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Adaptive Crop Management Strategies for Sustainable Wheat Production Under Changing Climate in Ethiopia

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ABSTRACT

Enhancing local adaptive capacities is of paramount importance to ensure the stability of regional food production in the context of a changing climate. This study was undertaken with the aim of identifying the most suitable crop management strategies in response to evolving climatic conditions. Daily climate data were sourced from the National Meteorology, while soil and crop management information were obtained from the Adet Agricultural Research Center. Future climate data were derived from the Fifth Coupled Model Intercomparison Project (CMIP5) database within the Climate Research Programme, encompassing 20 General Circulation Models (GCMs) for the RCP8.5 emission scenarios. The study's temporal scope encompassed the early-term horizon of 2010-2039. The Decision Support System for Agro-technology Transfer (DSSAT) crop model was harnessed as a computational tool to facilitate these investigations. The interactions between sowing date and plant density were found to yield non-significant effects on wheat yields ($P>0.05$). Conversely, significant effects ($P<0.05$) were observed in the interactions of plant density with fertilizer rate, as well as the interactions of sowing date with fertilizer rate, both contributing to variations in the yield of both wheat varieties. Additionally, the simultaneous impact of three agronomic practices, sowing date, plant density, and fertilizer rate were found to exert significant effects ($P<0.05$) on wheat yields. Within this framework, a noteworthy crop management approach emerges. Specifically, planting on June 25 with plant densities ranging from 250 to 350 plants m^{-2}, coupled with a fertilizer rate of 184 kg N ha^{-1}, is recommended as a robust strategy to optimize the yield of both Tay and Senkegna wheat varieties. This study suggested the critical role of informed decision-making in adapting agricultural practices to shifting climate dynamics, ensuring sustained and enhanced crop productivity in the face of evolving environmental conditions.

Keywords: Crop Management, Climate Change, Sustainable Wheat Production, Ethiopia

INTRODUCTION

Agriculture in tropical developing countries is significantly impacted by climate variability and change [1, 2, 3]. The susceptibility of these regions to the impacts of these changes is heightened due to the significant dependence of a substantial portion of their population on agricultural earnings, combined with their limited ability to adapt [4]. The low adaptive capacity might be due to a lack of resources, technology, knowledge, or infrastructure necessary to cope with and mitigate the impacts of climate variability. The limited adoption of improved crop varieties also contributes to low agricultural productivity [5]. Additionally, both living organisms (biotic factors) and non-living elements (abiotic factors) such as pests, diseases, soil quality, and other environmental factors can significantly reduce crop yields [5]. In Ethiopia, the spatial and temporal variability of rainfall during the rainy season alter national crop production by 90–95% [6]. Addressing these challenges requires a multi-faceted approach that includes improving agricultural practices, promoting the adoption of climate-resilient crop varieties, enhancing infrastructure for irrigation and water management, and providing education and resources to communities for better adaptation to changing conditions.

Climate complexity and the intricate physiological processes of crops make it challenging to directly observe or experimentally test certain behaviors in the field. This is where crop simulation models like the DSSAT crop model come into play [7, 8, 9]. DSSAT is composed of a collection of crop simulation models designed to simulate the growth, development, and yield of various crops under different conditions. These models utilize mathematical equations and algorithms to mimic the interactions between crops, soil, climate, and management practices. DSSAT also used to assess how different management options, such as planting dates, irrigation schedules, and fertilizer applications, influence crop growth and yield. This information can be invaluable for optimizing agricultural practices. Exploring potential crop management options to optimize wheat yield under future climate conditions is an important endeavor, especially given the challenges posed by climate variability and change. The adjustments of planting dates, altering planting density, and optimizing fertilizer application, are all critical strategies for enhancing crop resilience and productivity. Shifting planting dates by a few days can be a crucial adaptation strategy to mitigate the adverse effects of enhanced temperatures and elevated CO_2 levels [10]. By aligning critical stages of crop growth with more favorable climate conditions, such as avoiding heat stress during flowering can improve overall yield potential. Altering planting density, combined with early or late planting dates, offers an alternative approach to maximizing crop yield. This strategy allows to optimize resource utilization, including water, nutrients, and light, which can contribute to better crop performance [11]. The timing and level of fertilizer application also play a pivotal role in optimizing crop yield. Increasing nitrogen (N) fertilizer application can enhance the development of productive tillers, leading to higher grain yields. Balancing nutrient availability with crop demand is essential for achieving optimal results [12, 13].

