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Agro-ecosystem based sustainability indicators for climate resilient agriculture in India: A conceptual framework

Ch. Srinivasa Rao[a], K. Kareemulla[a], P. Krishnan[a,*], G.R.K. Murthy[a], P. Ramesh[a], P.S. Ananthan[b], P.K. Joshi[c]

[a] ICAR-National Academy of Agricultural Research Management (NAARM), Rajendra Nagar, Hyderabad 500 030, Telangana, India
[b] ICAR-Central Institute of Fisheries Education (CIFE), Versova, Mumbai 400 061, Maharashtra, India
[c] International Food Policy Research Institute (IFPRI), IFPRI South Asia Office, NASC Complex, Pusa, New Delhi 110 012, India

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ABSTRACT

The impending threats of changing climate have been well documented across sectors. The climate risks are best addressed through increasing adaptive capacity and building resilience. Ever since the global call during the Rio Summit in 1992 for establishing sustainability indicators across sectors, there have been several studies across the world on developing indicators for sustainability, vulnerability and climate resilience. Agriculture, the most vulnerable system to changing climate, depends on the resilience of both social and ecological systems. This paper focuses on integrating the variability of climate into the agricultural sustainability measurement with a broad base of indicators and bringing in the localized factors for representing the agroecosystem specificities. The paper also aims at identifying indicators for measuring climate resilient agriculture in Indian sub-continent and developing a conceptual framework for profiling the spatial resilience across various agro-ecosystems for appropriate location-specific policy interventions. In the current study 1209 indicators used in various research studies were screened, grouped for similarity and purpose and classified based on the various dimensions *viz.*, social, economic, ecological, etc. After a critical review based on their appropriateness as a measurable indicator, extent of overlap, relevance in Indian context and possible data availability, 41 indicators were shortlisted for validation through a comprehensive structured online survey among subject matter specialists (n = 225). The responses from the experts (n = 36) were analysed using weighted sum model (WSM) and analytic hierarchy process (AHP). The study identifies a list of 30 sustainability indicators for climate resilient agriculture in India, that are particularly suitable for different agro-ecosystems of the sub-continent. The authors advocate an action-oriented model called Climate Risk Management Package for Agriculture (CRiMPA) to aid in planning spatial/agro-ecosystem specific interventions, which in turn could strengthen the National Action Plan for Climate Change (NAPCC) of Government of India.

1. Introduction

Warming of climate is unequivocal and is more pronounced since 1950s (IPCC, 2013). Climate change has both direct and indirect effects on agricultural productivity including changing rainfall patterns, drought, flooding and the geographical redistribution of pests and diseases (IPCC, 2013). Climate change hampers the food production systems and thereby the livelihoods and food security of billions of people across the globe. Marginalized populations in developing economies will suffer from climate change impacts disproportionately in comparison with wealthier, industrial countries (IPCC, 2007a,b). Coupled with these imminent threats, these countries lack the resources to prepare for and cope with environmental risks. Further agriculture sector is most vulnerable to climate change due to its high dependence on weather and because people involved in agriculture tend to be poorer compared with their urban counterparts.

Climate change projections for Indian sub-continent indicate an increase in temperature by at least 3.3 °C by 2080s relative to pre-industrial times (IPCC, 2007a,b). There are already evidences of negative impacts on yields of wheat and paddy in some parts of India due to increased temperature, water stress and reduction in number of rainy days. Under medium-term (2020–2039) climate change scenario, crop yield is projected to reduce by 4.5 to 9%, depending on the magnitude and distribution of warming (NICRA, 2013). In view of the climate change implications, enhancing and sustaining agricultural productivity, is critical for ensuring food and nutritional security of future

* Corresponding author.
E-mail address: krishnanars@yahoo.com (P. Krishnan).

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Table 1
Basic Attributes of Sustainable Agricultural Systems.

No	Attributes
1	Use of local and improved crop varieties and livestock breeds for enhancing genetic diversity and adaptation to biotic and environmental changes
2	Avoid the unnecessary use of agrochemicals and other technologies that adversely impact the environment and human health like heavy machineries, transgenic crops,
3	Efficient use of resources (nutrients, water, energy, etc.), reduced use of non-renewable energy and reduced farmer dependence on external inputs
4	Harness agro-ecological principles and processes such as nutrient cycling, biological nitrogen fixation, allelopathy, biological control through diversified farming systems and functional biodiversity
5	Productive use of human capital through traditional and modern scientific knowledge and skills to innovate and the use of social capital. Reduce the ecological footprint of production, distribution and consumption practices, thereby minimizing GHG emissions and soil and water pollution
6	Promoting practices that enhance clean water availability, carbon sequestration, conservation of biodiversity, soil and water conservation, etc.
7	Enhanced adaptive capacity based on the premise that the key to coping with rapid and unforeseeable change is to strengthen the ability to adequately respond to change to sustain a balance between long-term adaptability and short-term efficiency
8	Strengthen adaptive capacity and resilience of the farming system by maintaining agroecosystem diversity, which not only allows various responses to change, but also ensures key functions on the farm
9	Recognition and dynamic conservation of agricultural heritage systems that allows social cohesion and a sense of pride and promote a sense of belonging and reduce migration

(Source: Koohafkan et al., 2012).

generations in India (Srinivasa Rao et al., 2017). Climate risks are best addressed through increasing adaptive capacity and building resilience that reduce adverse impacts of climate change (FAO, 2013).

Ever since the Brundtland definition of sustainable development (WCED, 1987), the concept of agricultural sustainability has gradually evolved (Schaller, 1993). Lewandowski et al. (1999) defined sustainable agriculture as the management and utilization of the agricultural ecosystem in a way that maintains its biological diversity, productivity, regeneration capacity, vitality, and ability to function, so that it can fulfil – today and in the future – significant ecological, economic and social functions at the local, national and global levels and does not harm other ecosystems. Koohafkan et al. (2012) derived criteria from the extensive literature on agro-ecology and sustainable agriculture suggested a series of attributes (Table 1) that any agricultural system should exhibit in order to be considered sustainable.

UNEP (2001) considers vulnerability as an aggregate measure of human welfare that integrates environmental, social, economic and political exposure to a range of harmful perturbations. IPCC (2001) defines vulnerability as the extent to which a natural or social system is susceptible to sustaining damage from climate change and the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including variability and extremes. Thus, vulnerability is a function of the character, magnitude and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity. In nutshell, vulnerability could be visualized as the inverse of sustainability.

Resilience is the ability of the system to bounce back and essentially involves judicious and improved management of natural resources, land, water, soil, and genetic resources through adoption of best practices (Srinivasa Rao et al., 2016). The concept of resilience is central to an understanding of the vulnerability of agriculture sector to climate change. Agriculture depends on the resilience of both social and ecological systems. In social systems, resilience pertains to households, communities, and regions, the degree of which depends both on the assets and knowledge the farmers can mobilize and the services provided by governments and institutions. Besides this, agriculture is a source of livelihood for billions of people—particularly poor people—the income from which directly contributes to society's resilience. As a result, implementing measures to build agricultural resilience needs an understanding of strategies to reduce vulnerability without compromising on income generation and reducing poverty (ADB, 2009). Climate resilient agriculture (CRA) encompasses the incorporation of adaptation and resilient practices in agriculture, which increases the capacity of the system to respond to various climate-related disturbances by resisting damage and ensures quick recovery.

