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Wheat yield response to input and socioeconomic factors under changing climate: Evidence from rainfed environments of Pakistan

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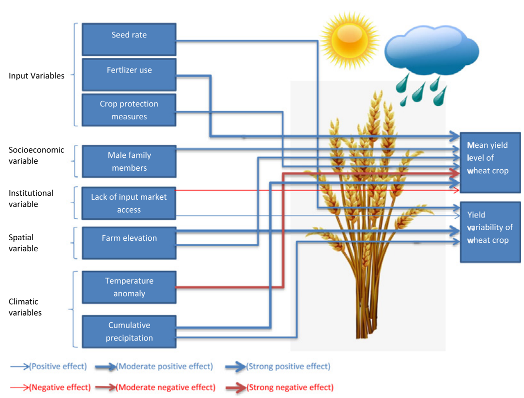
HIGHLIGHTS

- Analyzes the empirical relationship between climate variability, wheat mean yield, and yield variability
- Temperature anomaly (rise in temperature) lowers mean wheat yields.
- Cumulative precipitation increases both mean yield and yield variability.
- Lack of access to input markets causes a reduction in mean yield levels and increases yield variability.
- Timely and appropriate adaptation measures are needed to sustain and enhance wheat yields, hence food and livelihood security.

GRAPHICAL ABSTRACT



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ABSTRACT

More than three-quarters of the world's total cultivated land is under rainfed farming, producing almost 70% of total food. Most food production comes from developing and least favored nations. Pakistan, a developing country with an agro-based economy, is facing severe threats from climate change. Rainfed agriculture, especially wheat farming, is highly susceptible due to its heavy dependency on precipitation, one of the most important climatic parameters. Wheat is the main food crop, as well as a major source of calorific intake, for millions of people in Pakistan. This study aims to quantify the impacts of climate variability on mean yield levels and yield variability of wheat crop in the rainfed zone of Pakistan. Multistage random sampling technique is used for primary data collection from 400 rainfed wheat farmers during the 2016–17 crop season. The study uses primary data on crop input-output, management, socioeconomic, institutional, and historical climatic data (1980–2017). The data are analyzed employing the Just and Pope (J-P) stochastic production function approach with linear and nonlinear functional forms. The results reveal that temperature rise negatively affects observed wheat mean yields, while cumulative precipitation positively affected it. Further, input market access, seed rate, and cumulative precipitation also cause variability in yield levels, leading to yield instability. Further, farm elevation influences

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wheat mean yield positively while input market access influences it negatively. The findings of the study have important implications for climate resilient wheat farming. Timely and tailor-made adaptations need to be undertaken in the rainfed wheat farming systems of Pakistan. Creating awareness among farmers about the optimal use of agronomic inputs under changing climatic conditions could be an effective adaptation strategy that improves yields and copes with yield instability.

1. Introduction

Climate change is an alarming phenomenon for crop farming, particularly in developing countries. Rising temperatures, varying humidity, and changing precipitation levels lead to crop yield and farm income losses in developing nations (Prudhomme et al., 2003; Xia et al., 2012). A 2018 United Nations (UN) report states that, according to latest estimations, 700 billion USD are required to "*curb climate change and help developing countries withstand its worst impacts*" (UN, 2018). Farming is highly vulnerable to climate variability as it considerably affects crop growth and productivity (Yu et al., 2014; Ahmed et al., 2018). Climate change directly impacts temperature and precipitation, two of the most important parameters affecting rainfed crop farming. The importance of rainfed farming is clear: 80% of the world's agricultural land is under rainfed farming, producing around 70% of global staple foods, including a major share from developing and low-income countries (Sharma et al., 2010).

The existing cereal centered systems across South Asia are under heavy threat, mainly due to climate change and various other challenges, like declining soil health and water availability, that make farming less profitable and less attractive (Yadav et al., 2016). The situation could worsen if urgent and appropriate measures are not initiated: Around 30% of the world's malnourished people live in South Asian countries and climate change is likely to reduce the yields of wheat, maize, millet, and rapeseed in the region (Lobell et al., 2008). Climate change not only affects crop yields, it also affects crop income, farm livelihoods, and the consumption patterns of farmers (Amjath-Babu et al., 2016: Hossain et al., 2019a). Hence, yield losses from unexpected dry periods, floods, and rising temperatures can harm the livelihoods of farmers throughout the region (Wassmann et al., 2009; Lobell et al., 2012). There is a dire need to increase food supplies while combating climate variability in order to meet the food requirements of rapidly growing populations in South Asian countries, including Pakistan. Thus, South Asian countries must double their production of food crops by 2050 via efficient resource-utilization and by reducing environmental harms (Ladha et al., 2016).

Pakistan is an agricultural country comprising arid and semi-arid climates, with 25% of its total cultivated land under rainfed farming. This study focuses on the rainfed cropping zone of Pakistan, where crop farming is heavily dependent on temperature and unpredictable rainfall. Although some literature explores climatic variability and crop farming in Pakistan (Arshad et al., 2017b; Ahmed et al., 2018), the effects of climatic variability on rainfed farming is not yet explored. Therefore, this study attempts to estimate the impacts of changing climate on wheat farming systems in the rainfed zone of Pakistan, where wheat is a major crop. Although climate change affects all crops, those crops on the frontlines are food crops as food insecurity is a major issue in developing countries including Pakistan. In coming decades, rising temperatures and increasing rainfall fluctuations are predicted to further accelerate changes in the distribution and productivity of staple food crops (Loboguerrero et al., 2018).