The most crucial wheat varieties that commonly cultivated in the study area are Kubsa, Tay, Senkegna, and Gassay wheat varieties [14]. The study conducted by Abera et al. [15] provided valuable insights into the projected future climate conditions and their potential impacts on Tay and Senkegna wheat yield in western Ethiopia. The key findings of Abera et al.'s research highlighted the expected changes in temperature and their effects on wheat yield. According to

this result, the rainfall will increase by 2-5% in 2030 to 2080 time period. Conversely, the maximum temperatures are projected to increase by 1°C to 4.6°C, and the minimum temperatures is also expected to rise by 0.93°C to 4.73°C by the end of 2080s [15]. This warming trend indicated a significant temperature rise compared to the baseline, suggesting hotter conditions in western Ethiopia. Abera et al. [15] also assessed the overall climate impact on wheat production in western Ethiopia. The study's findings revealed that both positive and negative wheat yield change are observed. The yield of Tay wheat is projected to increase by 0.5% to 1.3% between 2030 and 2050, while it is expected to decrease by 3% at the end of 2080s [15]. Similarly, the grain yield of Senkegna wheat is predicted to increase by 0.8% to 2.5% [15]. While there are projected increases in certain time periods, there is also the anticipation of decreased yield in the long term due to changing climate. Abera et al. [15] focused primarily on how rising temperatures and climate change influenced wheat yield in western Ethiopia. However, the investigation into potential agronomic practices to counteract these negative impacts or optimize wheat yield was limited. The absence of exploration into potential agronomic practices to enhance wheat yield and resilience in the context of climate change leaves an opportunity for further study. Exploring different agronomic practices, such as adjusting planting dates, altering planting density, and optimizing fertilizer application have the potential to offer practical solutions to the challenges posed by climate variability and change. These strategies could be tailored to the specific conditions of the study area and have the potential to improve food security and livelihoods for the local communities. By addressing this research gap, this study therefore could significantly contribute to the knowledge base for sustainable agricultural practices in western Ethiopia and potentially serve as a foundation for future policy decisions and adaptation strategies. Therefore, the entire study seeks to bridge the gap in knowledge by investigating how different agronomic practices can optimize wheat yield under future climate conditions in western Ethiopia.

MATERIALS AND METHODS

Description of Study Area

The study was carried out at Adet Agricultural Research Center (AARC), situated in the Amhara Region, north western Ethiopia (Fig.1). The geographical coordinates are approximately 11°16'N latitude and 37°29'E longitude. Adet is located at an altitude of 2216 meters above mean sea level. The area receives an average annual rainfall of 1250 mm. The annual average maximum and minimum temperatures are 25.5°C and 9.2°C, respectively. The dominant soil types in the area are Nitosols, Vertisols, and Luvisols [16, 17].