The concept of 'agricultural sustainability' is both ambitious and ambiguous, as diverse factors influence its attainment and assessment. It has different components, attributes, and indicators at different scales that encompasses complex interactions among the environment, economics, and society (Lopez-Ridaura et al., 2005; Van Calker et al., 2006). Progress in designing indicators of sustainability has come from initiatives across the institutional spectrum (Dahl, 2012). At the highest level of intergovernmental organizations, the United Nations initiated the work on sustainable development indicators for the Commission on Sustainable Development after the Rio Earth Summit in 1992 and later several agencies followed suit (Hak et al., 2007). There is a consensus that an operational definition (quantitatively measured) of agricultural sustainability through indicators and indices is a prerequisite for the adequate design, implementation and monitoring of agricultural policies aimed at a more sustainable farming sector. The development of transparent composite indicators offers an opportunity to identify the aspects of agricultural sustainability that are relevant in practice (Gomez and Gabriel, 2010).

In view of the above context and the need for specific set of indicators for measuring the agricultural sustainability, this paper focuses on integrating the variability of climate into the agricultural sustainability measurement with a broad base of indicators and bringing in the localized factors for representing the agroecosystem specificities. In this study, the authors reviewed relevant studies in order to identify indicators for measuring climate resilient agriculture in Indian sub-continent, with special reference to the different agro-ecosystems. The indicators were assessed for their measurability, uniqueness and data availability and finalized through expert survey. The authors also provide a conceptual framework for planning interventions towards building climate resilient agriculture in the Indian sub-continent.

2. Methodology

2.1. Identification and screening of indicators

The indicators for climate resilient agriculture were collated through extensive review of published literature in peer reviewed journals. The literature were screened with the help of Mendeley Desktop Version (http://www.mendeley.com/download-mendeley-desktop) using various combination of key words *viz.,* climate resilient agriculture, sustainability indicators for agriculture, agricultural vulnerability indicators, agro-ecosystem based sustainability and ecological indicators for sustainable agriculture. Each of the papers were reviewed and those with clear and unambiguous indicators for measuring climate resilient agriculture in different parts of the world were shortlisted. The shortlisted papers were classified based on their primary objective of the study ie., use of indicators for climate resilient agriculture, vulnerability of agriculture to climate change, agro-ecosystem based sustainability and sustainable agriculture.

The indicators used in these studies were classified based on the dimension they have been considered to represent by various authors *viz.,* social, economic, ecological, cultural, demographic, governance, legal, institutional, etc. The closely related indicators were grouped based on individual examination of the context of the study.

Three types of procedure proposed by modelers for validation (Mayer and Butler, 1993) namely the visual procedure, the statistical procedure and the third based on the judgment of experts were employed by this study. Visual procedure relied primarily on authors' expertise and insights from literature review, appropriateness as a measurable indicator, contextual usage, extent of overlap, relevance in Indian context, and possible data availability. Prior to seeking cross section of opinions through online survey from a broad spectrum of experts, a brainstorming was held with statistician and economists to narrow down the number of indicators from the compiled list of global indicators. The step-by-step funnel approach adopted by authors for indicator selection as part of visual procedure is provided in Supplementary data 1. The references screened and the indicators culled and classified in the study are provided as Supplementary data 2 and Supplementary data 3, respectively.

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecolind.2018.06.038.

2.2. Expert validation of indicators

The shortlisted indicators were subjected to an online expert survey wherein about 225 experts, with demonstrated experience and expertise in climate resilient agriculture and assessment of agricultural vulnerability were involved. A structured online survey was administered with the help of Survey Monkey Software.

The survey was intended to capture the appropriateness of each of the shortlisted indicators for measuring climate resilient agriculture in India. The appropriateness of each indicator was measured on a 3 point Likert scale (3 – Appropriate; 2 – Not Sure/Can't Decide; 1 – Not Appropriate). The indicators were grouped under four broad themes *viz.,* ecological, social, economic and institutional dimensions, which they most appropriately represented. The survey captured the perception of the respondents on the relative importance of the indicators for climate resilient agriculture. The relative weightage for each appropriate indicator was measured on a 5 point scale.

2.3. Statistical analysis of expert responses

The expert opinion was analysed using two statistical methods ie., weighted sum model (WSM) and analytic hierarchy process (AHP).

2.3.1. Weighted sum model (WSM)

In decision theory, WSM is the widely used multi-criteria decision making method for evaluating a number of alternatives in terms of a number of decision criteria, especially when all criteria are measured on cardinal scales and weights are assigned per criterion (Hwang and Yoon, 1981). The criterion scores were normalized and multiplied by their respective weights. The products were called the weighted scores, which were summed up over all criteria yielding a total weighted score or priority score for each of the indicators Eq. (1) (Smith and Theberge, 1987).

$$A_i^{\text{WAM - score}} = \sum_{j=1}^{n} w_j a_{ij}, \quad \text{for } i = 1, 2, 3, \dots, m. \tag{1}$$

where, w_j denotes the relative weight of importance of the criterion (indicator) C_j and a_{ij} is the performance value of alternative A_i when it is evaluated in terms of criterion C_j.

2.3.2. Analytic hierarchy process (AHP)

Analytic Hierarchy Process (AHP), a robust multi-criteria decision technique proposed in the area of Operations Research (Saaty, 1990), was carried out following Ramasubramanian et al., (2014). An AHP tree was built by development of a hierarchy of "decision criteria" leading to "alternative courses of actions/factors". The AHP algorithm composed of determining the relative weights of the "decision criteria" and also determining the relative rankings (priorities) of "alternatives". Qualitative information using informed judgments were utilized to derive these weights and rankings, and prioritization of the alternatives was done based on the rankings obtained.

Based on the results obtained, in the first level of hierarchy, indicators with final weights of 3 and above were retained for inclusion in the composite *Index of Climate Resilient Agriculture (ICRA)*. The respective weights indicate their proportionate weightage in building the four intermediate dimensions or sub-indices that form the second level of hierarchy *viz.,* social, economic, ecological and institutional, for which weights were obtained. The final list of indicators were shortlisted by ensuring that at least 2 indicators from each of the four dimensions are represented, so as to build the overall index.

3. Results and discussion

Indicators have long been used for assessing and tracking specific environmental and ecological conditions (Niemi and McDonald, 2004), but their use for measuring overall sustainability is of recent origin. The Rio Summit called for the development of sustainability indicators. There are several organizations working on sustainability indicators such as Balaton Group, International Institute of Sustainable

Table 2
Climate resilience tools/indicators used at different levels.

Type	Organization	Indicator description	Data sets	Level
International	FAO, UNDP, UNFCCC, GIZ, ADB, World Bank CSIRO	• Risk screening index • Resistance indicators • Vulnerability index • Livelihood index	Country experiences Climate plans	• Global national community
National	ICAR, MOEF, NGOs, CSIRO	• Contingency preparation • Climate resilience • Risk reduction • Disaster management • Mitigation index • Community resilience	• Village institutions • State action plans • National	• Ecosystem • District • Village • Farm • Community • Landscape
Research Institutions	NAARM, CRIDA	• Adaptation • Carbon foot print	• Research data • Conceptual models • Technology packages	• Community • Local • Farm/farmers • Household • Village

Source: Compiled by authors from different sources.

Development (IISD) and several subsidiaries of United Nations like Commission on Sustainable Development (UNCSD), UN Development Programme (UNDP), UN Environment Programme (UNEP) etc. The design of an appropriate set of indicators is a crucial and complex problem (Bossel, 2001), as indicators should provide a representative picture of sustainability.

