

Assessing the impact of climate variations on wheat yield in north-west India using GIS

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Abstract We analyzed the spatial and temporal variations (40 years from 1974–75 to 2013–14 with an interval of four decades) in wheat yield as influenced by the three important potential determinants (climate, fertilizers and irrigation) in the three regions (North-west, Central and South-west) of Indian Punjab. Wheat productivity in Punjab has increased linearly at 60–64 kg ha⁻¹ year⁻¹. Although linear increase in productivity can be attributed to technological developments but large year-to-year oscillations depicted the effects of climatic variations. Mann–Kendall and Sen’s slope estimator statistical tests indicated that majority of the trends in maximum temperature and rainfall in different regions were not significant, but there was a significant increase in minimum temperature at 0.053 °C year⁻¹ in north-east, at 0.047 °C year⁻¹ in central and 0.044 °C year⁻¹ in south-west regions of Punjab. Step-wise regression was used to assess the relative influence of three determinants (climate, fertilizer and irrigation) on yield. Minimum temperature explained 44% of variability in yield. Out of the remaining 56% variability, 44% variability in wheat yield was explained by irrigation availability and 7% by fertilizer application. The spatial interpolation showed the decade-wise shift in area towards higher productivity, higher temperature and lower rainfall during the wheat growing season.

Keywords Climate · GIS · Non-parametric statistical test · Spatial interpolation · Wheat

1 Introduction

Wheat, an important cereal crop, is the staple food for billions of people. Climate change and global warming scenarios are adversely affecting wheat productivity in different regions of the world. Wheat requires cool climate during its early growth stages for expressing potential productivity. Higher temperature during the early growth period is unfavorable for tillering, while during later growth stages, it reduces the duration of grain formation and hinders proper grain filling. A rise of global surface temperature within the range of 0.4–2.6 °C by 2046–2065 and 0.3–4.8 °C by 2081–2100 relative to the reference period of 1986–2005 has been predicted [1]. In the Indo-Gangetic plains, the average temperature is predicted to increase by 0.5–1.0 °C during mid twenty-first century, by 3.5–4.5 °C rise towards the end of the twenty-first century and anticipates an increased frequency of extremely wet rainy seasons [2]. An increase in atmospheric temperature and carbon dioxide concentration, and altered precipitation under climate change are likely to have adverse impacts on agricultural productivity. Despite ongoing improvements in technology and crop varieties, weather and climate are still the main uncontrollable factors affecting agricultural production [3]. Changing temporal and spatial trends of hydro-climatic variables, rising sea levels and increasing incidence of extreme events pose new risks to future food insecurity over all parts of the globe [4, 5]. Anomalies in temperature and climatic regime of our earth system have raised the concerns that global climate change is a strong stressor for agriculture and world food production, as

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plants are directly related, and respond, to environment CO_2 and temperature [6].

Predictions of warming scenarios in future are likely to have severe impacts on wheat productivity. Crops would respond positively to increased CO_2 in the absence of climatic variability but the associated impacts of changing temperatures, rainfall pattern and frequency of damaging events (like floods) may unite to decrease yield and increase risks in agricultural productivity in different parts of the world [7]. The highly populated Asian countries have started suffering from the negative impacts of climate change [8, 9]. The most significant negative changes are observed for developing countries in Asia where 4–10% decrease in agricultural production are predicted under different socio-economic and climate change scenarios. Rising temperatures have been reported to reduce the wheat productivity by 40–45% [10]. Increase in temperature by $0.5\text{ }^\circ\text{C}$ resulted in decrease in the duration of wheat crop by 7 days which reduced the yield by 0.5 ton per hectare in north-India [11]. There is a possible loss of 4–5 million tons in wheat production in India with every $1\text{ }^\circ\text{C}$ rise in temperature, even after considering carbon fertilization, without other adaptation benefits and changes in irrigation water availability [12].

Indian Punjab is one of the most fertile regions on earth. However, temperature and rainfall fluctuations experienced during recent years have already started taking a toll on wheat productivity in the region. In Central Punjab, a significant increasing trend in minimum temperature (at $0.06\text{ }^\circ\text{C year}^{-1}$) and decreasing trend in sunshine hours (at 0.03 h day^{-1}) and wind speed (0.03 km h^{-1}) during wheat growing period was observed [13]. It was found that lower minimum temperature, relative humidity, rainfall and number of rainy days during the reproductive growth period of wheat (February and March) were favorable for higher grain yield. These results suggest that there is a need to evaluate the climate variability impact on productivity of wheat on regional level so that management strategies can be worked out accordingly. The integration of climate and yield data using geographic information system (GIS) is finding increasing application in crop-specific modeling of agricultural production. The use of remote sensing and GIS along with field and collateral data helps in deriving and assessing the important parameters required for environmental impact assessment [14]. In the present study, we analyze the spatial and temporal variation in wheat yield in Punjab for 40 years as influenced by the three important potential determinants climate, fertilizers and irrigation.

