Nitrogen

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Role of Nitrogen Fertilization and Sowing Date in Productivity and Climate Change Adaptation Forecast in Rice–Wheat Cropping System

Khalid Hussain [1,2], Erdoğan Eşref Hakki [2], Ayesha Ilyas [2,*], Sait Gezgin [2] and Muhammad Asif Kamran [3]

[1] Department of Agronomy, University of Agriculture, Faisalabad 38040, Pakistan; khalid.hussain@uaf.edu.pk
[2] Department of Soil Science and Plant Nutrition, Selçuk University, Konya 42079, Türkiye; eehakki@selcuk.edu.tr (E.E.H.); sgezgin@selcuk.edu.tr (S.G.)
[3] Agricultural Policy, Law and Governance Center, Institute of Agricultural & Resource Economics, University of Agriculture, Faisalabad 38040, Pakistan; asif.kamran@uaf.edu.pk
* Correspondence: ayeshailyas3053@gmail.com; Tel.: +90-3322232924

Abstract: Global food security is at risk due to climate change. Soil fertility loss is among the impacts of climate change which reduces the productivity of rice–wheat cropping systems. This study investigated the effects of varying nitrogen levels and transplanting/sowing dates on the grain yield (GY) and biological yield (BY) of rice and wheat cultivars over two growing seasons (2017–2019). Additionally, the impact of climate change on the productivity of both crops was tested under a 1.5 °C temperature increase and 510 ppm CO_2 concentration while nitrogen fertilization and sowing window adjustments were evaluated as adaptation options using the DSSAT and APSIM models. Results indicated that the application of 120 kg N ha^{-1} significantly enhanced both GY and BY in all rice cultivars. The highest wheat yields were obtained with 140 kg N ha^{-1} for all cultivars. Rice transplanting on the 1st of July and wheat sowing on the 15th of November showed the best yields. The statistical indices of the model's forecast results were satisfactory for rice (R^2 = 0.83–0.85, root mean square error (RMSE) = 341–441, model efficiency (EF) = 0.82–0.89) and wheat (R^2 = 0.84–0.89, RMSE = 213–303, EF = 0.88–0.91). Both models predicted yield loss in wheat (20–25%) and rice (28–30%) under a climate change scenario. The models also predicted that increased nitrogen application and earlier planting would be necessary to reduce the impacts of climate change on the productivity of both crops.

Keywords: fertilizer management; yield loss; DSSAT model; APSIM model; yield forecast; agronomic management; climate change

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1. Introduction

Climate change, environmental pollution and degradation of natural resources are the major environmental risks of the current era caused by anthropogenic activities. Extreme weather conditions, climate action failure and biodiversity loss are the main three severe risks to the earth over the next 10 years [1]. Food security is the global concern of the 21st century and will remain a challenge due to the rapid increase in population and low agricultural productivity. Population pressure is reducing global cultivated fertile land, so in the future, more food will be required from limited available land facing many environmental risks including climate change. Climate change adaptation is necessary to overcome the negative impacts of climate change. Low-income countries often see severe impacts from the changing climate due to low adaptation or resilience capabilities, whereas developed countries deal with climate-related extremes more precisely due to the availability of technologically and advanced adaptation strategies [2–4].

Agriculture is the most vulnerable sector to climate change globally. Carbon dioxide (CO_2) and temperature are increasing on the surface of the earth every year and are considered major climate change indicators [5]. CO_2 concentration is continuously increasing, which directly increases the temperature of the earth. A temperature rise reduces the soil organic matter due to fast decomposition and ultimately reduces soil fertility in arid and semi-arid areas as compared to humid regions [6]. Pakistan is losing agricultural productivity due to temperature rise, loss of soil fertility, changes in rainfall patterns, and shifts in sowing window and water availability. The contribution of the agriculture sector to GDP was 53% during the period 1949–1950, which sharply decreased to 31% in 1980–1981 with a further decline up to 21.4% during the period 2012–2013. During the period 2020–2021, drought caused serious damage to agriculture by reducing its growth rate up to 10% of the previous years. The country is facing annual financial losses of around USD 5.2 billion due to climate extremes [7].

Rice–wheat cropping systems are the oldest cropping systems in Asia and have been practiced for many decades. They have been expanded, and currently, around 23.5 million ha of land is under this system in Asia and 2.3 million ha in Pakistan. The rice–wheat cropping zone is the breadbasket of the Pakistani Punjab. It has a well-developed irrigation system and receives 425–1200 mm annual rainfall [8]. This cropping region is comprised of more than 1 million farm families. The rice–wheat cropping area is mainly situated in the central Punjab districts of Sialkot, Gujranwala, Narowal, Gujarat, Sheikhupura and Hafizabad. In this system, rice is traditionally grown by transplanting 25–35-day-old seedlings in well-puddled compacted soil having standing water conditions throughout the season. The wheat crop is sown on these poorly drained paddy soils by the broadcasting method. Both crops are the major crops of the region and hold key positions in ensuring the food security of the country.

The rice–wheat cropping system is continuously losing its productivity due to climate change (low rainfall, high temperature), a decrease in soil fertility and an increase in production cost per unit area. Moreover, the soil requirements of both crops are different, because rice grows well on puddled soil, whereas wheat needs well-drained soil. The hardpan settled with the puddling process is crucial for water retention and weed control in rice, but compacted soil creates problems of waterlogging for wheat crops. Soil organic matter content has been reduced, and soil structure is being damaged continuously in rice–wheat cropping systems due to the burning of rice crop residue. This is not only reducing soil fertility but also increasing air pollution, smog and greenhouse gas emissions.