3.1. Sustainability indicators for climate resilient agriculture

One straightforward approach to gauge the vibrancy of agriculture is sustainability, which is a positive measurement. Another approach to study the vibrancy is to measure the constraints that reckon the negative drift of indicators on the sustainability, which is called as vulnerability. There is obviously an inverse relationship between sustainability and vulnerability. Therefore, one can either workout the sustainability or vulnerability of a sector or region. As opposed to both sustainability and its inverse vulnerability, resilience is yet another purview to measure the vibrancy of agriculture systems. It may be noted that all agroecosystems move through the four phases of the adaptive cycle: growth/exploitation, conservation, release, and reorganization/renewal (Darnhofer et al., 2010; Gunderson and Holling, 2002).

Qiu et al. (2007) gave an illustrative list of sustainability indicators with the direction of influence i.e. positive and negative in their conceptualization. Several attempts have been made to assess and measure the vulnerability and resilience (Table 2). The challenges in quantification of sustainability using a combination of indicators has been addressed to a great extent by applying various methods of aggregating these combinations of multidimensional indicators into indices or composite indicators (Qiu et al., 2007; Rigby et al., 2000). Gómez-Limón and Sanchez-Fernandez (2010) argued for operationalizing the concept of sustainability as an element to support the "governance" of this sector. Some of the prominent features taken into account for reckoning the indicators of sustainability are stakeholder involvement level, linkage between and among the dimensions, validity, data availability, stability/reliability, flexibility, etc. (Guy and Kibert, 1998).

In the current study, extensive review of literature was undertaken to identify the indicators used in various studies across the world. About 140 peer reviewed research papers were reviewed, of which 60 papers with clear and unambiguous list of indicators, were identified. It was observed that there were 1209 indicators used for measuring climate resilience, sustainable agriculture and agricultural vulnerability. A close examination of the frequency of use of these indicators across studies showed that as many as 90 indicators were used at least in two studies (2–7) of which 22 indicators were found to have been used more than 13 times (Fig. 1). The indicators were classified based on broad goals of the study. It was observed that majority of the indicators used for measuring sustainable agriculture (795 indicators), followed by agro-ecosystem based sustainability (269 indicators), climate resilient agriculture (184 indicators) and agricultural vulnerability to climate change (88 indicators).

Most of the indicators used in the above studies were perceived to capture the environment dimension (219 indicators), followed by social (129 indicators), economic (127 indicators) and ecological dimensions (58 indicators). Some of the indicators were used to measure combinations of different dimensions by different authors (129 indicators were used across social and cultural dimensions). Accordingly, in the current study the cultural indicators were subsumed into the 'social' category. The extent of variation in the applications of different indicators is captured in Fig. 2. Based on this analysis, the authors adopted four major dimensions *viz.,* social (including cultural), economic, ecological (including environment) and institutional (including governance/political).

Broadly there are three sets of dimensions such as normative, spatial and temporal that are commonly used to measure the sustainability (Von Wiren-lehr, 2001; Zen and Routray, 2003). These dimensions conform to the ecological, economic and social sets of indicators. However, studies by Farkasne et al. (2004) indicate that agriculture's sustainability should be measured by a four-dimension matrix system of indicators, which is rather a regulatory than a descriptive model. They suggest Institutions as the fourth pillar, which is certainly a dimension that can strengthen the other three pillars akin to the press which watches the legislature, executive and the judiciary in the case of democracy. Lisanyi (2011) on the other hand categorized the fourth dimension/pillar as political. A balanced indicator matrix encompassing all these pillars would explain the vibrancy or otherwise of an agricultural system.

3.2. Development of climate resilient indicators

A good indicator must measure and describe explicitly the condition of sustainability (Zhen and Routray, 2003). Some of the attributes of indicators used for measuring sustainability could be – science based, reproducible, transparent, manageable and cost effective (Bos et al., 2007). Dale and Beyeler (2001) proposed that criteria for selecting ecological indicators should be (i) easily measurable; (ii) sensitive to stresses on the system (iii) respond to stress in a predictable manner; (v) anticipatory, meaning that they signify an impending change in the ecological system (v) predict changes that can be averted by management actions (vi) integrative, meaning that the full suite of indicators provides a measure of coverage of the key gradients across the ecological systems (such as soils, vegetation types and temperature); (vii) have a known response to natural disturbances, anthropogenic stresses, and changes over time, and (viii) have low variability in response.

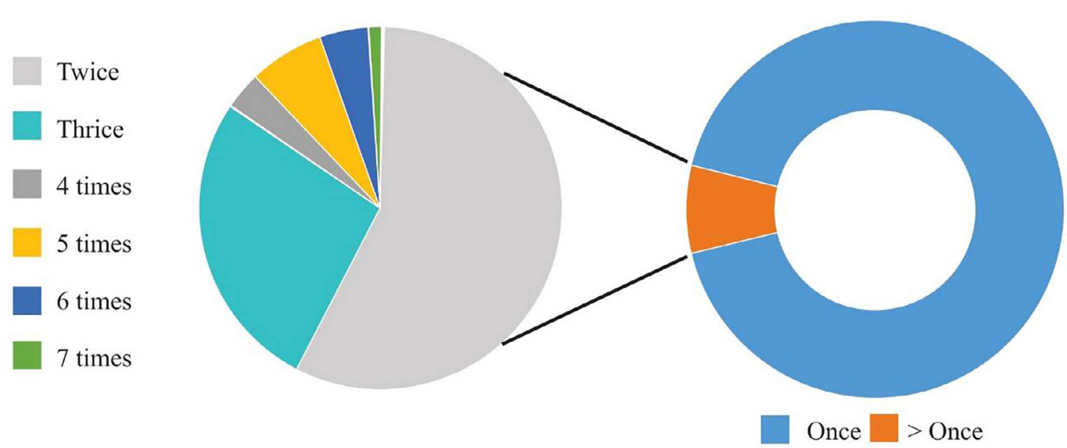

Fig. 1. Number of indicators screened from literature and their frequency of use across various studies.

