Assessment of Climate Change Impacts and Optimization of Climate Resilient Wheat Practices by Using DSSAT Model in Sindh, Pakistan

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Abstract

Climate change has significant impacts on wheat crop in Pakistan. This study evaluates the climate change impacts on the wheat crop with a model 'Decision Support System for Agro-technology Transfer' (DSSAT). The model was calibrated and validated with the data of plots sown on three planting dates (15th November, 25th November, and 05th December). Base line climatic data of 30 years from 1988-2018 was used to simulate ten future climatic scenarios (Current, 0.5°C rise in Temperature, 1°C rise in Temperature, 1.5°C rise in Temperature, 0.5°C rise in Temperature & 15% decrease in Rainfall, 1°C rise in Temperature & 15% decrease in Rainfall, 1.5°C rise in Temperature & 15% decrease in Rainfall, 0.5°C rise in Temperature & 15% increase in Rainfall, 1°C rise in Temperature & 15% increase in Rainfall and 1.5°C rise in Temperature & 15% increase in Rainfall) under the guidelines of Representative Concentration Pathway (RCP) 4.5 and 8.5. Climate, Soil and crop management data were used as an input. Among the plots sown on different planting dates, the best yield (3,458 kg/ha) was obtained from planting date of 25th

November, whereas 3,179 and 3,161 kg/ha yield obtained for 15th November and 05th December, respectively. The results showed that climate change will cause negative impacts ranging from 0.7 % to 9.5 % reduction in wheat yield. The results also revealed that the increase in temperature decreases the wheat yield. The simulations showed that the different adaptations like optimized NPK amount, application of farm yard manure, and drip irrigation showed up to 11.4 % increase in wheat yield.

Keywords: Decision Support System for Agro-technology Transfer (DSSAT), Climate Change Adaptations; Climate Change Resilience; Wheat Crop Modeling; Food Security; Sindh; Pakistan

INTRODUCTION

The issue of climate change has been seen as a burning topic for the last three decades (Stocker *et al*., 2013). Climate change can have many reasons like increasing population, industrialization pollution, urbanization, technological advancement, mechanization, infrastructural developments, deforestation, and agricultural land intensification (Park, 2013). Climate change includes unusual shifts in rainfall, wind, temperature, and precipitation (Mahato, 2014).

Agriculture is among the most sensitive systems to climate change due to its direct exposure to environmental conditions (Piao et al., 2010). Unprecedented changes and fluctuations in climate are significant danger to crop productivity. Increase in temperature disturbs the crop phenology, resulting in the reduction of yield (Rahman et al., 2018). According to projected data, climate change would further increase due to global warming. The frequency and intensity of floods and drought will increase significantly in this century, which would harm crop production (Stocker et al., 2013).

Pakistan is ranked on 7th number globally in Climate Risk Index (CRI) with a CRI score of 30.50. It is ranked 35th in the losses per unit GDP, ranked 5th in economic losses (Purchasing Power Parity) by losing around US$ 3,823.17 million in the list of global CRI for the period of 1996-2015 (Kreft et al., 2015). During this period, Pakistan suffered from 141 extreme events (Eckstein et al., 2017). Pakistan is highly vulnerable to climate change, so increasing the resilience and adaptive capacity of traditional agriculture systems is inevitable to ensure food security (Mahmood et al., 2019). Sindh is located in the sub-tropical region and becomes very hot in the summer season. Sindh faces extreme temperatures up to 46°C (Kazi et al., 2016). The annual report of the National Drought Monitoring Center (2016) stated that Sindh had experienced many droughts in the past ten years and likely to face many more in the future.

According to Agriculture statistics of Pakistan (2010), Pakistan covers 79 million ha of land area, in which 22 million ha used for agriculture purposes. Moreover, up to 56 % of labor also depends upon agriculture. According to the statement given by Janjua et al. (2010), the Agriculture sector of Pakistan is sensitive to these changes because of its arid and semi-arid weather conditions. Projected climate change scenarios also pinpoint the agriculture sector for a severe future decline. (Chaudhry, 2017).