Wheat is the most popular food grain crop in Pakistan and a major source of calorific intake for the population in its various forms. As the staple diet for millions of people in Pakistan, it comprises the largest share of total farm area under cultivation as well as in production, accounting for 9.1% of value added in agriculture and 1.7% of Pakistan's GDP (GOP, 2018). With its under developed infrastructure and limited adaptive capacity, Pakistan is among countries that are most affected by the climate change (Stocker, 2014). Although the country contributes very little to global warming, its vulnerability to climate variability is increasing (Fahad and Wang, 2018). According to the long-term Climate Risk Index (CRI), Pakistan was ranked at 12th, 8th, and then 7th in 2012, 2015, and 2016, respectively (Kreft et al., 2017). The arid and diverse geographical profile and scarce natural resources make its farming sector one of the most vulnerable sector to climate change (Schilling et al., 2013). In Pakistan, the agriculture sector contributes 18.9% to the overall gross domestic product (GDP), while providing livelihoods to 42.3% of its population (GOP, 2018).

Studies report that Pakistani farming communities are experiencing and perceiving a variety of climate-related risks, including rising temperatures, erratic rainfalls, pest attacks, and limited water availability. Reduced crop yields and water shortage are among the worst effects of climate variability reported by farming communities in Pakistan (Abid et al., 2015; Abid et al., 2016a). There are also studies on climate risk management, adaptations, and determinants of adaptations (Arshad et al., 2016: Abid et al., 2016b; Fahad and Wang, 2018). A few studies examine awareness among farming communities about the existence of the climate change phenomenon and its possible impacts on crop farming (Mustafa et al., 2018). A significant number of agronomic field studies, based on simulation and crop modelling, report negative effects of climate variability on a variety of crop yields (Ahmad et al., 2015; Gorst et al., 2018; Ahmed et al., 2018). Climate variability is also reported to lower the yields and efficiency of rice-wheat cropping systems across different agro-ecological zones in Pakistan (Arshad et al., 2017b; Arshad et al., 2018). According to FAOSTAT (2018), the 4.4% decline in wheat production observed in 2018, as compared to 2017, was mainly due to a water shortage. It means that rainfed wheat farming is under severe danger due to its complete dependency on rainfall for water requirements.

However, the aforementioned studies do not specifically focus on the rainfed cropping zone of Pakistan. Hence, the present study specifically investigates the physical impacts of climate variability on wheat crop farming in the rainfed zone of Pakistan, where livelihoods are mostly at the mercy of agriculture for subsistence. The uniqueness of the present study is centered around two points; first, it is the first zone-specific study that focuses purely on the rainfed (*Barani*) zone of Pakistan. Second, it models a relatively new geographic variable, altitude, recorded separately for each farm household in the selected study region. The study addresses two main research questions; (1) Do the climatic parameters affect the mean yield level of rainfed wheat crop? and (2) Do climatic parameters influence the yield variability of rainfed wheat crops in the presence of other agronomic and farm variables in the rainfed zone of Pakistan?

2. Conceptual and analytical support

2.1. Study area

As rainwater is an important factor underlying crop production in the rainfed zone of Pakistan, the increasing occurrence of weather extremes, including untimely and heavy rains is becoming a major threat (GOP, 2018). The contribution of agronomic inputs, like seed, fertilizers, and chemical crop protection measures, to enhance yield levels is obvious, but the importance of temperature and precipitation cannot be ignored as one-third of the variability in crop yield results from these climatic factors (Ray et al., 2015). Rainfed farming is of high importance in Pakistan as, out of the 23 Mha area under cultivation, around 4 Mha is under rainfed farming. Wheat is the single largest crop in the rainfed zone of Pakistan, with about 33% of the national crop cultivated in this area (Baig et al., 2013). Given these facts, there is an urgent need to estimate the relationship between climate variability and wheat farming in the rainfed zone of Pakistan.

2.2. Conceptual framework

This study follows the production theory i.e. the economic process of converting inputs into outputs. A producer (in this case, a farmer) uses all the required resources to produce a particular output(s) that is suitable for exchange in a market economy and, as a rational producer, they always seek to maximize output (Debertin, 1986).

The conceptual framework on the impact of climate variability on wheat crops in the rainfed zone of Pakistan can be partially explained using the concept of the “Driving force-Pressures-State-Impact-Response” (DPSIR) sustainability framework. Developed by the European Environment Agency (EEA), it is widely used in interdisciplinary impact assessment studies (Smeets and Weterings, 1999). The framework is helpful for describing environmental problems, in particular through the cause and effect relationships (EEA, 1999). Much of the literature using this framework focuses on environment and water issue research (Azarnivand and Chitsaz, 2015). The present study uses the DPSIR framework as a tool to organize sets of comprehensive information, similar to Suckall et al. (2014).

Suckall et al. (2014) also notes that the “Responses” under discussion are the adaptations and copping strategies used by the targeted respondents involved in natural resource based livelihoods. The ‘DPSIR framework’ is shown in Fig. 1. In this framework, *Drivers* of climate change exert *Pressures* and, consequently, *State* changes occur. This *Impacts* crop farming and, subsequently, a *Response* is issued (Turner et al., 1998). Responses must be approachable, maintainable, and technically viable (Elliott, 2013).

Fig. 1 highlights the series of casual relationships, starting with ‘drivers’ (in the present study, climate change) through ‘pressures’ (famers must grow wheat because it is the main food crop of the country), to ‘states’ (the state of the environment is affected through reduced, uneven, and untimely rainfall, along with rising temperatures) causing ‘impact’ (in the form of reduced crop yields, increased yield variability that ultimately could result in food and livelihood insecurity).

The ‘response’ could be in the form of different adaptations, like changing crop varieties, changing sowing dates, changing timings of fertilizer use, land fallowing, and planting shady trees in order to cope the adverse climate change impacts. These particular adaptations against climate change are beyond the scope of this study.

2.3. Analytical background

The existing literature uses different methods to examine the possible impacts of climate change on the agriculture sector; however, the impacts are not yet fully understood (Mendelsohn et al., 1996). The most common approaches to measuring climate change impacts on agriculture are: (1) Crop simulation models; (2) Ricardian approach; (3) Panel data studies; (4) General Equilibrium Models (GEMs); and (5) Just and Pope stochastic production function. Each approach is useful for addressing a particular research objective, coming with unique strengths and weaknesses.