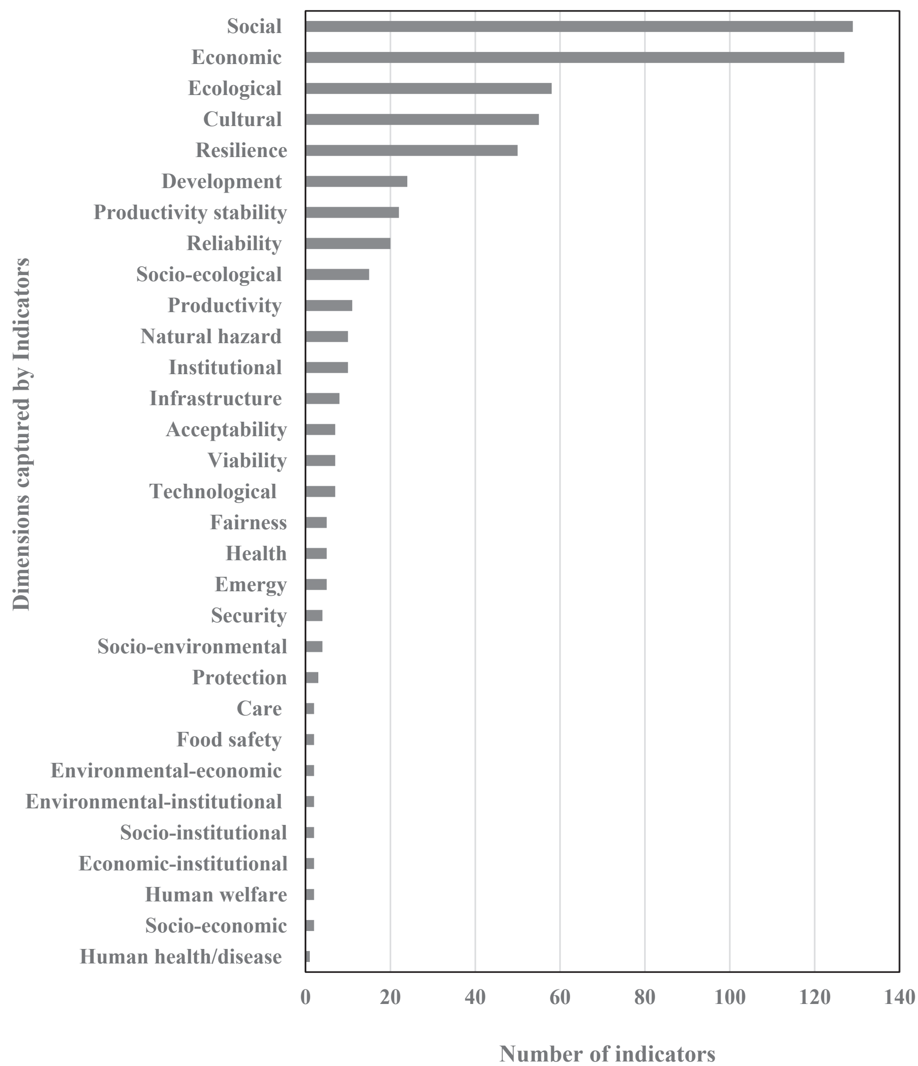

Fig. 2. Diversity of dimensions captured by the sustainability indicators in various studies.

The screening of indicators for assessing sustainability/vulnerability/resilience was done based on their frequency of use in earlier studies, data availability, degree of sensitivity to stresses on the system, existence of threshold values and guidelines, predictability, scope of integration and known response to disturbances, anthropogenic stresses, and temporal changes (Zhen and Routray, 2003). The indicators thus shortlisted (41 numbers) are summarized in Table 3 with the definition, rationale and original literature source.

An online survey was conducted among the subject matter experts to evaluate the shortlisted indicators as a potential tool for measuring climate resilient agriculture. Among the 225 experts who were reached through a structured online survey, 90 expressed their consent to be part of this survey and the responses from 35 experts, which were complete in all respects were considered for the analysis. The indicators for assessing the climate resilient agriculture were determined based on analysis of the responses of the experts (Fig. 3). The indicators were classified based on the four major dimensions they represent *viz.,* ecological, economic, social and institutional.

The results of Weighted Sum Model, containing the scores for each of the 41 indicators representing four dimensions of climate resilient agriculture, arranged in descending order, are provided in Table 4. Higher the score for an indicator, greater was its importance for assessing the status of climate resilient agriculture. In the current study, 30 indicators which had an AHP score of ≥ 3.5 and above (Fig. 3) were selected for assessing climate resilient agriculture. The cut-off (3.5) was kept low so as to ensure that no key indicator is left out of the framework. The AHP based weightage for the different dimensions showed that the contribution of ecological dimension to the composite index of climate resilient agriculture was maximum (55%) followed by economic, social and institutional dimensions (Fig. 4) (Table 5).

Gomez-Limon and Riesgo (2009) developed the Composite Indicator of Agricultural Sustainability (CIAS), using aggregation and weighting procedures such as Principal Component Analysis (PCA), Analytical Hierarchy Process (AHP) and Multi Criteria Decision Making (MCDM). In the context of climate change and agriculture performance, five types of indicators *viz.,* climate change indicators, climate impact indicators, climate adaptation indicators, climate resilient and climate vulnerability indicators (Ellis, 2014) need to be reckoned. While the purpose of climate change indicators is to understand the causes of impacts of climate change, the climate impact indicators help us understand the consequences of climate change and the vulnerability/adaptation indicators will be useful in monitoring and understanding vulnerability, identifying adaptation needs, evaluating strategies and action. The Pressure-State-Effects-Response model proposed by Kadir et al. (2013) for studying the climate change impacts on agriculture suggests that the pressure due to the drivers of climate change induces changes in the state, which in turn, bring in physical and biological impacts. These effects need appropriate responses such as emission reductions and other adaptation strategies.

Table 3
Indicators for climate resilient agriculture shortlisted for expert validation.

No.	Indicator	Definition	Rationale	References
Ecological				
	Crop Biodiversity	The summation of the square of acreage share across crops grown in the region	Diversification of crops is desirable for sustainability (Simpson diversity index, which is reciprocal of herfindahl index)	Apollonia et al. (2015)Belcher et al. (2004)Marchettini et al. (2003)
	Livestock Biodiversity	The summation of the square of population share across livestock species in the region	Diversification Livestock by population composition will give vibrancy in a system (Simpson Diversity Index, which is reciprocal of herfindahl index).	Apollonia et al. (2015)Fernandes et al. (2008)
	Pesticide Usage	The quantity of pesticides applied per unit area (ha)	Indicates the dependency and susceptibility level of the agriculture systems	Zahm et al. (2008)Zhen and Routray (2003)Halberg (2012)
	Rainfall Deviation	It indicates the deficiency or surplus over normal rainfall	Reflects the qualitative dimension of rainfall	Lopez-Ridaura et al. (2005)Apollonia et al. (2015)Belcher et al. (2004)Ellis (2014)Rao et al. (2016)
	Soil Organic Carbon	Amount of carbon in soil which indicates the overall soil health	It is the key soil health indicator	
	Cropping Intensity	The ratio between gross cropped areas divided by net sown area in a year (%)	This indicates the extent of double cropping or gross cropping extent in the area	Gómez-Limón and Riesgo (2009)
	Drought Frequency	The number of drought years in a span period	Gives vulnerability or otherwise of area to drought occurrence. Higher frequency will lead to negative influence on sustainability	Apollonia et al. (2015)
	Flood Frequency	The number flood years in a span period	Gives vulnerability or otherwise of area to flood occurrence. Higher frequency will lead to negative influence on sustainability	Cutter et al. (2010)Adger (2000)Ellis, 2014
	Frost Frequency	The number of frost years in a span period	Gives vulnerability or otherwise of area to frost occurrence. Higher frequency will lead to negative influence on sustainability	Lopez-Ridaura et al. (2005)Ellis (2014)
	Net Sown Area	The extent of land under cultivation to the total available geographical area	Higher net sown area share indicates higher income	Ellis (2014)
	Forest Area	The extent of land under forests to the total available geographical area	Higher proportion of forest area helps in conserving nature and acts as carbon sink	Farrell and Hart (1998)Belcher et al. (2004)
	Net Irrigated Area	Area under irrigation as a proportion of total cultivated area	Higher irrigated area is desirable and indicator of higher agricultural productivity	Ellis (2014)
	Soil Depth	Indicates the storage capacity of water and availability of nutrients	Higher depth is desirable	Kareemulla et al. (2017)Belcher et al. (2004)
	Water Productivity	Indicates the productivity of water	Low productivity is undesirable	Belcher et al. (2004)
	Fertilizer Usage	The extent of fertiliser use/unit area i.e. intensity	Optimum usage is desirable rather than low or high	Lopez-Ridaura et al. (2005)Zhen and Routrat (2003)
	Agriculture Waste Utilisation	Ratio of crop and or animal by-products tht are used up or recycled in agriculture itself	Higher proportion of utilization is an indication of integration as well as system sustainability	Bos et al. (2007)
	Organic/Conservation Agriculture	Proportion of cultivated area under organic farming, conservation agriculture, low external input agriculture, etc.	It's an indicator of diversification as well as sustainability of agricultural systems/practices	Halberg (2012)
	Groundwater Table	The depth from the soil surface at which the water is available for drawing	Reflects the ground water status and also exploitation level	
	GHG Emissions	The CO_2 equivalent of all GHG emissions	Reflects the quality of air and the level of pollution	Apollonia et al. (2015)Belcher et al. (2004)Marchettini et al. (2003)
	Fertiliser Use Efficiency	Yield response of fertilizers	Indicates fertilizer productivity; and soil & groundwater pollution due to imbalanced use	Belcher et al. (2004)
	Soil Drainage	The extent of area under poor drainage	Impacts the physical, chemical and biological status of soil	Zhen and Routray (2003)Belcher et al. (2004)Herendeen and Wildermuth, 2002Von Wirén-Lehr (2001)
	Renewable Power Supply	Extent of power (solar, wind & hydro power sources to total supply) demand met by this source	Higher ratio is desirable	Walter and Stutzel (2009)Belcher et al. (2004)Marchettini et al. (2003)
Economic				
	Gross Value Added from Crops	The gross value addition in monetary terms from various crop enterprises. Calculated per ha/year	The predominant income source adds to economic welfare and sustainability	Belcher et al. (2004)
	Gross Value Added from Livestock	Reflects the economic contribution from livestock – dairy, draught, meat animals. Calculated per 1000 animals/year	Higher contribution leads to absorption of climate shocks affecting crops	Bos et al. (2007)
	Gross Value Added 'from Fisheries	Reflects the economic contribution from fish & fish products. Calculated per fisher family/year	It adds to diversity of enterprises	Apollonia et al. (2015)Hansen (1996)Halberg (2012)
	Agricultural Employment	Number of people employed in agriculture sector.	Indicates the dependency of population on agriculture sector and reflects the livelihood security.	Nambiar et al. (2001)
	Non-farm Income	Earnings of members of agricultural household from non-farm sources	It's a measure of existence of alternative avenues for income and livelihood in rural areas	Lopez-Ridaura et al. (2005)Zhen and Routray (2003) Belcher et al. (2004)