It is predicted that CO_2 concentration may reach 510–700 ppm at the end of this century [9]. If these gases continue to increase at existing rates, the earth's average temperature will rise around 1.5–2.5 °C by the end of this century [5]. A high-global-warming scenario even estimated a 3.7 °C increase in temperature by the end of the 21st century in Pakistan [10]. Moreover, the rice–wheat cropping system of Punjab is highly vulnerable to climatic variability [11]. Scientists projected a 2–2.5 °C rise in temperature during the rice growing (Kharif) season and around a 2.4–2.7 °C rise during the wheat growing (Rabi) season in the mid-century (2040–2069), which could even go up to 5.8 °C at the end of this century [7,12]. These elevated temperature trends may cause a 15–35% yield reduction in rice and an 11–40% reduction in wheat in this cropping system at the end of the 21st century [13,14]. The extent of hazards due to climate change would be more devastating in the future for the productivity of rice–wheat cropping systems that can directly compromise the food security of the region.

The impact of climate change on agriculture can only be minimized through adaptation to these changes. Climate change adaptation in agriculture is the process that alters/manages the agricultural systems according to the changed behavior of the climate [15]. Optimizing nitrogenous fertilization and sowing windows, better resource management, improving agronomic practices, and heat and drought resistance cultivars are considered climate change adaptation strategies at the farmer's field level. Nitrogen is essential for crop growth, but climate change alters its availability and uptake through increased temperatures, variable precipitation, and higher atmospheric CO_2 levels. These changes may require adjusting nitrogen application rates and timings to maintain crop yields. Nitrogen fertilization and sowing dates must be strategically managed to cope with the uncertainties of changing climate, and their optimization will be key in maintaining or improving rice and wheat productivity [16]. Sowing dates are critical for synchronizing crop growth with favorable environmental conditions, helping crops avoid extreme heat, drought, or frost. For both rice and wheat, adapting nitrogen management and sowing schedules, combined with the use of climate-resilient varieties and precision farming techniques, is essential for sustaining productivity under changing climatic conditions [17]. Extensive experimentation on major crops having variable temperature regimes and adaptation options is required to devise viable adaptation strategies. Such experiments require huge investments in the form of sophisticated temperature control equipment, scientific knowledge, and labor and time intensity. Alternatively, decision support system tools such as crop models can be used for climate change impact assessment and adaptation package development for sustainable crop production [18]. Moghaddam et al. [19] simulated a drastic decrease in wheat yield during 2040 due to climate change scenarios and suggested that early sowing with nitrogen fertilization could alleviate climate change's negative impacts on wheat. Ding et al. [20] indicated that shifting the sowing date is a useful strategy in dealing with the impacts of climate change on paddy rice production.

Keeping in view the magnitude of the problem, it is time to quantify the impacts of climate change on rice–wheat cropping systems and to further develop an effective adaptation package for sustainable production and regional food security. Field experiments on variable nitrogen levels and sowing window variability along with decision support tools (DSSAT and APSIM) are indulged in the study (i) to define the role of nitrogen fertilization and sowing window on the productivity of both crops, (ii) to quantify the impacts of climate change on the rice–wheat cropping system at farm level and (iii) to define the role of nitrogen fertilization and sowing window as adaptation options against climate change for sustainable crop production in rice–wheat cropping systems.

2. Materials and Methods

2.1. Study Site and Experimental Description

Field experiments were conducted for two years at the agronomic research area University of Agriculture, Faisalabad (31°25′0′′ N 73°5′28′′ E). The study site has sandy loam soil with 8.2 pH, EC was 1.4 dSm^{-1}, and organic matter was 0.93%. The rice crop was sown in late May and transplanted in early to end of July according to treatments. Rice was harvested in October, whereas wheat was planted in mid-November. The wheat crop was harvested in April.

For rice cultivation, land was prepared by giving two cultivations after the harvest of the previous crop almost two months before transplanting. At the time of transplanting, 4–5 cultivations were done followed by planking in standing water to puddle the soil and create a hardpan to keep water standing in the crop to create anaerobic conditions. No fertilizer was applied at the time of land preparation; rather, it was applied one week after transplantation. Fertilizers were applied at a rate of 20:20 kg ha^{-1} P_2O_5:K_2O, respectively, while nitrogen was applied according to the treatments. Nitrogen was applied in the form of urea, and di-ammonium phosphate and potassium sulphate were sources of phosphorous and potassium, respectively. Three leading rice cultivars, i.e., Basmati Super, Basmati 515 and Kissan Basmati were part of the experiments. The rice nursery was transplanted 30–35 days after planting.

For wheat sowing, a 125 kg ha^{-1} seed rate was used. The seedbed was prepared with 4–5 cultivations followed by 2 plankings. The wheat crop was sown in lines, with the application of fertilizers at the rate of 61, 0 kg ha^{-1} P_2O_5 and K_2O, respectively, while nitrogen was applied according to treatments. The same sources of fertilizers were used as mentioned for rice crops. Wheat was grown with 3 irrigations with a 25–30-day interval depending on weather conditions. Three leading wheat cultivars, i.e., Galaxy-13, Ujala-2016 and Anaj-2017 were part of the experiments.

2.2. Treatments and Data Measurements

Four nitrogen levels (0, 60, 120 and 180 kg ha^{-1}) and three transplanting dates (1, 15 and 30 July) were tested in two experiments, respectively, using three leading basmati rice cultivars for two continuous years (2018 and 2019). The plot size was 45 m^2. The experiment was laid out in randomized complete block design (RCBD) with factorial arrangements with three replications each year. The recommended dose of fertilization (120:20:20 kg ha^{-1} N:P:K) was applied in the rice-transplanting experiment, while 1 July was the rice-transplanting time for the nitrogen experiment.

Four nitrogen levels (0, 70, 140 and 210 kg ha^{-1}) and three sowing regimes (1 November, 15 November and 1 December) were tested using three leading wheat cultivars in two experiments, respectively, for two consecutive years (2017–2018 and 2018–2019). The plot size was 30 m^2. Each experiment was carried out in RCBD with factorial arrangements having three replications every year.

In both crops, central four rows from each plot were harvested separately. The biological and grain yield of these eight rows was measured and then the values were converted into kg ha^{-1}.

