

Wheat Yield Under Climate Change: Effect of Temperature and Wind Speed on the Crop Life Cycle and Productivity Estimated by DSSAT-Icsim Model

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Abstract: Changing climatic conditions are the leading cause affecting the yield of grain crops, particularly in arid areas. In this study, we investigated the response of wheat yield under changing climatic variables using the DSSAT-ICSIm model. The effect of different temperatures and wind speeds on obtained yield and the wheat life cycle in the arid region of Chakwal was also estimated. In this study, we used ECMWF dataset from 1979 to 2005 along with different variables such as 2 m temperature, total precipitation, solar radiation, and u-v winds. Our findings revealed that climatic factors, such as temperature and wind speed, negatively affected wheat phenology and yield in arid regions. This indicates that arid regions are more prone to extreme temperatures and changing wind speeds. Moreover, high-temperature ranges and increasing wind intensity in arid areas contributed negatively to overall wheat performance. In conclusion, arid areas are more susceptible to extreme temperatures and high wind speeds in the future. Thus, measures should be taken to produce wheat cultivars with high tolerance to temperature extremes and wind intensity.

Keywords: Wheat; Yield; Models; DSSAT-ICSIm model; Arid region

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1. Introduction

The climate of Pakistan is uneven, with most regions in the southern and central parts being tremendously arid, while the mountains in the northern area are extremely dry, and the northern part is humid. Several research studies have documented that the weather of the country is fluctuating but primarily arid (Ahmed and Schmitz, 2011; Iqbal *et al.*, 2010; World Bank, 2006). The northern and northeastern sides have similarities with a temperate climate. Moreover, it has been well-stated that southern regions are characterized by arid and semi-arid climates having high temperatures and low precipitation (Adnan *et al.*, 2017). In Pakistan, which has a semi-arid to arid climate, crop cultivation and production largely depend on rainfall water and freshwater resources. In the Potohar region, the monsoon is a foremost resource for successful crop cultivation, particularly the rabi-season crops. This region is characterized as a semi-arid to arid climate where the precipitation is the only source of irrigation water for crop requirements. In the country, due to the non-environmentally friendly human activities and natural processes, temperatures are increasing beyond their normal limits. During the first decade of the 21st century, the mean temperature increased in the range of 0.09-

1.15°C (Chaudhry *et al.*, 2009). Extreme temperatures, over the optimal range, can have a significant influence on the production of many crops. At present, Pakistan ranks among the major countries that are susceptible to changing climatic conditions, which directly or indirectly impacts the agriculture sector (Burhan *et al.*, 2017). It is estimated that the agriculture sector of the country could lose about a billion dollars each year due to extreme weather events (Mendelsohn *et al.*, 2001; Adnan *et al.* 2017). Similarly, Pakistan is facing many problems such as a high melting rate of glaciers, summer floods, increasing heat index, and insufficient availability of freshwater for crops. Numerous climatic factors such as solar radiation, RH and wind intensity and agronomic-related factors including crop growth stages can determine the crop water requirements (Ghazala and Mahmood, 2009).

Wheat, maize, barley, and groundnut are among the major crops cultivated in the Potohar regions. In recent years, numerous studies have stated the crop performance in the Potohar region. Nonetheless, there is a lack of systematic research on the impact of wind speed, particularly through a modeling approach, on wheat productivity at different developmental stages. The Potohar region is situated between the valley of two famous

rivers i.e., Jhelum and Indus, encompassing major portions of Attock, Jhelum, Rawalpindi and Chakwal. Previously, Chaudhry and colleagues have found that approximately 70% of the total agricultural land is characterized by arid areas (Chaudhry and Rasul, 2004).

Agriculture is the most important sector of Pakistan, contributing about 24% to its GDP, and 47% of the population is linked to this sector either directly or indirectly for earnings (Azhar *et al.*, 2010). Agriculture plays a backbone role in Pakistan's economy; nevertheless, it is prone to extreme climatic vulnerabilities such as droughts, floods, and changing rainfall patterns (Burhan *et al.*, 2017). Climate change greatly influences agricultural products in several ways, both at the local and global scale (Ahmed and Schmitz, 2011).