(*continued on next page*)

Table 3 (*continued*)

No.	Indicator	Definition	Rationale	References
	Per Capita Food Supply	Proportion of population with secure food supply by self/ government support	Higher ratio is desirable	Zhen and Routray (2003)Herendeen and Wildermuth (2002)
	Agriculture Markets	Coverage of agri. Markets (No./10,000 ha)	Higher ratio is beneficial	Ellis (2014)
	Marketable Surplus	The cushion for revenue generation after meeting own consumption demand (% of agri. produce)	Generates revenue for investment and savings	Belcher et al. (2004)
	Poverty Rate	Share of population under Planning Commission/RD Ministry defined BPL (%)	Higher value indicates the vulnerability of population	Apollonia et al. (2015)Spangenberg (2002)Yli-Viikari et al. (2012)Morse et al. (2001)
Social				
	Human Development Index	Composite measure of life expectancy, Education, & Per capita income	Higher value indicates better resilience to climate change.	Fernandes and Woodhouse, 2008
	Population Density	Pressure on resources in an area. Number of people/km^2	Higher value indicates better resilience to climate change.	Adger (2000)
	Adoption of Improved Practices	Indicates the adoption of available technologies which will improve agricultural/farm productivity	Higher the adoption better will be the sustainability	Kareemulla et al. (2017)
	Marginal and Small Holdings	Proportion of susceptible category of farmers who normally get affected	Higher value indicates greater vulnerability	Gómez-Limón and Riesgo (2009)
	Labour Migration	A measure of unemployment resulting in seasonal or permanent migration of labour from rural to urban areas	It is desirable to a threshold, beyond which it is undesirable	Spangenberg (2002)
Institutional				
	Agriculture Insurance	Extent of crop and livestock insurance coverage	Reflects back up support for falling back in case of risk exposure	Zhen and Routray (2003)Kareemulla et al. (2017)Belcher et al. (2004)
	Access to Extension Services	Proportion of farmers having access to or availing extension services	Higher value indicates better resilience to climate change.	Belcher et al. (2004)
	Farm Credit	Institutional and other sources of credit disbursed or availed per unit area	Credit brings in access to inputs for production	
	Community Managed Institutions	Presence of institutions for collective actions in agriculture	Enable knowledge and skill upgradation besides resources sharing	Gómez-Limón and Riesgo (2009)
	Disaster Preparedness	Infrastructure, interventions, and trainings done for disaster preparedness	Higher value indicates better resilience to climate change.	Apollonia et al. (2015)Cutter et al. (2010)Zhen and Routray (2003)

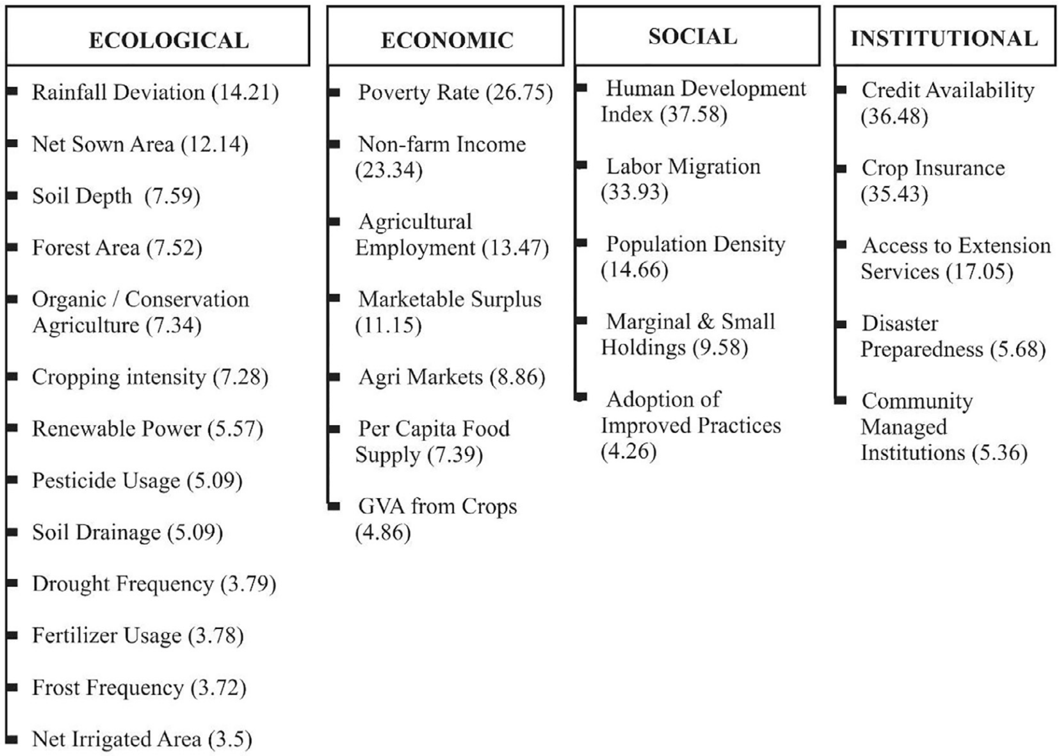

Fig. 3. Analytic Hierarchy Process (AHP) – Dimension-wise prioritized indicators with scores (%) for climate resilient agriculture.