2.3. Model Data Set, Calibration, and Evaluation

Grain yield data of rice and wheat obtained from two consecutive field experiments were used as the input data set for model calibration and evaluation. Weather data (daily max. and mini. temperature, relative humidity, solar radiation and rainfall) along with soil information (soil horizon, soil NPK status, soil Particles, pH, soil color, % carbon, etc.) and all agronomic management operations carried out in both crops were also part of the input data set used for model parameterization.

Both models were calibrated with the 1st-year experimental data set of each crop while the 2nd-year experimental data were used for model evaluation. During the model calibration process, the genetic coefficients of crops were changed (Supplementary Tables S1–S4) to bridge the gap between experimental (measured) data and the model-generated (modeled) data. Once the genetic coefficients were set during the calibration process, no further changes in genetic coefficients were made during the model evaluation process.

2.4. Climate Change Impact Assessment and Adaptation Scenarios

After calibration and evaluation of both models, various scenarios were developed to identify the impacts of changing climate on the productivity of the rice–wheat cropping system and to develop feasible adaptation packages for sustainable rice and wheat production. Climate change impact assessment on rice and wheat crops was tested by increasing mean aerial temperature by 1.5 °C and keeping 510 ppm CO_2 concentrationin the 'Environmental Modification' option available in the model management input file (Scenario 1). It is indicated from several studies that a 1.5 °C mean temperature and 100 ppm CO_2 increase is expected before the end of the current century [5,9], while the expected increase in temperature and CO_2 is quite high for Pakistan [10].

Scenarios 2 and 3 were developed as adaptation strategies in both rice and wheat crops to minimize the negative impacts of elevated temperature and CO_2. In rice crops, Scenario 2 was a 10% increase in fertilizer application than used in rice field experiments, while Scenario 3 was the early transplanting of rice under a 1.5 °C mean temperature increase and a 510 ppm level of CO_2 condition.

An increase in nitrogen fertilizer application and earlier wheat sowing were the scenarios used as climate change adaptation strategies in wheat crops. A 10% increase in fertilization under changing climatic conditions was used as Scenario 2 in wheat, while sowing wheat 10 days earlier under changing climatic conditions was tested as Scenario 3 in wheat.

All the scenarios were tested against baselines. The planting/transplanting time, fertilizer application and climatic conditions of the 2nd-year experiment for the rice crop and the 1st-year experiment for the wheat crop were used as baseline scenarios. The complete description of scenarios is presented in Table 1.

Table 1. Description of scenarios used for climate change impact assessment and adaptation strategies in rice and wheat.

Scenarios	Description
Baseline for rice and wheat productivity	
Baseline *	Average grain yield (kg ha^{-1}) measured from field experiments of rice transplanted on 15 July under recommended fertilizer application and wheat planted on 15 November under recommended fertilizer application were used as baseline.
Forecasting increased temperature and CO$_2$ impacts on rice and wheat productivity	
Scenario 1 +1.5 °C, 510 ppm level of CO$_2$	1.5 °C was added in the experimental year mean temperature with 510 ppm level of CO$_2$ (this was carried out in the environmental modification facility of models)
Climate change adaptation strategies for rice under changing climate scenario	
Scenario 2 10% increase in nitrogen fertilization (132 kg N ha^{-1})	Models were run with a 10% increase in recommended fertilization (120 kg N ha^{-1}) under climate change conditions (+1.5 °C, 510 ppm level of CO$_2$)
Scenario 3 15 days earlier transplanting of rice	Models were run with a 1 July transplanting date under climate change conditions (+1.5 °C, 510 ppm level of CO$_2$)
Climate change adaptation strategies for wheat under changing climate scenario	
Scenario 2 10% increase in fertilization (154 kg N ha^{-1})	Models were run with a 10% increase in standard fertilization (140 kg N ha^{-1}) under climate change conditions (+1.5 °C, 510 ppm level of CO$_2$)
Scenario 3 10 days earlier planting of wheat	Models were run with 10 days earlier planting of wheat (5 November) under climate change conditions (+1.5 °C, 510 ppm level of CO$_2$)

* Indicating best grain yield producing field experimental years for rice and wheat.

2.5. Statistical Analysis

A two-way ANOVA at the 5% level of significance was executed for the analysis of experimental data and treatment means were compared using the Least Significant Difference (LSD) test to identify significant differences among treatments, whereas the goodness of fit (GOF) procedure suggested by Loague and Green [21] was followed for the assessment of model performance and also to justify the authenticity of model output and predictions. The mathematical expressions were as follows:

Modeling efficiency (EF):

$$\mathrm{EF} = \left(\sum_{i=1}^{n}\left(Oi-\overline{O}\right)^2 - \sum_{i=1}^{n}(Pi-Oi)^2\right)/\sum_{i=1}^{n}\left(Oi-\overline{O}\right)^2$$

Coefficient of determination (CD):

$$\mathrm{CD} = \sum_{i=1}^{n}\left(Oi-\overline{O}\right)^2/\sum_{i=1}^{n}\left(Pi-\overline{O}\right)^2$$

Root mean square error (RMSE):

$$\mathrm{RMSE} = \left[\sum_{i=1}^{n}\left(Pi-\overline{O}\right)^2/n\right]^{0.5}.\frac{100}{\overline{O}}$$

Maximum error (ME):

$$\mathrm{ME} = \mathrm{Max}|Pi-Oi|_{i=1}^{n}$$

Coefficient of residual mass (CRM):

$$\mathrm{CRM} = \left(\sum_{i=1}^{n} Oi - \sum_{i=1}^{n} Pi \right) / \sum_{i=1}^{n} Oi$$

where Oi is the observed value, Pi is the predicted value, n is the number of observations or samples and $\bar{O}$ is the mean of observed values.

For a good performance of the model, it is better to obtain the values of EF, CD, RMSE, ME and CRM as close as possible to 1, 1, 0, 0, and 0, respectively.