Crop simulation models are commonly used under controlled and calibrated conditions to forecast the impacts of climate change on crop productivity employing different climate scenarios (Parry et al., 2004; Geethalakshmi et al., 2011). Its weakness is that the models are field oriented and purely experiment based, therefore, only focusing on crop physiology and determining yield levels in different climate scenarios without accounting for the adaptation behavior of farmers under changing climatic conditions (Eitzinger et al., 2003).

The Ricardian approach is used to measure the impacts of climate change as well as additional socioeconomic and agronomic variables on farmland values and crop incomes (Kumar, 2009; Deressa and Hassan, 2009; Arshad et al., 2017b; Hossain et al., 2019b). In panel data studies, climate variables, like maximum and minimum temperature, precipitation and relative humidity, are recognized as fluctuating across geography and across time. The approach is extensively used to measure the impacts of climate change on agricultural productivity in developed nations (cf. Seo et al., 2005; Poudel and Kotani, 2013), but reliable panel data on crop input-output and management in case of

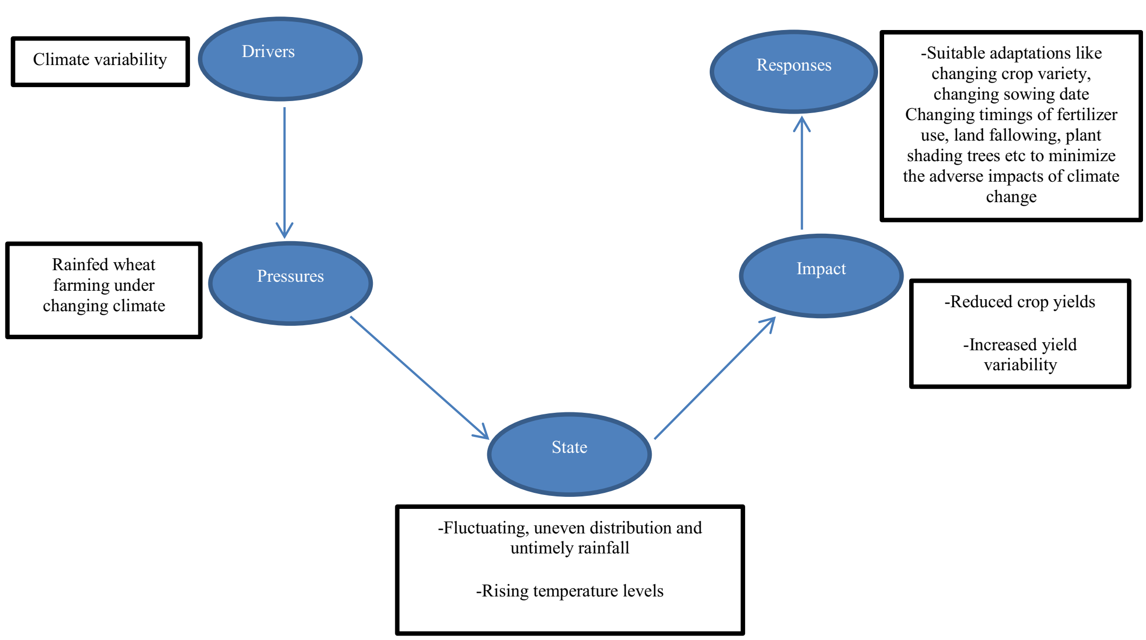

Fig. 1. DPSIR framework showing impacts of climate variability on wheat mean yield and yield variability in rainfed zone of Pakistan.

Pakistan is unavailable (Arshad et al., 2017a). The GEMs link climate change with agriculture, taking into account its connection with other sectors of the economy (Calzadilla et al., 2010). This method examines the composite system of relationships simultaneously (Calzadilla et al., 2013) but suppresses typical features of variables (Mendelsohn and Dinar, 2009). In developing countries, farmers face uncertainty and stochastic threats to agricultural productivity; such uncertainties should be addressed in the production function data distribution.

Therefore, to estimate the stochastic effect of climate variability on yield distributions, the method described by Just and Pope (1978) is used for this study. The main advantage of the J-P model is its flexibility in using farm household level cross-sectional data, including crop input-output and management data, when time series and panel data sets are not available (Koundouri and Nauges, 2005; Guttormsen and Roll, 2014; Arshad et al., 2017a). The J-P production function is widely used in climate and crop farming studies (Sarker et al., 2014; Arumugam et al., 2015; Arshad et al., 2017a, 2017b; Husnain et al., 2018). It provides a clarification of yields with allied yield variability, where the input affects the mean yield level as well as yield variability. Hence, this study uses the Just and Pope production function to measure the impacts of climate variability on mean yield and yield variability of wheat in the rainfed zone of Pakistan.

3. Data collection and estimation technique

3.1. Primary data

The Pakistan Agricultural Research Council (PARC) divides Pakistan into 12 agro-ecological zones, with the current study focusing on the rainfed (*Barani*) zone of Pakistan (PARC, 2015). All 12 agro-ecological zones are different with respect to climate and geography; hence subject to a variety of environmental and socioeconomic constraints. Fig. 2 shows the map of Pakistan and its agro-ecological zones.

The study focuses on the wheat cropping system of the rainfed zone because it is the main food crop cultivated in this zone. Multistage random sampling technique is used to collect primary data. We interviewed 400 wheat farmers, all of whom were growing wheat as their main food crop. The sampling procedure consisted of five stages, we initially selected (1) the rainfed zone as the core study area; and subsequently we randomly selected (2) four out of thirteen districts from the whole rainfed zone; (3) one sub-district (*tehsil*) from each selected district; (4) one union council (*UC*) from each selected tehsil; and finally (5) we interviewed 100 respondents from each UC, all at random.