In Pakistan, the wheat crop is mainly cultivated in the winter season. The sowing is mainly done in October while harvesting is mainly taken place in March-May (Rasul, 1993). In Pakistan, wheat flour is mainly consumed as a stable source of calories. It is estimated that wheat is consumed at 124 kg per capita per year (Punjab Agri. Dept., 2014), showing the significance of wheat crops in the country. Nonetheless, every year, several factors such as weather conditions and climatic variabilities can directly

influence economic stability and social balance.

In this study, the Decision Support System for Agro Technology Transfer (DSSAT 4.6.1.0) model was used to investigate the influence of wind intensity and changing temperature conditions on wheat performance. This model assists offer sustainable decision-making along with reduced time consumed and human resources (Tsuji *et al.*, 1998).

The main objective of this study was to (i) investigate the response of wheat yield under the scenario of changing climate via DSSAT-ICSIm and (ii) to analyze the effect of different temperatures and wind speeds on obtained yield and crop life cycle under changing climate in arid region Chakwal.

2. Materials and Methods

2.1. Experimental site

The following experiment was conducted in the Chakwal District (32.56°N, 72.52°E, 513 m above sea level), located in the Punjab Province, Pakistan. The arid region in Chakwal is categorized as a zone of medium rainfall with 600 mm average annual rainfall and 22.4°C annual average temperature. During the growing season of wheat (November to April), rainfall is extremely variable, with the maximum amount received

during the late growth stages (Mukhtar *et al.*, 2013).

2.2. Climate dataset

In this study, we utilized the ECMWF dataset from 1979 to 2005, which includes specific variables such as 2-meter temperature, total precipitation, solar radiation, and u-v winds. The European Centre for Medium-Range Weather Forecasts (ECMWF) was established in 1975, with its headquarters located in the United Kingdom. The spatial resolution of the used model is 0.125 x 0.125 degrees or approximately 14 kilometers.

2.3. Soil dataset

The experimental soil characteristics are sandy clay loam (Mukhtar *et al.*, 2013). Soil parameter data such as soil depth, pH, and total-nitrogen, soil organic carbon, EC, sand, silt, clay percentage and bulk density were analyzed using typical laboratory techniques and stored in a soil file. The data are provided in Table 1.

2.4. Standard deviation values

The average weather data for 26 years (1979-2005) were compiled and arranged for each year (12 months). Subsequently, the standard deviation of the organized data was calculated and considered as normal standard deviation (SDev.1). The value of SDev.1 was

then multiplied by 0.25, 0.50, and 0.75, resulting in Sdev.2, Sdev.3, and Sdev.4, respectively. These values are provided in Table 2.

2.5. DSSAT Model

The crop growth model DSSAT 4.6 was used for this investigation. DSSAT is a collection of numerous models that link the decision support system with crop simulation models (Jones *et al.*, 2003). The Decision Support System for Agro Technology Transfer (DSSAT) simulates crop growth, crop development, and yield according to given parameters of minimum weather and soil profile. Minimum data for weather includes minimum and maximum temperature, rainfall, and solar radiation, while soil parameters include chemical characters, soil texture, and soil depth (Ngwira *et al.*, 2014). Additionally, crop management data such as crop type and cultivar, planting date, plant and row spacing, tillage practices, fertilizer levels, and organic amendments are also included (Jones *et al.*, 2003). Additionally, crop management data such as crop type and cultivar, planting date, plant and row spacing, tillage practices, fertilizer levels, and organic amendments are also included (Jones *et al.*, 2003).

