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Synergies and trade-offs for climate-resilient agriculture in India: an agro-climatic zone assessment

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Abstract

Globally, agriculture is recognized as a highly vulnerable sector to climate change and risks from climatic aberrations pose an imminent danger to the food security and sustainability of livelihoods. To bring robustness in climate adaptation planning, evaluation of resilience across homogenous regions is essential for developing and scaling suitable location-need-context specific interventions and policies that build the resilience of the agricultural system. In this paper, we present an analysis and discussion of multi-scalar and multi-indicator assessment, by profiling resilience across agro-climatic zones of India, based on the development of a Climate-Resilient Agriculture Index embracing environmental, technological, socio-economic, and institutional and infrastructural dimension. A total of 26 indicators, spread across these four dimensions, were employed to purport inter- and intra-agro-climatic zone differentials in the level of resilience. Among the zones, it was found that West Coast Plains & Ghats and Tans-Gangetic Plains had the highest degree of resilience to manage climate risks. Most of the districts lying within Eastern Himalayan Region, Middle Gangetic Plains, Eastern Plateau & Hills, and Western Dry Region had a lower degree of resilience. The study places greater emphasis on deciphering region-specific drivers and barriers to resilience at a further disaggregated scale for improving rural well-beings. It is construed that devising action plans emphasizing awareness, preservation of natural resources, diversification, building physical infrastructure, strengthening of grass-root institutions, and mainstreaming climate adaptation in the developmental policy is crucial for climate-resilient pathways.

Keywords Agriculture · Agro-Climatic Zones · Climate change · Resilience · Indictors · Index · India

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1 Introduction

Climate change emanating in the form of unpredictable weather patterns, seasonal shifts, and recurrence of natural hazards is increasingly considered as a threat multiplier to the path of sustainable development. Unequivocally, environmental shocks undermine the sustainability of food systems and livelihood means for resource-dependent communities, predominantly in poor and developing tropical regions (FAO 2017). Such disturbances manifest into vulnerability arising from crop failures, land degradation, increased market volatility, exploitation of the natural resource, income variability, consumption erosion, displacements and migration, rise in poverty levels, inequalities, and social conflicts (Singh et al. 2014a, 2018a; Birthal and Hazrana 2019).

India has diverse climatic conditions that vary from tropical climate in the southern peninsular region to subtropical climate that exist in most parts of the northern region, and the temperate climate in the Himalayan states. Such heterogeneity across physiographic and climatic conditions has resulted in different land use pattern, technology adoptions, and socio-economic attributes across agricultural systems in the country. Most of the studies that analyse temporal changes in temperature showed a significant warming trend in both the minimum and maximum temperature in India, the pace of which is projected to intensify in the foreseeable future (Kothawale et al. 2010; Jain and Kumar 2012; Srivastava et al. 2016; Krishnan and Sanjay 2017). On the other spectrum, in the recent past, a decreasing trend has been observed in the south west monsoon precipitation (Jain and Kumar 2012; Mondal et al. 2015; Roxy et al. 2015; Kothawale and Rajeevan 2017), which supply 80% of the country's annual rainfall and is crucial for agriculture production. Moreover, several climate-crop modelling studies imply a progressive reduction in major crop yields such as wheat, rice, sorghum, maize, and many others to climate change, the magnitude of which vary across regions (Mishra et al. 2013; Rao et al. 2014; Singh et al. 2014b, c; Birthal et al. 2015). The studies capturing micro-level senstivity to climate change reported large number of barriers that impede adaptation among rural households. The most cited among these include lack of credit facilities and access to finance (Banerjee 2014; Singh et al. 2018b), lack of information and knowledge about climate change (Panda 2016; Pandey et al. 2018), inadequate infrastructure facilities, lack of access to market, high cost of inputs and technology (Palanisami et al. 2011; Rao et al. 2017), weak collective actions, limited participation of SHGs and other institutions (Jodha et al. 2012), fewer livelihoods diversification options (Barua et al. 2014; Singh et al. 2018b), and poor human capital.

As the harmful effects of climate change intensify over time, it becomes essential to deploy measures that limit vulnerability and build resilience of the socio-ecological system against climate shocks and stresses. The concept of '*resilience*' has been recognized as an important policy perspective within sustainability science and development paradigm (Adger 2000; Folke 2006; Smit and Wandel 2006). Resilience seeks to regulate the capacity of a system to absorb and recover from perturbations or disturbances in a timely and efficient manner, while ensuring the preservation, restoration, or improvement of its structures and functions (IPCC 2012). The pattern of vulnerability on agriculture arising out of climatic changes and the potential reaction to the stimulus vary geographically and temporally based on the ecological zone, production systems, and prefabricated social and economic conditions. Regional disparities mediate the possible responses and choices of the population to deal with climate-induced risks, resulting in disproportionate concentrations of suffering and losses. In the recent years, robust elucidation of spatial dimensions has become an important mechanism, facilitating the process of climate responsive planning. This allow the generation of socially, economically, and technologically differentiated and need-based interventions which assume a critical role in the development of climate-resilient pathways.

Thus, in the light of the above using an integrated approach, this study attempts to quantify *inter* and *intra* agro-climatic zone (ACZ) variations in the level of resilience to climate change in India, by defining a Climate-Resilient Agriculture (CRA) Index. It gives a comprehensive view to the policymakers into the relative strengths and weakness of different zones. Moreover, suchbroad-base and multi-indicator regional assessment of resilience contributes to the climate adaptation discourse, highlighting the need for developing context-need-region based interventions and risk management strategies to enhance the capacity of the agricultural system to deal with climatic shocks.

The rest of this paper is organized as follows. In the following section, we describe the features of ACZ of India. The third section describes the analytical framework along with empirical specifications, adopted for assessing resilience. The fourth section analyses *inter* and *intra* ACZ variations across various dimensions of resilience and the composite index. Finally, the last section brings out the discussion and conclusion.

2 Agro-climatic zonation in India

Information and assessment of agro-climatic zones is crucial for managing vulnerability and enhancing resilience. In the past, the failures or underperformance of several agricultural developmental projects in various parts of the world were linked with the failure to classify the agro-climatic regions (Reddy 2002; Motha and Murthy 2007). In retrospect, several successive attempts were made towards the regionalisation of the Indian agricultural economy into homogenous zones (Mandal et al. 2014). One such agro-climatic zonation was done by the Planning Commission of India (1989), wherein the mainland of India was retrenched into 15 ACZs based on physical conditions, topography, soil, geological formation, rainfall pattern, cropping system, development of irrigation, and mineral resources (Singh and Singh 1993). The objective of agro-climatic zoning was to harness an optimum synergy between the technology-led growth and resource use efficiency through the integration of plans and policies of the agro-climatic regions with the state and national plans. Table 1 gives a detail view into the characteristics of the 14 ACZs (excluding island region) in the country. A high contrast is observed between the zones in terms of climate, area, soil type, temperature, precipitation, and population. The typology of climate varies from cold arid to humid conditions in WHR, to semi-arid and arid climate in WPH and SPH, and to extreme aridity in WDR with a variety of soil types. Humid regions such as WCG and EHR receives the highest amount of rainfall of about 2904 and 2312 mm, respectively. The average minimum temperature was the lowest in WHR, TGP, and EHR. On the other hand, the maximum temperature was highest in GPH and WDR. In terms of geographical coverage, SPH comprising parts of Andhra Pradesh, Karnataka, and Tamil Nadu states had the largest area while the LGP had the lowest area. MGP comprising Bihar and parts of Uttar Pradesh state had the maximum proportion of the rural population (18.03%), followed by the UGP (10.78%).