The primary data were collected using a well-structured and pre-tested survey questionnaire. The survey questionnaire sought detailed information on wheat crop input-output, crop management, as well as farmers' household and farm characteristics. The pre-testing of the questionnaire and final data collection was done by trained field researchers. Following the Kabubo-Mariara and Karanja (2007), and Arshad et al. (2017a, 2017b), this study uses cross-sectional field survey data, observed data of climatic parameters during the study period, and time series data from November 1980 through April 2017 (details are provided in Table 1).

3.2. Secondary data

Climate data from 38 years of weather observations (November 1980 to April 2017) were converted into monthly mean averages of

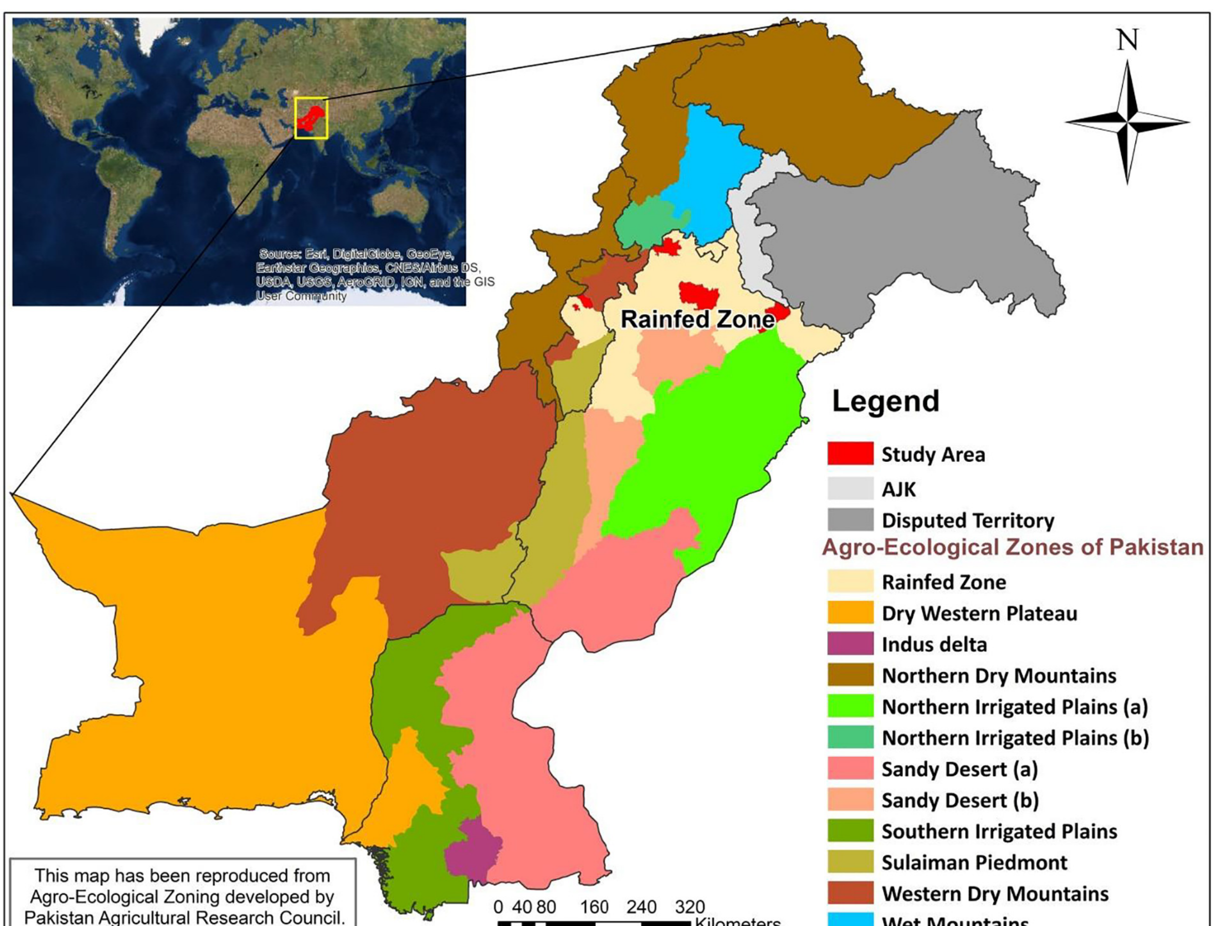

Fig. 2. Map of Pakistan with all 12 agro-ecological zones and highlighted study zone.

Table 1
Summary statistics of the variables used in the models.

Variables	Unit	Mean	Std. dev.	Minimum	Maximum
Dependent variable					
Yield	Kg ha^{-1}	364.52	172.31	80.93	809.37
Explanatory variables					
Altitude of farm[a]					
1	meters	0.29	0.45	0	1
2	meters	0.45	0.50	0	1
Male family members	n	2.69	0.46	1	7
Age of respondent	years	48.98	13.81	18	82
Education of respondent	schooling years	6.52	5.12	0	16
Distance from input market	km	8.86	5.58	0.5	25
Availability of input market within the village of residence[b] (*Mandi*)	n	0.13	0.34	0	1
Area cultivated	Hectare	2.60	2.24	0.40	15.38
Ploughings	Passes season^{-1}	5.99	2.80	1	15
Seed rate	kg ha^{-1}	102.14	17.61	59.30	148.26
Farmyard manure	kg ha^{-1}	10,141.19	9940.64	0	39,536.80
Nitrogen-phosphorus[c]	kg ha^{-1}	92.30	52.73	0	192.74
Chemical crop protection measures (fungicides, pesticides & herbicides)	liters ha^{-1}	1.81	1.83	0	7.41
Cumulative precipitation during wheat season	mm	229.2104	98.99	96.71	340.69
Deviation of the wheat season's cumulative precipitation from historical mean	mm	−85.66	64.54	−166.60	−18.63
Deviation of the wheat season's mean temperature from historical mean	°C	1.88	1.69	−0.011	4.60