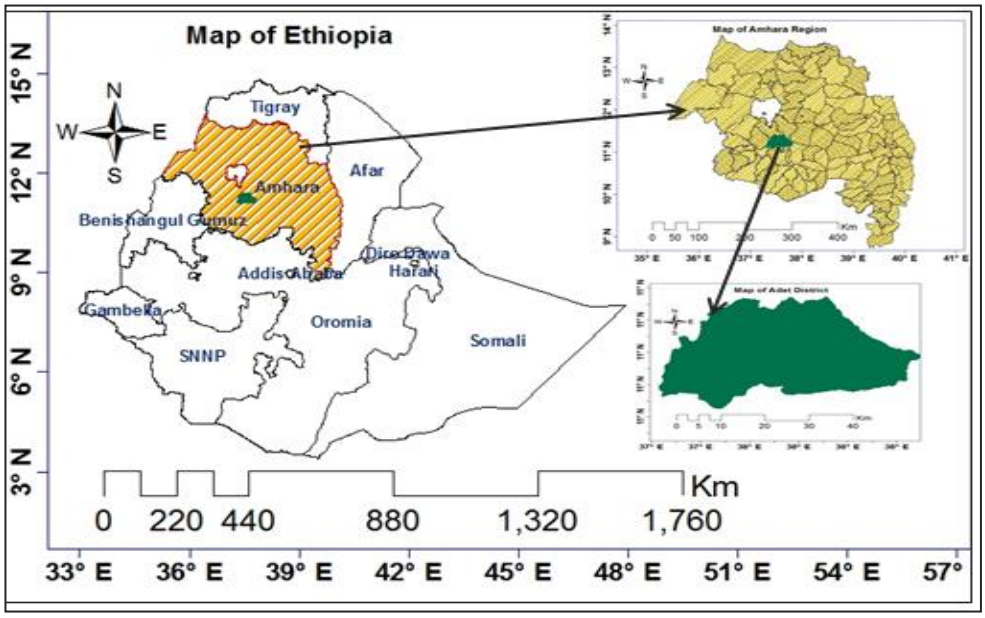


Figure 1: Location map of the study area

Materials and Methods

The methodology for this study involved a well-structured approach that utilized a combination of climate, soil, and crop genetic data to explore potential crop management strategies to the impact of climate change on wheat production. The observed climate data (1980 – 2009) for daily rainfall, minimum and maximum temperatures, wind speed, relative humidity, and solar radiation were collected from National Meteorology of Ethiopia, while future climate data also obtained from the Fifth Coupled Model Intercomparison Project (CMIP5) multi-model database systems pertained to the early-term period of 2010-2039 under RCP8.5 emission scenario [18]. The Delta factors method was applied to generate future climate data using AgMIP scenario generation scripts in the R analytical tool [19, 20].

The Delta factors method has been previously employed to assess the influence of climate change on maize and wheat production in Ethiopia [21, 15]. This approach involved perturbing observed baseline climate data (1980-2009) to generate future climate scenarios, enabling researchers to explore potential impacts on crop yields.

The utilized soil data was collected from the Adet Agricultural Research Site. This data served as a foundational element for yield simulation using different crop managements for both the Tay and Senkegna bread wheat varieties.

By incorporating this soil data, it is working to ensure that the simulation results accurately reflect the real-world conditions in the study area. This integration of soil data into the simulation study enhances the accuracy and relevance of this findings, and enabling us to explore the potential crop management strategies that offset the climate change impacts on wheat yield. The Table 1 suggests all soil information used in this study

Table 1: Physical and chemical soil properties of the experimental site

	Soil depth (cm)			
Parameters	**0 - 30**	**30 - 90**	**90 - 140**	**140 - 200**
Clay	66	69	68	64
Silt	24	15	18	24
Sand	12	16	14	12
LL	0.345	0.332	0.328	0.307
DUL	0.478	0.436	0.433	0.413
Bulk density (g/cm3)	1.13	1.19	1.21	1.29
Organic carbon (%)	1.31	0.98	0.77	0.51
Total N (%)	0.11	0.09	0.06	0.04
pH	5.2	6.3	6.8	7.1
CEC (meq/100g soil)	50.1	52	55.2	55.8

DUL: Drainage Upper Limit, LL: Lower Limit, CEC: Cation Exchange Capacity

The genetic coefficients in table 2 were used to generate potential crop management option. These genetic coefficients were calibrated and evaluated using DSSAT crop model for Tay and Senkegna bread wheat varieties particularly in this study environment condition [15]. The performance of the model or goodness of fits (R^2) for model calibration are 79 and 92% for Tay and Senkegna wheat yield, respectively. Similarly, in model evaluation, the values of R^2 are 70 and 82% for Tay and Senkegna wheat yield, respectively [15].

Table 2: Genetic coefficients used to develop adaptation option for both bread wheat varieties

Symbols	**Definitions**	**Senkegna variety**	**Tay variety**
P1V	Days, optimum temperature required for vernalization (°C)	10	9
P1D	Photoperiod response (% reduction in rate/10 h drop in pp)	31	25
P5	Grain filling (excluding lag) phase duration (°C. d)	745	727
G1	Kernel number per unit canopy weight at anthesis (#/g)	41	42
G2	Standard kernel size under optimum conditions (mg)	52	45
G3	Standard non-stressed mature tiller wt (incl grain) (g dwt)	2.3	2.8
PHINT	Interval between successive leaf tip appearances (°C. d)	135	139

Crop Management Options Set Up

The CERES-Wheat model was employed in this study involving two bread wheat varieties (Senkegna and Tay) to establish the best fit adaptive strategies based on planting density, fertilizer rate, and planting dates. The CERES-Wheat model is a process-oriented management-level model used to simulate the growth, development, and yield of wheat under DSSAT crop model [7, 8, 9].