3. Results

3.1. Impact of Nitrogen Levels and Transplanting Dates on Rice Grain and Biological Yield (kg ha^{-1})

The impact of varying nitrogen levels on the grain yield (GY) and biological yield (BY) of three rice cultivars (Basmati Super, Basmati-515, and Kissan Basmati) was assessed over the 2018 and 2019 growing seasons (Table 2). In 2018, the application of 120 kg N ha^{-1} significantly increased both GY and BY across all cultivars compared to lower and higher nitrogen levels. Basmati Super exhibited a GY of 4453 kg ha^{-1} and a BY of 11,553 kg ha^{-1} at 120 kg N ha^{-1} nitrogen level, compared to 980 kg ha^{-1} and 2401 kg ha^{-1}, respectively, at 0 kg N ha^{-1}. Similar trends were observed for Basmati-515 and Kissan Basmati, with GY and BY. The observed differences among treatments were statistically significant ($p < 0.05$).

Table 2. Rice grain yield (GY) and biological yield (BY) (kg ha^{-1}) at different nitrogen levels transplanted on 1 July during the years 2018 and 2019.

2018						
Nitrogen Levels (kg ha^{-1})	Basmati Super		Basmati-515		Kissan Basmati	
	GY	BY	GY	BY	GY	BY
0	980 d	2401 c	1001 d	2510 d	1012 d	2439 d
60	2510 c	6782 b	2409 c	6830 c	2501 c	6799 c
120	4453 a	11,553 a	4512 a	11,005 a	4482 a	11,174 a
180	3938 b	10,190 a	4001 b	10,211 b	3919 b	10,111 b
LSD value	453	532	405	554	434	498
2019						
Nitrogen Levels (kg ha^{-1})	Basmati Super		Basmati-515		Kissan Basmati	
	GY	BY	GY	BY	GY	BY
0	1008 d	2640 d	1099 d	2709 d	1102 d	2707 d
60	2810 c	6978 c	2710 c	6976 c	2854 c	6890 c
120	4686 a	11,690 a	4656 a	11,650 a	4671 a	11,670 a
180	4055 b	10,344 b	4050 b	10,373 b	4043 b	10,281 b
LSD value	389	620	390	590	423	510

The letters a–d show the significant differences among the treatment means at a 5% level of probability.

In 2019, the application of 120 kg N ha^{-1} again resulted in the highest yields for all cultivars. Basmati Super recorded a GY of 4686 kg ha^{-1} and a BY of 11,690 kg ha^{-1} at 120 kg N ha^{-1}, compared to 1008 kg ha^{-1} and 2640 kg ha^{-1}, respectively, at 0 kg N ha^{-1}. The differences between nitrogen treatments were consistent with the previous year, reinforcing the importance of sufficient nitrogen application for maximizing rice yields.

The impact of transplanting dates was statistically significant on grain and biological yield production in all three Basmati cultivars during field experiments of 2018–2019 (Table 3). Maximum rice grain yield was observed on the 15 July transplanting date, whereas the lowest grain yield was depicted on the 30 July transplanting date in all rice cultivars under study. Among cultivars, the maximum grain yield of 4512 kg ha^{-1} was observed in Bamsati-515 transplanted on 15 July 2018, whereas the minimum grain yield (3591 kg ha^{-1}) was obtained in Basmati Super on the 30 July 2018 transplanting date. Similar trends in grain yield were observed in 2019. Moreover, the highest biological yield was also observed on 15 July in all the cultivars, while the lowest biological yield was observed when rice was transplanted on 30 July in both studied years in all rice cultivars studied. Rice produced a higher yield in 2019 as compared to 2018.

Table 3. Grain yield (GY) and biological yield (BY) (kg ha^{-1}) at different transplanting dates of rice cultivars during the years 2018 and 2019.

2018						
Transplanting date	Basmati Super		Basmati-515		Kissan Basmati	
	GY	BY	GY	BY	GY	BY
1 July	4106 b	10,543 b	4171 b	10,645 b	4138 b	10,689 a
15 July	4453 a	11,553 a	4512 a	11,005 a	4482 a	11,174 a
30 July	3591 c	10,243 c	3796 c	10,207 c	3693 c	10,225 b
LSD value	215	235	280	302	256	222
2019						
Transplanting date	Basmati Super		Basmati-515		Kissan Basmati	
	GY	BY	GY	BY	GY	BY
1 July	4066 b	10,947 b	4143 b	10,945 b	4105 b	11,394 b
15 July	4686 a	11,690 a	4656 a	11,650 a	4671 a	11,670 a
30 July	3852 b	10,573 c	4003 b	10,534 c	3928 c	11,004 c
LSD value	245	282	202	186	190	204

The letters a–c show significant differences among the treatment means at a 5% level of probability.

3.2. Impact of Nitrogen Levels and Sowing Dates on Wheat Grain and Biological Yield

The impact of fertilizer application on wheat grain yield was statistically significant in all the wheat cultivars during both years of field experiments (Table 4). Wheat grain yield highlighted that in two-year field experiments, Anaj-2017 performed best at nitrogen level 140 kg ha^{-1}, while its grain yield was lowest without nitrogenous fertilizer application. The trends of fertilizer impacts were similar in all wheat cultivars. The lowest grain yield was observed in Galaxy-13 in both years of the experiment. Biological yield data showed that nitrogen application @ 140 kg ha^{-1} maximized the values for Anaj-2017, Ujala-2016, and Galaxy-13, respectively, whereas the highest biological yield was also observed in Anaj-2017 at 140 kg ha^{-1} nitrogen application. Both studied years showed similar trends of grain and biological yield production in wheat, while the 2017–2018 cropping season produced a higher yield as compared to 2018–2019.

The effect of different sowing dates on the grain yield and biological yield of the wheat cultivars was analyzed for the 2017–2018 and 2018–2019 seasons (Table 5).

