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Agricultural Vulnerability to Climate Change in Punjab: A Spatio-temporal Analysis

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Abstract: Changing climate and its variability at the regional scale has become a constraint to development in general and poverty reduction specific for low-income countries. The mapping of climatic vulnerability provides a wider approach to understanding its dynamics across space and over time. The study analysed the vulnerability index of 22 districts of Punjab state at four different points of time i.e., 1990, 2000, 2010, and 2020. The uneven weight approach of Iyengar and Sudershan is used to calculate the vulnerability index, which is the sum of exposure and sensitivity minus adaptive capacity. The indicator-wise analysis of vulnerability in Punjab from 1990 to 2020 reveals significant regional disparities. Majha improved its resilience, reducing exposure from 0.47 to 0.19, while Doaba's vulnerability sharply increased from 0.19 to 0.86. Malwa's exposure moderately rose from 0.29 to 0.40, and overall sensitivity slightly declined, yet both Doaba and Malwa became more susceptible to climate risks. The findings emphasize the need for targeted interventions to address rising vulnerabilities, especially in districts like Barnala and Bathinda, which have seen sharp increases in their vulnerability indices.

Keywords: Climatic vulnerability, Vulnerability index, Adaptive capacity, Climate-resilient technologies

Anthropogenic greenhouse gas emissions, driven by economic and population growth, are causing global temperature increases and altering the Earth's climate (Edmonds, Lovell, and Lovell 2020). This shift is significantly impacting both biological and human systems in various regions. Climate change is manifested through rising global air temperatures, extreme weather events, and changes in sea levels, including coastal flooding and the melting of snow and ice (Thornton et al 2014). The impacts are not uniform, as regions like India, with its unique geophysical and hydro-climatic conditions, experience heightened vulnerability to these changes (Gulati et al 2009). India's agricultural sector, which relies heavily on natural resources, faces mounting challenges as global warming exacerbates water scarcity and land degradation. These effects are more pronounced in developing countries, where agriculture plays a significant role in GDP and employment, and where adaptive capacity is often limited. As climate change continues to affect agroecological conditions, the vulnerability of rural populations, who rely heavily on rain-fed agriculture, increases. Climate-induced droughts further exacerbate food insecurity and water shortages (Lyimo and Kanglawe 2010).

The concept of vulnerability to climate change, as outlined by the Intergovernmental Panel on Climate Change (IPCC), includes three key elements: exposure, sensitivity, and adaptive capacity (Füssel and Klein 2006). These factors vary based on biophysical and socioeconomic conditions, which determine how communities respond to climate risks. The vulnerability of systems, particularly in agriculture, is shaped by both internal factors like resource scarcity and external threats such as climate-induced shocks (Hiremath and Shiyani 2013). In India, Punjab is a key agricultural region with a tropical and semi-arid climate. The state has experienced increasing climate variability in recent years, adversely affecting agricultural productivity, groundwater levels, and energy usage, all of which are critical for food security and livelihoods. Given the importance of Punjab's agricultural output to the nation's food supply, it is crucial to understand how climate change is influencing the vulnerability of its districts. Therefore, this study seeks to analyze the vulnerability of different districts in Punjab over time, providing a comprehensive district-level assessment of the agricultural challenges posed by climate change.

MATERIAL AND METHODS

The study encompasses all districts of Punjab, India, except Malerkotla, and focuses on the state's predominantly agrarian economy, which is sustained by an advanced irrigation infrastructure. Nearly 99.6 per cent of the gross sown area and 99.9 per cent of the net sown area are irrigated, with 75 per cent of the irrigation depending on groundwater, a resource that is depleting at an alarming rate (GoP 2021). Punjab's climate exhibits considerable spatial variability, with the Himalayan foothills receiving substantial rainfall, while the southern and western regions experience arid conditions with limited precipitation. Temperature extremes are notable, with May and June being the hottest months (over 40°C), while December to February is the coldest, with average temperatures dropping below 5°C. For this study, secondary data encompassing climatic parameters, crop area, and yield were obtained from Punjab's Statistical Abstracts. Missing data were addressed using interpolation and extrapolation methods. The temporal analysis covers the years 1990, 2000, 2010, and 2020, providing a comparative framework across these time intervals.