In the current condition, the recommended crop management practices for the targeted wheat varieties across the study area are 92 kg ha^{-1} N fertilizer rate, 150 plants m^{-2} and the optimal planting date is on June 15. However, due to very nature of agriculture is dynamic, and constantly evolving environmental factors, the study investigated as an alternative crop

management strategy. Specifically, the research has examined two alternative scenarios, one involving a reduced N fertilizer rate of 46 kg ha^{-1} and another involving an increased rate of 184 kg ha^{-1} in addition to the established recommended rate of 92 kg ha^{-1}. Similarly, the study also introduced a range of planting densities, encompassing 120 plants m^{-2}, 250 plants m^{-2} and 350 plants m^{-2}. Furthermore, the comprehensive investigation extended beyond the planting dates of June 10th and June 25th in addition to the established June 15th normal planting date. This exploration is driven by the need to ascertain how varying the N fertilizer, planting density and planting time might influence wheat growth and yield, providing invaluable insights for sustainable crop management strategies under changing climate.

This study delved into a comprehensive study that spans the years from 2010 to 2039, examining the yield simulation of two wheat varieties under the RCP8.5 emission scenario. The study considered the carbon dioxide concentrations for the baseline as 380 ppm and for projected as 432 ppm by the end of 2040 [18]. Statistical analysis and graphical presentation were facilitated by the R environmental tool [22].

RESULT AND DISCUSSION

Potential Crop Management Options for Yield Optimization

The response of wheat yield to variations in planting time and plant density is vividly illustrated in Figure 2. Notably, a late sowing date of June 25, coupled with a high plant density of 350 plants m^{-2}, exhibited a promising response, resulting in optimal yields for both the Tay and Senkegna wheat varieties across the study area. (Fig. 2). Conversely, the scenario of early planting on June 10, combined with a lower plant density of 120 plants m^{-2}, displayed a diminished response, leading to reduced yields for both wheat varieties. Similarly, the interplay between fertilizer application and plant density revealed intriguing patterns. Figure 3 demonstrated that employing a higher fertilizer rate in conjunction with a higher plant density contributed to the optimization of wheat yields for both varieties. The nuanced dynamics of agronomic practices are now further illuminated through the interaction of sowing date and fertilizer rate. Figure 4 unveiled the optimal outcome when utilizing 184 kg ha^{-1} N fertilizer alongside a late sowing date of June 25. Moreover, the culmination of three pivotal agronomic practice high fertilizer rate, high plant density, and a late sowing date emerged as a potent synergy for optimizing wheat yields, as depicted in Figure 5. Conversely, a departure from this optimized approach resulted in diminished yields. Specifically, sowing during the early days of June (June 10), coupled with a lower plant density of 120 plants m^{-2} and a reduced fertilizer rate of 46 kg ha^{-1}, led to decreased yields for both Tay and Senkegna wheat varieties. To achieve the highest possible yields for both wheat varieties, the study recommended a range of planting densities, spanning from 250 to 350 plants m^{-2} with 184 kg ha^{-1} N fertilizer and sowing the seeds on June 25. The concept of plant population and its influence on crop performance revealed a dynamic interplay between canopy size and resource availability. In various scientific studies, it is recognized and acknowledged that an augmented plant population inherently translates to a larger canopy cover phenomenon [23]. Reports from previous research endeavored echo the premise that the grain yield in wheat cultivation is achieved when the plant population reaches its highest ratio [24]. Specifically, the establishment of a robust canopy directly impacts light absorption, a fundamental driver of both qualitative and quantitative crop production [25]. However, this expansion of the canopy also ushers in a notable consequence for escalation in

the competition for essential resources within the wheat crop ecosystem. Yet, these narrative gains depth when coupled with the dynamic interplay between plant density and nitrogen fertilizer, a pairing that exerts a profound influence on canopy establishment. Notably, this interaction unfolds as a potent determinant of key physiological processes. Thus, the combined effect of plant density and nitrogen fertilizer on canopy development fosters an environment primed for heightened photosynthesis, the cornerstone of resource assimilation and subsequent yield enhancement. As agricultural systems grapple with the intricacies of resource allocation and yield augmentation, these findings stand as beacons of guidance.

Different reports also argue that wheat crop can have different response for different fertilizer levels with different planting date [26]. Early and normal planting date can enhance seedling establishment and productivity aligned with common agricultural knowledge [26]. Early planting can provide wheat crop with a longer growing period, allowing them to establish better root systems and potentially escape adverse conditions later in the season [27]. Late planting, on the other hand, could expose the crop to unfavorable conditions, such as a late-season dry period [27]. Research reports argued that changing sowing dates as an effective adaptation strategy to climate change impacts, and can be a practical way to mitigate the challenges posed by changing climate conditions [28, 29, 30]. For instance, altering planting dates in response to the variable characteristics of rainfall distribution can be a valuable strategy to mitigate the adverse impacts of severe dry spells on crop production [31].