In 2017–2018, sowing on 15 November produced statistically highest yields across all cultivars. Anaj-2017 sown on 15 November yielded 5534 (GY) and 12,540 kg ha^{-1} (BY), which were significantly higher than yields obtained from sowing on 1 December (GY = 4435 kg ha^{-1}, BY = 11,382 kg ha^{-1}). Ujala-2016 and Anaj-2017 also demonstrated similar yield responses to the different sowing dates, with 15 November sowing generally resulting in higher yields.

The 2018–2019 results supported these findings, with 15 November sowing again yielding the highest results. Anaj-2017 recorded the highest GY of 5469 kg ha^{-1} and a BY of

11,561 kg ha^{-1} at this sowing date compared to the lowest yields in Glaxy-13 when sowed on 1 December (e.g., 3702 kg ha^{-1} GY, 10,001 kg ha^{-1} BY).

Table 4. Grain yield (GY) and biological yield (BY) (kg ha^{-1}) at different nitrogen levels for wheat cultivars during the years 2017–2018 and 2018–2019.

2017–2018						
Nitrogen Levels (kg ha^{-1})	Galaxy-13		Ujala-2016		Anaj-2017	
	GY	BY	GY	BY	GY	BY
0	1849 d	6005 c	1817 d	6656 d	1861 d	6923 d
70	3678 c	10,301 b	3633 c	10,205 c	4262 c	10,161 c
140	5420 a	12,749 a	5290 a	12,386 a	5534 a	12,540 a
210	5039 b	10,730 b	5034 b	10,897 b	5012 b	10,912 b
LSD value	266	622	430	566	389	539
2018–2019						
Nitrogen Levels (kg ha^{-1})	Galaxy-13		Ujala-2016		Anaj-2017	
	GY	BY	GY	BY	GY	BY
0	1422 d	5210 d	1536 d	5305 d	1667 d	5323 d
70	3231 c	10,022 c	3422 c	10,010 c	3255 c	10,001 c
140	4698 a	11,449 a	4893 a	11,820 a	5469 a	11,561 a
210	4022 b	10,640 b	4021 b	10,643 b	4109 b	10,709 b
LSD value	338	520	300	590	376	501

The letters a–d show significant differences among the treatment means at a 5% level of probability.

Table 5. Grain yield (GY) and biological yield (BY) (kg ha^{-1}) of various wheat cultivars having different sowing dates during the years 2017–2018 and 2018–2019.

2017–2018						
Sowing Dates	Galaxy-13		Ujala-2016		Anaj-2017	
	GY	BY	GY	BY	GY	BY
1 November	5054 b	11,991 b	5023 a	11,799 b	5080 b	11,692 b
15 November	5420 a	12,749 a	5290 a	12,386 a	5534 a	12,540 a
1 December	4435 c	11,382 c	4521 b	11,081 c	4612 c	11,091 c
LSD value	382	504	253	533	423	412
2018–2019						
Sowing Dates	Galaxy-13		Ujala-2016		Anaj-2017	
	GY	BY	GY	BY	GY	BY
1 November	4009 b	10,630 b	4034 b	10,980 b	5387 b	11,072 b
15 November	4698 a	11,449 a	4893 a	11,820 a	5469 a	11,561 a
1 December	3702 c	10,001 c	3865 c	10,121 c	4439 c	10,982 c
LSD value	203	520	311	620	389	587

The letters a–c show significant differences among the treatment means at a 5% level of probability.

3.3. Models Calibration and Evaluation

DSSAT calibration results showed a significant relationship between measured and modeled rice grain yield (Figure 1a). The goodness of fit parameter showed very satisfactory results of DSSAT calibration, i.e., EF was 0.94, R^2 was 90, RMSE was 144, ME was 48, and

CRM was 0.29. After calibration of DSSAT, the model was tested for evaluation with an independent data set to check the authenticity and validity of model simulations. DSSAT evaluation with an independent data set also showed very promising results of rice grain yield simulation with a significant relationship between measured and modeled values. DSSAT evaluation results of EF, RMSE, ME and CRM were 0.89, 0.85, 180, 120, and 0.34, respectively (Figure 1b).

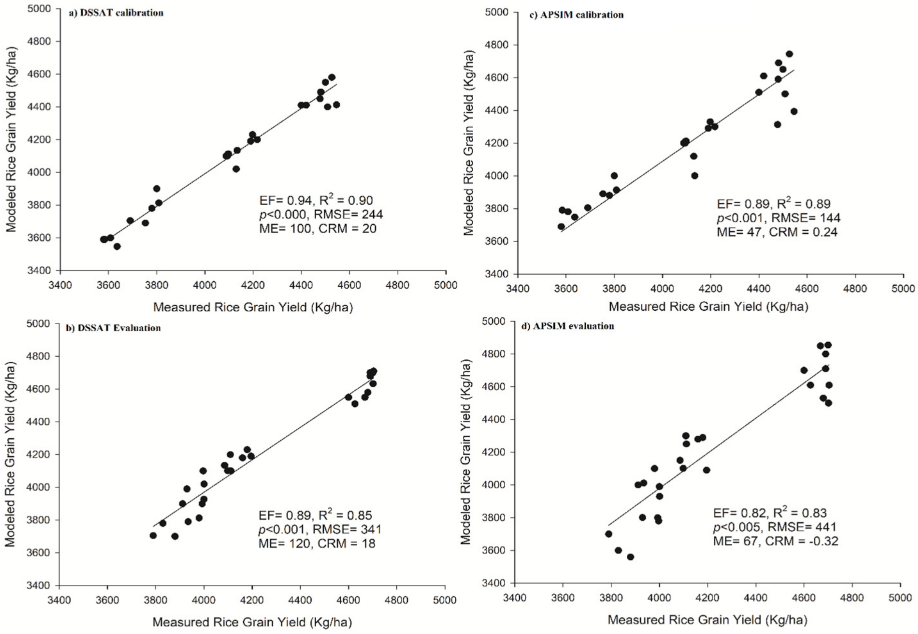

Figure 1. Relationships between modeled and measured rice grain yield during (**a**) DSSAT calibration, (**b**) DSSAT evaluation (**c**) APSIM calibration and (**d**) APSIM evaluation.