Table 1: Soil properties of the experimental site which are used as input data for this model

Soil depth (cm)	pH	Total N (%)	Organic carbon (%)	EC (dS/m)	Clay (%)	Silt (%)	Sand (%)	Bulk density (g/m ³)
0-15	8.1	0.04	0.72	0.32	21	33	56	1.29
15-30	8.1	0.03	0.65	0.30	22	33	56	1.45
30-45	8.6	0.02	0.47	0.34	23	33	56	1.55
45-60	8.8	0.02	0.45	0.26	24	33	56	1.65
60-75	8.5	0.02	0.33	0.32	25	33	56	1.70
75-90	8.5	0.02	0.31	0.28	26	33	56	1.75

Table 2: Standard deviation values for different weather conditions

Variable	SDev.1 Normal	SDev.2 0.25	SDev.3 0.50	SDev.4 0.75
Maximum Temperature	7.81	1.95	3.90	5.86
Minimum Temperature	7.92	1.98	3.96	5.94
Wind Speed (Km/day)	57.51	14.37	28.75	43.13

After creating the soil and weather files in DSSAT, the Introductory Simulation (ICSIm) was initiated by inputting the requirements of the experimental site, including the name, year, crop type and cultivar, sowing date, irrigation and fertilizer requirements. The sowing time was set to 15 November, using the cultivar Chakwal-97. The total number of irrigations was 4 and the amount of irrigation water was applied 350 mm manually and remaining water requirement of the crop was fulfilled through rainfall which occurred during the whole season (November-April). The initial simulation proceeded without environmental modification (Normal or

SDev.1 data). Later modifications in environmental parameters such as maximum and minimum temperatures (°C) and wind speed (Km/day) by SDev.2, SDev3 and SDev.4 values were added.

3. Results and discussion

3.1. Growth phases and crop phenology

The effect of climate change on crop performance has been studied through various studies utilizing statistical models to measure the relationships between climatic variables and seed yield (Lobell *et al.*, 2005; Tao *et al.*, 2008; Zhang Yao, 2012). Typically, the wheat crop completes its life

cycle within 145-150 days. According to the findings of this experiment, under optimum climatic conditions during the crop season, with standard temperature and wind speed, the crop duration was noted as 145 days, and the predicted yield via the DSSAT crop growth model was 3047 kg/ha. However, an increase in maximum temperature by about 1.95°C, followed by a minimum temperature increase of 1.98°C and a wind speed increase to 14.38 km/h, reduced the crop cycle from 145 to 138 days, as well as decreasing the crop yield by 12.73% (Sdev.2).

Gradually increasing temperatures due to global warming ultimately affect all agricultural commodities, including wheat, in Pakistan. Crop phenology is greatly influenced by temperature, leading to changes in the thermal time (growing degree days) of wheat, a cereal crop. The results of Iqbal et al. (2009b, 2009c) also support the outcomes of this manuscript; according to them, the length of the growing season in Pakistan will decline for major cereals (wheat, rice, maize) with increased temperatures across all agroecological zones. However, a shortened growing season due to climate change ultimately reduces crop yield, as confirmed by the findings of our research. Ali (2011) has also demonstrated that a shorter growing period could result in a 6-11% decline in wheat yield.

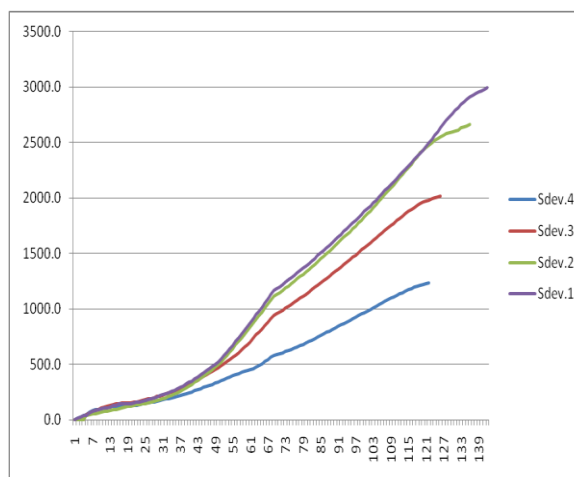


Figure 1. The relation between crop and growing degree days is predicted by different models.