Wheat is the largest sown crop across the globe (FAO, 2014) as it is sown on more than 220 million hectares and the production of wheat is more than 670 million tons every year across the globe (Shiferaw et al., 2013) . Sustainable production of wheat is a challenge in the changing climate (Porter et al., 2014). It has been estimated that the climate change can badly affect the wheat crop that holds around 21% of food production worldwide (Ortiz et al., 2008). An increase in temperature threatens the wheat productivity in the flowering and grain filling period (Asseng et al., 2019). It was observed from the experiments that higher temperatures decrease crop water productivity in terms of yield (Kingra and Singh, 2016). Studies have shown that 1°C increase in temperature will decrease around 6 % of wheat yield in different areas of the world (Liu et al., 2016). An increase of 70 % in food production will be required to meet the global need for wheat in 2050 (FAO, 2009). Sindh is the province whose economic and social growth depends upon the agricultural sector heavily. The overall contribution of Sindh province in the national agriculture production of significant crops goes like:

- 32% in the production of rice
- 24% in the production of sugarcane
- 12% in the production of cotton
- 21% in the production of Wheat

Wheat is the most vital food crop of Pakistan. It contributes 1.6 percent in the GDP of Pakistan. In spite of all the efforts of government to increase per hectare yield, no significant change has been observed in the last five years in wheat production. The production of wheat was 25,086 tons in 2014-15 and 25,195 tons in 2018-19 (Kazi et al., 2016).

Different studies have identified climate change impacts on crop production across the globe (Chen, 2016). It has become crucial to investigate the impacts of climate change on agriculture so that food security can be ensured (Piao et al., 2010). Developing countries, like Pakistan have adaptation issues due to the lack of technical and capital resources, unskilled human resources, and high dependence on agriculture (Stern and Stern, 2006). According to He et al (2014), global food production can be increased by sustainable farming practices. Similarly, Ali et al*.,* (2011) stated that climate change adaptations especially practicing sustainable farming technologies, can increase wheat production. Thus, knowledge of scientific and technological tools can prove to be a milestone for the agricultural issues of Pakistan.

Crop models have been used worldwide for decision support systems for crop management under changing climatic situations. Some of the models that are being used are DSSAT, APSIM, CropSyst, WOFOST, Info Crop, and RZWQM. All these models can produce accurate predictions if they are provided with valid and reliable data used by expertise (Bhatti, 2018). The DSSAT-CERES-Wheat model comprises of different independent programs that work simultaneously with the help of crop management, climate and soil data. In order to simulate accurately, it requires data sets about crop management, climate, soil type and genotypes to align them with seven genetic coefficients that simulate phenological responses of crops under different conditions (Jones et al., 2003). Three genetic coefficients related to crop development (P1V, P1D and P5), three genetic coefficients related to growth (G1, G2 and G3) are necessary to be determined for model calibration (Maldonado, Rodriguez and Castillo, 2015). This statistical program has got various software that can be used to evaluate the vulnerability of agriculture to climate change, and then suitable adaptations could be figured out (Iglesias et al*.,* 2012). Studies showed that the expected decline in wheat yield could be avoided by different adaptations such as changing sowing dates, irrigation schedule, and crop management (Challinor et al., 2014). These adaptations can be practiced depending on local context and need (Howden et al., 2007). In the present study, calibration and validation of

DSSAT-CERES-Wheat model have been done for lower Sindh and the impacts of climate change under different climate projections have been studied to optimize different possible adaptations to mitigate the negative impacts.

MATERIALS AND METHODS

Site Selection

The experiment of wheat sowing on different dates was done in the Tandojam district of Sindh, Pakistan. Wheat was sown on a one-acre plot each for three planting dates during the Rabi season of 2018-2019. Sindh is widely known as a rich agricultural area in Pakistan as it produced the 25,195 tons of wheat in the cropping year of 2018-2019. Tandojam is located in the subtropical region. According to Koppen-Geiger climate classification, Tandojam is classified as BWh, which describes a hot and arid climate. Tandojam is located at a latitude of 25°25' N and longitude of 68°33' E with an altitude of 23 meter. The annual rainfall of Sindh ranges from 145-155mm. The map of experimental site is shown in Figure No. 1.