2 Study area, materials and methods

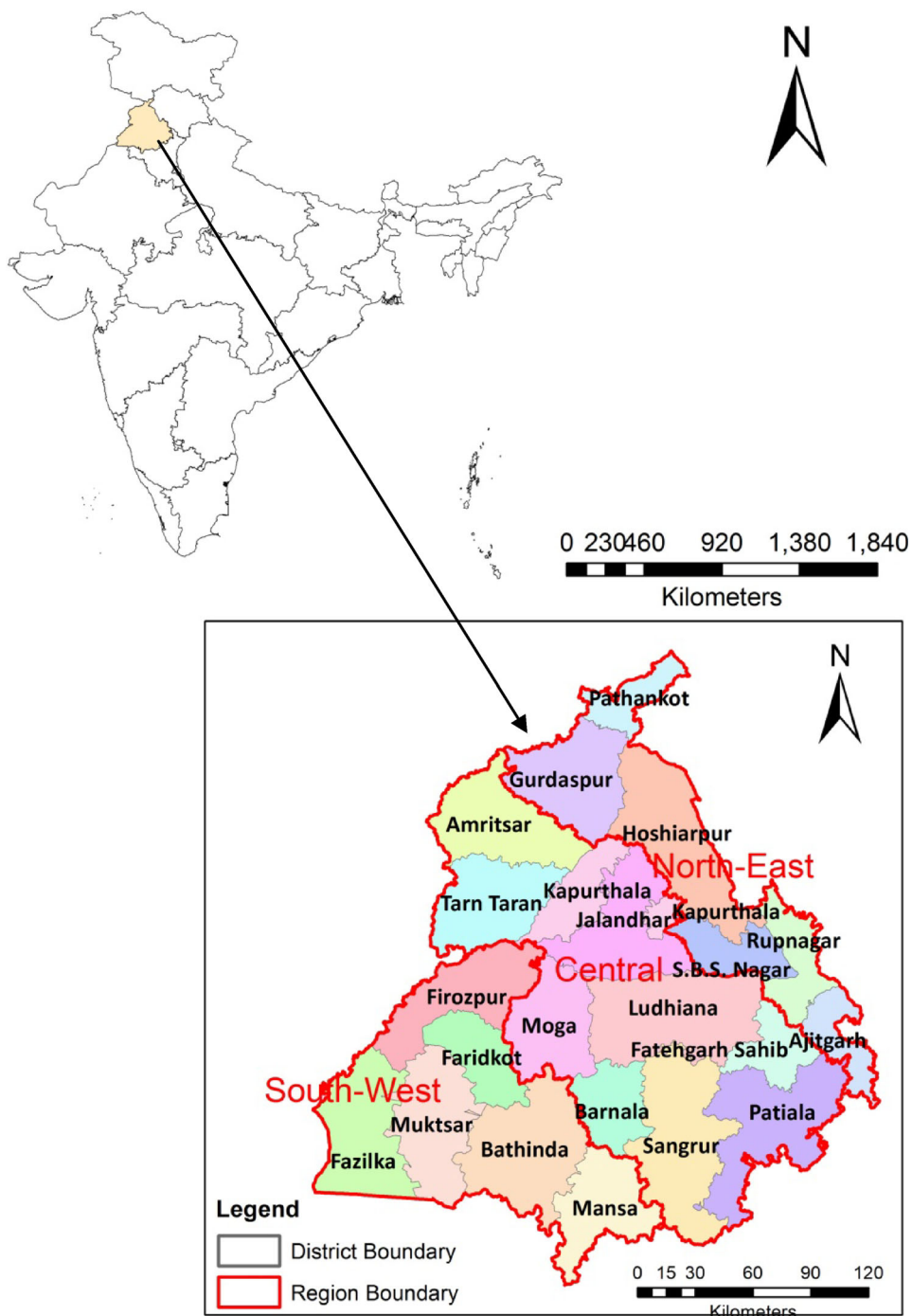
This study was conducted for Punjab, covering the north-west region of Indo-Gangetic plains of India. It extends from $29^\circ33'\text{N}$ to $32^\circ31'\text{N}$ and from $73^\circ55'\text{E}$ to $76^\circ55'\text{E}$ covering an area of 50,362 sq. km, which is 1.54% of country's total geographical area (Fig. 1). The climate of Punjab is dominantly semi-arid and monsoon type, which is highly influenced by the Himalayas in the north and north-east as well as the Thar Desert in the south and south-west. The major part of the rainfall is received from monsoon between the months of July and September, which is essential for growing summer (*Kharif*) crops and subsequent sowing of winter (*rabi*) crops. Rainfall is also received from western disturbances during winter season. Based on the climatic variability in different regions, the whole state was divided into three regions: North-east, Central and South-west.

Wheat yield and three climatic parameters (maximum temperature, minimum temperature and rainfall) during wheat growing period (November to March) from 1974–75 to 2013–14 for 22 locations were collected from different sources including Statistical Abstracts of Punjab, India Meteorological Department and Punjab Agricultural University, Ludhiana. The data of fertilizer consumption and irrigated area was also collected from Statistical Abstracts of Punjab.

The following statistical techniques were used to find the trend and interpolation of wheat yield and climate parameters:

- (a) Descriptive statistics (mean, standard error and coefficient of variation) was used for studying temporal variation in wheat yield, rainfall, minimum and maximum temperature.
- (b) Non-parametric methods: In this study, two non-parametric methods (Mann–Kendall and Sen's slope estimator) were used to detect the meteorological variables' trends. Mann–Kendall test evaluates whether meteorological values tend to increase or decrease over time. The Mann–Kendall test analyzes the sign of the difference between later-measured data and earlier-measured data [15]. Each later-measured value is compared to all values measured earlier, resulting in a total of $n(n - 1)/2$ possible pairs of data, where n is the total number of observations. In this test, the difference between the later-measured value and all earlier-measured values, $(y_j - y_i)$, where $j > i$, is calculated. The test statistic, S , is then computed as the sum of the integers:

Fig. 1 Location of the study area



Where sign $(y_j - y_i)$ is equal to $-1, +1$ or 0 . The variance associated with S is calculated from the following equations:

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^m t_k(k-1)(2t_k+5)}{18}$$

where m is the number of tied groups and t_k is the number of data points in group k . The standardized

Mann–Kendall test statistic Z which follows the standard normal distribution with mean of zero and variance of one is given by

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & \text{for } S > 0 \\ 0 & \text{for } S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & \text{for } S < 0 \end{cases}$$

When the Z values computed by above equations are greater than the critical values of Z at a given level of significance, the null hypothesis (no trend in the data) is rejected. The positive values of S indicate an increasing trend, the negative values a decreasing trend and the smaller values no trend. If a significant trend is found, the rate of change can be calculated using the Sen slope estimator [16].

$$Q = \text{median} \left(\frac{y_j - y_i}{x_j - x_i} \right)$$

for all $i < j$ and $i = 1, 2, \dots, n - 1$ and $j = 2, 3, \dots, n$. The median of those slopes is the Sen slope estimator.

- (c) Stepwise regression: It was used to identify the climate factors (rainfall, maximum- and minimum temperature) affecting wheat yield and the relationship of residuals with fertilizer and irrigation. In stepwise regression, only one independent variable is considered at a time and another variable is added to the model at each step until no significant improvement in percentage of explained variance is obtained. The

regression analysis was performed by SPSS Statistical Software 17.0

- (d) Interpolation of wheat yield and climate parameters: Spatial distribution of wheat yield and climate parameters was carried out by using Inverse Distance Weighted (IDW) Method in Arc GIS 9.3. IDW is a type of deterministic method for multivariate interpolation with a known scattered set of points. The assigned values to unknown points are calculated with a weighted average of the values available at the known points.