According to the Ministry of Environment, Government of Pakistan, as stated in their Annual Report (2009), South Asia is expected to face larger devastating impacts of climate change, with the potential for a 50% reduction in wheat yield by 2050 (MoE, 2009). The results of this study also predict a reduction in the production of agricultural field crops, mainly wheat, in Pakistan due to uneven changes in climatic variables, as demonstrated in Table 3.

3.2. Growth indices

Our data revealed that changing temperatures and wind speed significantly affected the yield potential of wheat, particularly in terms of leaf area index. A linear and negative trend was observed between wind speed and the yield potential of wheat. The maximum decline was estimated during the mid-growth phases (60-80 days after planting).

Conversely, during the early seedling establishment and late maturity stage, a non-significant relationship was observed between wind speed and the yield potential of wheat (see Figure 2).

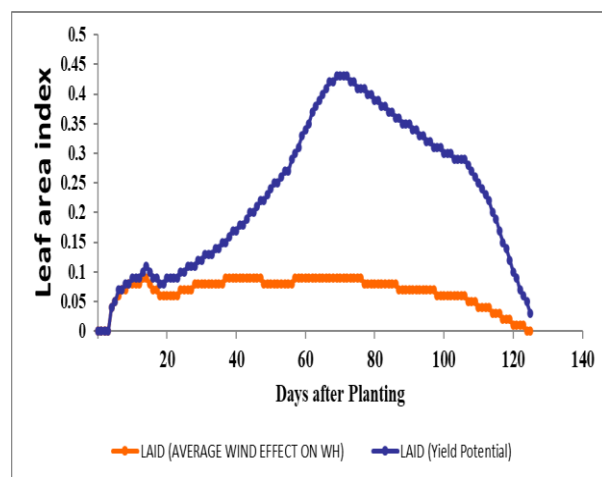


Figure 2. The influence of changing temperatures and wind speed on the leaf area index of wheat.

3.3. Aboveground biomass

Our data revealed that changing temperatures and wind speed significantly affected the yield potential of wheat, particularly in terms of above-ground biomass production. A linear and simultaneous increasing trend was observed between wind speed and the yield potential of wheat. The maximum increase was estimated during the late growth stage (100-120 days after planting). Conversely, during the early seedling establishment, a non-significant relationship was observed between wind speed and the yield potential of wheat (see Figure 3). Overall, the data showed that increasing wind speed would

increase the biomass production of wheat, which might be due to the lodging effect.

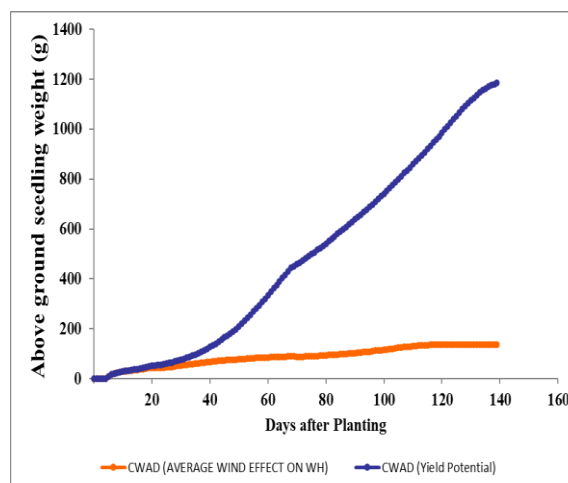


Figure 3. The influence of changing temperatures and wind speed on above-ground seedling weight of wheat.

3.4. Crop yield

Several pieces of evidence also authenticate our results. Zia Mustafa (2011) stated that the estimated decline in seed yield of wheat is 6-9% with a 1°C increment in atmospheric temperature within Pakistan. Similarly, a rise of 1°C in mean temperature can reduce wheat yield by 5-7%, which is a significant concern given that wheat is a primary staple food in the whole country (Sivakumar and Stefanski, 2011). These findings align with the results of the current study. Table 3 illustrates the levels of maximum and minimum temperature, as well as wind speed, along with the duration of the crop, crop yield, and the change in yield.