Figure 1 here

Model Calibration and Validation

In this study, three crop variables (days to anthesis, days to maturity and yield) were used for model calibration and validation. Calibration is defined as the method of adjusting the model according to local conditions and validation is used to double check the performance of model. In DSSAT model, genetic coefficients that control the model algorithm for simulation of different crop parameters (Ritchie, 1998) must be calibrated and validated in particular ecological conditions before it can be used for more climate impact researches. (Hunt and Boote 1998).

Soil Data

Six parameters (Electric conductivity, pH, Nitrogen, Potassium, Phosphorus, and Organic matter) were required to run the model. The soil was tested from the Agriculture chemistry section, Agriculture research institute, Tandojam. The required soil data for model simulation is mentioned in table 1.

Table 1 here

Weather Data

Weather data was obtained from the Regional Agro-met Center (RAMC) Tandojam. Six weather parameters were required to run the model. Average values of maximum temperature showed a higher temperature trend across the whole winter season which is one of the major reasons of yield decline. Precipitation was found approximately near to zero. Averages of all those required parameters, which include Solar radiation, Maximum and minimum temperature, Daily precipitation, Wind speed, and Relative humidity for the wheat season from November to March, are written in table 2.

Table 2 here

Climatic Scenarios

Ten climatic scenarios were generated under the lights of suggestions given in Fifth Assessment Report of Intergovernmental Panel on climate change (IPCC). The

Representative Concentration Pathways (RCPs) described different climatic pathways for the future. Future climatic scenarios were proposed and projected for simulating crop response in different scenarios. The projected scenarios are written below in table 3.

Table 3 Here

Temperature and rainfall are among the most influential environmental factors on wheat yield as both of them affect the wheat crop directly during grain filling time. Especially in water-scarce areas, higher temperatures, and less rainfall exaggerates the difficulties for wheat growth (Lopez et al*.,* 2003). Temperature affects the photosynthesis rate of wheat; photosynthesis rate plays a vital role in wheat growth; higher temperatures decrease the photosynthesis rate, which ultimately decreases the yield of wheat (Djanaguiraman et al*.,* 2018). Under all the above-written scenarios, the DSSAT model simulated the expected impacts of climate change on wheat yield.

Crop Management Data

Crop management data was taken from three experimental plots. Wheat was sown on three planting dates, each one of one acre. All three plots were managed with the same inputs except sowing dates. Detailed crop management data is written below in table 4.

Table 4 Here

DSSAT-CERES-Wheat Model

DSSAT CERES-Wheat model is a computer model that simulates different factors impacting the growth and yield of crop, based on input information including soil, climate and crop management data. DSSAT-CERES-Wheat model has been widely used in the identification of climatic risks and reckoning the optimum use of resources at micro to regional scale. Moreover, the DSSAT CERES-wheat model and its' various applications have been tested widely across the globe. The CERES-Wheat model has been broadly used for discovering better agronomic options, breeding preferences, edaphic and climatic factors. This model has the capability to simulate the wheat crop development stages, growth of leaves, grains, stems and biomass based on light interference and stresses. Methodological flow chart of Decision support system for agrotechnology transfer (DSSAT) is shown in Figure No.2.

RESULTS AND DISCUSSIONS

Model Calibration and Validation

The genetic coefficients of the experimental conditions were calibrated using the observed data of experimental plot No.2, which was sown on 25th November. The validation of the model was done by using data of plots No. 1 and 3. Different factors affect phenological development; anthesis and maturity dates were used to estimate the three coefficients (P1V, P1D, and P5) number of grains, grain weight, and the number of spikes determined by G1, G2, and G3, respectively.

Table 5 Here

Table No. 5 shows the calibration results of the DSSAT model, which is done on the data of plot No.2 that was sown on 25th November 2018. Three variables (days to anthesis, days to maturity, and yield) were used for calibration. Percent errors were found -3.1 %, 5.2 %, and 2% for days to anthesis, days to maturity, and yield, respectively. Error-values were between

2-6 % that is far below the acceptable level of 15%. The calibration of these parameters showed the reliability of the DSSAT model. The difference between simulated and observed values suggested that the calibrated model and coefficients can be used for the projected simulations.