3 Results

3.1 Temporal and spatial variability in wheat yield

There was an increase in wheat yield in the three regions of Punjab from 1974–75 to 2013–14 (Table 1). Trend analysis showed a linear increase in wheat yield in different regions of the state (Fig. 1S, Supporting Information). The rate of increase was $61 \text{ kg ha}^{-1} \text{ year}^{-1}$ in north-east,

Table 1 Temporal variability in wheat yield and climate parameters during its growing period in different regions of Punjab (India)

| Region/parameter | 1974–75 to 1983–84 | 1984–85 to 1993–94 | 1994–95 to 2003–04 | 2004–05 to 2013–14 |
|---|--------------------|--------------------|--------------------|--------------------|
| Average Yield (kg ha^{-1}) \pm SE | | | | |
| North-east region | 2219 \pm 71.58 | 3240 \pm 165.37 | 3429 \pm 89.40 | 4032 \pm 126.59 |
| Central region | 2840 \pm 102.98 | 3757 \pm 122.70 | 4423 \pm 106.26 | 4629 \pm 110.69 |
| South-west region | 2779 \pm 107.25 | 3401 \pm 95.47 | 4246 \pm 118.44 | 4578 \pm 125.95 |
| State average | 2613 \pm 96.20 | 3466 \pm 126.56 | 4033 \pm 105.09 | 4413 \pm 118.48 |
| State range | 2055–3302 | 2992–4118 | 2524–4560 | 3914–4852 |
| Maximum temperature ($^{\circ}\text{C}$) \pm SE | | | | |
| North-east region | 21.2 \pm 0.26 | 21.7 \pm 0.20 | 21.6 \pm 0.27 | 21.7 \pm 0.46 |
| Central region | 22.6 \pm 0.25 | 23 \pm 0.23 | 22.9 \pm 0.27 | 23.1 \pm 0.25 |
| South-west region | 24.4 \pm 0.32 | 24.7 \pm 0.22 | 24.6 \pm 0.28 | 23.4 \pm 0.47 |
| State average | 22.7 \pm 0.27 | 23.1 \pm 0.22 | 23.0 \pm 0.28 | 22.7 \pm 0.36 |
| State range | 20.5–25.8 | 21.1–26.2 | 21.0–26.2 | 20.3–23.4 |
| Minimum temperature ($^{\circ}\text{C}$) \pm SE | | | | |
| North-east region | 7.2 \pm 0.16 | 7.6 \pm 0.09 | 7.8 \pm 0.22 | 9.0 \pm 0.39 |
| Central region | 7.7 \pm 0.22 | 8.1 \pm 0.11 | 8.4 \pm 0.25 | 8.9 \pm 0.21 |
| South-west region | 7.9 \pm 0.19 | 8.4 \pm 0.09 | 8.6 \pm 0.22 | 9.2 \pm 0.28 |
| State average | 7.6 \pm 0.20 | 8.0 \pm 0.10 | 8.3 \pm 0.23 | 9.0 \pm 0.27 |
| State range | 6.7–8.0 | 6.5–8.8 | 7.3–8.9 | 8.1–10.0 |
| Rainfall (mm) \pm SE | | | | |
| North-east region | 193.7 \pm 31.19 | 290.1 \pm 17.72 | 141.6 \pm 24.49 | 118.4 \pm 21.85 |
| Central region | 142.2 \pm 25.6 | 108.3 \pm 18.1 | 109.2 \pm 19.6 | 88.7 \pm 18.1 |
| South-west region | 71.7 \pm 7.5 | 60.1 \pm 10.8 | 55.5 \pm 11.5 | 50.9 \pm 10.7 |
| State average | 135.9 \pm 22.45 | 152.8 \pm 16.20 | 102.1 \pm 18.79 | 86 \pm 17.17 |
| State range | 67.3–234.7 | 57.4–173.6 | 44.4–163.3 | 40.7–151.8 |

SE standard error

60 kg ha⁻¹ year⁻¹ in central and 64 kg ha⁻¹ year⁻¹ in the south-west region. Spatial interpolation of wheat yield showed that a larger area of the state had wheat yield of 2000–3000 kg ha⁻¹ from 1974–75 to 1983–84. During 1984–85 to 1993–94, most parts of the state produced more than 3000 kg ha⁻¹ but the part of central plains produced 4000–4200 kg ha⁻¹. The yield was further increased in the third decade (from 1994–95 to 2003–04) and the average yield was 3800–4800 kg ha⁻¹. In the last decade (2003–04 to 2013–14), wheat yield in the larger area of the state was 4400–4800 kg ha⁻¹ with one or two pockets of central plains produced > 5000 kg ha⁻¹ during this decade (Fig. 2).

3.2 Temporal and spatial climate variability during wheat growing period

3.2.1 Maximum temperature

Decade-wise analysis did not show any significant pattern of variability in maximum temperature during wheat season, but large fluctuations were depicted during different decades. Average maximum temperature was observed 22.7 °C with a range of 20.5–25.8 °C during 1974–75 to 1983–84, 23.1 °C with a range of 21.1–26.2 °C during 1984–85 to 1993–94, 23.0 °C with a range of 21.0–26.2 °C during 1994–95 to 2003–04 and 22.7 °C with a range of 20.3–23.4 °C during 2004–05 to 2013–14 (Table 1). Results of the applied Mann–Kendall and Sen's slope estimator statistical tests for maximum temperature are presented in Table 2. As shown, the majority of the trends in maximum temperature in different decades were not significant (Fig. 2S, Supporting Information and Table 2). On a seasonal timescale over the period of 40 years, a significant increasing trend was observed in February and March in the north-east region and in March in the central region, but a significant decreasing trend in January in central and south-west regions.

Spatial variability of maximum temperature showed a shift in area from lower to higher temperature (Fig. 3). During 1974–75 to 1983–84, the parts of north-east regions had maximum temperatures of 19–21 °C, whereas south-western parts experienced 23–25 °C. Maximum temperature increased by 2 °C over the following decade (1984–85 to 1993–94) in the areas with maximum temperature of 19–21 °C during the first decade (1974–75 to 1983–84). The area under 23–25 °C expanded in the last two decades (1994–95 to 2013–14), indicating an increase in maximum temperature in all of the regions.

3.2.2 Minimum temperature

Minimum temperature increased from 7.2 °C to 9.0 °C in the north-east region, from 7.7 to 8.9 °C in the central region and from 7.9 to 9.2 °C in the south-west region during 74–75 to 2013–14 (Table 1). There were large yearly fluctuations in minimum temperature in all of the regions (Fig. 3S). Based on Mann–Kendall and Sen's slope estimator statistical tests, the majority of the trends in minimum temperature across different months of all the three decades were not significant. Over the period of 40 years, a significant increasing trend was observed during wheat growing period in all the three regions of Punjab. During wheat growing period from November to March, the rate of increase in minimum temperature was highest in March (Table 3).

Spatial interpolation showed the higher minimum temperature in the south-west than north-east part of the state. During the first two decades, parts of the state had a minimum temperature of 6–8 °C, whereas other area had minimum temperature of 8–10 °C (Fig. 4). However, during 1994–95 to 2003–04, an area under 6–8 °C decreased, but an area under 8–10 °C increased, indicating a shift in the area from 6–8 to 8–10 °C. During the recent decade, the whole state had a minimum temperature of 8–10 °C, indicating an increasing trend in minimum temperature during wheat season in the state.