3.3. Agro-ecosystem-specific climate resilient sustainability indicators

3.3.1. Agroecosystems in India

An agro-ecosystem is a homogenous geographical area, wherein the production environment of the region in terms of agro-climate, resource endowments and socio-economic conditions is homogenous, and majority of the farmers have similar production constraints and research needs. Specific advantages of agro-eco-regional approach for research planning are (i) better identification of production constraints and research needs; (ii) better targeting of prospective technologies; (iii) improved assessment of farmers' responses to new technologies, and (iv) wider adoption and larger impact of research outputs.

The production system research (PSR) under the National Agricultural Technology Project (NATP) funded by the World Bank during the early 21st century in India sharpened the approach for agricultural research in India. This approach delineated the country into five agroecosystems that examines and prioritizes research needs of a production system taking care of all sub-systems like crops, livestock, natural resources and socio-economic, and their inter-linkages. Accordingly, the NATP divided the entire country into 5 broad agro-ecosystems (namely Arid, Coastal, Hill and Mountain, Irrigated and Rainfed), which were further divided into 14 production systems (Fig. 5), using cluster analysis with the cropping patterns. These agro-ecosystems and production systems have been described in systematic and objective manner (ICAR, 1998; Saxena et al., 2001).

3.3.2. Agroecosystems-specific indicators

There exists a vast heterogeneity of agricultural production systems and it is necessary to do specific analyses for every agro-ecosystem to define indicators of agricultural sustainability (Pesic, 2017). Among the 41 indicators shortlisted and submitted for expert validation, those which were representing the social (5), economic (9) and institutional (5 dimensions were considered to be applicable across the five agro-ecosystems in India. However, ecological indicators (22), though would be applicable in more than one agro-ecosystems, shall capture the sensitivity of the certain agro-ecosystems more precisely, than others. Such indicators shall require assigning more weightage while being used to assess the climate resilient agriculture, in the respective agro-ecosystems. The priority scores for the various ecological indicators as determined through the AHP showed that the scores were maximum for pesticide usage (14.21), followed by net sown area (12.14), soil depth (7.59), etc. (Fig. 6). Table 4 shows the ecological indicators with specific utility for measuring the climate resilient agriculture in the identified agro-ecosystems. Nevertheless, these indicators may not underestimate the influence of generic indicators across agroecosystems.

3.4. Interventions for climate resilience agriculture

Various researchers used different reference models for interventions in response to climate change referred to as adaptive capacity strategies or response strategies (UNFCCC, 2006). The technologies for adaptation to climate change are broadly categorized into interventions and response strategies, which pertain to crop selection and its management and soil conservation measures. Prasad et al. (2014) used the rationale for technology in adopting to different climate resilient contexts like availability of technologies, availability of indigenous practices, inherent resilience with the community for coping with disasters and long experience of NARS in evolving drought/flood resilient technologies.

National Innovations on Climate Resilient Agriculture (NICRA), the flagship programme to tackle the ills of climate change on agriculture in India identified four broad categories of interventions (NICRA Annual Report, 2014–15) *viz.,* natural resource management, crop production, livestock and fisheries and institutional. Singh et al. (2014) used institutional, technological and governance related interventions to tackle the climate induced drought and suggested the indicative policy points to strengthen the capacity to drought at the micro-level *viz.,* coordination through a country level program for efficient resource utilization (institutional); better relief delivery mechanism (institutional); capacity building on climate related information management by various stakeholders and policy interventions in climate change plans (social); establishing good information network sharing mechanism

Table 4
Validation of indicators using linear combination weighted scoring model.

Indicators	Weighted score
Ecological (EL)	
EL1. Rainfall Deviation	12.00
EL2. GHG Emissions	12.00
EL3. Crop Biodiversity	11.83
EL4. Livestock biodiversity	11.83
EL5. Flood Frequency	11.83
EL6. Water Productivity	11.83
EL7. Agriculture Waste Utilization	11.83
EL8. Soil Organic Carbon	11.67
EL9. Net Irrigated Area	11.67
EL10. Groundwater Table	11.67
EL11. Drought Frequency	11.50
EL12. Frost Frequency	11.50
EL13. Fertilizer Usage	11.50
EL14. Fertilizer Use Efficiency	11.33
EL15. Soil Drainage	11.33
EL16. Renewable Power Supply	11.33
EL17. Cropping Intensity	11.17
EL18. Forest Area	11.17
EL19. Soil Depth	11.17
EL20. Organic/Conservation Agri.	11.17
EL21 Pesticide Use	10.67
EL22. Net Sown Area	10.67
Economical (EC)	
EC1. Agriculture Markets	12.00
EC2. Marketable Surplus	11.50
EC3. GVA from Crops	11.33
EC4. Per Capita Food Supply	11.33
EC5. GVA from Fisheries	11.17
EC6. Non-farm Income	11.17
EC7. Poverty Rate	11.17
EC8. GVA from Livestock	11.00
EC9. Agricultural Employment	10.67
Social (SO)	
SO1. Human Development Index	11.83
SO2. Population Density	11.83
SO3. Adoption of Improved Practices	11.50
SO4. Marginal and Small Holdings	11.17
SO5. Labour Migration	10.67
Institutional (IN)	
IN1. Access to Extension Services	11.83
IN2. Disaster Preparedness	11.83
IN3. Community Managed Institutions	11.67
IN4. Agriculture Insurance	11.50
IN5. Availability of Farm Credit	11.50

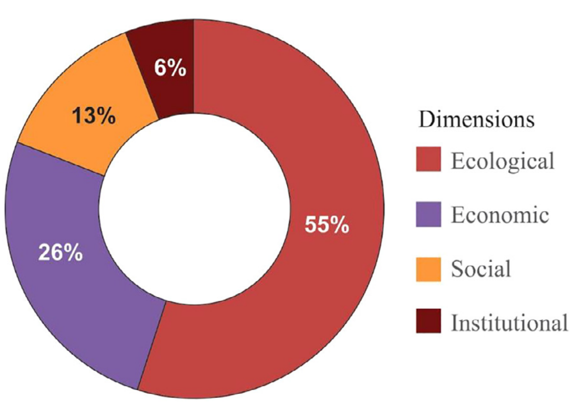

Fig. 4. AHP based weightage (%) for each dimension of composite index for climate resilient agriculture.

(technological); GIS based mapping of resources allocation and management (technological and institutional); resource regulation like ground water (governance); documentation of information in proper validated framework for future action plans; credit support and enterprise training for farmers (institutional); involvement of stakeholders in mitigation programs through effective governance; support of Research and Development programs on interventions to mitigate climate change (technological); Priyanka and Singh (2014) highlighted the importance of biotechnology as a tool to manage the environmental hazards like drought through development of drought tolerant crops.

Table 5
Agro-ecosystem specific ecological indicators identified in the study.

No	Agro-ecosystems				
	Arid	Coastal	Hill and Mountain	Irrigated	Rainfed
1	Draught frequency	Soil drainage	Soil depth	Water productivity	Rainfall deviation
2	Ground water table	Flood frequency	Frost frequency	Net irrigated area	Forest area

Notwithstanding the nature and type of measurement of the intensity, frequency and longevity of climate change impacts on agriculture or vice versa, it is inevitable for the researchers, planners and the extension agencies to integrate the knowledge and skills for tackling the impacts both on a short and long run basis. The basic framework proposed for climate change adaptation and mitigation indicating the levels of operation is provided in Fig. 6. Buildup of greenhouse gases is a result of deforestation, inappropriate agriculture practices among other things. This leads to global warming resulting in climate change making agriculture unsustainable and irreparable loss of socio-economic capital (Fig. 7). The climate resilient indicators at farm, village and national level are illustrated in Fig. 8.