[a] Altitude is a categorical variable with 1 = low altitude, 2 = moderate altitude & 3 = high altitude, with base 3 = high altitude.
[b] It is a binary variable with 1 = yes & 0 = no.
[c] Kilograms of nitrogen and phosphorus were calculated form the Urea and di-ammonium phosphate (DAP) fertilizer bags used during wheat growing season.

temperature and cumulative precipitation for the wheat growing season. The deviation of the wheat season's mean temperature from the historical mean (temperature anomaly) and wheat season's cumulative precipitation were also calculated and used in the analysis. Data of climatic parameters were collected from the Pakistan Metrological Department (PMD) for all the meteorological stations located in each selected district of the rainfed zone of Pakistan. Climate data were then abstracted according to the season during which the wheat crop is grown, from early November to end April (Ahmad et al., 2014).

3.3. Estimation technique and model specification

To examine the effect of climatic variability on mean yield level and yield variability, we use the J-P stochastic production function (Just and Pope, 1978). The J-P production function provides not only an estimate of the effect of the explanatory variables on the expected mean yield level but also their effect on the yield variability. Koundouri and Nauges (2005) state that the basic concept of the idea proposed by Just and Pope is to construct a production function as the sum of two components; one linked with the output level and the other to the variability of the output. This type of model specification allows the econometrician to distinguish the impact of inputs on output and output variability. The first step in our analysis is to investigate whether any significant yield variability (as measured by yield variance) is observable. For this, the Breusch and Pagan (1980) test is applied to the null hypothesis that our models are homoscedastic such that no yield variability is present. This is followed by the estimation of two separate production functions, including both mean and variance functions that employ a maximum likelihood estimator to the wheat crop. Both parts of this model allow the agronomic management and climatic variables to affect the mean yield level of wheat as well as yield variability, on an independent basis. The J-P production function used in this study has the following specification:

$$Y = f\ (X, \alpha) + v\ (X, \beta)\ \epsilon$$

where 'Y' is a measure of yield level, '$f(\cdot)$' is deterministic component of the mean yield level function, 'X' is a vector of explanatory variables, 'α' is vector of estimable parameters associated with 'X', '$v\ (\cdot)$' is a "variability function" associated with 'X', 'ϵ' is heteroscedastic noise term and 'β' is a vector of estimable parameters associated with the variability function. The explanatory variables include climate variables (wheat growing season's cumulative precipitation and deviation of wheat growing season's mean temperature from the historical mean). Spatial variables include farm altitude (where we categorized the farm households into farm with low altitude as '1', farm with moderate altitude as '2', and farm with high altitude as '3'). Socioeconomic variables include number of male family members, as well as the age and education of the respondent; institutional variables include distance from input market and the presence of a small market within the village as a dummy variable; input variables include area under cultivation, seed rate, fertilizer use, farm yard manure, and chemical crop protection measures like fungicides, herbicides, and pesticides. All the analyses were conducted using STATA V. 15.1 (Stata Corporation, College Station, Texas).

To estimate the yield functions, accurate specifications of the climate and input variables are essential. Previous studies use either a linear form of the explanatory agronomic variables along with climatic variables (e.g., Holst et al., 2013; Arshad et al., 2017a) or a non-linear production function (e.g., Quiggin and Horowitz, 1999; Horowitz, 2009; Schlenker and Roberts, 2009). Holst et al. (2013) report that it is superior to use a linear form of the yield function when estimating the relationship between crop yields and climatic variables. Our study focuses on estimating the relationship between crop yields and climatic variables plus agronomic inputs, socioeconomic and institutional variables. Hence, we estimate the Just and Pope models with both linear and non-linear functional forms (i.e. quadratic form by taking square of agronomic input variables and climatic variables), reporting the results of both models. We follow the fundamental procedure of Just and Pope (1978) as described by McCarl et al. (2008) and Poudel and Kotani (2013):

(1) Run an ordinary least square regression of yield on independent variables; (2) Regress the logarithm of squared residuals against independent variables, which is reported as the "yield variability" regression in the section of results; (3) Get the predicted values of these residuals, which are calculated as the antilogarithm of the predictions from the second step; and lastly (4) Estimate the original model by weighted least squares (WLS) using the square root of the variance predictions as weights.

4. Results and discussion

4.1. Assessment of homoscedasticity

We perform a Breusch and Pagan (1980) test to assess homoscedasticity. The test reveals the presence of heteroscedasticity (a sign of yield variability). Therefore, the null hypotheses of homoscedasticity is rejected (Table 2). The presence of heteroscedasticity ($Chi^2 = 52.49$) for the wheat model with ($P < 0.000$) directed us to continue with estimating the mean yield and yield variance functions (representative of yield variability) using the maximum likelihood estimators for the wheat crop.

4.2. Impact of climate variability on wheat mean yield and yield variability with linear model

The results of the J-P estimations show that the temperature anomaly is highly significant ($P < 0.01$), with a strong negative effect on the mean yield level of wheat. The large, negative and significant coefficient value of temperature anomaly is due to the fact that there is an overall increase of 1.86 °C during the study period as compared to the historic mean (see Fig. 3). Although the coefficient of the temperature anomaly is negative – -0.3538597 – it does not show a significant effect on the yield variability of wheat. These results imply that wheat farmers in the study area need to be provided with heat resistant wheat varieties. In addition, farmers must adjust their crop management practices based on the historical trend of temperatures if they are to sustain production levels. Similar results are reported by studies conducted in Asia and China (Holst et al., 2013; Arshad et al., 2017a; Husnain et al., 2018). Our results clearly show that warmer temperatures cause a strong reduction (coefficient − 63.06474) in wheat crop yield per hectare for the study period. The coefficient of cumulative precipitation during the wheat growing season is also highly significant ($P < 0.01$), indicating a strong positive effect on the mean yield level. This result is plausible, as wheat farming in the studied rainfed zone largely depends on precipitation levels. Cumulative precipitation during the wheat growing season is also positively associated with yield variability, with the P-value <0.01, indicating large fluctuations in wheat yields.