3.2.3 Rainfall

The rainfall was significantly higher in the north-eastern region followed by central and lowest in the south-western region. There was a slight decrease in rainfall in all of the regions of Punjab, but Mann–Kendall and Sen's slope estimator statistical tests did not show any significant trend, thereby indicating a highly erratic nature of rainfall during wheat season in the state (Fig. 4S, Supporting Information and Table 4). Spatial interpolation showed a decreasing trend of rainfall over a period of four decades in the state during wheat season. During 1974–75 to 1984–85, south-western parts of the state had < 100 mm rainfall followed by 100–200 mm in most of the central and 200–300 mm in the parts of north-eastern regions (Fig. 5). During 1984–95 to 1993–94, the area under 200–300 mm rainfall shifted to 100–200 mm and the entire state experienced up to 200 mm rainfall, with extension in areas under < 100 mm rainfall during the past decades.

3.2.4 Relative importance of climate parameters, fertilizer and irrigation

Among three climatic variables, 44% of the variance in wheat yield was explained by minimum temperature. The

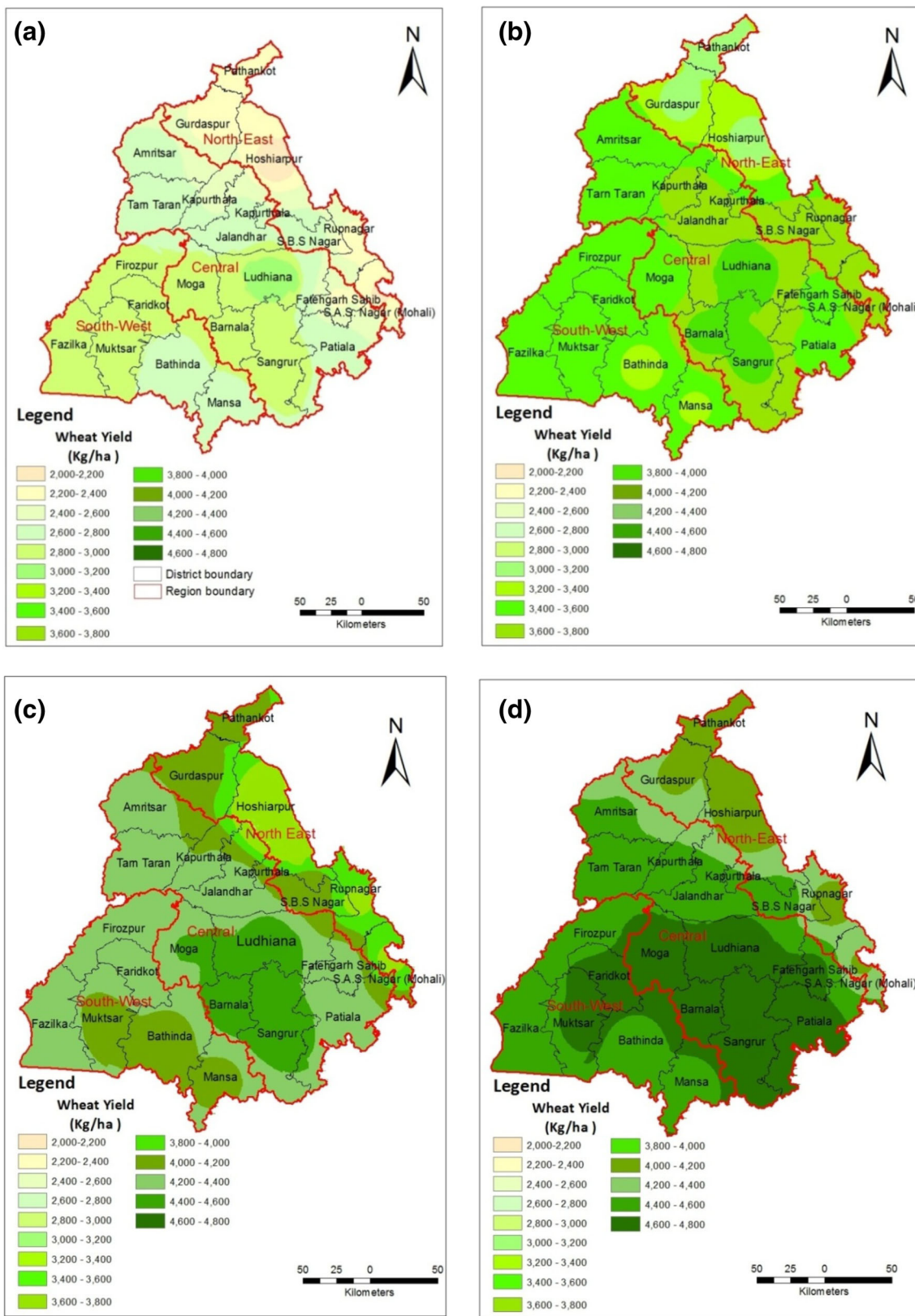


Fig. 2 Spatio-temporal variability in wheat productivity from **a** 1974–75 to 1983–84, **b** 1984–85 to 1993–94, **c** 1994–95 to 2003–04 and **d** 2004–05 to 2013–14 in Punjab (India)

Table 2 Results of the statistical tests for variability in maximum temperature during wheat growing season in different regions of Punjab (India)