Table 6 Here

Table No. 6 shows the validation results of the DSSAT model, which is done on the data of Plot No.1 and Plot No.3 that were sown on 15th November 2018 and 05th December 2018, respectively. Errors were found 4, 5, and -2% for days to anthesis, days to maturity, and yield, respectively for plot sown on 15th November 2018, and errors of plot sown on 05th December 2018 were found -6, -8, and 3% for days to anthesis, days to maturity and yield, respectively. Error-values were between 2% to 8 % that too are far below than allowable limit of 15% (Choudhury et al., 2018). The calibration of these parameters showed the reliability of the DSSAT model. The difference between simulated and observed values suggested that the calibrated model can be used for the projected simulations. Validation further ratified that the DSSAT model can be used with the desired certainty.

Wheat Crop Response to Future Climate Scenarios

Figure 3 shows the mean yield and the percent reduction of wheat in future climatic scenarios for 30 years. From the results, it is shown that with an increase in temperature, there is a decrease in wheat yield with respect to current yield, which further declines with a decrease in rainfall. A rise of 0.5°C, 1°C, and 1.5°C caused a decline of -1.1, -5.7, and -9.5% in yield. Adding a 15% decrease in rainfall with 0.5°C, 1°C, and 1.5°C rise in temperature further decreased the yield and showed the -1.4, -5.9, and -10% decline, respectively. Increasing the rainfall by 15% with temperature increments showed a decline of -0.7, -3.4, and -7.9%, respectively, which shows that increase in rainfall has a positive impact as compared to a decrease in rainfall. A study conducted by (Qu *et al.,* 2019) in China revealed that an increase of 0.57°C, 1.64°C, and 2.3°C under RCP 4.5 would cause a decline of -1.92, -4.08, and – 5.24% in wheat yield, respectively. Furthermore, it can be observed that an increase in rainfall has some positive impacts on wheat yield.

Table 7 Here

Figure 3 Here

Application of Adaptations

Optimum Values of NPK

Optimization of NPK doze was done by trying the range of amount recommended by FAO for irrigated wheat crop in Sindh region which are (N=130-170 kg/ha, P=60-90 kg/ha & K=50 kg/ha). The maximum yield was simulated on the application of 170-60-50 (Kg/ha) NPK. An increase of around 3-10% yield was observed on the application of this amount. On simulating with different NPK values, and in all different climatic scenarios, the wheat yield showed varied results. The maximum increase of 10 % was observed in Scenario No.10 where yield was increased from 2,945 kg/ha to 3,242 kg/ha and the minimum increase was observed 4.2 % in Scenario No. 4 where yield was increased from 2,895 kg/ha to 3,017 kg/ha. Overall, the positive results indicated that there is a dire need to define optimum dozes of NPK for wheat crop with decision support systems to enhance the best possible yield as compare to the conventional dozes of NPK which have been applied in Sindh region.

Drip Irrigation System

Winter wheat water requirement ranges from 180 mm to 420 mm depending on the various factors (Mahmood and Ahmad, 2005). A total of 390 mm was applied with conventional flood irrigation in three irrigation (130 mm of water for each irrigation). The crop used around 253 mm of water with an efficiency of 65 %. On other hand, application of 250 mm of water with drip irrigation system was simulated and the results showed that no significant increase or decrease was observed. The results revealed that 140 mm of water can be saved by using this system. Though, the maximum increase in yield with drip irrigation was observed only 0.8 % in scenario No.1. Maximum decline in yield on using drip irrigation was observed -1.9 % in scenario No.4. It can be said that this 1.9 % decline can be due to the 1.5°C rise in temperature so drip irrigation was unable to overcome temperature impacts. Though, there was no considerable increase or decrease in yield was observed but still the crop water productivity in terms of yield was observed greater in drip irrigation system than the conventional irrigation system.