Conceptual framework: Assessing vulnerability of a phenomenon requires a solid conceptual framework. The most prevalent method for assessing climate change vulnerability is based on the Intergovernmental Panel on Climate Change (IPCC)'s suggested definition. This approach emphasizes three main components: exposure, sensitivity and adaptive capacity.

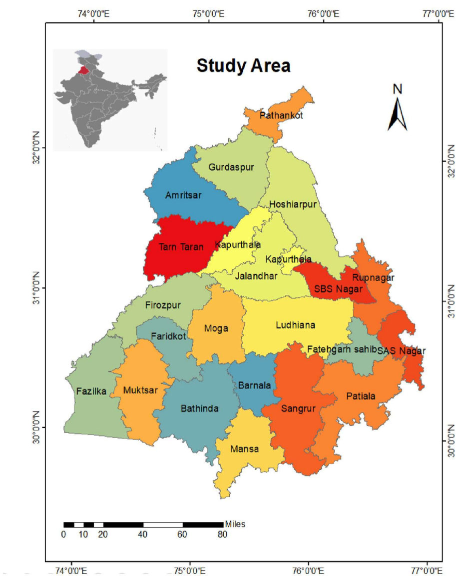

Fig. 1. Study area

Exposure: As indications of exposure, historical changes in climate variables and the occurrence of extreme climatic events are considered, including the rate of change in annual mean maximum temperature, annual mean minimum temperature, and yearly mean precipitation (Table 1). It is expected that as the rate of change of climate variables increased, higher will be the exposure of the households to climate change.

Sensitivity: Degree to which a system is affected or improved either by internal disturbances or external disturbances or both is sensitivity (Gallopin 2003). In this study, the major indicators of sensitivity are percent rural population, crop diversification index, cropping intensity and percentage of marginal and small farmers, percent area under paddy and irrigated land (Table 2).

Adaptive capacity: Adaptive capacity is the third indicator of vulnerability index. It is the ability or potential of a system to adjust to climate variability and extremes, and to cope with its consequences. The major indicators of adaptive capacity are literacy rate, farm holding size, area under food crops, main workers and marginal workers (Table 3).

Iyengar and Sudershan's unequal weight method is used

Table 1. Indicators for exposure

Indicators	Description of the indicator	Unit	Hypothesized relation
Change in Climate variables (from selected base year)	Change in maximum and minimum temperature	Coefficient of trend	+ve
	Change in rainfall	Coefficient of trend	+ve

Table 2. Indicators for sensitivity

Indicators	Description of the indicator	Unit	Hypothesized relation
Percent Rural population	Rural population/Total population × 100	Per cent	+ve
Crop diversification Index	Simpson index	Unit less	-ve
Cropping intensity	Gross cropped area under agriculture with reference to net cropped area under agriculture	Per cent	-ve
Percentage of marginal and small farmers	Percentage	Per cent	+ve
Percent area under paddy	Paddy area/net area sown × 100	Per cent	+ve

Table 3. Indicators for adaptive capacity

Indicators	Description of the indicator	Unit	Hypothesized relation
Literacy rate	Proportion of persons aged 15 years or older who are able to read and write	Per cent	+ve
Farm holding size	Average farm size	Hectare	+ve
Area under food crops	How much area under food crops	Thousand hectare	+ve
Main workers	Number of total main worker	Number	+ve
Marginal workers	Number of marginal workers	Number	+ve

to work out a composite index from multivariate data. The determination of the weights in this manner would ensure that large variation in any one of the indicators would not unduly dominate the contribution of the rest of the indicators and also distort inter-regional comparisons. The vulnerability index is the sum of exposure and sensitivity minus adaptive capacity. A lower index value implies low vulnerability, whereas a larger value indicates high vulnerability. The districts are classified into three categories; low, medium, and high using the Jenks optimization method in ArcGIS 10.2.2 software. It is one of the methods of data clustering into different classes (Chaudhary and Sirohi 2022).