| Period | Test | 1974–75 to 1983–84 | 1984–85 to 1993–94 | 1994–95 to 2003–04 | 2004–05 to 2013–14 | 1974–75 to 2013–14 |
|-------------------|------|--------------------|--------------------|--------------------|--------------------|--------------------|
| North-east region | | | | | | |
| November | Z | - 1.431 | 1.431 | 0.000 | 0.000 | 1.153 |
| | Q | - 0.144 | 0.076 | 0.004 | 0.031 | 0.018 |
| December | Z | - 0.537 | 1.789 | 0.894 | 0.000 | 0.804 |
| | Q | - 0.060 | 0.169 | 0.134 | 0.002 | 0.015 |
| January | Z | - 0.179 | - 0.537 | 0.000 | 0.090 | 0.303 |
| | Q | - 0.019 | - 0.054 | - 0.031 | 0.001 | 0.003 |
| February | Z | - 0.716 | 0.358 | 0.358 | 1.431 | 2.657** |
| | Q | - 0.082 | 0.065 | 0.075 | 0.260 | 0.054 |
| March | Z | - 1.789 | - 1.968* | 0.179 | 0.808 | 3.449*** |
| | Q | - 0.445 | - 0.380 | 0.026 | 0.170 | 0.100 |
| Rabi season | Z | - 1.968* | - 0.358 | 0.179 | 0.358 | 2.365* |
| | Q | - 0.088 | - 0.032 | 0.024 | 0.071 | 0.028 |
| Central Region | | | | | | |
| November | Z | - 1.431 | 0.537 | 0.716 | 0.894 | 1.876 |
| | Q | - 0.116 | 0.039 | 0.029 | 0.107 | 0.023 |
| December | Z | - 0.894 | 1.252 | 0.716 | - 0.716 | - 0.454 |
| | Q | - 0.082 | 0.138 | 0.086 | - 0.101 | - 0.008 |
| January | Z | 0.000 | - 0.894 | - 1.073 | - 1.073 | - 2.342* |
| | Q | 0.029 | - 0.099 | - 0.110 | - 0.184 | - 0.035 |
| February | Z | - 0.894 | 0.000 | 0.716 | - 0.894 | 1.084 |
| | Q | - 0.079 | 0.027 | 0.080 | - 0.149 | 0.019 |
| March | Z | - 1.789 | - 1.789 | 0.894 | 0.894 | 3.157** |
| | Q | - 0.480 | - 0.482 | 0.108 | 0.217 | 0.087 |
| Rabi season | Z | - 1.789 | - 0.537 | 0.537 | - 0.358 | 1.619 |
| | Q | - 0.100 | - 0.055 | 0.065 | - 0.056 | 0.018 |
| South-West region | | | | | | |
| November | Z | - 1.431 | 0.000 | 0.000 | - 0.358 | - 0.548 |
| | Q | - 0.145 | 0.009 | 0.004 | - 0.038 | - 0.007 |
| December | Z | - 0.537 | 0.894 | 0.894 | - 0.179 | - 1.783 |
| | Q | - 0.099 | 0.041 | 0.100 | - 0.121 | - 0.027 |
| January | Z | - 0.894 | - 1.252 | - 0.179 | - 1.610 | - 3.414*** |
| | Q | - 0.096 | - 0.045 | - 0.071 | - 1.125 | - 0.050 |
| February | Z | - 0.894 | 0.000 | 0.000 | - 1.252 | - 0.676 |
| | Q | - 0.088 | - 0.006 | - 0.002 | - 0.282 | - 0.010 |
| March | Z | - 1.431 | 1.073 | 0.000 | - 0.179 | 1.503 |
| | Q | - 0.458 | 0.159 | 0.067 | - 0.121 | 0.046 |
| Rabi season | Z | - 2.326* | - 0.537 | 0.179 | - 1.968* | - 1.946 |
| | Q | - 0.124 | - 0.067 | 0.037 | - 0.396 | - 0.034 |

Z: Mann–Kendall test, Q: Sen's slope estimator

*Statistically significant trends at the 5% significance level; **statistically significant trends at the 1% significance level; ***statistically significant trends at the 0.1% significance level

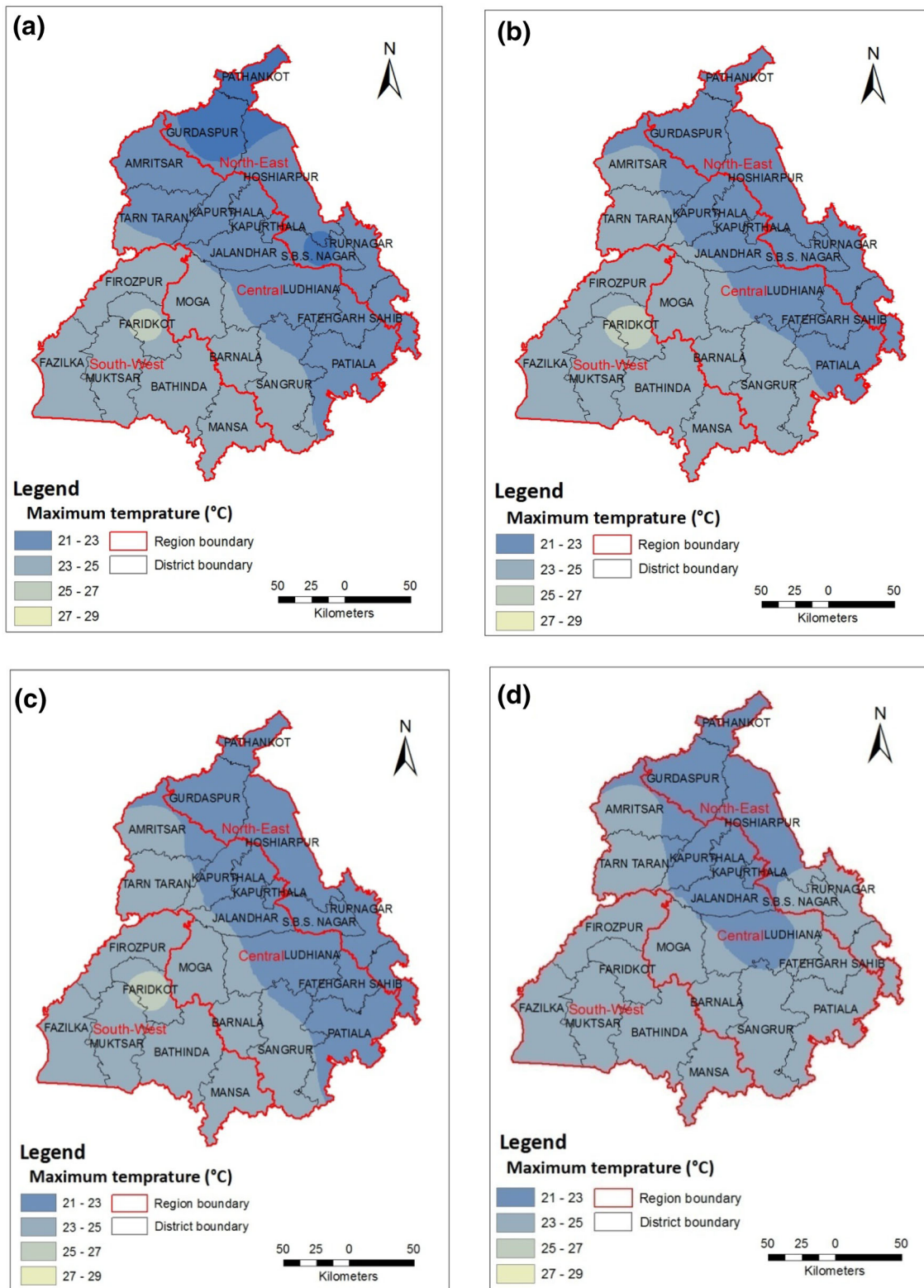


Fig. 3 Spatio-temporal variability in maximum temperature during wheat growing season from **a** 1974–75 to 1983–84, **b** 1984–85 to 1993–94, **c** 1994–95 to 2003–04 and **d** 2004–05 to 2013–14 in Punjab (India)