Application of Farm Yard Manure

Organic carbon stocks and the soil continues to decrease due to increased environmental temperatures. It ultimately decreases soil fertility. The decomposition of organic matter in soil and carbon storage of soil depends on temperature and other environmental factors. Amending the soil with farmyard manure to increase soil fertility has been a common practice throughout history (Griffin et al., 2003). In this study, different amounts of farm yard manure were simulated by DSSAT-CERES-Wheat model to obtain the optimum value of FYM to increase the wheat yield. It was observed from the simulations that 8 t/ha application of farmyard manure is the optimum value for yield improvement. Aatif et al*.,* (2017) stated that the application of 9 tons/ha of farmyard manure combined with phosphorus improves the grains spike^{-1}, spike length, and grain yield. Furthermore, (Jan et al., 2011) found out that combining the use of farmyard manure and inorganic fertilizer increases the yield of wheat, especially under the dry conditions. (Ahmed et al., 2010) compared the wheat yield under application of farmyard manure, poultry manure, and controlled (no treatment), and results showed the best yield of wheat was obtained by applying the farm yard manure. Moreover, in the case of saline irrigation water for wheat farmyard manure helps in giving a better yield as compared to poultry manure (treatment) and controlled (no treatment) plots (Ahmed et al., 2010). The results showed that by applying 8 tons/ha of farm yard manure a maximum increase of 2.17 % was observed for the scenario No.1 and a minimum increase of 1.21 % was observed for the scenario No. 8. Though, the results did not show a considerable increase but still an increase in yield is better than the decline in yield.

Combine application of all adaptations

In previous sections, simulation results for each adaptation were shown individually. The simulation results for combined application of all adaptations showed significantly positive results for wheat yield. Combination of organic and inorganic fertilizer gives the maximum yield in wheat at rate of 160 Kg N ha^{-1} and 30 Mg/ha of compost and also improve the soil characteristics (Abedi, Alemzadeh and Kazemeini, 2010). Simulation results showed a maximum of 11.4 % increase in wheat yield under scenario No.1. The yield was increased from 3,200 kg/ha to 3,567 kg/ha. A minimum increase of 5.1 % in wheat yield was observed in scenario No.7 where yield was increased from 2,880 kg/ha to 3,029 kg/ha. It can be observed from the Table No. 8 that on applying all adaptations combinedly. It was observed that percentage improvement in the wheat yield under all treated scenarios is comparably more significant in the combined application of adaptations as compare to individual adaptation.

Table 8 here

CONCLUSION AND REECOMMENDATIONS

In this study, the DSSAT-CERES-Wheat model was calibrated and validated with three variables (days to anthesis, days to maturity, and yield) of wheat crop. The data was obtained from the experimental plots sown under planting dates of 15 Nov, 25 Nov and 05 Dec, respectively. Calibration and validation showed that the model is fit for the study as the error was only found under the acceptable limits. Ten future climatic scenarios based on RCP 4.5 and 8.5 were projected, and their impacts on wheat production were observed. Simulations showed that a rise in future temperature will decrease wheat yield. Yield analysis showed that wheat yield varies under different climatic scenarios. Results revealed that the increasing temperature has a negative impact on wheat yield. Results further revealed that the increase in rainfall has a positive impact on wheat yield. Different adaptations were simulated in order to obtain optimum input values to face climate change impacts. The simulations with optimum values for adaptations (Optimum dose of NPK (170-60-50 kg/ha), optimum dose of farmyard manure (8 tons/ha), and use of drip irrigation) showed significantly positive results. The results showed that adaptations can increase wheat yields up to 11.4 % and can save the hefty amount of water in expected climatic conditions.

In this modern era, farmers have access to smart phones so government should spread the awareness of decision based agrotechnology among farmers by developing user friendly mobile applications based on the principles of DSSAT. This will enhance the adaptive capacity of farmers with sustainable farming practices.

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Table 1: Chemical and physical properties of soil

S. No.	Variable	Unit	Value Obtained
1.	Electric Conductivity	dsm^{-1}	0.67
2.	pH	1-14	8.6
3.	Available K	ppm	117
4.	Available N	%	0.022
5.	Available P	ppm	2.4
6.	Organic Matter	%	0.45

Table 2: Weather data of experimental site for cropping year 2018-19

Month	Solar Radiations MJ/m²/day	Maximum Temperature (°C)	Minimum Temperature (°C)	Daily precipitation (mm)	Wind Speed (km/hour)	Relative humidity (%)
November	12.5	31.6	14.9	0	1.	57
December	15.6	25.9	9.3	0	1.2	59
January	19.4	24.2	8.3	0.9	1.4	61
Februray	23.2	25.9	9.9.	0.1	1.5	55
March	26.4	31.7	14.6	0	1.6	50

Source: Regional Agromet Center, Tandojam (2019)