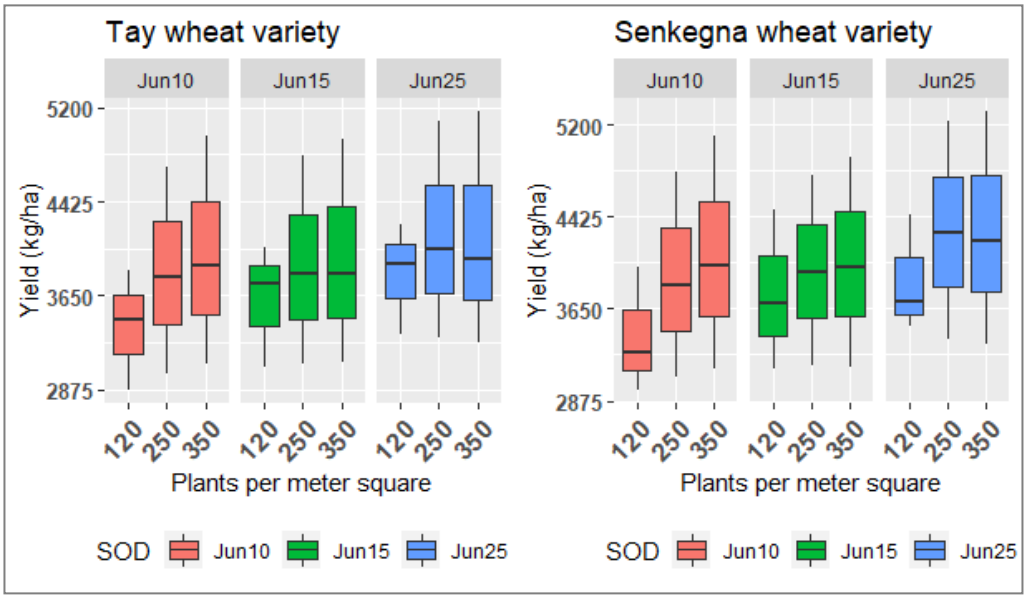


Figure 2: Yield response to plant density and sowing date

Note: PD=Plant Density (plants m^{-2}); SOD= Sowing date; N_F = Fertilizer (kg ha^{-1}); YIELD.kg. = Yield (kg ha^{-1})