Table 1 Major characteristics of ACZs

ACZ^	Distribution of states	Climate	Major soils	Annual rainfall	Annual temperature (Min, Max)	Area$ (km^2)	Rural population* (millions)
WHR (47)	Himachal Pradesh, Jammu and Kashmir[w], Uttarakhand	Cold arid to humid	Hills soils, Alluvial	1200	10.40, 21.34	331,392 (10.08)	22.32 (2.68)
EHR (89)	Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura, West Bengal	Per humid to humid	Red, sandy laterite, acidic, alluvial, red loamy, terai	2313	18.43, 28.45	274,942 (8.36)	43.83 (5.26)
LGP (15)	West Bengal	Moist sub humid to dry sub humid	Red and yellow alluvial, deltaic, alluvium	1583	21.15, 31.29	69,730 (2.12)	53.17 (6.38)
MGP (61)	Uttar Pradesh, Bihar	Moist sub humid to dry sub humid	Alluvium, calcareous, terai	1045	20.06, 31.54	163,793 (4.98)	150.30 (18.03)
UGP (41)	Uttar Pradesh	Dry sub-humid to semi-arid	Alluvial and terai	849	19.51, 31.63	141,881 (4.32)	89.88 (10.78)
TGP (54)	Chandigarh, Delhi, Haryana, Punjab, Rajasthan	Extreme Arid to Dry Sub-Humid	Alluvial and calcareous	615	17.88, 31.13	147,044 (4.47)	38.72 (4.64)
EPH (68)	Chhattisgarh, Jharkhand, Madhya Pradesh, Maharashtra, Odisha, West Bengal	Moist sub-humid to dry sub-humid	Medium to deep black red and yellow, red sandy and red loamy	1321	20.21, 31.62	378,178 (11.50)	73.09 (8.77)
CPH (56)	Madhya Pradesh, Rajasthan, Uttar Pradesh	Semi-arid to dry sub-humid	Mixed, red and black, red and yellow, deep black and alluvial	896	19.71, 32.40	334,700 (10.18)	65.65 (7.87)
WPH (40)	Madhya Pradesh, Maharashtra	Semi-arid	Medium to deep black, and sandy alluvial	959	20.14, 32.95	332,979 (10.13)	67.08 (8.05)
SPH (51)	Andhra Pradesh, Karnataka, Tamil Nadu	Semi-arid	Medium black, red loamy, red sandy, coastal alluvium, laterite, deltaic alluvium	865	20.97, 31.92	407,014 (12.38)	80.93 (9.71)

Table 1 (continued)

ACZ^	Distribution of states	Climate	Major soils	Annual rainfall	Annual temperature (Min, Max)	Area$ (km^2)	Rural population* (millions)
ECH (42)	Andhra Pradesh, Odisha, Puducherry, Tamil Nadu	Semi-arid to dry sub-humid	deltaic alluvial, coastal alluvial lateritic, red loamy, red sandy	1286	23.05, 32.28	199,900 (6.08)	60.01 (7.20)
WCG (31)	Goa, Karnataka, Kerala, Maharashtra, Tamil Nadu	Dry Sub-Humid to Per Humid	Lateritic, red loamy, coastal alluvium, mixed red and black	2904	21.51, 30.06	118,634 (3.61)	31.41 (3.77)
GPH (29)	Gujarat, Dadra & Nagar Haveli, Daman & Diu	Arid to dry sub-humid	Deep black, coastal alluvium, deltaic alluvium	1051	21.00, 33.52	196,846 (5.99)	34.94 (4.19)
WDR (12)	Rajasthan	Arid to extremely arid	Desert soil, grey brown	388	19.76, 33.04	182,157 (5.54)	22.18 (2.66)

WHR, Western Himalayan Region; *EHR*, Eastern Himalayan Region; *LGP*, Lower Gangetic Plains; *MGP*, Middle Gangetic Plains; *UGP*, Upper Gangetic Plains; *TGP*, Tans-Gangetic Plains; *EPH*, Eastern Plateau & Hills; *CPH*, Central Plateau & Hills; *WPH*, Western Plateau & Hills; *SPH*, Southern Plateau & Hills; *ECH*, East Coast Plains & Hills; *WCG*, West Coast Plains & Ghats; *GPH*, Gujarat Plains & Hills; *WDR*, Western Dry Region

Source: Authors compilation and estimation. NICRA, Singh (2007), Information on area and population were estimated from the district level data, obtained from Census of India (2011); data on rainfall and temperature (1991–2015) was compiled from India Meteorological Department (IMD), Ministry of Earth Sciences, Government of India

^ Number of districts under ACZ

[w] Includes illegal occupied J & K area by Pakistan and China

$ Figures in the parentheses include percentage share of ACZ in the total geographical area of the country

*Figure in the parenthesis include percentage share of ACZ in the total rural population of the country

3 Analytical framework and empirical specifications

Composite indices have emerged as a preferred mechanism for assessing and representing the relative performance of different entities (Becker et al. 2017; Greco et al. 2019) across spatial and temporal scales. Composite indices are formed when individual indicators are encapsulated into a single index, on the basis of an underlying model of the multi-dimensional concept that is being measured (OECD 2008). The index approach has several characteristics that have facilitated its widespread utilization in the planning process and policy communication over the years, which includes the ability (Adger 2000) to consolidate a large volume of information into a manageable format, which is easy to comprehend; (Agrawal and Lemos 2005) to determine the current state of performance for complex and elusive fields that are not directly measurable; (Banerjee 2014) to identify, prioritize, and rank the vulnerable regions or hot-spots; (Barua et al. 2014) to delineate the plausible barriers in the developmental process of a region; and (Becker et al. 2017) to monitor and evaluate the progress of an intervention, for better decision-making. The approach has ‘multiplier effects’ towards regulating a state’s behaviour or activities in response to ranking and evaluation via, several channels such as domestic politics, peer criticism, and transnational pressure (Kelley and Simmons 2015). Thus, it remains an important preliminary tool in strategic policy decision-making. In our assessment, to capture different facets of resilience, multiple indicators were integrated to form different indices, which are not directly observable. In doing so, we followed a five-step procedure in seriatim as described below.

3.1 Theoretical underpinning

The structure of the CRA Index is essentially premised on the concept of resilience which is central to both the vulnerability assessment and in achieving agriculture sustainability. Resilience is inherently a complex and multidimensional agenda. Evidences increasingly suggest that the capacity of a system to flexibly respond and absorb shocks and stresses is embedded within and constrained by its social institutions, physical infrastructure, natural resources, social attributes, economic opportunities, and governance structure that foster or impede the direction of change (Smit and Pilifosova 2001; Brooks and Adger 2004; Engle et al. 2013; Rao et al. 2019). The progress over these domains not only entail a short-term response to weather instability but also tacitly create a fertile ground for climate adaptations while enhancing the agility of rural and farm communities to manage long-term changes in climate. A mix of such factors that aims to enhance resilience is also closely linked with the state of development (Agrawala and Lemos 2015; Singh et al. 2019) and is neither independent nor mutually exclusive. Limits to resilience emerge whenever the actual state of dimensions exceeds/falls short of thresholds/desired level resulting in economic and environmental instability, weak institutional enforcement and infrastructures, less developed social capital, and lack of access to information and technology. This leads to spatial variations in the capacity to deal with contemporary climate-induced risks, which poses significant challenges for agriculture sustainability. Hence, the approach to resilience should identify the importance of recognizing, protecting, and strengthening the inherent capacity of a system to deal with shocks, to facilitate future adaptations, and to function under new climate conditions leading to sustainable improvements of rural well-being. Therefore, in an attempt to quantify the resilience of agriculture, we followed an integrated approach that combines environmental, technological, socio-economic, and infrastructural and institutional factors in determining resilience capacities of ACZs in India. It is to be noted that since CRA is a composite index, variations in the resilience level can be assessed through individual dimension indices as well as through indicators included.