RESULTS AND DISCUSSION

The classification of districts based on vulnerability using a single index value facilitates the identification of shifts in vulnerability status across the districts of Punjab state. The study also presents below the descriptive statistics for the variables assessed regarding exposure, sensitivity, and adaptive capacity at the state level.

Descriptive statistics: The mean value of exposure during 1990 and 2020 was observed at 0.43 and 0.48, respectively showing an increase of 11.63 per cent in the last four decades. The trend of maximum temperature is more or less the same, but minimum temperature and rainfall declined over time attributed to the increased exposure of agriculture.

In case of sensitivity, the mean value was 0.18 during 1990 and 0.83 during 2020 which increased about five times during the study period. The percent rural population is declining in Punjab over time due to urbanization and migration. During 1990 to 2020, Simpson crop diversification index declines from 0.65 in 1990 to 0.41 in 2020 due to adoption popular wheat-paddy crop rotation which provided assured income to the farmers. Changing tenancy structure of the state (Sharma 2010) due to increase in the lease-in land over time (Sachdeva et al 2017), resulted in the decline in the proportion of marginal and small farmers in the state over time. Significant increase in the per cent paddy area to net area sown was found to be the major factor responsible for increasing the sensitivity in the Punjab state (Ali et al 2017).

The mean value for adaptive capacity was recorded 0.09 during 1990 and 0.49 during 2020 showing five times increase in last 40 years. The mean value of the vulnerability index was found 0.52 in the year 1990 and 0.82 for the year 2020 which showed an increase of 57.69 per cent. Increased average literacy rate, number of marginal workers and average farm size holdings were the major factors contributing to the increase in adaptive capacity of across the districts of the Punjab state. The decline in main workers and non-workers along with decrease in area under food crops has decreased the adaptive capacity.

Indicator-wise analysis of vulnerability index

Exposure assessment: Exposure refers to the presence of people, ecosystems, and assets that are vulnerable to negative impacts in specific areas, as defined by the IPCC (2014). In the context of the table provided, the regions of Punjab (Majha, Doaba, and Malwa) display different exposure levels for the years 1990 and 2020, reflecting changes over time due to climatic variations. In 1990, Majha had a relatively high exposure index of 0.47, indicating significant vulnerability, but by 2020, this index decreased to 0.19, suggesting reduced exposure. This reduction could be attributed to less variation in climatic factors in this region, similar to how some districts moved from high to low exposure. Conversely, the Doaba region saw an increase in exposure from 0.19 in 1990 to 0.86 in 2020, reflecting greater susceptibility over time, possibly due to higher variability in climate patterns, such as temperature and rainfall trends.For the Malwa region, there was a moderate shift from 0.29 in 1990 to 0.4 in 2020, signifying an increase in exposure, though not as drastic as in Doaba region.

Overall, the combined index for Punjab shows an increase from 0.37 in 1990 to 0.61 in 2020, suggesting that the state as a whole became more exposed to potential risks, primarily due to fluctuating climate variables like temperature and rainfall, paralleling the observed shifts in district-level exposure.

Sensitivity assessment: The degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. The effect may be direct (e.g., increase in area under paddy due to assured irrigation through power subsidy) or indirect (e.g., decrease in crop diversification due to assessed grain market in the state) (Fig. 3). The sensitivity index measures how susceptible a region is to adverse impacts when exposed to risks, such as climate variability. The sensitivity of different regions in Punjab-Majha, Doaba, and Malwa-over the years 1990 and 2020 is compared. In Majha, the sensitivity index decreased from 0.57 in 1990 to 0.38 in 2020, indicating that this region became less vulnerable over time. This could be due to adaptive measures or a decrease in the factors that heighten vulnerability, such as dependency on sensitive ecosystems or agriculture practices that were more prone to climate change impacts in the past. Doaba, on the other hand, experienced a substantial increase in sensitivity, from 0.35 in 1990 to 0.92 in 2020. This sharp rise suggests that the region became more vulnerable to adverse effects, possibly due to changes in agricultural patterns, water availability, or socio-economic factors, making it more susceptible to environmental stressors. For Malwa, the sensitivity index also increased significantly, from 0.08 in 1990 to 0.59 in 2020, reflecting growing vulnerability in this region. The increase indicates that previously, Malwa had a relatively low sensitivity to environmental changes, but over time, it has become more sensitive, likely due to shifts in land use, resource depletion, or socio-economic pressures.