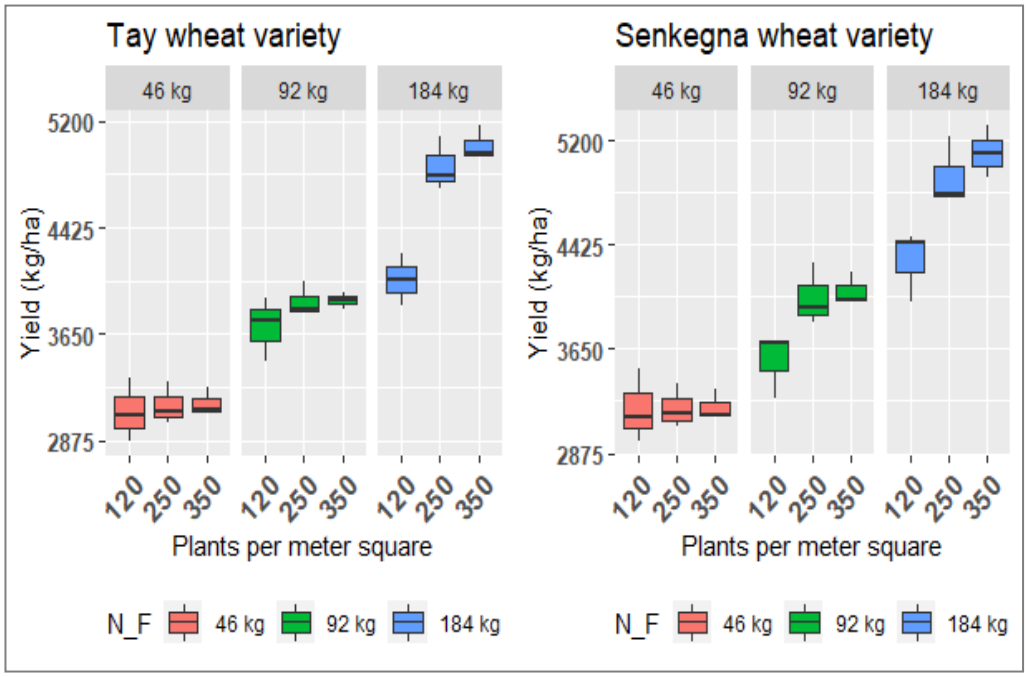


Figure 3: Yield response to plant density and fertilizer rate

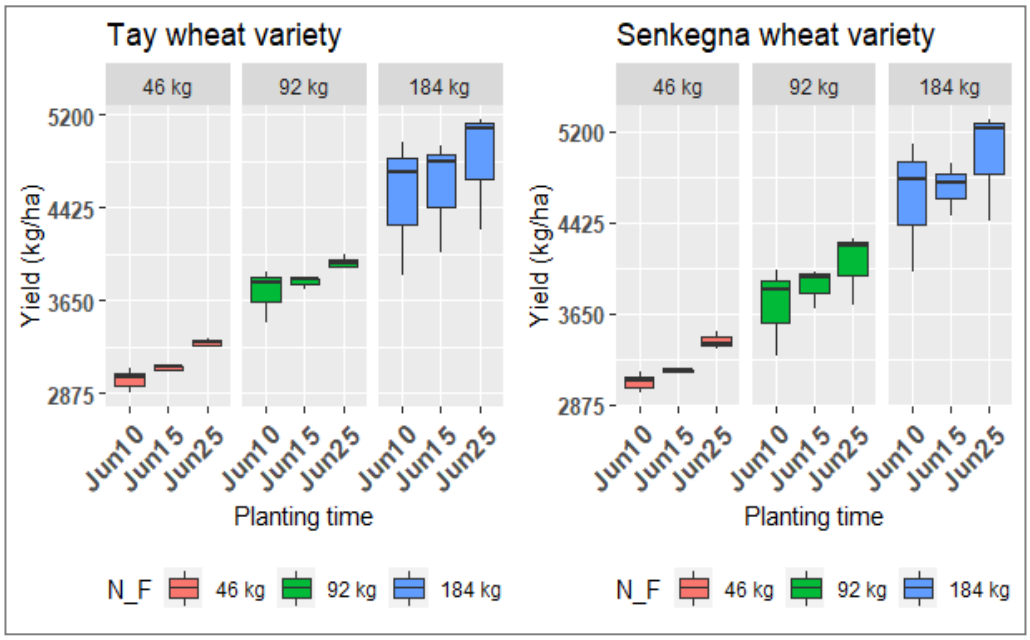


Figure 4. Yield response to sowing date and fertilizer rate

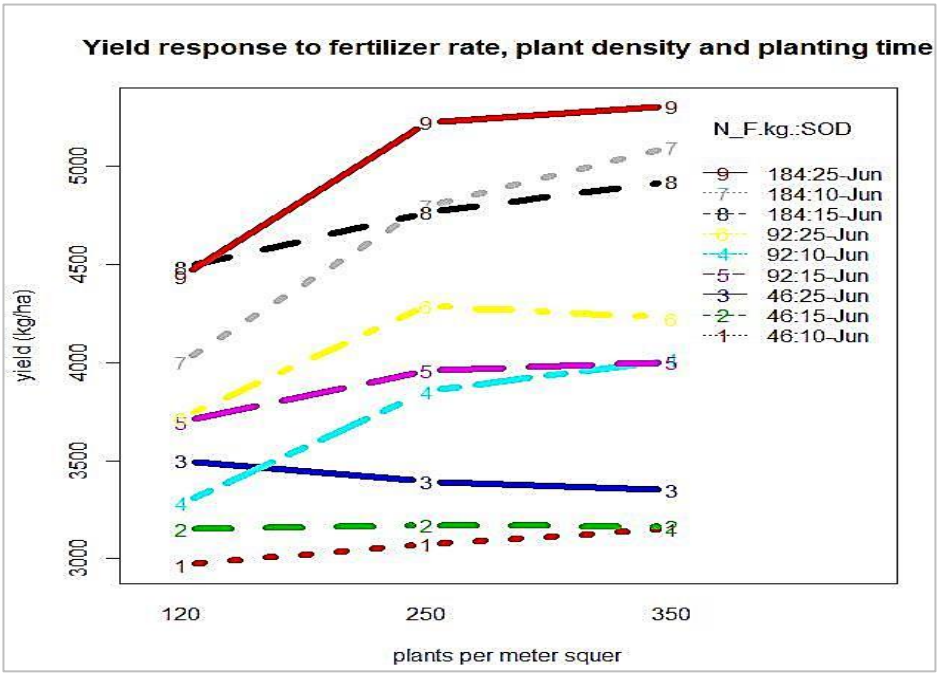


Figure 5: Yield response to the interaction of plant density, sowing date and fertilizer rate for wheat