3.2 Indicators and data collection

The credibility of a composite index is largely reflected by the ability of its indicators to explain and justify the phenomena being quantified and measured. Given the multidimensional nature of social and economic goals, it is argued that no indicator completely reflects the actual conditionality, it can only proximate the one. Our portfolio of indicators was built on the basis of three major aspects: dimensionality of resilience, the relevance of indicator in policy stance, and availability and accessibility of data. A total of 26 indicators were selected and segregated into four dimensions which stand at the intersection of agriculture and climate resilience. For the study, information was collected and estimated for 616 districts on the selected indicators. Table 2 presents the description of the selected indicators, sources, and their alliance to resilience.

3.3 First-level weights and aggregation

The district-level values were aggregated at the ACZ level using suitable weights. Here, it is important to understand that the relative significance or contribution of each of the district may vary within an ACZ. Thus, based on the nature of dimension and the indicators included, we employed three different types of weights to estimate ACZ values, which include a proportion of geographical area for environmental indicators, net sown area for technological indicators, and rural population for socio-economic and institutional and infrastructural indicators. Symbolically, district values were converted to ACZ values using Eq. (1),

$$X_{ki} = \sum_{d=1}^{D_k} w_{dk}(S) X_{di(k)} \tag{1}$$

where $X_{di(k)}$ is the value of i^{th} indicator for the d^{th} district within the k^{th} agro-climatic zone. $w_{dk}(S)$ are the weights and S represent the type of weight, i.e. geographical area, net sown area, and rural population.

3.4 Normalization

Rescaling of original indicators into homogenous units is a necessary step (Nardo et al. 2005; Pollesch and Dale 2016) before aggregation. The process of normalization is undertaken to enhance comparability among the variables which are expressed in different units and range and also to smoothen the variability that could arise due to the presence of extreme values (Booysen 2002; Freudenberg 2003; Ebert and Welsch 2004). Several normalization functions are available in the literature with different statistical properties, scaling factors, and assumptions (OECD 2008). We employed the Min-Max method as adopted by UNDP (1990), Hahn et al. (2009), Kumar et al. (2016), and Rao et al. (2016) to standardize indicators into a common range (0, 1) depending on their functional relationship with the dimension. Therefore, Eqs. (2) and (3) were adopted for larger-the-better- and smaller-the-better-type indicators, respectively,

Table 2 Description of indicators and their relevance towards climate resilient agriculture

Dimension	Indicators (FR)	Definition (unit of measurement)	Description	Source (data period)
Environment	Forest coverage (+)	Area of land under forest to the total geographical area (%)	Forest balances the flow of ecosystem services, stocks carbon and has direct bearing on the functioning of various biological and socio-economic systems	Forest Survey of India (2017)
	Stage of ground water extraction (−)	Ratio of existing gross ground water extraction for all uses to the Annual Extractable Ground Water Resources (%)	Indiscriminate use of ground water lowers future ability to extract water for irrigation leads to de-saturation of aquifer zones, decline in water quality due to saline intrusion and extensive use of energy to harness water	Ministry of Water Resources, River Development and Ganga Rejuvenation (2017)
	Waste land (−)	Proportion of area classified as waste land to the total geographical area (%)	Higher proportion of wasteland indicates over-exploitation of land resource, un-utilization of the potential cultivatable area and lower productivity of land making farming risky.	Ministry of Rural Development (2015)
	Rainfall deviation index (−)	Rainfall deviation Index was estimated for *kharif* (June–September) rainfall during the period from 1991 to 2015, $RD_i = \frac{\left(R_i - R_i^{\text{normal}}\right)}{sd(R_i)}$, where R_i^{normal} is the normal rainfall and $sd(R_i)$ is the standard deviation for i^{th} district.	The index depicts an average degree of dryness (rainfall deficit) over the period from 1991 to 2015 during *kharif* season which accounts for more than 80% of the rainfall in the country. Lower rainfall, yields higher value of index.	India Meteorological Department, Ministry of Earth Sciences. (1991–2015)
	Agriculture emission index (−)	Following the methodology of Patra and Babu (2017), Emission Index is estimated as sum of the share of GHG emission by four major subsectors of agriculture. These include livestock; $\text{ESL} = \frac{\text{Livestock/ha}}{\text{maximum livestock/ha}} \times \text{EC}$, Nitrogen consumption; $\text{ESN} = \frac{\text{Nitrogen Consumption/ha}}{\text{maximum nitrogen consumption/ha}} \times \text{EC}$, rice cultivation; $\text{ESR} = \frac{\text{\%area under rice cultivation}}{\text{maximum\%area under rice cultivation}} \times \text{EC}$; and crop residue and burning; $\text{ES} = \frac{\text{\%of gross cropped area}}{\text{maximum\%gross cropped area}} \times \text{EC}$, where EC represents contributions of each subsector, i.e. livestock (0.628); nitrogen consumption (0.174); rice cultivation (0.151); and crop residue and burning (0.047) to the total agricultural emissions.	Higher emission from agriculture, further contribute towards climate change.	19th Livestock Census (2012), MoAFW; Fertilizer association of India (2015); DES--MoAFW (2015)

Table 2 (continued)

Dimension	Indicators (FR)	Definition (unit of measurement)	Description	Source (data period)
Technology	Net sown area (+)	Proportion of net sown area to the geographical area (%)	Larger net sown area indicates higher level of farm income	DES-MoAFW (2015)
	Food grain yield (+)	Production of food grain (cereals and pulses) per unit area of net sown area (tonnes/hectare)	Higher crop yields reflect technological improvements and food sufficiency	DES-MoAFW (2015)
	Cropping intensity (+)	Ratio of gross sown area to net sown area (%)	Cropping intensity indicates the extent of multiple cropping during an agricultural year. Higher intensity reflects more productivity per unit of arable land.	DES-MoAFW (2015)
	Irrigation coverage (+)	Ratio of net irrigated area to net sown area (%)	Higher irrigation coverage reflects less dependency on monsoon and improves productivity.	DES-MoAFW (2014)
	Livestock density (+)	Proportion of number of livestock (cattle, buffalo, sheep, goat, pig, horses & ponies, mules, donkeys, camels, mithun and yak) to the geographical area. (no./sq.km)	Livestock ensures an alternate source of income, employment, energy (residue) and promotes gender equality	19th Livestock Census (2012), MoAFW; Population Census (2011)
	Crop diversification index (+)	To evaluate the extent of crop diversification, Simpson Diversification Index was computed as $1-\sum s_i^2$, where s_i is the proportionate area of the crop i in the total cropped area. Our crop portfolio consisted of Cereals (rice, wheat, sorghum, pearl millet, maize, finger millet, and barley) pulses (chickpea, pigeon pea and minor pulses) oilseeds (groundnut, sesamum, rapeseed and mustard, safflower, castor, linseed, sunflower and soya bean), sugarcane, cotton, fruits and vegetables. (scale of 0–1)	Diversified cropping systems spread production and income risks	DES-MoAFW, (2015)
	Fertilizer usage (+)	Ratio of consumption of fertilizer nutrients (N+P+K) to the gross sown area (kg/hectare)	Application of fertilizer enhances crop yields and reflects adoption of modern technologies	Fertilizer association of India (2017); DES--MoAFW (2014)
Socio-economic	Share of Primary Sector in Gross Domestic Product (−)	Proportion of GDP from Primary sector (agriculture and allied services) to the total GDP of the district (constant prices 2004–2005 series) (%)	Higher share of primary sector indicates lower economic diversification, reflected by underdevelopment of secondary and tertiary sectors	DES of State Governments. (2013)
	Households below poverty line (−)	Number of persons who live below the poverty line to the total population of the area (%)	Poor are more dependent on natural resources and have limited financial assets to cope up with climate induced stresses.	Household Consumption Expenditure, NSSO 68th Round, (2011–2012)