Overall, the combined sensitivity index for Punjab decreased slightly from 0.83 in 1990 to 0.72 in 2020. While some regions like Majha showed improved resilience, the overall sensitivity remains high, largely due to the significant increases in Doaba and Malwa. This reflects a complex interplay of environmental and socio-economic factors, where certain areas have become more adaptable, while others have seen their vulnerability increase

Adaptive capacity: The adaptive capacity index measures the ability of a region to adjust to, mitigate, or recover from adverse impacts, such as those caused by climate change (Table 5, Fig. 4). In Majha, the adaptive capacity index increased from 0.38 in 1990 to 0.6 in 2020, indicating that the region has improved its ability to cope with and adapt to changing conditions. This could be due to better infrastructure, technology adoption, or improved socio-economic conditions that enhance resilience against environmental challenges. Doaba saw a dramatic improvement in adaptive capacity, with the index rising from 0.13 in 1990 to 0.79 in 2020. This suggests significant advancements in the region's ability to manage and mitigate the effects of climate change, likely through improved agricultural practices, access to resources, and development initiatives aimed at increasing resilience. In Malwa, the adaptive capacity also increased, though less drastically, from 0.04 in 1990 to 0.48 in 2020. While this is a notable improvement, it shows that Malwa had very low adaptive capacity in 1990, and despite the progress, it remains

Table 5. Indicator-wise analysis of vulnerability index

Indices	1990	2020
Exposure (Index)		
Majha	0.47	0.19
Doaba	0.19	0.86
Malwa	0.29	0.40
Overall Index	0.37	0.61
Sensitivity Index	1990	2020
Majha	0.57	0.38
Doaba	0.35	0.92
Malwa	0.08	0.59
Overall Index	0.83	0.72
Adaptive capacity (Index)	1990	2020
Majha	0.38	0.60
Doaba	0.13	0.79
Malwa	0.04	0.48
Overall Index	0.47	0.88

Table 4. Descriptive statistics of selected variables (Mean ± SD)

Variables	1990	2000	2010	2020
Exposure	0.43 ± 0.23	0.45 ± 0.21	0.39 ± 0.23	0.48 ± 0.26
Minimum temperature (Coefficient of trend)	0.06 ± 0.001	0.06 ± 0.01	0.07 ± 0.01	-0.03 ± 0.01
Maximum temperature (Coefficient of trend)	0.04 ± 0.01	0.04 ± 0.01	-0.02 ± 0.02	0.03 ± 0.01
Rainfall (Coefficient of trend)	27.13 ± 20.08	-11.41 ± 11.62	16.06 ± 12.70	-26.71 ± 18.5
Sensitivity	0.18 ± 0.18	0.58 ± 0.32	0.61 ± 0.29	0.83 ± 0.19
Rural population (%)	71.9 ± 8.79	68.96 ± 11.46	66.15 ± 13.02	66.65 ± 12.7
Crop diversification index	0.65 ± 0.19	0.68 ± 0.05	0.65 ± 0.05	0.41 ± 0.19
Cropping intensity (%)	163.56 ± 24.49	182.89 ± 11.69	188.56 ± 11.51	190.48 ± 8.24
Marginal and small farmers (%)	46.21 ± 10.09	29.97 ± 13.30	33.94 ± 13.58	34.70 ± 12.13
Area under paddy (%)	5.81 ± 3.94	32.27 ± 8.83	18.05 ± 6.21	73.60 ± 18.46
Adaptive capacity	0.09 ± 0.14	0.39 ± 0.18	0.56 ± 0.18	0.49 ± 0.21
Literacy rate (%)	40.55 ± 7.95	68.79 ± 8.56	74.32 ± 7.11	74.79 ± 7.13
Main worker (number)	508198 ± 341217	455043 ± 255951	385596 ± 257789	363597 ± 246608
Marginal worker (number)	10478 ± 9022	75981 ± 42914	68921 ± 34709	65747 ± 33795
Non-worker (number)	1006858 ± 443334	895975± 532088	859995± 489541	811181 ± 471823
Area under food crops (000' ha)	479 ± 171	385 ± 201	345 ± 156	321 ± 138
Farm size holdings (ha)	3.61 ± 0.97	4.36 ± 1.20	3.81 ± 1.34	4.18 ± 2.05

somewhat less adaptive compared to other regions. This could indicate that while efforts have been made to enhance resilience, challenges such as resource limitations or socio-economic constraints persist.