The rainfed zone of Pakistan is spread across two provinces, namely Punjab and Khyber Pakhtunkhwa (KPK), with altitudes ranging from 226 m to 541 m. This study models "farm altitude" as one of the spatial explanatory variables because studies report a significant relationship between farm elevation and crop yields (Xiao et al., 2008; da Silva and Silva, 2008; Poudel and Kotani, 2013). The surveyed farms are categorized into low elevation (225–350 m), moderate elevation (351–475 m), and high elevation (above 475 m) based on altitude. The results of the J-P estimations show that farm elevation positively, and highly significantly ($P < 0.00$), influences the mean yield level and yield variability of wheat crop for both low and moderate elevation, while taking the high elevation as base of this variable, as shown in Table 3. These results are consistent with Poudel and Kotani (2013) and Da Silva and Silva (2008), who report that yields and elevation are directly related with each other. Poudel and Kotani (2013) also emphasize the heterogeneity of the effects of elevation on crop yield due to changing climate in developing countries. The ultimate impact of changing climate could be positive or negative depending upon season, elevation, and crop type. Similar results on the heterogeneous effects of altitude on crop yield are reported by Xiao et al. (2008).

The number of male family members shows a positive effect ($P < 0.1$) on the mean yield level of wheat crops. This is mainly because, in the rainfed zone of Pakistan, most farms are male headed, given the cultural norms and the very low female participation in field activities in the country overall. Moreover, male farmers are reported to be highly adaptive to changing climate as compared to their female counterparts (Abdul-Razak and Kruse, 2017). Agricultural productivity of male laborers is higher as compared to female laborers (Palacios-López and López, 2015). The number of male family members does not show any significant effects on yield variability. Input market access (measured as distance in kilometers from input markets) has a negative and significant effect ($P < 0.1$) on mean yield level, but a positive and significant effect on yield variability of wheat crop. Farmers' access to input markets is very important in the context of changing climate because it is useful for farmers to be closer to inputs markets in order to acquire better information about new technologies (Murage et al., 2015), along with timely purchases of various agronomic inputs (Katungi et al., 2011; Iqbal et al., 2018). This is also helpful for farmers to make decisions regarding best farm management practices (Abid et al., 2015), with easy market access expected to boost the specialization effect of farmers, ultimately enhancing crop productivity (Katungi et al., 2011). More importantly, the positive effect of input market access on yield variability reveals the importance of locating input markets within the premises of farms to reduce the fluctuations in crop yield levels. This result implies that there is a need to bridge the gap between farms and input markets. Various agronomic inputs, like seed rate, chemical crop protection measures, and fertilizer are used in the model. Fertilizer use (i.e. Nitrogen-Phosphorus) shows a positive and significant effect ($P < 0.05$) on the mean yield level of wheat crops. This result is similar to those reported in various studies (Katungi et al., 2011; Holst et al., 2013; Arshad et al., 2017a). Higher yield levels could be achieved by changing the fertilizer composition because rainfed wheat farmers in the study area only use nitrogen and phosphorus fertilizers and do not use potassium fertilizer (see Appendix 1). The seed rate has no effect on the mean yield level of wheat crop in the study period but has a positive and significant effect ($P < 0.05$) on yield variability. It shows that the seed rate is a potential factor underlying fluctuations in wheat yields. The coefficient of the area under wheat cultivation has no effect, neither on the mean yield level, nor on the yield variability of wheat crops, as reported by Holst et al., 2013 and Poudel and Kotani, 2013. Farmers owning land equal to or <2 ha make up 48.25% of the total farm households (see Appendix A). The non-significance of the variable 'land under wheat crop' on mean yield and yield variability appears to be mainly due to the uneconomical land holdings of the farmers in study area. Other socioeconomic variables, including age and education of the farmers, do not show any significant effect on mean yield and yield variability. This is mainly because one-third (33.25%) of the farmers are illiterate and almost half of the farmers in study area are around the age of fifty years (see Appendix A). Other variables, such as the availability of an input market within the village, chemical crop protection measures (like fungicides, pesticides and pesticides), farmyard manure, and ploughing numbers do not show a significant effect on mean yield level and yield variability of wheat. Only 57.5% farmers in the study area use chemical crop protection measures in small quantities, thus highlighting their negligible effect on crop output for the study period (see Appendix A). Around three-quarters (72%) of rainfed wheat farmers raise only one crop (i.e. wheat) per year in study period.

Table 2
Breusch-Pagan/Cook-Weisberg test details.

Breusch-Pagan/Cook-Weisberg test	Null hypothesis	χ^2	$P > \chi^2$
Wheat crop	Constant variance	52.49	0.0000

4.3. Impact of climate variability on wheat mean yield and yield variability with non-linear model

The results of the non-linear (quadratic) form of J-P production function are shown in Table 4. The significance of a large number of