Evidently, the Senkegna variety displayed a notable advantage, yielding approximately 5307 kg ha^{-1} on average, whereas the Tay variety exhibited a slightly lower yield, approximately 5166 kg ha^{-1}. Importantly, these observations were made under identical crop management conditions, accentuating the inherent variability between the two wheat varieties (Fig. 5). Given these disparities, the study's overarching goal to optimize wheat yield was met by establishing specific crop management options that could harmoniously elevate the yields of both Senkegna and Tay wheat varieties. According to the results presented in Table 3, the interaction between sowing date and plant density was found to be statistically non-significant ($P>0.05$). This implies that there is no strong evidence to suggest that the combination of sowing date and plant density significantly affected wheat yields. Therefore, it is not appropriate to conclude that the treatments (different combinations of planting windows and planting density) are significantly different from each other in terms of their impact on yield. This suggested that this approach might not be the best strategy for optimizing yields under future climate conditions. When examining the R-squared (R^2) values in Table 3, it was observed that the factors of planting time and planting density together accounted for 12% of the variability in yield production. In other words, these two factors could explain only a small portion (12%) of the differences in wheat yields among the experimental conditions. The remaining 88% of the variability in yield production could not be explained by the combination of planting time and planting density. This unexplained variation is represented by the residuals, which constitute 88% of the total variation in the outcome. Essentially, this means that factors other than planting time and planting density, which were not considered in this study, have a more substantial influence on wheat yields. In the case of the interaction between plant density and fertilizer rate (Table 4), the results suggest that varying the density of plants along with different levels of fertilizer application had a significant ($P<0.05$) impact on wheat yields.

Similarly, when analyzing the interaction between sowing date and fertilizer rate (Table 5), it was found that different sowing dates combined with varying fertilizer rates significantly ($P<0.05$) affected wheat yields. Furthermore, the study indicated that increasing plant density in conjunction with higher nitrogen (N) fertilizer rates, while also considering variations in planting time, led to significant increases in wheat yield for both wheat varieties. This information provides insights into potentially more effective strategies for optimizing wheat yields under certain conditions. It suggested that the combination of specific planting densities, fertilizer rates, and sowing dates can have a substantial positive influence on wheat production. This indicated that when both fertilizer application rates and plant populations are increased simultaneously, there is a notable improvement in wheat production. This finding aligned with the understanding that providing crops with an optimal balance of nutrients (achieved through appropriate fertilizer application) and ensuring that they are adequately spaced (achieved through optimal plant density) can contribute to enhanced growth, development, and ultimately higher yields. The results aligned with Menge and Kirby [32] who reported that wheat yield is significantly increased because of increased rate of N application. Scientists argued that as plant density rises, the nutrient competition rises, and the demand for nutrients also rises [33]. While nitrogen is essential for promoting plant growth and enhancing yield, overapplication of nitrogen can lead to negative impacts that counteract its potential benefits. Applying excessive amounts of nitrogen can lead to delayed maturity, reduced reproductive allocation, and altered nutrient balances [34]. Therefore, managing fertilizer application with respect to plant density is a key aspect of crop management. Balancing plant density with other management practices, such as appropriate fertilization and irrigation, is crucial to ensure that plants have access to the necessary resources for optimal growth. Crop scientists and agronomists often study these interactions to develop strategies that maximize crop yield while minimizing resource competition and potential negative impacts.

Table 3: Wheat yield response to plant density and sowing date

	Treatments	Senkegna wheat variety	Tay wheat variety
Planting density (plants/m^2)	Planting time	Mean yield (Kg ha^{-1})	Mean yield (Kg ha^{-1})
250	25-Jun	4301.7[a]	4137.7[a]
350	25-Jun	4293.5[a]	4126.9[a]
350	10-Jun	4087.2[a]	3979.9[a]
350	15-Jun	4029.9[a]	3956.2[a]
250	15-Jun	3965.5[a]	3907.5[a]
250	10-Jun	3908.2[a]	3841.8[a]
120	25-Jun	3883.6[a]	3827.4[a]
120	15-Jun	3777.0[a]	3614.3[a]
120	10-Jun	3417.5[a]	3394.2[a]
Mean		3962.7	3865.1
CV		20.4	20.6
LSD		1387.6	1364.2
R^2		0.12	0.1
P-value		0.94	0.97