The overall adaptive capacity index for Punjab rose significantly from 0.47 in 1990 to 0.88 in 2020. This overall increase suggests that, as a state, Punjab has greatly improved its capacity to adapt to environmental and climatic challenges. The rise in adaptive capacity indicates better preparedness, likely through improved infrastructure, agricultural techniques, and policy interventions aimed at sustainability. This enhanced adaptive capacity positions the state to better withstand future environmental and socio-economic pressures.

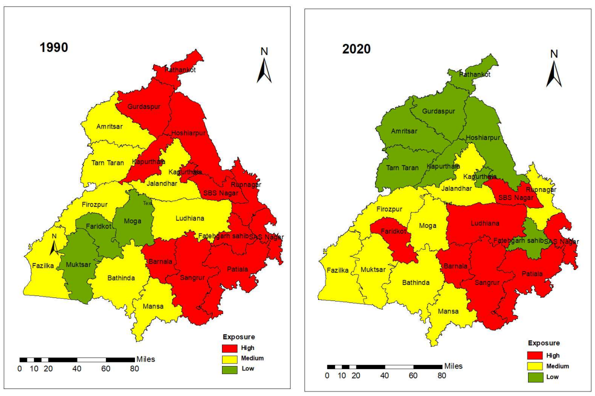

Fig. 2. Exposure composite index among districts of Punjab, 1990 and 2020

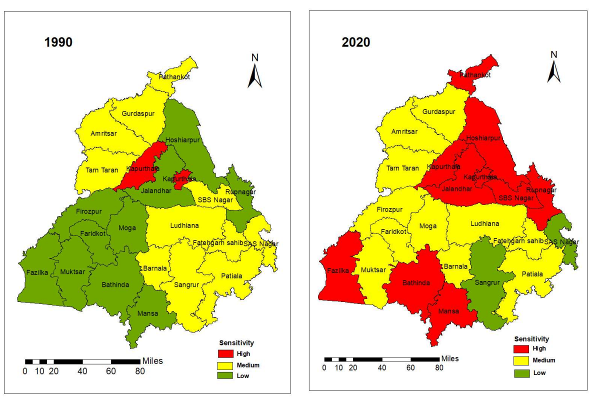

Fig. 3. Sensitivity composite index among districts of Punjab, 1990 and 2020

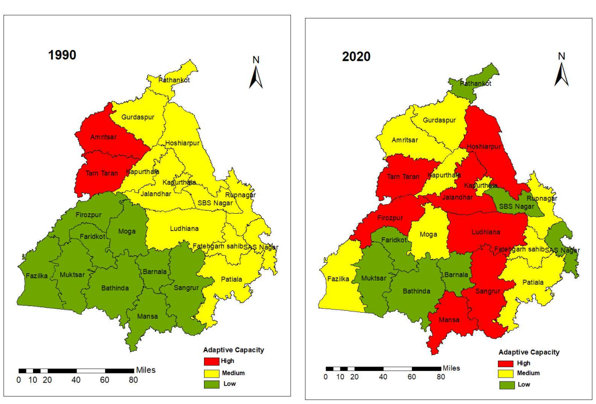

Fig. 4. Adaptive capacity composite index among districts of Punjab, 1990 and 2020