Table 3 Results of the statistical tests for variability in minimum temperature during wheat growing season in different regions of Punjab (India)

| Period | Test | 1974–75 to 1983–84 | 1984–85 to 1993–94 | 1994–95 to 2003–04 | 2004–05 to 2013–14 | 1974–75 to 2013–14 |
|-------------------|------|--------------------|--------------------|--------------------|--------------------|--------------------|
| North-east region | | | | | | |
| November | Z | 0.358 | 0.894 | 1.610 | 1.073 | 3.554*** |
| | Q | 0.127 | 0.069 | 0.167 | 0.232 | 0.063 |
| December | Z | 0.537 | 0.537 | 1.431 | 1.252 | 3.845*** |
| | Q | 0.065 | 0.068 | 0.140 | 0.302 | 0.060 |
| January | Z | 0.894 | 1.252 | 0.000 | 0.000 | 1.992* |
| | Q | 0.050 | 0.141 | – 0.026 | 0.019 | 0.025 |
| February | Z | 1.252 | 1.431 | 1.252 | 0.358 | 3.763*** |
| | Q | 0.093 | 0.280 | 0.095 | 0.071 | 0.070 |
| March | Z | – 1.073 | – 1.886 | 0.358 | 0.269 | 3.647*** |
| | Q | – 0.117 | – 0.236 | 0.031 | 0.050 | 0.073 |
| Rabi season | Z | 0.179 | – 0.179 | 1.252 | 1.073 | 4.509*** |
| | Q | 0.021 | – 0.014 | 0.073 | | 0.053 |
| Central region | | | | | | |
| November | Z | 0.894 | 1.252 | 2.147* | 0.000 | 2.901** |
| | Q | 0.456 | 0.118 | 0.202 | 0.010 | 0.049 |
| December | Z | 0.358 | 0.716 | 1.610 | 0.000 | 2.458* |
| | Q | 0.037 | 0.092 | 0.183 | 0.010 | 0.045 |
| January | Z | 1.073 | 1.252 | 0.179 | – 0.179 | 1.736 |
| | Q | 0.122 | 0.172 | 0.035 | – 0.048 | 0.027 |
| February | Z | 1.610 | 1.610 | 1.431 | – 0.894 | 3.554*** |
| | Q | 0.189 | 0.297 | 0.112 | – 0.156 | 0.063 |
| March | Z | – 0.179 | – 2.326* | 1.073 | 0.179 | 3.996*** |
| | Q | – 0.035 | – 0.206 | 0.139 | 0.002 | 0.071 |
| Rabi season | Z | 1.431 | 0.537 | 2.504* | 0.000 | 4.602*** |
| | Q | 0.169 | 0.076 | 0.165 | 0.003 | 0.047 |
| South-west region | | | | | | |
| November | Z | 0.716 | 0.358 | 1.252 | 0.358 | 2.994** |
| | Q | 0.216 | 0.030 | 0.159 | 0.081 | 0.056 |
| December | Z | 0.537 | 0.716 | 1.610 | 0.358 | 2.645** |
| | Q | 0.042 | 0.088 | 0.103 | 0.108 | 0.039 |
| January | Z | 1.252 | 1.431 | – 0.179 | – 0.179 | 1.550 |
| | Q | 0.074 | 0.187 | – 0.025 | – 0.065 | 0.022 |
| February | Z | 1.252 | 1.610 | 1.073 | 0.358 | 3.390*** |
| | Q | 0.213 | 0.256 | 0.115 | 0.020 | 0.060 |
| March | Z | – 0.537 | – 2.236* | 0.179 | 0.000 | 3.833*** |
| | Q | – 0.026 | – 0.222 | 0.038 | – 0.043 | 0.060 |
| Rabi season | Z | 1.252 | 0.000 | 1.252 | 0.000 | 4.416*** |
| | Q | 0.073 | – 0.008 | 0.080 | – 0.014 | 0.044 |

Z: Mann–Kendall test, Q: Sen's slope estimator

*Statistically significant trends at the 5% significance level; **statistically significant trends at the 1% significance level; ***statistically significant trends at the 0.1% significance level