The authors advocate an action-oriented model called Climate Risk Management Package for Agriculture (CRiMPA) (Fig. 9), which provides a holistic approach for climate resilience. The model envisages the climate resilient solutions to come from research and development organizations, duly validated by the traditional knowledge. When the assessment framework is applied, agro-ecosystem sustainability shall be measured – indicator wise (for each of 30 indicators), dimension wise (for each of the four dimension index). The sustainability index shall be obtained spatially at various levels *viz.*, village, *gram panchayat,* taluk/development block, district, state/province, by aggregation of weighted scores at appropriate levels. In order to determine the sustainability index for a particular agro-ecosystem region, the weighted scores of villages located within an agro-ecosystem shall be aggregated. Based on such scores, specific interventions to address issues of sustainability at a particular spatial level could be planned, using the CRiMPA framework.

The critical inputs for designing interventions shall be derived from the researchers as well as the traditional knowledge available with farmers, which shall be made available across different levels by harnessing information and communication technology (ICT). R&D institutions and the network of Krishi Vigyan Kendras (KVKs – Farm Science Centres located in each district) and state level extension agencies working closely with the key stakeholders i.e. farming communities, shall be the key players. The process flow is perceived through the establishment of a knowledge repository, to network the various players *viz.,* scientists, *Krishi Vigyan Kendra* (KVKs), line departments and extension agencies, so as to facilitate better technology adoption by the primary stakeholders. While some knowledge-driven interventions directly percolate to the farming communities (eg. choice of drought/submergence tolerant varieties), some other interventions require the intervention or mediation of the policy making bodies (eg. incentives to be given to farmers). Such a mechanism shall be made operational, through an enabling policy framework, involving all stakeholders. The action plan/intervention plan that might result from such a process may contain broadly, *but not necessarily*, the following: technological solutions to address some specific problems, solutions that require collective action, issues that require active institutional/

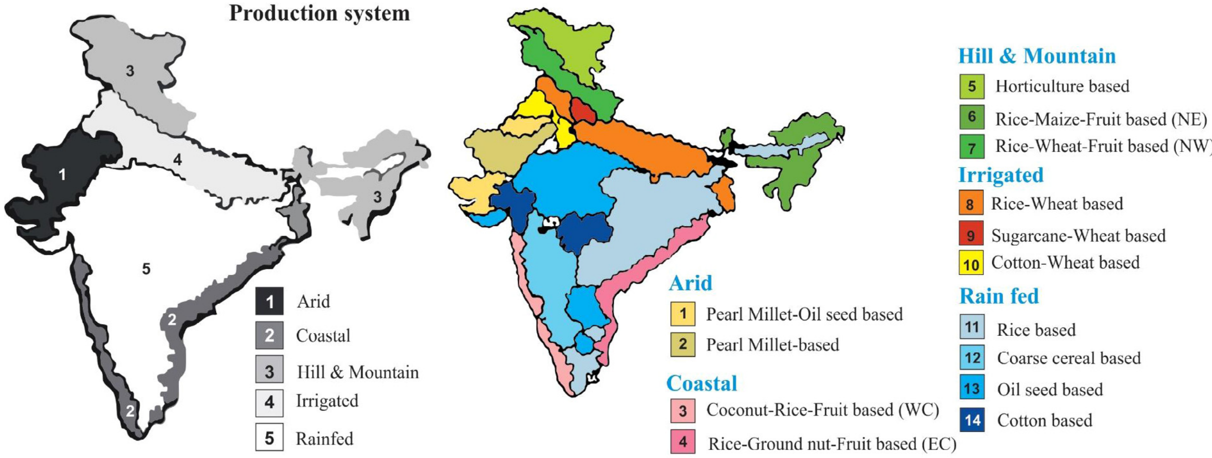

Fig. 5. Agro-ecosystem and production system map of India.

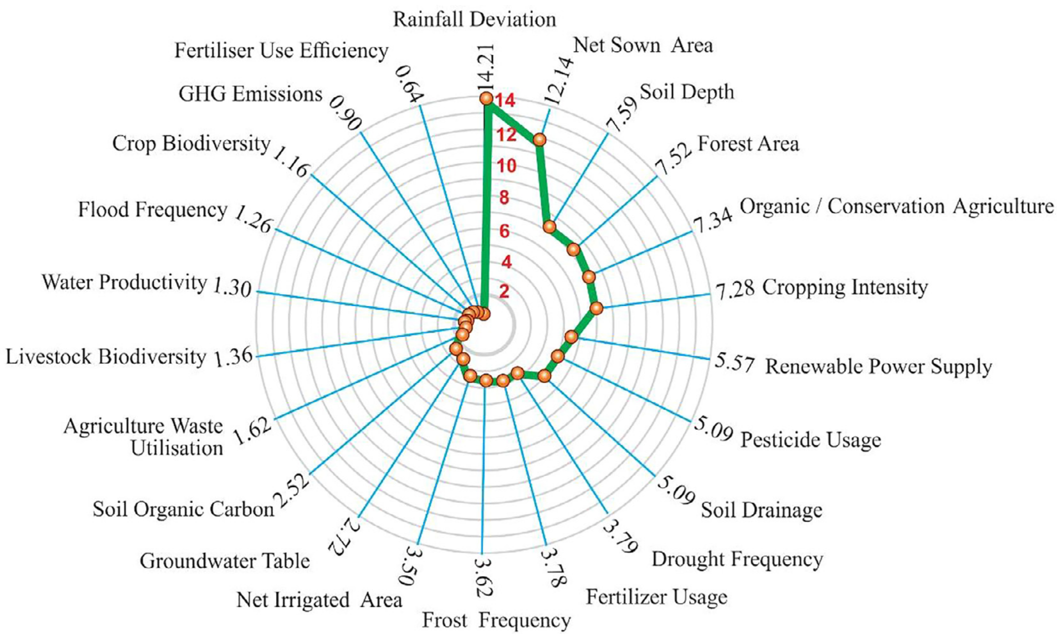

Fig. 6. Analytic Hierarchy Process (AHP) priority scores (%) for ecological indicators.

government intervention and some climate events that might require contingency/mitigation/adaptive plan.

CRiMPA has been conceived as an illustrative conceptual model, to guide in the design of the spatial/agro-ecosystem specific *interventions*. It doesn't have *a priori* data, before applying the assessment framework using 30 agro-ecosystem based sustainability indicators, and hence needs to be validated before applying for a particular situation, which would eventually take into account the variables and their corresponding weightages. The CRiMPA model illustrated here may get evolved and refined after its application.

