Gujarat	0.34	0.44	0.35	0.66	0.01	0.00	0.16	1.00	0.10	0.93	0.70	0.21	0.33	0.42	0.51	0.05	0.26
Haryana	0.85	0.86	0.09	1.00	1.00	1.00	1.00	1.00	0.21	0.93	0.34	0.59	0.12	0.82	0.30	0.14	0.38
Himachal Pradesh	0.90	0.13	1.00	0.29	0.03	0.23	0.38	0.31	0.83	0.00	0.93	0.37	0.04	0.44	0.20	0.42	0.26
Jharkhand	0.66	0.01	0.79	0.06	0.13	0.00	0.14	0.00	0.39	0.79	0.91	0.38	0.80	0.00	0.25	0.26	0.73
Karnataka	0.05	0.17	0.14	0.20	0.02	0.00	0.20	0.05	0.35	0.86	0.32	0.29	0.17	0.37	0.51	0.04	0.91
Kerala	0.76	0.94	0.95	0.80	0.03	0.00	0.00	0.04	0.79	0.94	0.91	0.22	0.29	1.00	0.02	0.27	0.19
Madhya Pradesh	0.13	0.20	0.33	0.42	0.06	0.72	0.77	0.39	0.16	0.56	0.89	0.21	0.20	0.19	0.61	0.04	0.83
Maharashtra	0.10	0.17	0.17	0.45	0.02	0.00	0.09	1.00	0.30	0.85	0.74	0.02	0.17	0.42	0.43	0.03	0.38
Manipur	0.05	0.13	1.00	0.13	0.09	0.00	0.21	0.00	0.21	0.98	0.96	0.76	0.00	0.18	0.36	0.93	0.89
Meghalaya	0.24	0.06	1.00	0.00	0.00	0.00	0.08	0.00	0.61	0.88	1.00	0.18	0.98	0.16	0.97	0.09	0.09
Mizoram	0.26	0.18	1.00	0.32	0.06	0.00	0.00	0.00	1.00	0.94	0.97	1.00	0.48	0.00	0.95	0.09	0.79
Odisha	0.18	0.05	0.33	0.16	0.07	0.00	0.20	0.00	0.39	0.78	0.89	0.39	0.79	0.47	0.34	0.19	1.00
Punjab	0.85	1.00	0.08	1.00	0.87	1.00	1.00	1.00	0.49	0.94	0.32	0.24	0.05	0.97	0.32	0.22	0.26
Rajasthan	0.08	0.30	0.41	0.78	0.01	0.35	0.48	1.00	0.00	0.50	0.85	0.23	0.09	0.28	1.00	0.00	0.17
Tamil Nadu	1.00	0.27	0.30	0.58	0.02	0.00	0.11	0.29	0.64	0.82	0.00	0.58	0.29	0.58	0.18	0.18	0.77
Telangana	0.38	0.26	0.00	0.33	0.07	0.11	0.33	0.08	0.46	0.86	0.25	0.08	0.49	0.27	0.46	0.12	0.55
Uttar Pradesh	0.46	0.18	0.14	0.65	0.25	0.17	0.35	0.84	0.21	0.80	0.74	0.00	0.02	0.07	0.11	0.02	0.49
Uttarakhand	0.64	0.18	0.16	0.44	0.02	0.04	0.24	0.81	1.00	0.59	0.81	0.77	0.13	0.55	0.32	1.00	0.28
West Bengal	1.00	0.31	0.32	0.33	0.36	0.04	0.25	0.00	0.20	0.53	0.86	0.37	1.00	0.58	0.00	0.32	0.67
All India	0.35	0.22	0.21	0.46	0.15	0.13	0.32	1.00	0.27	0.76	0.70	0.17	0.34	0.30	0.31	0.09	0.54

Note: LP –land productivity; LABP – labour productivity; FP – fertilizers productivity; LSP – livestock productivity; FI – fish productivity; CALORIES – calories availability; PROTEIN – protein availability; FODDER – area under cultivated fodder; LMR – land-man ratio; PPH – land fragmentation; TOT – terms of trade (agriculture to non-agricultural); ISA – input subsidies in agriculture; FPO – farmers producer organisations; SHG – self-help groups; COOP – co-operatives; AGINVEST – investment in agriculture; R&DINVEST – investment in agricultural research and development.

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भाकृअनुप–राष्ट्रीय कृषि आर्थिकी एवम् नीति अनुसंधान संस्थान
ICAR - NATIONAL INSTITUTE OF AGRICULTURAL ECONOMICS AND POLICY RESEARCH
(Indian Council of Agricultural Research)
Dev Prakash Shastri Marg, Pusa, New Delhi - 110 012, INDIA
Ph: +91(11) 2584 7628, 2584 8731 Fax: +91 (11) 2594 2684
Email : director.niap@icar.gov.in, Website : www.niap.icar.gov.in