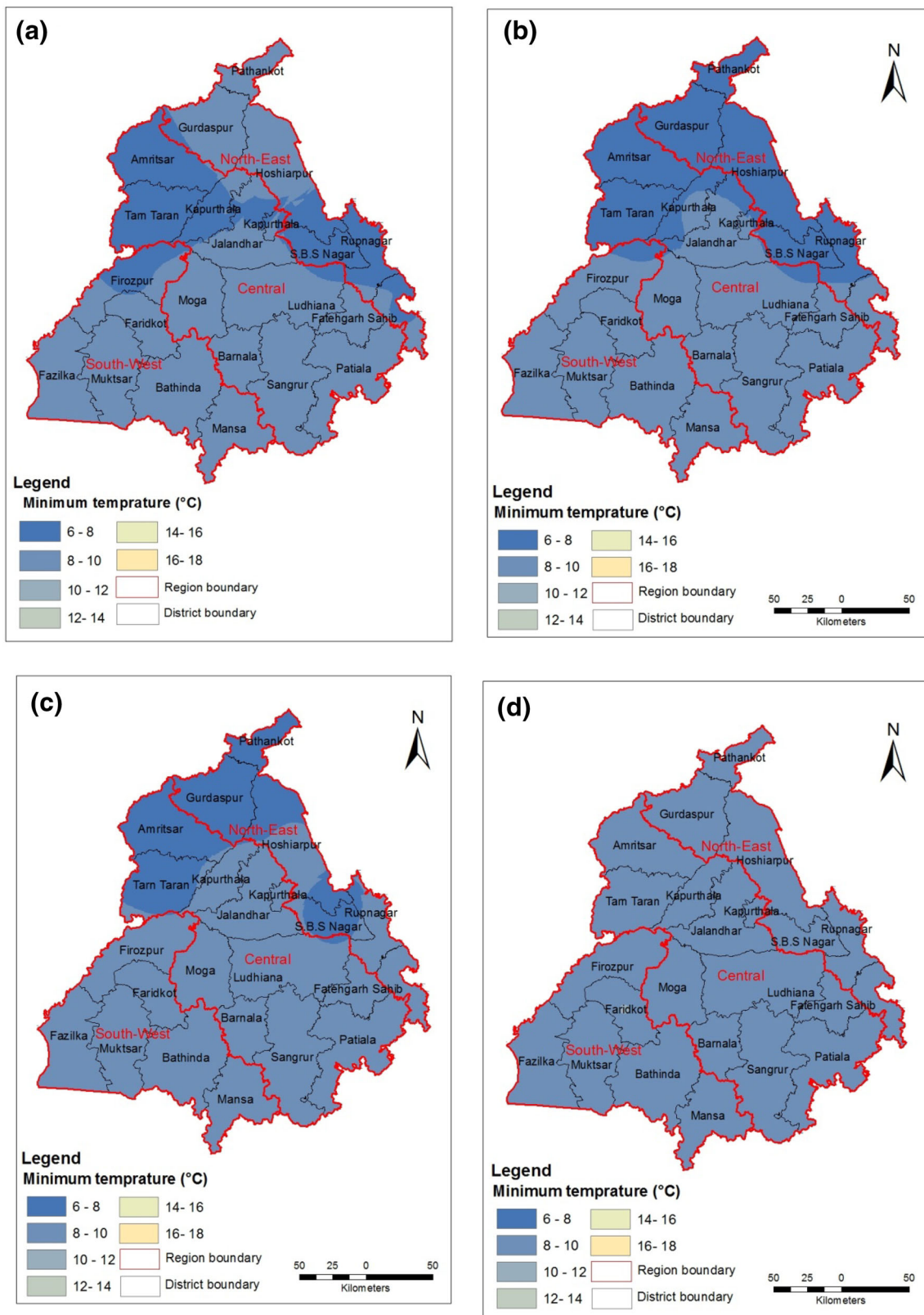


Fig. 4 Spatio-temporal variability in minimum temperature during wheat growing season from **a** 1974–75 to 1983–84, **b** 1984–85 to 1993–94, **c** 1994–95 to 2003–04 and **d** 2004–05 to 2013–14 in Punjab (India)

Table 4 Results of the statistical tests for variability in rainfall during wheat growing season in different regions of Punjab (India)

| Period | Test | 1974–75 to 1983–84 | 1984–85 to 1993–94 | 1994–95 to 2003–04 | 2004–05 to 2013–14 | 1974–75 to 2013–14 |
|-------------------|------|--------------------|--------------------|--------------------|--------------------|--------------------|
| North-east region | | | | | | |
| November | Z | 1.669 | – 0.179 | 0.999 | – 0.179 | 0.129 |
| | Q | 2.892 | – 0.183 | 0.213 | – 0.388 | 0.000 |
| December | Z | 0.716 | – 0.358 | 0.894 | 0.000 | 0.117 |
| | Q | 0.313 | – 0.928 | 0.479 | – 0.200 | 0.013 |
| January | Z | 1.610 | 0.358 | – 0.894 | – 0.537 | – 0.722 |
| | Q | 7.950 | 1.075 | – 4.525 | – 2.600 | – 0.314 |
| February | Z | 0.537 | 0.000 | – 1.073 | 0.716 | – 0.128 |
| | Q | 3.393 | 2.250 | – 4.481 | 2.792 | – 0.084 |
| March | Z | 1.610 | 1.968* | 1.073 | 0.000 | – 1.410 |
| | Q | 10.629 | 5.050 | 2.375 | 0.138 | – 0.658 |
| Rabi season | Z | 2.504* | 0.716 | – 0.537 | 0.179 | – 1.247 |
| | Q | 4.707 | 1.325 | – 1.183 | 0.580 | – 0.292 |
| Central region | | | | | | |
| November | Z | 1.854 | 0.629 | – 0.454 | – 0.269 | 0.118 |
| | Q | 1.433 | 0.111 | – 0.221 | – 0.086 | 0.000 |
| December | Z | 0.629 | – 0.716 | 0.894 | 1.431 | 0.210 |
| | Q | 0.133 | – 0.840 | 0.817 | 1.041 | 0.026 |
| January | Z | 2.147* | 1.347 | – 0.537 | – 1.252 | – 0.233 |
| | Q | 6.158 | 1.033 | – 1.214 | – 2.925 | – 0.052 |
| February | Z | 0.894 | 0.000 | 0.000 | 0.537 | 0.151 |
| | Q | 2.385 | – 0.783 | – 0.483 | 0.978 | 0.036 |
| March | Z | 1.252 | 0.179 | 0.358 | 0.090 | – 1.352 |
| | Q | 9.056 | 0.925 | 0.739 | 0.233 | – 0.443 |
| Rabi season | Z | 2.862** | 0.358 | – 0.179 | – 0.179 | – 1.340 |
| | Q | 4.184 | 0.433 | – 0.087 | – 0.137 | – 0.157 |
| South-west region | | | | | | |
| November | Z | 1.854+ | – 0.269 | 0.102 | 0.192 | – 0.474 |
| | Q | 0.150 | – 0.010 | 0.000 | 0.000 | 0.000 |
| December | Z | 1.262 | – 0.091 | 0.556 | – 0.361 | 0.342 |
| | Q | 0.329 | 0.000 | 0.089 | – 0.388 | 0.000 |
| January | Z | 1.431 | 0.716 | – 0.894 | – 0.537 | – 0.268 |
| | Q | 3.238 | 0.279 | – 1.613 | – 0.250 | – 0.029 |
| February | Z | 0.269 | – 0.537 | 0.000 | 0.716 | 1.003 |
| | Q | 0.208 | – 1.258 | 0.060 | 3.775 | 0.163 |
| March | Z | 0.988 | – 0.537 | – 0.537 | – 0.272 | – 1.830 |
| | Q | 2.813 | – 1.313 | – 0.510 | – 0.800 | – 0.275 |
| | Z | 1.610 | – 0.358 | – 0.894 | 0.000 | – 0.920 |
| | Q | 1.317 | – 0.053 | – 0.420 | – 0.164 | – 0.078 |

Z: Mann–Kendall test, Q: Sen's slope estimator

*Statistically significant trends at the 5% significance level; **statistically significant trends at the 1% significance level; ***statistically significant trends at the 0.1% significance level