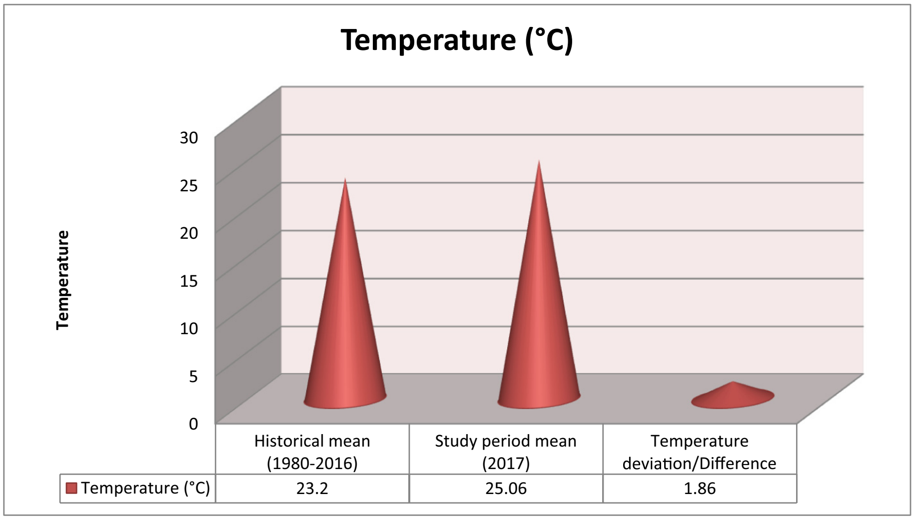

Fig. 3. Deviation of observed wheat cropping season's mean temperature from the historical mean.

variables in non-linear model is in-line with the results of linear model, except for chemical crop protection measures. The significant and positive effect ($P < 0.05$) of this variable on the mean yield level of wheat crop shows that optimally using chemical crop protection measures increases wheat crop productivity (Usman et al., 2012; Hussain, 2015) for study period.

Cumulative precipitation during the wheat crop growth period and temperature anomaly again show a positive-significant ($P <$ 0.05) and negative-significant ($P < 0.05$) effect on the mean yield of wheat crop, respectively. The positive and significant effect ($P <$ 0.05) of cumulative precipitation on yield variability reveals high fluctuations on the crop yield in the study region. It shows the importance of rainfall in the rainfed zone of Pakistan for improving the yields of wheat crops and, ultimately, ensuring the food security in the region. In fact, significant rainfall is essential for ensuring optimal moisture levels that improve wheat crop yields in the rainfed zone of Pakistan (Baig et al., 2013). If rains are sufficient, crop yields will be higher, and vice versa.

A highly significant and positive effect ($P < 0.05$) of nitrogen phosphorus fertilizer use on the mean yield level of wheat crops in the non-linear model shows that there is still scope to increase the amount of fertilizer use, in general, and recommended fertilizer-composition, in particular, for maintaining and boosting the output of wheat crops in study area. Farmers in the study area only use nitrogen phosphorus fertilizer; potash fertilizer is not used (see Appendix A). Even though the recommended ratio of nitrogen, phosphorus, and potash fertilizer in rainfed zone is N:P:K = 80 kg:57 kg:74 kg (PARC, 2018), only 2% of the farmers in study area use the recommended ratio of just nitrogen phosphorus fertilizers and none use potash. The variable of distance of farm from an input market has a negative-significant effect on the mean yield level and a positive-significant effect on yield variability in both models. This reveals the importance of infrastructure development to provide easy access to input markets for farmers: proper access to input markets is directly related to agricultural productivity (Ahmed et al., 2016; Tamene and Megento, 2017). The seed rate shows a positive and significant effect

Table 3
Estimates of the effects of studied climatic parameters on mean yield level and yield variability of wheat crop (kg ha^{-1}) using Just-Pope (J-P) linear model.

	J-P mean yield level		J-P yield variability	
	Coefficient	Std. error	Coefficient	Std. error
Farm altitude	–	–	–	–
'1' for low altitude (meters)	147.2128***	46.53108	1.8189916**	0.7889447
'2' for moderate altitude (meters)	181.7588***	156.3738	1.833058*	1.10517
Male family members (n)	10.65595**	5.442226	0.0053572	0.0922741
Age of respondent (years)	−0.7157348	0.4845648	−0.0010566	0.0082159
Education of respondent(schooling years)	−1.275079	1.421784	0.0076759	0.0241067
Distance from input market (km)	−2.696289*	1.439833	0.0393821*	0.0244127
Availability of small input market within the village of residence (n)	9.82421	25.01519	−0.0313941	0.4241381
Area cultivated (hectare)	−2.3292	2.851451	−0.0089386	0.048347
Ploughings (passes season^{-1})	3.339147	4.342806	0.0272138	0.0736332
Seed rate (kg ha^{-1})	−0.1447356	0.3867998	0.0128617**	0.0065583
Farmyard manure (kg ha^{-1})	0.0006329	0.0006608	−0.014500	0.0000112
Nitrogen-phosphorus (kg ha^{-1})	0.3894273**	0.1510004	0.000021	0.0025602
Chemical crop protection measures (liters ha^{-1})	4.698728	3.612108	−0.0379217	0.0612441
Cumulative precipitation during wheat season (mm)	1.734539***	0.3109998	0.0113908**	0.0052731
Deviation of the wheat season's mean temperature from historical mean i.e. temperature anomaly (°C)	−63.06474***	15.43758	−0.3538597	0.2617476
Constant	−53.47515	85.69245	3.244127**	1.452934
Total observations (n)	400	–	400	–
R^2	0.5345		0.1360	

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

Table 4
Estimates of the effects of studied climatic parameters on mean yield level and yield variability of wheat crop (kg ha^{-1}) using Just-Pope (J-P) non-linear (i.e. quadratic) model.