Although SDev.3, with twice the temperature and wind speed of SDev.2, reduced the crop

Table 3. Impact of changing temperature ranges and wind speed on crop duration, yield and change in yield of wheat in arid areas

Levels of standard deviation	Maximum temperature (°C)	Minimum temperature (°C)	Wind Speed (Km/h)	Duration of crop (d)	Yield (kg/ha)	Change in yield (%)
SDev. 1	7.81	7.92	57.51	145	3047	00.00
SDev. 2	1.95	1.98	14.37	138	2659	12.73
SDev. 3	3.90	3.96	28.75	126	2013	24.29
SDev. 4	5.86	5.94	43.13	120	1231	38.84

period to 126 days and resulted in a 24.29% decline in yield, extreme conditions as shown in SDev.4, with a 3% rise in wind speed and temperature, decreased yield by 38.84% and shortened the crop duration to 120 days. This intense decline in both crop cycle and yield could lead to a severe reduction in food production in the future if temperature and wind trends continue to rise in the country. The average global temperature is projected to increase by 1.1°C to 6.4°C by the end of this century, according to the IPCC 2007. Additionally, Table 3 describes how much agriculture in the country will be affected if temperatures increase from 1.95°C to 5.86°C.

3.5. Harvest index

Our data revealed that changing temperatures and wind speed significantly affected the harvest index of wheat, with maximum values observed during the late growth stage. A linear and simultaneous increasing trend was found between wind speed and the harvest index in wheat. For different growth stages, the maximum increase was estimated

during the late growth stage (100-120 days after planting), where values increased with increasing wind speed. Conversely, during the early seedling establishment, a non-significant relationship was observed between wind speed and the harvest index in wheat (see Figure 4).

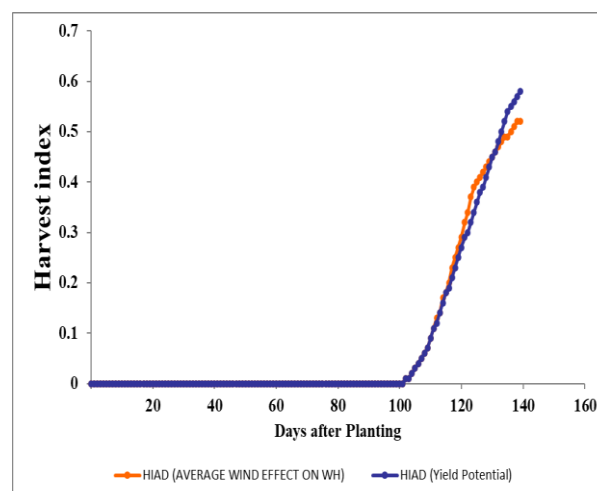


Figure 4. The influence of changing temperatures and wind speed on harvest index in wheat in arid areas.

Overall, the data showed that increasing wind speed would increase the harvest index in wheat, which might be due to higher biomass production and the lodging effect, ultimately reducing grain yield (see Figure 4).

4. Conclusion and recommendations

In Pakistan, agricultural production is highly vulnerable to changing climatic variables, which are expected to pose negative consequences on crop cultivation and production. The study indicates that the predicted increase in temperature and wind speed poses an extreme danger to wheat production in the Potohar (arid) region of Punjab, Pakistan. The harmful effects of high temperatures on crop (wheat) production have been reported in various studies by scientists. There exists a direct relationship between crop cycle, yield, and increased temperature, meaning that an increase in temperature would decrease the crop cycle and grain yield. The results show that wheat production is more susceptible to changes in wind and temperature compared to rainfall in arid regions of Pakistan. Wheat crop is a major staple food in Pakistan, and the recent increase in threats due to climate change may influence its production levels. To mitigate the vulnerability of the country's agriculture sector to climate change, adaptive approaches must be adopted. Measures to address rising temperatures include modifying wheat cultivation practices, such as delaying sowing by 15-20 days to avoid high temperature levels from mid-October to November. Global warming presents a significant challenge regarding climate

change. Therefore, researchers and scientists should develop short-duration, drought-resistant, and cold- and heat-tolerant high-yielding varieties of field crops like wheat, rice, maize, etc.

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