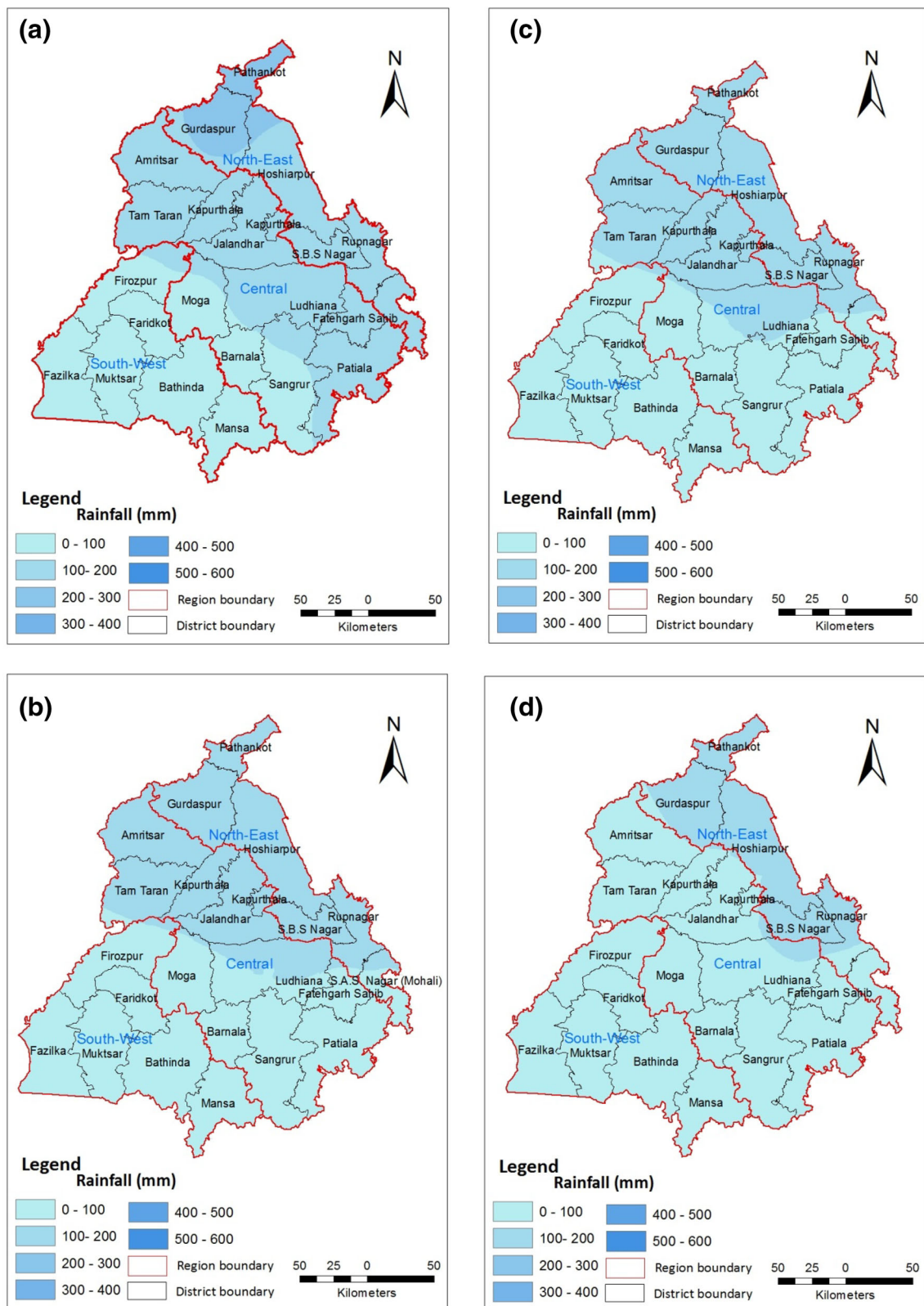


Fig. 5 Spatio-temporal variability in rainfall during wheat growing season from **a** 1974–75 to 1983–84, **b** 1984–85 to 1993–94, **c** 1994–95 to 2003–04 and **d** 2004–05 to 2013–14 in Punjab (India)

relationship of residual of wheat yield was studied with irrigation and fertilizers. Out of the remaining 56% variation, 44% variation in wheat yield was explained by irrigation availability and 7% by fertilizer application. It shows that minimum temperature is one of the main determinants affecting wheat yield in Punjab.

4 Discussion

A linear increase in wheat productivity was observed in the Indian Punjab, but annual oscillations can be attributed to biotic (disease, insect-pest etc.) and abiotic (temperature, rainfall etc.) stresses. In general, there was an increase in minimum temperature and decrease in rainfall. Over the period of four decades, fertilizer consumption in Punjab has increased from 41 to 218 kg ha⁻¹, total cropped area from 5950 to 7870 thousand ha and irrigated area from 78 to 99% during the period from 1974–75 to 2013–14. There was not any single parameter explained the major variations in wheat yield, but it was the combined effect of different meteorological and technological variables particularly minimum temperature, irrigation and fertilizer during its growing period. Wheat yield is affected when any of the meteorological and technological parameters undergoes significant variation from normal. Among climate variables, minimum temperature significantly affected wheat yield. Increase in minimum temperature can have detrimental effect on wheat productivity in the region. An average yield loss of 217 kg ha⁻¹ (4.5%) during a heat wave year and a gain of 356 kg ha⁻¹ (7.4%) during a cold wave year has been reported under Punjab conditions [17]. Between the two continuous cold wave years, wheat yield was higher by 400 kg ha⁻¹ in the relatively colder year (2011–2012). Wheat yield was observed to be more sensitive to minimum temperature especially during post-anthesis period [18]. Increase in minimum temperature results in shortening of cool period for wheat [19, 20]. Intra-seasonal variability indicated the highest rate of increase in minimum temperature during February and March in all the regions of state, which is particularly detrimental because it coincides with the grain filling period of the crop. This leads to a significant reduction in grain size and yield due to increased respiratory losses and decreased net photosynthesis under the effect of increase in minimum temperature [18]. In Central Punjab, average wheat yield during 2011–12 was 5.38 t ha⁻¹ but it decreased by 0.53 t ha⁻¹ during 2012–13 [13]. The higher yield in 2011–12 was mainly due to favorable weather conditions (like lower minimum temperature, relative humidity, rainfall and number of rainy days) during the reproductive growth period (February and March) of wheat [13]. These

results suggest that inter- and intra-seasonal weather fluctuations lead year-to-year variability in crop yield.

There were large variations in rainfall over 40 years but it decreased over the years. This warns of an increasing pressure on water resources in the state. The water resources are already over-exploited in most of the regions of Punjab which may affect wheat yield [21]. It was observed that rainfed wheat biomass could decrease by 90, 72 and 53% with rainfall reduction of 65, 50, and 30%, respectively [22].

These results suggest that adjustments are necessary to counter balance the negative impacts of changing climate [23]. Farmers must have the ability to adjust to changes by adapting farming practices. Since rice–wheat is the main cropping system in Punjab, growing of short duration varieties of rice to ensure timely sowing of wheat and adoption of minimum tillage in the rice–wheat system for earlier emergence of wheat can help in avoiding terminal heat stress. In addition to this, weather forewarning for agricultural practices can also play a significant role in predicting and managing the effect of climate change on crop yields and water requirements.

5 Conclusions

This study has analyzed the impact of climate, irrigation and fertilizer on wheat yield in Punjab. Our study indicates that minimum temperature has significant impact on wheat yield, regardless of irrigation and fertilizers. Significant increase in minimum temperature can have detrimental effects on wheat productivity in the coming years and is of great concern for food security in the region. Although irrigation facilities are available in the region, ground water resources are being depleted at alarming rate. This requires careful planning of judicious water resources, but erratic rainfall and its decreasing reliability can further aggravate the problem. Under such conditions, adaptation strategies need to be devised to meet food security in view of future climatic changes and their likely impacts on wheat productivity in the region. Adaptations such as changes in crop varieties, improved water management and irrigation systems, changes in planting schedules and tillage practices will all be important in limiting the negative effects and taking advantage of the beneficial effects of changes in climate. The study concludes that both climate and technology need to be considered in future policy development and spatio-temporal differences in observed yield allow interpretation of potential determinants that are important for food policy development in Punjab.

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