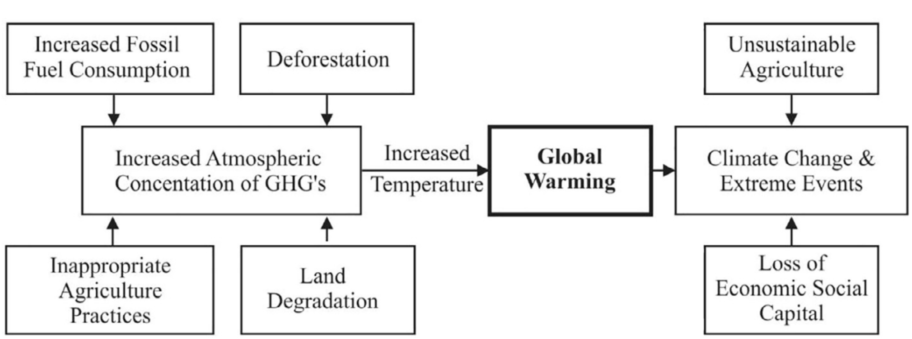

Fig. 7. The process of climate change and vulnerability of agriculture.

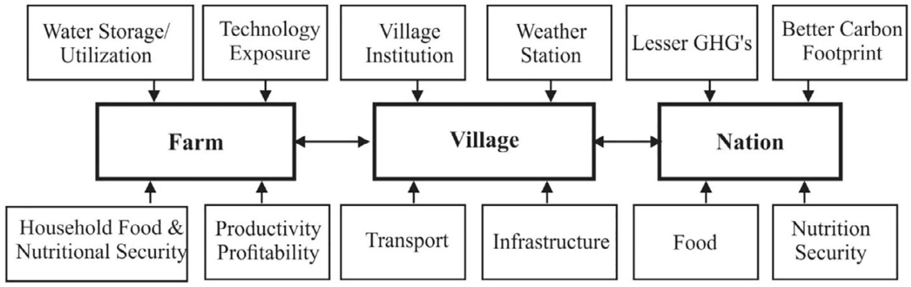

Fig. 8. Dimensions of climate resilience indicators at farm, village and national level.

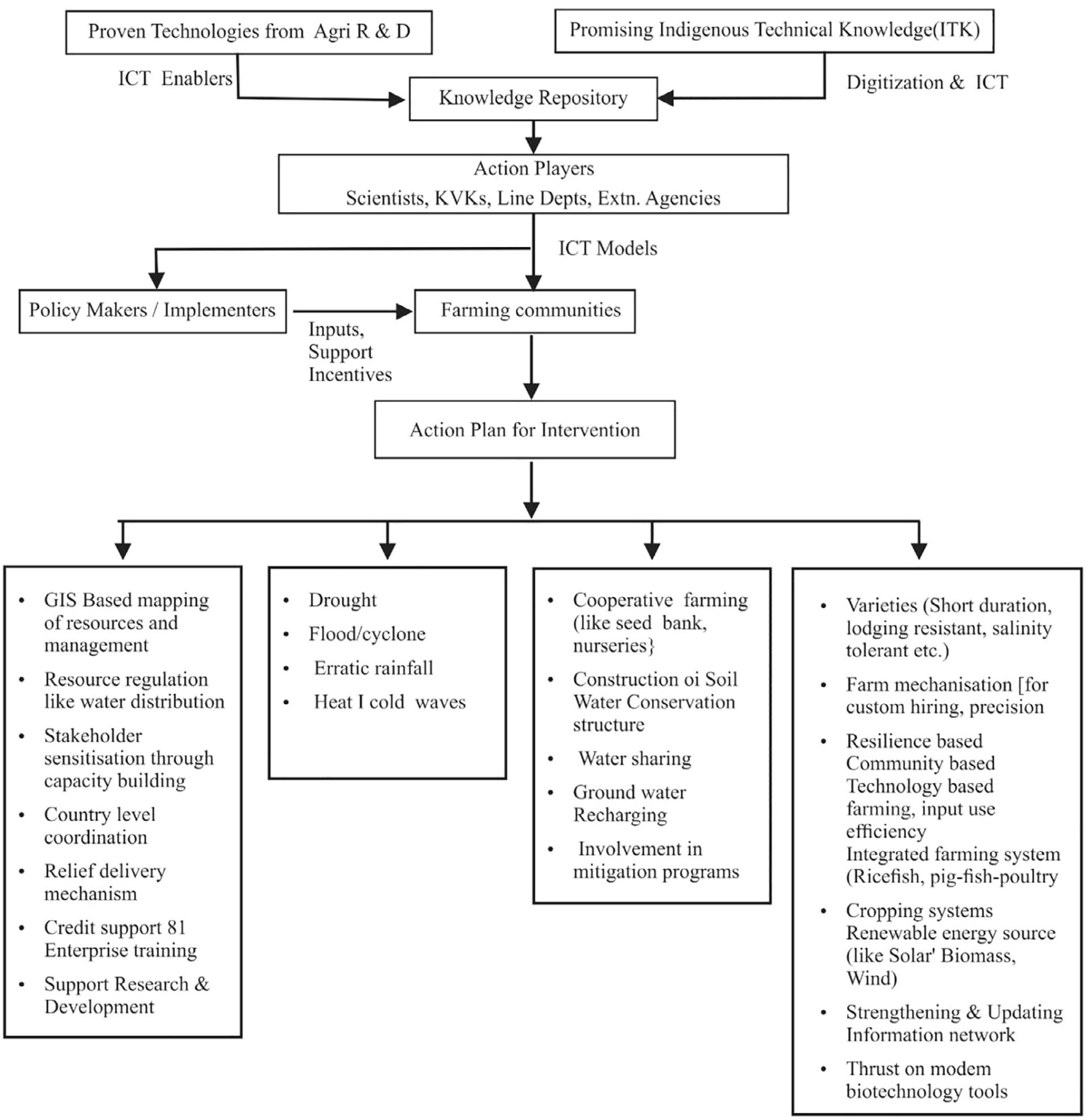

Fig. 9. Climate Risk Management Package for Agriculture (CRiMPA): A framework for climate resilient agriculture in India.

4. Conclusions

Agricultural sustainability, in an era of climate change, concerns the farmers, communities, policy makers and the researchers alike. Scientifically evolved indicators for measuring sustainability and resilience to climate change aid in planning interventions that are most appropriate for a given agro-ecosystem. Although several studies have focused on climate change dimensions and resultant impacts on agriculture and allied sectors, a comprehensive and composite set of indicators, representing major dimensions, have not been developed, especially at a large biome/sub-continent level. The Indian subcontinent with its diverse geography and agro-ecosystem adds to the complexity dimension, thus necessitating a specific study for the agro-ecosystem specific climate resilient indicators.

In the current study, 30 sustainability indicators for climate resilient agriculture have been identified through extensive review, rigorous screening, expert validation and statistical analysis of the responses. The widely recognized pillars of sustainability are ecological, economic and social, while there are specific studies, covering various other dimensions. In the current study, the authors propose 'institutional' dimension as the fourth pillar, which is essentially a binding force for the other dimensions. In view of the variability in a country of 329 million ha and 138 million farm holdings, 15 agro-climatic zones falling under five agro-ecosystems, it was reckoned to develop the indicators to capture the differences in climate change implications across these ecosystems. These final set of indicators provide a broad framework, which need to be subjected to appropriate statistical validation, after collection of data pertaining to specific spatial dimensions, for profiling the resilience of an area.

The study provides a basic framework for climate change adaptation and mitigation indicating the levels of operation and a conceptual model for Climate Risk Management Package for Agriculture (CRiMPA). The authors call for development of a knowledge repository, in order to network the various players and to enable realization of the benefits, envisioned through the implementation of the model. It is envisaged that the framework would aid in evolving location-specific action plans and development programmes, by the researchers and planners, which in turn can be integrated into the National Action Plan for Climate Change (NAPCC) of Government of India.

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