	J-P mean yield level		J-P yield variability	
	Coefficient	Std. error	Coefficient	Std. error
Farm altitude (base is high altitude)	–	–	–	–
1 for low altitude (meters)	604.4669***	123.4013	4.459133**	2.212963
2 for moderate altitude (meters)	638.5399***	145.1725	4.488956*	2.603387
Male family members (n)	10.61321**	5.423218	0.0094568	0.0972549
Age of respondent (years)	−0.68698	0.4824647	0.0019191	0.0086521
Education of respondent(schooling years)	−1.243576	1.415454	−0.0089194	0.0253834
Distance from input market (km)	−2.783193**	1.434586	0.048057*	0.0257265
Availability of input market within the village of residence (n)	8.174241	25.01558	0.1294747	0.4486057
Area cultivated (hectare)	−2.047346	2.847437	0.0018834	0.0510633
Quadratic term of 'ploughings' (passes season^{-1})	0.2394806	0.2844804	0.018657	0.0051016
Quadratic term of 'seed rate' (kg ha^{-1})	−0.000559	0.0018846	0.0000662**	0.0000338
Quadratic term of 'farmyard manure' (kg ha^{-1})	0.14700000	0.22500000	−0.00000079	0.0000004
Quadratic term of 'nitrogen-phosphorus' (kg ha^{-1})	0.0020601**	0.0009295	−0.000012	0.0000167
Quadratic term of 'chemical crop protection measures' (liters ha^{-1})	1.428496**	0.6670597	−0.0014309	0.0119624
Quadratic term of 'cumulative precipitation during wheat season' (mm)	0.0082786***	0.0014067	0.00051**	0.000252
Quadratic term of 'deviation of the wheat season's mean temperature from historical mean' (°C)	−27.57974***	5.686003	−0.1530659	0.1016974
Constant	−442.2531**	151.1523	1.569823	2.710623
Total observations (n)	400	–	400	–
R^2	0.5368		0.1340	

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

($P < 0.05$) in both linear and non-linear models but only on the yield variability of wheat crops. This means that seed rates can cause significant fluctuations in the yield of wheat crops. This is because there is a wide range – from 59 kg ha^{-1} to 148 kg ha^{-1} – with respect to seed rates in the study area. More importantly, during the study period, only 30% farmers in study area use the recommended seed rate for wheat crops, which is 124 kg ha^{-1} (PARC, 2018); the average seed rate was 102 kg ha^{-1} during the study period.

5. Challenges and limitations of study

Although the relationship between climate variability and crop yield is studied across different agro-ecological zones of Pakistan, this is the first to focus exclusively on rainfed wheat farming in Pakistan. Furthermore, this is the first study of wheat farming in Pakistan that includes farm elevation in order to discern its impact. However, this study uses cross-sectional data instead of panel data because the latter is not available. We use the averages of weather data, obtained from meteorological department, for the wheat growing season, even though a more precise picture could be captured by using the temperatures and precipitation rates for the different growth stages of wheat. Future studies may also consider day and night temperatures, humidity levels, wind velocity, and precipitation rates for each growth stage of the wheat crop. A comparative analysis of rainfed and irrigated wheat farming across Pakistan is another possible direction for research.

6. Conclusions and policy recommendations

The documented impacts of climate variability indicate severe consequences for agricultural productivity, especially in the developing world. In this study, we empirically investigate the impacts of climate variability on the mean yield levels and yield variability of wheat crop in the rainfed zone of Pakistan. The study employs climate and farm household level data collected from 400 farmers with respect to their various agronomic management practices. The analytical findings show that deviation of current mean temperature from the historical mean negatively influences the wheat mean yield, while cumulative precipitation positively influences both mean yield and yield variability. A significant and positive relationship between cumulative precipitation and yield variability proves our hypothesis of heavy dependency of wheat farming on precipitation in the study area. These findings have important implications for both future research and policy formulations seeking to facilitate adaption of rainfed farming to climate variability not just in Pakistan, but also more generally across South Asia. The study also highlights the importance of infrastructure development that facilitates easy input market access in order to significantly improve wheat crop yields in the study area. Large numbers of farmers in study area do not use the recommended quantities of various agronomic inputs like seed, fertilizers, and chemical crop protection measures. Better extension services are needed to create awareness among rainfed farmers about the recommended use of various agronomic inputs and how these ultimately impact wheat yields and yield stability. These extension services can also spark increased awareness among rainfed wheat farmers about sound adaptations against climate change, like using heat-tolerant seed varieties, changing sowing timings, and changing fertilizer composition, among others, through trainings and informative seminars. At the same time, the government must prioritize investments in the agricultural sector that help combat the negative effects of climate change on rainfed wheat farming. Appropriate adaptation and policy support options could include the development of heat resistant wheat varieties as well as the provision of subsidies for various agronomic inputs like seeds, fertilizers, and chemical crop measures. Lastly, investments in rainwater harvesting could positively impact food production, sustainability, and security in the rainfed areas of Pakistan.

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Appendix A. Socioeconomic and farm characteristics of sampled farmers

1. Farm elevation

Low elevated farms	Moderately elevated farms	Highly elevated farms
29.75%	45.25%	25%

2. Age of respondent (years)

Less than or equal to 25	26 to 50	51 to 75	Above 75
5.5%	49%	44.25%	1.25%

3. Education of respondent (schooling years)

Illiterate	=5 to 8	=10	Above 10
33.25%	22%	30.5%	14.25%

4. Distribution of farmers with respect to land ownership (hectares)

Equal or <2	2.1 to 4	4.1 to 6	>6
48.25%	31.75%	11%	9%

5. Distribution of farmers with respect to usage of seed rate (Kgh^{-1})

1 to 100	101 to below 124	124 (Recommended use)
63%	7%	30%

6. Distribution of farmers with respect to nitrogen(N), phosphorus (P) and potash (K) fertilizers use

Only 'N' users	Only 'NP' users	'NPK' users	No fertilizer use
1.25%	92.5%	0%	6.25%
Recommended use = 2%		Below recommended use = 98%	

7. Distribution of farmers with respect to usage of chemical crop protection measures (liters ha^{-1})

Fungicide users	Pesticide users	Herbicides users	Using any type
22.25%	8%	43%	57.5%

8. Distribution of farmers with respect to crops being grown in rainfed zone

Only wheat	Wheat and chickpea	Wheat and groundnut	Wheat and millet	Wheat and Mung bean	Wheat and Mustard
72%	15.5%	8.75%	1.5%	1.25%	1%

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