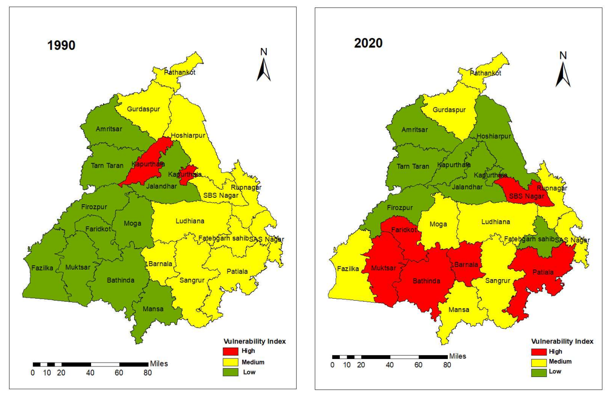

Fig. 5. Vulnerability composite index among districts if Punjab, 1990 and 2020

Table 6. District-wise comparison of vulnerability index between 1990 and 2020

District	1990	2020
Amritsar	0.45	0.5
Barnala	0.00	1.00
Bathinda	0.52	1.00
Faridkot	0.10	1.00
Fatehgarh Sahib	0.52	0.53
Fazilka	0.52	0.75
Firozpur	0.52	0.55
Gurdaspur	0.74	0.68
Hoshiarpur	0.16	0.48
Jalandhar	0.65	0.27
Kapurthala	0.00	0.61
Ludhiana	0.55	0.91
Mansa	0.52	0.77
Moga	0.10	0.75
Sri Muktsar Sahib	0.10	1.00
Pathankot	0.74	0.91
Patiala	0.52	1.00
Rupnagar	0.23	0.97
Sangrur	0.00	0.96
SAS Nagar	0.52	0.67
SBS Nagar	0.52	1.00
Tarn Taran	0.45	0.34

District-wise analysis of vulnerability index: Vulnerability is the propensity or predisposition to be adversely affected (Table 6). Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

The vulnerability analysis across the districts in Punjab between 1990 and 2020 reveals significant shifts in exposure to environmental risks. Several districts, such as Barnala, Bathinda, Faridkot, Sri Muktsar Sahib, Patiala, SBS Nagar, and Sangrur, which were categorized as low or moderately vulnerable in 1990, saw a sharp increase in their vulnerability index, reaching close to or at 1.00 by 2020. This shift highlights the increasing susceptibility of these regions to climatic and environmental changes over time. The rise in vulnerability in districts like Rupnagar and Ludhiana further emphasizes the growing concerns related to resource degradation and climate variability. In contrast, districts like Jalandhar and Tarn Taran exhibited a decline in vulnerability, shifting from moderate levels in 1990 (0.65 and 0.45, respectively) to low levels in 2020 (0.27 and 0.34). This reduction in vulnerability indicates some improvement in resilience and adaptive capacity within these regions. Hoshiarpur, Kapurthala, and Gurdaspur, which initially had moderate exposure, remained in similar vulnerability classes, showing more stability over the decades. Furthermore, the analysis identifies districts like Fazilka, Moga, and Mansa as regions that shifted from low to moderate vulnerability. These districts, along with others that have become more exposed, are reflective of the variability in environmental stressors, such as fluctuations in temperature and rainfall patterns, which contribute to rising risks.

Overall, the findings suggest that while some districts have made strides in reducing vulnerability, a significant portion of Punjab has experienced worsening conditions, particularly in the Malwa region. This trend underscores the need for targeted interventions to mitigate environmental risks and enhance adaptive capacities, especially in districts that have transitioned from being relatively safe to highly vulnerable over the past three decades.

CONCLUSIONS

In conclusion, while Punjab's agriculture has been a cornerstone of India's food security since the Green Revolution, significant challenges such as groundwater depletion and paddy stubble burning have emerged over time, necessitating government interventions to enhance adaptive capacity. Despite these efforts, the region remains vulnerable due to decreased agricultural diversification, driven by market assurances for grains and improved irrigation facilities. This study highlights a concerning upward trend in climatic vulnerability, underscoring the urgent need to enhance adaptive capacity alongside reducing sensitivity. Strategies such as promoting crop diversification through cooperatives, implementing a "one district, one product" initiative, and enhancing literacy and labor force participation are essential to mitigate vulnerability. Additionally, fostering the establishment of new farmer producer organizations (FPOs) and NGOs, coupled with training programs and the dissemination of climate-resilient technologies, can significantly bolster the region's capacity to adapt and thrive in the face of climatic challenges.

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