Table 3: Description of ten future climatic scenarios

S. No.	Scenario
1	Current
2	0.5°C rise in Temperature
3	1°C rise in Temperature
4	1.5°C rise in Temperature
5	0.5°C rise in Temperature & 15% decrease in Rainfall
6	1°C rise in temperature & 15% decrease in Rainfall
7	1.5°C rise in temperature & 15% decrease in Rainfall
8	0.5°C rise in Temperature & 15% increase in Rainfall
9	1°C rise in temperature & 15% increase in rainfall
10	1.5°C rise in Temperature & 15% increase in rainfall

Table 4: Crop management data of three experimental plots

No.	Crop Management	Plot No.1	Plot No.2	Plot No.3
1.	Planting Date	15 Nov	25 Nov	05 Dec
2.	Seed Rate (Kg)	50	50	50
3.	No. of Tillage	3	3	3
4.	No. of Irrigations	3	3	3
5.	Fertilizer Applications	1 DAP 3 Urea	1 DAP 3 Urea	1 DAP 3 Urea
6.	Yield (Kg/acre)	1,287	1,400	1,279
7.	Yield (Kg/ha)	3,179	3,458	3,161

Table 5: Model calibration of DSSAT with three crop variables

S.No.	Variable	Observed value	Simulated Value	% Error
1	Days to Anthesis	94	97	-3.1
2	Days to Maturity	134	127	5.2
3	Yield (Kg/ha)	3,458	3,360	2

Table 6: Model validation of DSSAT with three crop variables

No.	Variable	NOV 15, 2018			DEC 05, 2018		
		Observed	Simulated	% Error	Observed	Simulated	% Error
1.	Days to Anthesis	100	96	4	91	97	-6
2.	Days to Maturity	138	130	5	109	118	-8
3.	Yield (Kg/ha)	3,179	3,250	-2	3,161	3,050	3

Table 7: Future climatic scenarios and mean yield for 30 years

No.	Treatments	Mean Yield (Kg/ha)	% change
1	Current	3.200	
2	0.5°C rise in Temperature	3,163	-1.1
3	1°C rise in Temperature	3,015	-5.7
4	1.5°C rise in Temperature	2,895	-9.5
5	0.5°C rise in Temperature & 15% decrease in Rainfall	3,155	-1.4
6	1°C rise in Temperature & 15% decrease in Rainfall	3,010	-5.9
7	1.5°C rise in Temperature & 15% decrease in Rainfall	2,880	-10
8	0.5°C rise in Temperature & 15% increase in Rainfall	3,175	-0.7
9	1°C rise in Temperature & 15% increase in Rainfall	3,091	-3.4
10	1.5°C rise in Temperature & 15% increase in Rainfall	2,945	-7.9

Table 8: Mean yield with and without application of adaptations

S. No.	Treatments	Mean Yield (Kg/ha)	Mean Yield (After NPK) (Kg/ha)	Mean Yield (Kg/ ha) (Drip Irrigation)	Mean Yield (Kg/ha) (FYM)	Mean Yield Combined Application of All Adaptations (Kg/ha)	% change
1.	Current	3,200	3,425	3,229	3,271	3,567	11.4
2.	0.5°C rise in Temperature	3,163	3,318	3,165	3,208	3,497	10.5
3.	1°C rise in Temperature	3,015	3,215	3,008	3,071	3,237	7.3
4.	1.5°C rise in Temperature	2,895	3,017	2,840	2,953	3,105	7.2
5.	0.5°C rise in Temperature and 15% decrease in Rainfall	3,155	3,370	3,150	3,208	3,413	8.1
6.	1°C rise in Temperature and 15% decrease in Rainfall	3,010	3,190	2,986	3,076	3,223	7.0
7.	1.5°C rise in Temperature and 15% decrease in Rainfall	2,880	3,075	2,834	2,928	3,029	5.1
8.	0.5°C rise in Temperature and 15% increase in Rainfall	3,175	3,312	3,133	3,214	3,378	6.3
9.	1°C rise in Temperature and 15% increase in Rainfall	3,091	3,383	3,082	3,140	3,364	8.8
10.	1.5°C rise in Temperature and 15% increase in Rainfall	2,945	3,242	2,941	2,986	3,218	9.2