APSIM calibration trends between measured and modeled rice grain yield were also significant in all cultivars sown at various transplanting dates (Figure 1c). EF, R^2, RMSE, ME and CRM values were 0.89, 0.89, 144, 47, and 0.24, respectively. APSIM evaluation was carried out with an independent data set of another year which was used for DSSAT evaluation with EF 0.82, R^2 83, RMSE 441, ME 67, and CRM was -0.32 (Figure 1d).

3.4. Climate Change Impact Assessment and Adaptation Strategies in Rice

DSSAT model predicted a drastic reduction in rice grain yield (kg ha^{-1}) (around 28%) with the increase of 1.5 °C temperature along with elevated CO_2 (Scenario 1) as compared with the grain yields (kg ha^{-1}) of Basmati Super, Basmati-515, and Kissan Basmati under baseline (the climatic condition of experimental year without temperature and CO_2 rise) under the 1 July transplanting condition (Figure 2), whereas APSIM predicted a 33% yield loss under Scenario 1 as compared to baseline. DSSAT suggested an increase of 17% in rice grain yield when applying 10% more nitrogen than the current recommendations as compared to rice grain yield under Scenario 1 in Basmati Super, Basmati-515, and Kissan Basmati transplanted on 1 July. Moreover, rice grain yield increased by around 20% when the rice crop was transplanted 15 days earlier than 1 July with the current level of fertilization used as the baseline as compared to Scenario 1 in all the cultivars, whereas APSIM predicted a 17% grain yield increase in rice planted under Scenario 2 as compared to Scenario 1 with a 10% increase in fertilization, while yield was increased by 18% in Scenario 3 as compared to Scenario 1 when transplanting the rice 15 days earlier.

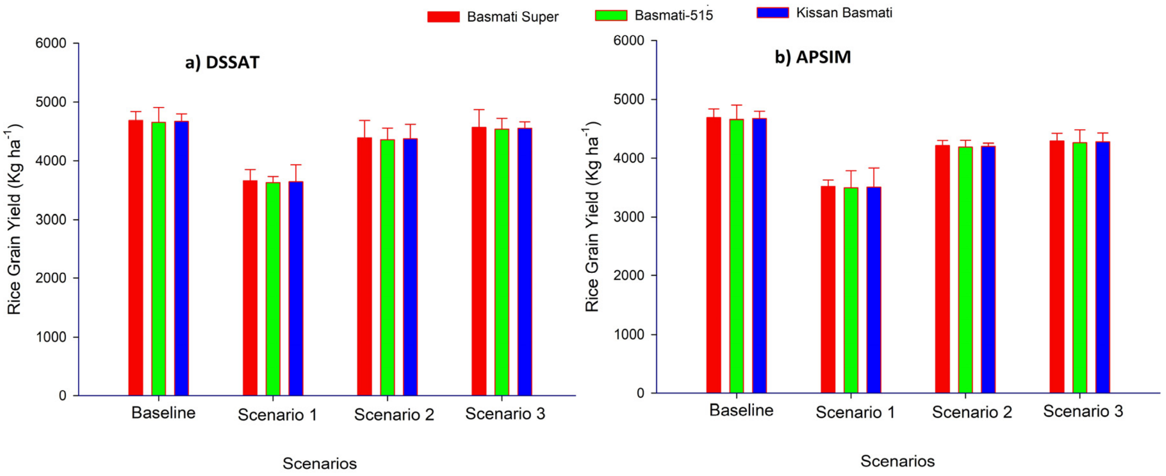

Figure 2. Climate change impact assessment and adaptation strategies in three high-yielding rice cultivars at baseline (2017–2018 conditions), Scenario 1 (+1.5 °C with 510 ppm CO_2), Scenario 2 (Scenario 1 with 10% fertilizer increase), Scenario 3 (Scenario 1 with 10 days earlier sowing) by using (**a**) DSSAT and (**b**) APSIM after calibration and evaluation. Standard error is presented as error bars.

3.5. Climate Change Impact Assessment and Adaptation Strategies in Wheat

DSSAT predicted a 25% grain yield reduction (Figure 3) in all wheat cultivars (Galaxy-13, Ujala-2016, and Anaj-2017) under a 1.5 °C increase in temperature and a 510 ppm CO_2 concentration (Scenario 1) as compared to the baseline (experiment year's temperature and CO_2 concentration), whereas APSIM predicted a 40% average grain yield reduction in all wheat cultivars planted under Scenario 1 as compared to the baseline. The DSSAT model predicted an average 10% grain yield increase in all cultivars when nitrogen application is increased by 10% from baseline standard nitrogen application (Scenario 2) as compared to Scenario 1, while APSIM predicted a 13% yield increase under the same adaptation (Scenario 2) as compared to Scenario 1. Moreover, DSSAT predicted a 12–13% yield increase when wheat is planted 10 days earlier (Scenario 3) than that of baseline sowing time (15 November), while APSIM predicted a 15–16% increase when wheat is planted 10 days earlier than 15 November.