Table 2 (continued)

Dimension	Indicators (FR)	Definition (unit of measurement)	Description	Source (data period)
	Agriculture worker (−)	Proportion of the sum of cultivator and agriculture labourers to the total workers (%)	Higher proportion of agriculture workers reflects higher dependence on agriculture for livelihood	Population Census (2011)
	Literacy rate (+)	Number of literates in the age-group 7 years and above to the total population (%)	Literacy indicate capacity of the population to make appropriate agricultural and livelihood adjustments	Population Census (2011)
	Population density (−)	Number of persons inhabited per square kilometre of the area (no./sq.km)	Higher population density reflects low per capita availability of land	Population Census (2011)
	Area under small and marginal landing holdings (−)	Ratio of area under by small and marginal holdings to the total area (%)	Larger area under small and marginal holdings indicates greater fragmentation of land, reduces application of advanced and resilient technologies, limits ability to diversify cropping system, lowers investment and restrain marketable surplus.	Agriculture Census, MoAFW (2010)
	Agriculture credit disbursed (+)	Ratio of the amount of farm loan (crop loan and term loan) to gross sown area (Rs. /hectare)	Access to credit encourages adoption of modern and climate smart practices and promotion of farm mechanization.	National Bank for Agriculture and Rural Development (2015–16)
Institution and Infrastructure	Villages with pucca road (+)	Proportion of villages with connectivity to all weather roads to the total number of villages (%)	Road connectivity ensures expanded market opportunities, promotes agricultural commercialization and diversification, dispersion of economic development and bridge the link between agriculture and non-agriculture activities	Population Census (2011)
	Access to market (+)	Ratio of number of agriculture markets to the total farm holdings (no./lakh holdings)	Access to markets guarantees remunerative prices for the agri-produce, ensures better income and encourages farm investment.	Agriculture Census, MoAFW, (2015)
	Farmers who availed technical guidance (+)	Number of farmers who accessed technical advice from extension agent, KVK, agricultural university /college, private commercial agents (including drilling contractor), progressive farmer, radio/ TV/ newspaper/ internet, veterinary department, NGO to the total number of farmers (%)	Access to technical advisories or farm extension facilities fasten *ex ante* adaptation by generating awareness and educating farmers to adopt climate smart practices	Situation Assessment Survey, NSSO 70th Round, (2012–2013), Ministry of Statistics and Programme Implementation
	Villages with access to transport communication facilities (+)	Proportion of villages with access to Transport communication which includes bus service, rail facility and navigable waterways to the total villages (%)	Access to transportation is an indicator of overall rural development	Population Census (2011)

Table 2 (continued)

Dimension	Indicators (FR)	Definition (unit of measurement)	Description	Source (data period)
	Electrified villages (+)	Proportion of villages which have access to power supply to the total villages (%)	Connectivity to power is the basic tenet of rural development which ensures adoption of modern practices and farm machinery, reach of farm advisories and digitalisation	Population Census (2011)
	Farmers who took crop insurance (+)	Ratio of number of farmers who took crop insurance to the total farmers (%)	Crop insurance is an important *ex ante* risk management strategy that protects farm households against income variability, encourage investment and reduce debt burden	Situation Assessment Survey, NSSO 70th Round, (2012–2013), Ministry of Statistics and Programme Implementation
	Villages with access to banks (+)	Proportion of villages which have access to commercial and cooperatives banks to the total villages (%)	Access to banks provides access to financial products and facilities	Population Census (2011)

DES, Directorate of Economics & Statistics; *MoAFW*, Ministry of Agriculture and Farmers' Welfare; *NSSO*, National Sample Survey Office; *FR*, functional relationship: positive (+)/negative (−)

$$Z_{ie} = \frac{X_{ie} - \mathrm{Min}(X_{ie})}{\mathrm{Max}(X_i) - \mathrm{Min}(X_i)} \tag{2}$$

$$Z_{ie} = \frac{\mathrm{Max}(X_{ie}) - X_{ie}}{\mathrm{Max}(X_i) - \mathrm{Min}(X_i)} \tag{3}$$

where Z_{ie} is the normalized value and X_{ie} is the observed value of the i^{th} indicator in original units for the e^{th} entity (ACZ or district). Max(X_i) and Min(X_i) are the maximum and minimum values of indicator across the entity, respectively.[1]

3.5 Second-level weights and aggregation

Assignment of weights and aggregation are the two crucial and conceptually perplexing issues that must be carefully addressed, before integration of indicators into the composite index (Nardo et al. 2005; Saltelli 2007). Weights indicate the relative contribution of indicators in influencing the overall performance of a dimension and the possible trade-off between the factors towards the ultimate policy objective (Gan et al. 2017). The selection of weights and its assignment can make a significant change in the final ranking of entities (Becker et al. 2017), where inappropriate weighting could lead to invalid information. A variety of weighting methods are offered by the literature (Booysen 2002; OECD 2008) for constructing composite indices, along with the potential merits and demerits of using a particular approach. These techniques can be broadly classified into equal weighting, normative/ subjective approaches, and positive/statistical approaches (OECD 2008; Gan et al. 2017). In this study, we used the positive approach, wherein the multivariate technique of principal component analysis (PCA) was applied to elicit weights for the indicators. In practice, PCA is a data analytical method used for simplifying the dimensionality of the dataset on the basis of the underlying patterns. The technique has found wide application in the quantification of several developmental and business indices such as environmental degradation index, KOF Index of Globalization, Internal Market Index, Science and Technology, and also used by studies assessing climate vulnerability and well-being (Booysen 2002; Singh et al. 2012; Kumar et al. 2016; Gygli et al. 2019). Under PCA, the dataset is represented by a set of linear combination of the variables where the highest proportion of variation in the sample is accounted by the first component and the remaining variations by the successive components, all uncorrelated with each other (Nicoletti et al. 2000). The major benefits of using PCA are its simplicity, transparency, and ability to reduce double weighting and analyse large datasets (Greyling and Tregenna 2017; Gan et al. 2017).

In our elicitation of weights using PCA, we found that the first principal component was not sufficient enough to explain the variation in the indicators; hence, we included more components that could explain the largest proportion of the variation in the data set. The choice for retaining the principal components was based on the standard thresholds as given by the OECD, (2008) according to which those components are chosen (a) whose eigenvalues are more than one, (b) individually contribute

[1] In our estimation, the minimum and maximum values of an indicator are not pre-selected rather they are data driven values.

to explain more than 10% of the overall variance, and (iii) cumulatively explain more than 60% of the overall variance. Once the components were extracted, the absolute value of the loadings under each component was multiplied with their respective eigenvalues and averaged to generate weights. Finally, the weights obtained for the dimension were scaled to unity.