*Means sharing the same superscript letter do not differ significantly at P = 0.05

Table 4: Wheat yield response to plant density and fertilizer rate

	Treatments	Senkegna wheat variety	Tay wheat variety
Planting density (plants/m^2)	N fertilizer rate (Kg ha^{-1})	Mean yield (Kg ha^{-1})	Mean yield (Kg ha^{-1})
350	184	5109.1^{a}	5024.1^{a}
250	184	4930.0^{a}	4870.7^{a}
120	184	4308.3^{b}	4046.2^{b}
350	92	4081.3^{b}	3895.8^{bc}
250	92	4034.0^{b}	3885.3^{bc}
120	92	3564.8^{c}	3704.1^{c}
350	46	3220.1^{c}	3143.2^{d}
250	46	3211.5^{c}	3131.1^{d}
120	46	3205.0^{c}	3085.6^{d}
Mean		3962.7	3865.2
CV		5.4	4.3
LSD		367.1	284.8
R^2		0.94	0.96
P-value		0.002***	0.004***

Table 5: Wheat yield response to planting time and fertilizer rate

	Treatments	Senkegna wheat variety	Tay wheat variety
Planting Time	N fertilizer rate (Kg ha^{-1})	Mean yield (Kg ha^{-1})	Mean yield (Kg ha^{-1})
25-Jun	184	4989.8^{a}	4831.0^{a}
15-Jun	184	4724.8^{a}	4598.0^{a}
10-Jun	184	4632.8^{a}	4511.9^{a}
25-Jun	92	4076.3^{b}	3964.8^{b}
15-Jun	92	3886.5^{bc}	3802.3^{bc}
10-Jun	92	3717.4^{bc}	3718.1^{bc}
25-Jun	46	3412.8^{cd}	3296.3^{cd}
15-Jun	46	3161.1^{d}	3077.7^{d}
10-Jun	46	3062.6^{d}	2985.8^{d}
Mean		3962.7	3865.2
CV		7.96	8.2
LSD		539.2	545.5
R^2		0.87	0.86
P-value		0.001***	0.003***

CV= Coefficient of variation (%); GM = Grand Mean (kg ha^{-1}); LSD = Least Significant Difference (kg ha^{-1})

CONCLUSION AND RECOMMENDATION

Based on the study, the combination of high nitrogen levels (184 kg ha^{-1}) and high planting density (250-350 plants m^{-2}) when sown on the 3rd dekad of June is identified as the best approach for optimizing wheat yield. This combination is associated with predicted yield ranges of 3865 - 3962 kg ha^{-1} across the study area. Conversely, the study indicated both wheat varieties have lower yield performance if planting is done earlier than 10th of June. Early

planting could potentially expose the crop to adverse conditions or stressors, impacting overall yield.

The study also suggested that focusing solely on different planting windows with varying planting densities may not be the best effective strategy for optimizing wheat yield under future climate conditions. In other words, the interaction between planting date and planting density may not significantly impact wheat yield, and suggested the need to consider additional factors beyond planting date and density for yield improvement.

On the other hand, the combination of planting density and fertilizer rate has a significant effect on wheat yield. This underscored the importance of considering both factors (planting density and fertilizer rate) together in order to optimize crop production. The interaction between planting density and fertilizer rate can influence resource availability, competition among plants, growth dynamics, all of which contribute to the final yield outcome.

Furthermore, the study found that when considering the interactions of sowing date, plant density, and fertilizer rate had a significant impact on wheat yield. This suggested that the interplay of these three variables is crucial in determining the yield outcomes for both wheat varieties. When comparing the two wheat varieties (Senkegna and Tay), the combined effects of all the treatments led to a higher yield for the Senkegna wheat variety compared to the Tay wheat variety.

Agricultural practices are multifaceted and interconnected. They don't follow a simple cause-and-effect pattern. Instead, every decision and interaction among various factors can have a significant impact, especially in diverse and variable environmental conditions. Therefore, these findings emphasized the importance of a comprehensive approach to crop management, where multiple factors are considered together to achieve optimal yields, even under the challenges posed by changing climate conditions by applying dynamical crop simulation model. Adjusting planting time, fertilizer rate and planting density are a crucial approach to enhance crop resilience in the face of climate variability. By carefully timing planting, fertilizer rate and planting density based on climate conditions, farmers can better adapt their crops to changing weather patterns and improve overall management. This information provides valuable insights for farmers and researchers aiming to improve wheat production by understanding the complex interactions between different agronomic practices and their effects on yield for specific crop varieties.

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