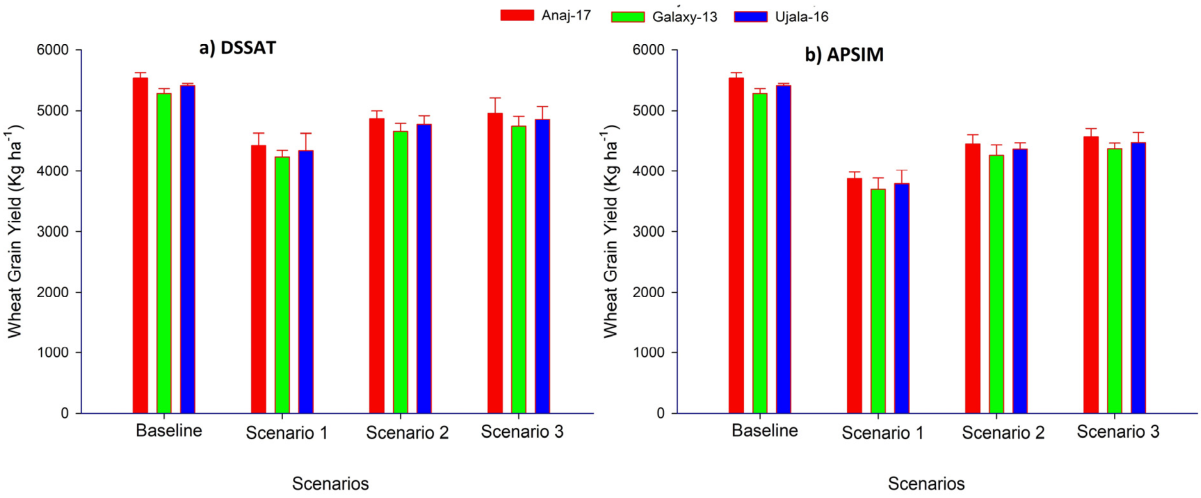

Figure 3. Climate change impact assessment and adaptation strategies in three high-yielding wheat cultivars at baseline (2017–2018 conditions), Scenario 1 (+1.5 °C with 510 ppm CO_2), Scenario 2 (Scenario 1 with 10% fertilizer increase), Scenario 3 (Scenario 1 with 15 days earlier transplanting) by using (**a**) DSSAT and (**b**) APSIM after calibration and evaluation. Standard error is presented as error bars.

4. Discussion

4.1. Impact of Nitrogen Fertilization and Transplanting Dates on Rice Yield

The application of nitrogen significantly influenced the grain and biological yields of the rice cultivars examined in this study. The nitrogen level of 120 kg ha^{-1} consistently produced maximum GY and BY across all cultivars in both the 2018 and 2019 growing seasons. These results are consistent with Fageria et al. [22]'s research, which indicated that nitrogen is a critical nutrient for rice crops, directly influencing photosynthesis, biomass accumulation, and, ultimately, yield. A significant increase in yield at 120 kg ha^{-1} nitrogen application is attributed to enhanced chlorophyll content and improved nitrogen use efficiency, which are essential for optimal plant growth and grain filling [23], whereas a lesser rice grain yield at 180 kg ha^{-1} than 120 kg ha^{-1} nitrogen application was due to law of dimensioning return.

The timing of transplanting also played a crucial role in determining rice yields. Transplanting on 15 July consistently resulted in the highest yields across all cultivars. This early transplanting likely allowed the rice plants to fully utilize the growing season, benefiting from favorable environmental conditions such as optimal temperature and solar radiation during critical growth stages [24].

Delayed transplanting, particularly on 30 July, resulted in significant yield reductions. Singh et al. [25] reported that yield penalties are associated with late transplanting, primarily due to shorter growing periods and increased exposure to adverse climatic conditions toward the end of the growing season. The significant differences in yield among the transplanting dates highlight the importance of timely field preparation and planting to maximize yield potential.

4.2. Impact of Nitrogen Fertilization and Sowing Dates on Wheat Yield

For wheat, nitrogen application had a similar positive impact on yield, with the nitrogen level (140 kg ha^{-1}) producing the greatest GY and BY across all cultivars in both the 2017–2018 and 2018–2019 growing seasons. The results are consistent with those reported by Ali et al. [26], indicating that nitrogen is essential for wheat growth, influencing tillering, spike formation, and grain filling.

The increased yields at balanced nitrogen levels can be attributed to improved nitrogen uptake and assimilation, which are critical for maximizing grain production. However, excessive nitrogen application can lead to environmental issues such as nitrate leaching and greenhouse gas emissions [27].

The timing of sowing was another key factor influencing wheat yields. Sowing on 15 November produced the highest yields in both growing seasons, with significant reductions observed for later sowing dates. Liu et al. [28] reported that optimal sowing dates align the crop's critical growth stages with favorable environmental conditions, thus enhancing yield potential.

Late sowing, particularly on 1 December, likely exposed the wheat plants to suboptimal temperatures during critical periods such as anthesis and grain filling, leading to reduced yields. The significant yield differences among the sowing dates highlighted the need for timely sowing to maximize wheat productivity, particularly in regions with similar climatic conditions.

4.3. Models Performance

Statistical analysis is the only way to evaluate model performance. A number of statistical procedures are followed for testing model calibration and evaluation results, but the goodness of fit (GOF) procedure is the most common procedure used for said purpose. GOF assesses the model's ability to predict output within the acceptable range with precision and accuracy [21,29–31] during the model calibration and evaluation process. Model calibration and evaluation values obtained from DSSAT and APSIM were within the acceptable range of GOF parameters. Model efficiency (EF) and R^2 values close to 1 and a root mean square error (RMSE) value closer to zero (Figure 2) between the observed and simulated values indicate the models' accuracy [30].

Independent input data are important to evaluate the accuracy and precision of a model [21]. In DSSAT and APSIM during the calibration process, the genetic coefficients are manipulated to fill the yield gap between observed and modeled values. That is why in most cases, the GOF parameter results of the calibration remain within the acceptable statistical range while the main test of model accuracy is the statistical analysis of evaluation results obtained with an independent data set when the user is restricted in any further change in the genetic parameters. Both DSSAT and APSIM evaluation results were within good range of accuracy and acceptability, which made the model suitable for any scenario analysis.