The next step, in the sequence to formulate the composite index, is aggregation, where indicators are combined together using a suitable algebraic functional form (Becker et al. 2017). Here, we adopted *additive* linear aggregation to estimate our dimension indices and the CRA Index. This is the most widely used aggregation methods (OECD 2008), wherein a linear-weighted average is taken of the normalized set of indicators as follows;

$$Q_{ec} = \frac{\sum_{i=1}^{I} w_i Z_{ie}}{\sum_{i=1}^{I} w_i} \quad (4)$$

where Q_{ec} represents the value of c^{th} dimension for the e^{th} entity, w_i are the weights assigned, and Z_{ie} is the normalized value of the indicators. Once the dimension indices were determined, the CRA index was calculated as;

$$\text{CRA}_e = \frac{\sum_{c=1}^{4} w_c Q_{ec}}{w_c} \quad (5)$$

where CRA_e is the Climate-Resilient Agriculture Index for the e^{th} entity, which is expressed as linear weighted aggregation over the four dimensions of resilience with w_c as the dimension weights. Furthermore, based on their index scores, the 14 ACZs were categorized into three homogenous clusters, depicting *low*, *medium*, and *high* levels of resilience. Furthermore, 616 districts were segregated and mapped (ArcGIS, ESRI 2019) into *five* quantiles. Here, it should be noted that the values of dimension indices and the CRA Index, as obtained from Eqs. 4 and 5, do not reflect the absolute resilience; rather, it only indicates the relative strength of ACZ or district to withstand climatic risks.

4 Results and discussion

4.1 Inter-ACZ climate resilience

4.1.1 Environmental resilience

The relative status of ACZs showed that EPH, EHR, WCG, and CPH exhibit high resilience in terms of environmental parameters (Table 3). It was found that Indo-Gangetic Plains (covering states of Bihar, Uttar Pradesh, Haryana, Punjab, and West Bengal) emitted the highest amount of GHGs from the agricultural sector. Over the period from 1991 to 2015, WCG, LGP, and MGP showed greater deviation in the annual rainfall. The extent of waste land was higher in Himalayan hills and Western Dry Region, while it was lower in Gangetic Plains. Among the zones, EHR (north-eastern states and parts of West Bengal), WCG, and EPH had the highest expanse of forest resources in the country. Environmental resilience was found to be the lowest in the TGP comprising states of Haryana and Punjab and WDR (parts of Rajasthan) primarily due to lesser forest coverage and extensive extraction of groundwater resources.

Table 3 ACZ-wise index values of environmental indicators, ranks, and degree of resilience

ACZ	Forest area	Waste land	Rainfall deviation	Ground water extraction	Emission	Environmental Index	Rank	Degree
EPH	0.131	0.169	0.192	0.180	0.099	0.771	1	High
EHR	0.235	0.143	0.066	0.212	0.104	0.760	2	High
WCG	0.191	0.172	0.000	0.170	0.137	0.670	3	High
CPH	0.069	0.152	0.200	0.134	0.116	0.670	4	High
ECH	0.071	0.174	0.101	0.163	0.084	0.593	5	Medium
WPH	0.033	0.166	0.111	0.145	0.123	0.578	6	Medium
WHR	0.088	0.000	0.208	0.172	0.064	0.532	7	Medium
GPH	0.021	0.167	0.065	0.141	0.106	0.500	8	Medium
UGP	0.010	0.200	0.087	0.135	0.046	0.478	9	Medium
SPH	0.051	0.168	0.031	0.132	0.096	0.476	10	Low
LGP	0.049	0.208	0.013	0.161	0.000	0.430	11	Low
MGP	0.023	0.189	0.020	0.158	0.033	0.424	12	Low
WDR	0.000	0.108	0.119	0.000	0.125	0.352	13	Low
TGP	0.003	0.181	0.030	0.058	0.069	0.340	14	Low
Weights	0.235	0.208	0.208	0.212	0.137			

Agro-climatic zones with index scores more than 0.593, 0.593–0.476, and less than 0.476 are classified as has having high, medium, and low level of environmental resilience

4.1.2 Technological resilience

The spatial distribution in the level of technological resilience reflects high inter-ACZ variation, with the scores ranging from a minimum of 0.189 in WCG to 0.777 in UGP (Table 4). The net sown area was relatively higher in Indo-Gangetic Plains and WPH (covering parts of Maharashtra and Madhya Pradesh). Cropping intensity was higher in LGP, while it was the lowest in SPH and WCG. Irrigation coverage was more than 60% in Indo-Gangetic Plains and CPH. On the other spectrum, access to irrigation was the lowest in the Himalayan Region, and Plateau and Hills regions. The application of fertilizer was relatively lesser in zones such as CPH, EHR, and WDR. Indo-Gangetic Plains followed by ECH and CPH registered higher food grain yields, while WDR and WPH (parts of Maharashtra and Madhya Pradesh) recorded the lowest. Furthermore, higher livestock densities were observed in LGP, UGP, and EHR, while it was lower in WCG and WPH. Overall, it was found that Indo-Gangetic Plains exhibit high technological resilience among the zones.

4.1.3 Socio-economic resilience

The level of socio-economic resilience was found to be the highest in WCG and TGP as shown in Table 5. On an average, the literacy rate was above 60% in all the zones, with a relatively higher proportion of literates found in WCG and lower in MGP. LGP, MGP, and UGP exhibit higher population densities. The prevalence of poverty was more in EPH, MGP, UGP, and CPH. A large fraction of land was owned by small and marginal farmers in ECH, WCG, WHR, and Gangetic Plains except TGP. In nearly all the ACZs, about half of total workers consist of agriculture workers. The regional assessment also indicates that the disbursement of farm credit was more towards WCG and ECH primarily comprising southern states of Kerala, Andhra Pradesh, and Tamil Nadu followed by Trans-Gangetic Plains. On the other hand,

Table 4 ACZ-wise index values of technological indicators, ranks, and degree of resilience

ACZ	Net sown area	Cropping intensity	Irrigation	Fertilizer consumption	Food grain yield	Livestock density	Crop diversification index	Technological Index	Rank	Degree
UGP	0.127	0.080	0.160	0.132	0.085	0.100	0.092	0.777	1	High
TGP	0.147	0.107	0.137	0.118	0.157	0.041	0.069	0.774	2	High
LGP	0.110	0.151	0.092	0.114	0.110	0.135	0.034	0.745	3	High
MGP	0.110	0.068	0.112	0.133	0.087	0.106	0.076	0.691	4	High
CPH	0.080	0.068	0.110	0.045	0.073	0.034	0.113	0.522	5	Medium
ECH	0.057	0.022	0.089	0.118	0.075	0.049	0.066	0.477	6	Medium
GPH	0.074	0.029	0.071	0.094	0.061	0.043	0.092	0.464	7	Medium
SPH	0.071	0.000	0.045	0.096	0.061	0.050	0.118	0.441	8	Medium
WPH	0.107	0.049	0.030	0.078	0.024	0.020	0.113	0.420	9	Medium
WHR	0.000	0.081	0.042	0.071	0.064	0.050	0.076	0.385	10	Low
EHR	0.042	0.064	0.000	0.029	0.071	0.068	0.011	0.286	11	Low
WDR	0.091	0.015	0.022	0.000	0.000	0.047	0.091	0.266	12	Low
EPH	0.031	0.008	0.021	0.044	0.062	0.031	0.000	0.195	13	Low
WCG	0.052	0.006	0.010	0.062	0.048	0.000	0.011	0.189	14	Low
Weights	0.147	0.151	0.160	0.133	0.157	0.135	0.118			

Agro-climatic zones with index scores more than 0.522, 0.522–0.385, and less than 0.385 are classified as has having high, medium, and low level of technological resilience

Table 5 ACZ-wise index values of socio-economic indicators, ranks, and degree of resilience