4.4. Climate Change Impact Assessment in Rice–Wheat Cropping System

Rice–wheat cropping systems are among the major cropping zones of Pakistan having 1.1 million hectare cultivated land. Bokhari et al. [7] projected a 2–2.5 °C increase during the rice growing (Kharif) season and a 2.4–2.7 °C increase during the wheat growing (Rabi) season in the mid-century (2040–2069), and Krishna et al. [12] indicated a probability of a 1.4–5.8 °C increase in temperature by the end of this century. In this study, a 1.5 °C average temperature rise reduced rice grain yield by 28% for DSSAT and 33% for the APSIM, whereas a 1.5 °C average temperature rise during wheat the growing season reduced wheat grain yield by 25% for DSSAT and 40% for APSIM. A similar trend of yield reductions was observed by Anser et al. [14]. The variability in yield reduction predicted by DSSAT and APSIM could possibly be due to different genetic input parameters. Krishnan et al. [12] explained that rice is cultivated in areas having temperatures above optimal and any further increase in temperature directly reduces rice productivity due to a reduction in grain weight and quality. Peng et al. [32] suggested rice yield declined by 15% per 1 °C temperature increase on average, which agrees with our findings. Studies by Horie et al. [33] and Prasad et al. [34] also indicated that yield increased under elevated CO_2, while high air temperatures can reduce grain yield even under elevated CO_2 in both wheat and rice. Interestingly, a night temperature increase is commonly associated with increased respiration rates, leading to a decline in yield [35], and in this study, a 1.5 °C average increase in night temperature would also be responsible for the yield decrease in rice. Asseng et al. [36] indicated a 50% wheat yield reduction with an increase of 2 °C in average temperature throughout the growing season, which supports the current findings. Hossain et al. [13] also indicated an 11–40% wheat yield reduction with an increase in temperature, which was in accordance with our results.

4.5. Climate Change Adaptation Strategies for Rice–Wheat Cropping System

In rice, early transplanting and an increase in fertilization were used as adaptation strategies which increased the yield by 11–16% under adverse conditions during the rice growing period. Rice–wheat cropping systems have a slim planting window for the sowing of both crops due to climate shifts triggered by changing climate [37]. Rice transplanting is delayed due to several reasons including availability of farm inputs, seedbed preparation, nursery availability, etc. Delayed rice transplanting ultimately increased the age of nursery. Liu et al. [38] also confirmed that rice yield decreased due to delayed transplanting of rice with aged nursery plants and that the yield reduction can be improved by early transplanting with young nurseries, as indicated by both models.

Soil is the medium for plant growth and development. Any change in soil characteristics directly affects the potential of the crop. The Earth is heating up and the increase will continue with an expected high temperature (around 4 °C increase) at the end of the 21st century [5,10,39]. A high temperature depletes plant nutrients from the soil and ultimately reduces the overall fertility of the soil. The model indicates that an increase in fertilizer increases the productivity of rice. Additional fertilizer compensated for the yield induced by soil fertility loss due to changing climate [40].

Crop productivity is always dependent on climate and agronomic practices, while cereals' response to these factors is more complicated than wild crops [41]. Wheat is a widely grown cereal crop globally and is under direct threat from climate change. Pequeno et al. [42] indicated that a nitrogen increase in wheat can increase or at least sustain the genetic potential of wheat productivity. Both models indicated the same effects of additional nitrogen applications under future climate conditions in Pakistan. This addition of nitrogen is just due to soil nutrient depletion under increased temperatures due to changing climate [40]. The response of DSSAT to high nitrogen conditions is better as compared to APSIM [18].

Studies indicated a 6–15% reduction in wheat grain yield in semi-arid and arid environments of Pakistan if the increase in temperature would be 1–2 °C up to the mid-century [43,44]. The same was indicated by both the models in the current study. High temperatures under changing climate coincide with sensitive stages of crop development, severely reducing crop yield and affecting its quality [45–47]. Both models simulated that sowing of wheat earlier than current farmer practice can sustain wheat productivity under changing climate effects in semi-arid countries like Pakistan.

5. Conclusions

Rice–wheat crop systems are losing productivity, and this loss will be severe under future changing climate scenarios. The results of this study have important implications for agronomic practices in rice and wheat cultivation. The consistent yield increases observed with higher nitrogen application emphasize the need for adequate nitrogen fertilization, tailored to the specific requirements of each crop and cultivar.

The findings suggest that rice transplanting should be carried out at the start of July, which is currently being carried out late in July, while wheat should be sown by mid-November to optimize yield potential. These practices align the crop's development with favorable environmental conditions, thereby enhancing productivity. DSSAT predicted a 25–28% yield decrease in rice–wheat cropping systems, while APSIM predicted a 25–30% yield loss in rice–wheat cropping systems with a 1.5 °C increase in temperature and CO_2 level up to 510 ppm as compared to the experimental year (baseline). Both DSSAT and APSIM suggested 15 days early transplanting of rice with a 10% increase in fertilization to build somewhat sustainable rice production, while early planting of wheat with 10% increase in the application of fertilizer as compared to baseline will sustain the yield decrease in wheat under changing climatic conditions. Both models indicated planting time and fertilization modifications as adaptation strategies for sustainable productivity of rice–wheat cropping systems under changing climate. The multi-model approach developed confidence in productivity analysis of rice–wheat cropping under elevated CO_2 and temperature conditions continuously being observed in the country. The simulation technique was promising for developing climate change impact assessment and adaptation strategies for sustainable crop production and food security in developing countries. Rice and wheat productivity decrease can be addressed by the above-mentioned practices as viable adaptation strategies devised by DSSAT and APSIM models.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/nitrogen5040062/s1, Table S1: Description of DSSAT Genetic coefficients for wheat crop modified during model calibration; Table S2: Description of DSSAT Genetic coefficients for Rice crop modified during model calibration; Table S3: Description of APSIM Genetic coefficients for wheat crop modified during model calibration; Table S4: Description of APSIM Genetic coefficients for Rice crop modified during model calibration.

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