ACZ	Literacy	Population density	Poverty	Credit disbursed	Primary GDP	Small & marginal holdings	Agriculture workers	Socio-economic Index	Rank	Degree
WCG	0.152	0.055	0.156	0.163	0.143	0.035	0.166	0.870	1	High
TGP	0.061	0.076	0.166	0.098	0.064	0.114	0.096	0.674	2	High
WDR	0.013	0.108	0.164	0.033	0.096	0.113	0.042	0.568	3	High
ECH	0.067	0.077	0.122	0.129	0.083	0.031	0.054	0.563	4	High
WHR	0.058	0.097	0.163	0.053	0.082	0.031	0.065	0.549	5	Medium
GPH	0.072	0.088	0.107	0.039	0.098	0.086	0.052	0.541	6	Medium
SPH	0.031	0.101	0.134	0.081	0.053	0.057	0.037	0.494	7	Medium
WPH	0.079	0.101	0.106	0.033	0.046	0.070	0.008	0.443	8	Medium
EHR	0.058	0.083	0.062	0.012	0.040	0.057	0.071	0.382	9	Medium
CPH	0.020	0.104	0.061	0.028	0.000	0.079	0.004	0.296	10	Low
LGP	0.068	0.000	0.099	0.031	0.016	0.000	0.079	0.293	11	Low
EPH	0.016	0.100	0.000	0.026	0.051	0.053	0.004	0.250	12	Low
UGP	0.016	0.033	0.056	0.051	0.009	0.034	0.044	0.242	13	Low
MGP	0.000	0.008	0.039	0.043	0.074	0.014	0.000	0.179	14	Low
Weights	0.152	0.108	0.166	0.151	0.143	0.114	0.166			

Agro-climatic zones with index scores more than 0.549, 0.549–0.296, and less than 0.296 are classified as has having high, medium, and low level of socio-economic resilience

EHR covering all north-eastern states and some parts of West Bengal had the lowest access to farm credit.

4.1.4 Institutional and infrastructural resilience

WCG, GPH, SPH, and TGP were grouped as zones with high-level resilience as measured by institutional and infrastructural indicators (Table 6). It was found that technical advices to the farmers were more accessible in SPH and TGP, while it was the least in WDR, CPH, and MGP. In the Himalayan regions, most parts of the Indo-Gangetic region, and WCG, a very low proportion of the farmers availed crop insurance. Among the zones, TGP had the largest access to markets for farm produce. In most of the ACZs, more than 90% of the villages were electrified, though still improvement in electrification is required in MGP, EPH, and CPH. Connectivity to roads was inadequate in zones such as WDR, EHR, and LGP. The penetration of banks in villages was relatively better in WCG while it was insufficient in EPH and EHR.

4.1.5 Composite CRA Index

Based on the relative performance of ACZs across different dimensions of resilience, the CRA index was prepared as shown in Table 7. The score of the CRA Index varies from 0.361 to 0.624. In the order of ranking, high climate resilience was found in WCG, TGP, GPH, and ECH. On the other hand, MGP (Bihar and parts of Uttar Pradesh) and EPH (comprising Chhattisgarh, Jharkhand, Odisha, and parts of other states) registered the lowest resilience capacities. In addition zones namely, WDR, EHR, and UGP, were also categorized under a low degree of resilience to climatic risks.

4.2 Intra-ACZ variation: scouting district resilience

For assessing *intra*-ACZ variation as reflected by district resilience, we used the same weightage across indicators and dimensions as applied in examining the *inter*-ACZ variation. Most of the districts falling within the Gangetic Plains region and WDR had *very low* level of environmental resilience (Fig. 1). Among the districts lying within EHR, about 67% had very high resilience in terms of environmental indicators. Of the districts with *very low* to *low* level of technological resilience, about 54% were concentrated in the EHR and EPH. Districts lying in the SPH had medium level of socio-economic resilience. Moreover, in WCG, *Raigarh*, *Sindhudurg*, *Thane*, *Dakshina Kannada*, *Kodagu*, *Udupi*, *Theni*, *Kanniyakumari*, and all districts within Goa and Kerala had *very high* socio-economic resilience. It can be seen that districts in southern India particularly districts of Kerala state and those falling within GPH and TGP showed better institutional and infrastructural foundation to deal with climatic aberrations. Overall, in the case of the CRA Index, about 40% of total districts were placed at the bottom of the resilience pyramid. Among such districts, nearly 20% had *very low* level of resilience primarily falling under north-eastern states forming part of EHR, EPH with maximum concentration from the state of Jharkhand and Chhattisgarh, and MGP particularly from Bihar state. Besides, *very low* level of resilience was also found in districts which include *Barmer*, *Jaisalmer*, *Jodhpur*, *Nagaur*, and *Rajsamand* in WDR; *Kargil*, *Doda*, *Kishtwar*, *Reasi*, *Bageshwar*, *Chamoli*, *Pithoragarh*, *Rudraprayag*, and *Uttarkashi* in WHR; *Dungarpur*,

Table 6 ACZ-wise index values of institutional and infrastructural indicators, ranks, and degree of resilience

ACZ	Access to technical advice	lCrop insurance	Access to roads	Electrified villages	Access to transportation	Access to markets	Access to banking facilities	Institutional and Infrastructural Index	Rank	Degree
WCG	0.162	0.010	0.140	0.134	0.168	0.033	0.135	0.783	1	High
GPH	0.155	0.078	0.138	0.135	0.179	0.032	0.017	0.733	2	High
SPH	0.176	0.061	0.127	0.134	0.144	0.027	0.021	0.691	3	High
TGP	0.143	0.003	0.117	0.132	0.124	0.118	0.028	0.665	4	High
WPH	0.094	0.066	0.105	0.130	0.119	0.064	0.021	0.599	5	Medium
ECH	0.089	0.071	0.107	0.115	0.089	0.031	0.019	0.521	6	Medium
WHR	0.115	0.004	0.053	0.132	0.054	0.046	0.008	0.411	7	Medium
LGP	0.107	0.040	0.023	0.135	0.009	0.072	0.011	0.396	8	Medium
EPH	0.084	0.068	0.092	0.011	0.004	0.079	0.000	0.337	9	Medium
CPH	0.043	0.117	0.028	0.112	0.000	0.026	0.006	0.333	10	Low
WDR	0.000	0.098	0.000	0.121	0.068	0.003	0.030	0.319	11	Low
UGP	0.071	0.001	0.088	0.111	0.005	0.013	0.004	0.293	12	Low
EHR	0.072	0.000	0.012	0.078	0.042	0.074	0.002	0.280	13	Low
MGP	0.050	0.008	0.074	0.000	0.009	0.000	0.010	0.151	14	Low
Weights	0.176	0.117	0.140	0.135	0.179	0.118	0.135			

Agro-climatic zones with index scores more than 0.599, 0.599–0.333, and less than 0.333 are classified as having high, medium and low level of institutional and infrastructural resilience

Table 7 ACZ-wise CRA Index, ranks, and degree of resilience

ACZ	Environmental Index	Technological Index	Socio-economic Index	Institutional and Infrastructural Index	Climate Resilient Agriculture Index	Rank	Degree
WCG	0.152	0.050	0.223	0.200	0.624	1	High
TGP	0.077	0.203	0.173	0.170	0.622	2	High
GPH	0.113	0.122	0.139	0.187	0.561	3	High
ECH	0.134	0.125	0.144	0.133	0.536	4	High
SPH	0.108	0.115	0.127	0.176	0.526	5	Medium
WPH	0.131	0.110	0.113	0.153	0.507	6	Medium
LGP	0.098	0.195	0.075	0.101	0.469	7	Medium
WHR	0.121	0.101	0.141	0.105	0.467	8	Medium
CPH	0.152	0.137	0.076	0.085	0.449	9	Medium
UGP	0.108	0.203	0.062	0.075	0.449	10	Low
EHR	0.172	0.075	0.098	0.072	0.417	11	Low
WDR	0.080	0.070	0.146	0.082	0.377	12	Low
EPH	0.175	0.051	0.064	0.086	0.376	13	Low
MGP	0.096	0.181	0.046	0.039	0.361	14	Low
Weights	0.227	0.262	0.256	0.255			

Agro-climatic zones with index scores more than 0.526, 0.526–0.448, and less than 0.448 are classified as having high, medium, and low level of resilience

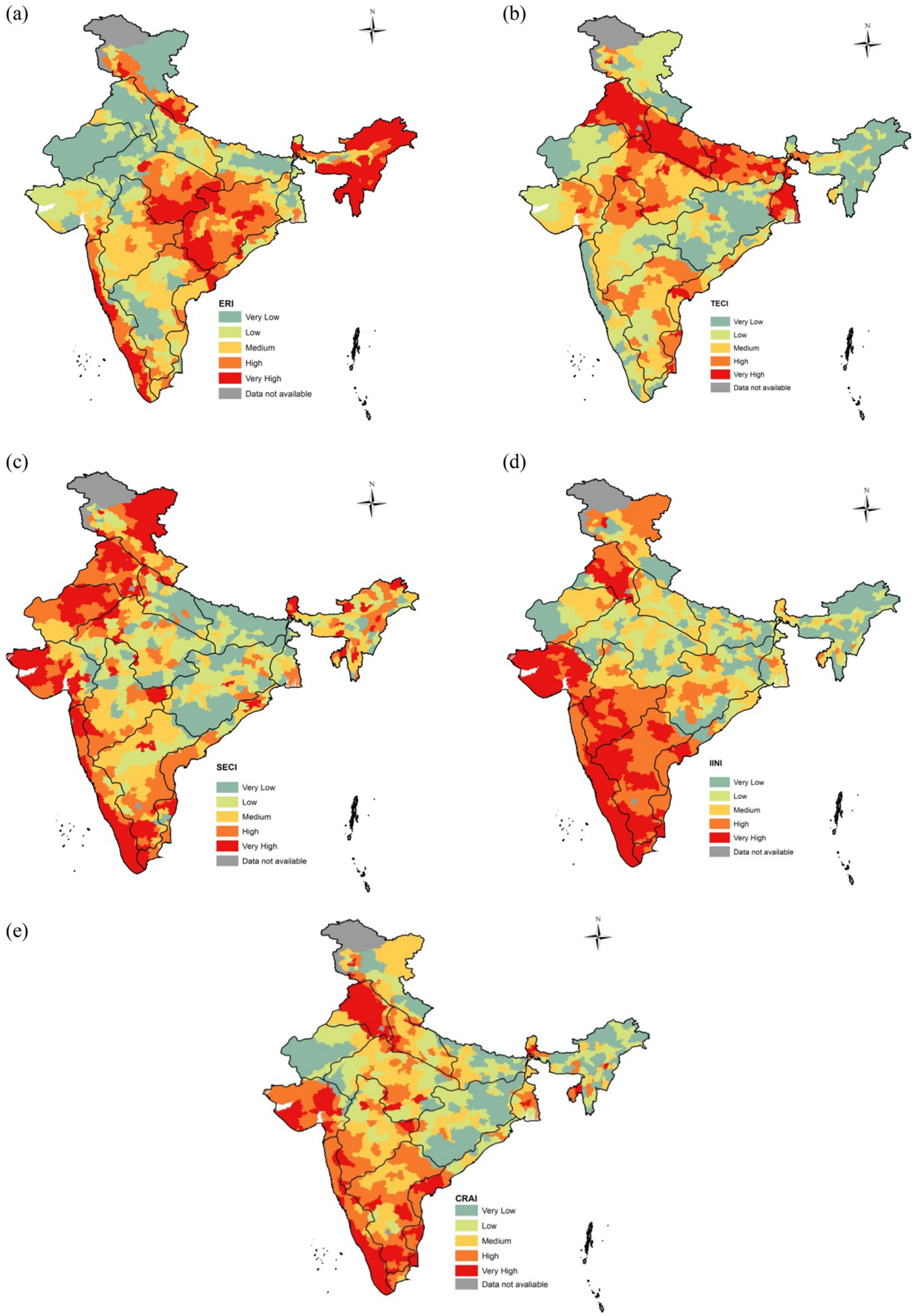

Fig. 1 Maps (not to be scaled, for illustration only) showing intra-ACZ variation in the level of resilience based on (a) Environmental Index, (b) Technological Index, (c) Socio-economic Index, (d) Institutional and Infrastructural Index, and (e) Climate-Resilient Agriculture Index (ACZ demarcation is shown with black boundary line)

Sirohi, *Udaipur*, *Alirajpur*, *Jhabua*, and *Rewa* in CPH; *Ratlam* from WPH; and *Baudh*, *Gajapati*, *Kandhamal*, *Nayagarh*, and *Rayagada* in ECH. On the other hand, most of the districts in TGP and WCG showed *very high* resilience to manage climate risks (List of districts showing *very low* and *very high* level of resilience measured in terms of overall CRA Index is shown in Appendix Table 8).

5 Discussion and conclusion

Building resilience of agro-ecosystem to climate change is the most critical and urgent bottom-line requirement for achieving sustainable development and well-being. There has been an emerging shift in developmental policy to recognize and mainstream changes, instability, and capacity within social-ecological systems to deal with climatic uncertainty and to manage risks unleashed by such changes. In recognition of the complex and dynamic link formed between environment and social systems and spatial differentials in impacts and ability, an integrated or hybrid approach should be adopted that focuses on building strategies along the regional/local level to enhance the resilience of the agricultural system. The intrinsic structure and potential of the resilience approach to capture multiple dimensions and direct transition to a new state is important particularly for developing nations where the existing response space and capacity is not desirable to absorb climate shocks and stresses. Moreover, evaluation of resilience begins a way of interactions, feedbacks, and transformation to build developmental trajectories for achieving goals of sustainable development.

In India, vulnerability to climatic aberrations and extremes is more conspicuous in the case of the agriculture sector. Such impending threat over the agriculture and agriculture-based livelihoods necessitates resilience assessment across homogenous regions. Therefore, this study made an attempt to assess inter- and intra-ACZ levels of resilience in India. The analysis reveals how resilience is influenced by multiple factors and is spatially differentiated in the country. In particular, our results showed that resilience was the highest in WCG, TGP, and GPH. Overall, we observed that the southern states majorly forming parts of WCG, ECH, and SPH, relatively, had a greater strength to respond to the climatic-related risks. On the other hand, MGP and EPH recorded the least resilience to manage climatic stresses. Even within the ACZs, wide variations were observed among the districts. The analysis indicates that special policy attention must be given to the north-eastern region, western dry region, and eastern parts of the country.

To reduce spatial disparities in resilience capacities, we reinforce the importance of regional planning in the course of climate change, the growing need to develop sustainable production systems and livelihood perspective. In zones with injudicious extraction of groundwater, a comprehensive water resource management policy must be developed along with rationalization of subsidies. For reducing agriculture emissions, mitigation alternatives should be researched with appropriate management of agri-activities and operations. Under climate change, enhancing equitable accessibility to irrigation along with suitable location-based cropping pattern is crucial for the optimization of returns, water use efficiency, and value creation. Moreover, to sustainably improve productivity, penetration, and adoption of micro-irrigation systems, such as drip and sprinklers, it must be evolved with the appropriate building of farm capacity. Both agriculture and livelihood diversification has been emphasized as a key response strategy to manage future risks and uncertainty associated with climate change. In particular, diversifying to agro-forestry in ecologically fragile regions, increasing thrust on crop diversification and strengthening crop-livestock system promote farm resilience. Besides, opportunities for non-farm activities can potentially reduce vulnerability arising from lower income and consumption. Imparting awareness via effective scientific extension services, weather, and seasonal forecasts can help farmers adapt to the foreseeable climatic aberrations. Diffusion of crop insurance and development of innovative region-specific weather insurance products serve as a major risk management mechanism. Furthermore, strengthening credit support to the zones with limited access to finance especially in the eastern region of the country could expand both the ex ante and ex post climate response space. Policy interventions must bridge institutional inefficiencies at the grass-roots level to facilitate learning and more suitable adaptation choices. In addition, mainstreaming climate change in the developmental planning will refine the policy interventions and programmatic objectives that will entail optimal adaptation and improve prospects for poverty reduction for diverse agro-climatic regions. This needs to be supported with a proactive approach towards developing multi-stakeholder partnership, investments, and reorientation of research agenda towards developing farm practices and technologies suited to agro-ecology for climate-resilient pathways.

There remain some limitations in our capacity to assess the conundrum of resilience level across agro-climatic zones. First, due to the limitation of data, there was an element of subjectivity involved in the selection of indicators. Second, weights and aggregation method adopted for assessment was to the best of our understanding. Third, the resilience of the ACZs or districts is subject to the indicators included under the dimensions. Fourth, the determination of specific factors that constraints and develop resilience of a region is an important activity for future context-specific researches. Notwithstanding, the aforesaid limitations have in no way drifted the essence and purpose of the study.

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Data availability Data will be available on request.

Compliance with ethical standards

Conflict of interest This is to certify that the reported work in the paper entitled '*Synergies and Trade-offs for Climate Resilient Agriculture in India: An Agro-Climatic Zone Assessment*' submitted for publication is an original one and has not been submitted for publication elsewhere. I/we further certify that proper citations to the previously reported work have been given and no data/tables/figure have been quoted verbatim from other publications without given due acknowledgment and without the permission of the author(s).

Code availability Not applicable

Appendix

Table 8 List of districts showing *very low* and *very high* climate resilience in different agro-climatic zones of India

ACZ	State	Districts (*very low* level of resilience)	Districts (*very high* level of resilience)
WHR	Jammu and Kashmir	Kargil, Doda, Kishtwar, Reasi	Pulwama, Kulgam, Jammu
	Himachal Pradesh		Una
	Uttarakhand	Bageshwar, Chamoli, Pithoragarh, Rudraprayag, Uttarkashi	Udham Singh Nagar
EHR	Arunachal Pradesh	Anjaw, Dibang Valley, East Kameng, Kurung Kumey, Lohit, Lower Subansiri, Tawang, Tirap, Upper Subansir, West Siang	
	Assam	Baksa, Barpeta, Bongaigaon, Chirang, Dhemaji, Dhubri, Dibrugarh, Dima Hasao, Goalpara, Golaghat, Karbi Anglong, Kokrajhar, Marigaon	
	Manipur	Churachandpur. Senapati, Ukhrul	
	Meghalaya	West Khasi Hills	
	Mizoram	Lawngtlai, Mamit, Saiha	Kohima
	Nagaland	Mon, Tuensang, Zunheboto	
	Sikkim		East District
	Tripura		Dhalai, North Tripura
	West Bengal		Darjeeling
LGP	West Bengal		Hooghly
MGP	Bihar	Arwal, Banka, Darbhanga, Gaya, Gopalganj, Jamui, Katihar, Kishanganj, Lakhisarai, Madhepura, Madhubani, Pashchim Champaran, Purba Champaran, Purnia, Saran, Sheohar, Sitamarhi, Siwan, Supaul	
	Uttar Pradesh	Ballia, Balrampur, Basti, Shrawasti, Siddharthnagar	
UGP	Uttar Pradesh	Bahraich	Agra, Aligarh, Gautam Buddha Nagar, Ghaziabad, Mahamaya Nagar (Hathras)
TGP	Haryana		Kaithal, Kurukshetra, Panchkula, Yamunanagar, Sonipat, Ambala, Panipat, Karnal, Sirsa, Fatehabad, Jind, Jhajjar, Hisar, Gurgaon, Bhiwani, Mewat, Mahendragarh, Rewari, Palwal, Faridabad, Rohtak
	Punjab		Amritsar, Barnala, Bathinda, Faridkot, Fatehgarh Sahib, Firozpur, Gurdaspur, Hoshiarpur, Jalandhar, Kapurthala, Ludhiana, Mansa, Moga, Muktsar, Patiala, Rupnagar, Sahibzada Ajit Singh Nagar, Sangrur, Shahid Bhagat Singh Nagar, Tarn Taran

Table 8 (continued)

ACZ	State	Districts (*very low* level of resilience)	Districts (*very high* level of resilience)
EPH	Chhattisgarh	Uttar Bastar Kanker, Narayanpur, Dakshin Bastar Dantewada, Bijapur, Jashpur, Korba, Bastar	
	Jharkhand	Chatra, Deoghar, Dhanbad, Dumka, Garhwa, Giridih, Godda, Gumla, Jamtara, Khunti, Latehar, Lohardaga, Pakaur, Palamu, Pashchimi Singhbhum, Purbi Singhbhum, Ranchi, Sahibganj, Seraikela-Kharsawan, Simdega	
	Madhya Pradesh	Dindori, Mandla	
	Odisha	Balangir, Debagarh, Kalahandi, Kendujhar, Koraput, Mayurbhanj, Malkangiri, Nabarangapur, Subarnapur (Sonapur), Nuapada	
	West Bengal	Purulia	
CPH	Rajasthan	Dungarpur, Sirohi, Udaipur	
	Madhya Pradesh	Alirajpur, Jhabua, Rewa	Bhopal, Hoshangabad, Jabalpur
WPH	Madhya Pradesh	Ratlam	Indore
	Maharashtra		Kolhapur, Nagpur, Pune
SPH	Andhra Pradesh		YSR, Kadapa (Cuddapah)
	Karnataka		Bellary, Dharwad
	Tamil Nadu		Coimbatore, Erode, Karur, Namakkal, The Nilgiris, Salem, Tiruchirappalli, Tiruppur
ECH	Andhra Pradesh		Guntur, Krishna, West Godavari
	Tamil Nadu		Ariyalur, Kancheepuram, Madurai, Nagapattinam, Thanjavur, Tirunelveli, Thiruvallur, Thiruvarur, Vellore
	Puducherry UT		Karaikal, Puducherry
	Odisha	Baudh, Gajapati, Kandhamal, Nayagarh, Rayagada	
WCG	Karnataka		Dakshina Kannada, Kodagu, Udupi
	Tamil Nadu		Theni, Kanniyakumari
	Goa		North Goa, South Goa
	Kerala		Alappuzha, Ernakulam, Idukki, Kannur, Kasaragod, Kollam, Kottayam, Kozhikode, Malappuram, Palakkad, Pathanamthitta, Thiruvananthapuram, Thrissur, Wayanad
GPH	Gujarat		Mahesana, Sabar Kantha, Porbandar, Junagadh, Anand, Kheda, Vadodara, Gandhinagar, Ahmadabad, Rajkot, Jamnagar, Navsari, Surat
WDR	Rajasthan	Barmer, Jaisalmer, Jodhpur, Nagaur, Rajsamand	

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