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Modelling rice yield from biochar-inorganic fertilizer amended fields

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A R T I C L E I N F O

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A B S T R A C T

Rice yield is vulnerable to climatic changes. High concentrations of atmospheric CO_2 is noted to increase yield by improving upon nutrient uptake and water use efficiency of plants. Temperature variations also affect plant growth and eventually crop yield as it has an effect on respiration and photosynthesis. Soil fertility is an important parameter affecting the production of most crops and rice is not an exception. The cost as well as the environmental consequences of using inorganic fertilizers makes it necessary to use other soil amendments such as biochar. Field experiments are often time consuming and involves a lot of drudgery. This research was therefore conducted to model the quantities of biochar-inorganic fertilizer combinations that give optimum yields of rice and assess the effect of changes in climatic parameters on the yield of rice. CERES-Rice model was used to simulate the yield of rice using different combinations of biochar-inorganic fertilizer as soil amendments. Effects of changes in climatic parameters on the yield of rice were also simulated. The yield of rice from the simulations were sensitive to the soil amendments especially the biochar. Treatments with no biochar had relatively low rice yields compared with those with biochar. The average simulated yields were 1.5 t/ha, 5.6 t/ha and 5.5 t/ha for treatments with 0 t/ha, 20 t/ha and 30 t/ha of biochar respectively. Increasing or decreasing rainfall resulted in reduction in the yield of rice. Increasing carbon dioxide concentrations generally led to an increase in the simulated yields of rice. On the other hand, decreasing the carbon dioxide concentrations resulted in decreased simulated rice yields. It was observed that increasing temperature resulted in a reduction in rice yield for the various treatments. The reduction in the yield of rice ranged from 7.64% to 34 .67%.

1. Introduction

Rice remains a major staple food across the world with more than half of the world's population using it as their main food. Rice is increasingly becoming the fastest growing indispensable food in the case of Sub - Saharan Africa. The demand for rice in Africa is far more than its production, hence the need to import millions of tonnes of this staple food [1]. In Ghana, rice is a key staple crop grown in most parts of the country. The global annual rice production needs to be increased by 1.2–1.5% in order to meet the growing demand [2]. Rice is thus a critical crop in terms of food security.

Systematic research is required to elucidate the complex mechanisms that take place in agricultural systems. As public funding for agricultural field research is dwindling, there is the need to resort to crop models to complement field experiments [3,4]. Modeling is now an important tool that is used to evaluate the complex interactions between the various factors that impact crop performance. It provides researchers and farmers the avenues for simulating the effects of various factors (i.e. soil types, climate, soil amendments, etc) on crop production. Crop models are increasingly being used to forecast the performance of rice. Examples of rice models include SIMRIW, ORYZA, CERES-Rice, RICAM, RICEGROW, etc.

Rice yield is vulnerable to climatic changes. High concentrations of atmospheric CO_2 is noted to increase yield by improving upon nutrient uptake and water use efficiency of plants [5,6].

Temperature variations affect plant growth and eventually crop yield as it has an effect on respiration and photosynthesis. It was observed by Ref. [7] that high temperatures are able to reduce yields of maize by 80–90%. The growth of rice plant (number of tillers, straw weight and root weight) is decreased with an increase in temperature as observed by Ref. [8].

Soil fertility is an important parameter affecting the production of most crops and rice is not an exception. Rice needs adequate plant nutrients for optimum yield and to ensure this, fertilizer is needed to be applied during every cropping season, especially because of leaching losses. The cost of inorganic fertilizer as well as the environmental

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consequences of using these inorganic fertilizers makes it necessary to use other soil amendments such as biochar. Field experiments are time consuming and involves a lot of drudgery. The objectives of this research were to model the quantities of inorganic biochar-fertilizer combinations that give optimum yields of rice and assess the effect of changes in climatic parameters on the yield of rice.

2. Materials and methods

2.1. Study area

Data from a field experiment conducted at Nobewam during the major and minor seasons of 2018 were used for this research. Nobewam is a community in the Ejusu Juaben District of the Ashanti region of Ghana. Nobewam lies on latitude 6°37′ and longitude 1°18'. It has a large hectare of hand which is used for rice cultivation and thus is noted for production of large quantities of rice in the Ashanti Region.

2.2. Description of model

The model used in this study is Crop Estimation Resource and Environment Synthesis (CERES-rice), which is embedded in Decision Support System for Agrotechnology Transfer (DSSAT). The version of DSSAT is used in this study is 4.7. The DSSAT is a software package that integrates weather, crop phenotype, soil properties and other crop management options to simulate results of experiments in minutes using desktop computers. The use of the model thus saves a significant amount of time that would otherwise be needed for a field experiment. The DSSAT CERES-rice model was developed through the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) for the prediction the growth and yield of rice varieties under various agro-climatic conditions [9].

2.3. Data collection

Climate data for the community in which the experiment was conducted was taken from the meteorological agency. Soil data was obtained from the laboratory analysis of soil samples from the field. The soil data include pH, particle size (percentage of sand, silt and clay), total nitrogen, total phosphorus, bulk density, organic carbon, etc. data regarding the variety of rice (AGRA) that was used was obtained from Council for Scientific and Industrial Research - Crops Research Institute (CSIR - CRI). The yield of rice used in calibrating the modelling was from the results of the field experiment conducted.

2.4. Input parameters

The following parameters were input into the model for running and validation: Soil pH - 5.2, bulk density - 1.2 g/cm^3, top soil - sandy loam, plot size - 2 m × 1 m (2 m^2), daily climate data (maximum temperature, minimum temperature, sunshine hours and rainfall) for the year 2018, carbon dioxide (CO_2) concentration - 350 ppm, method of planting - transplanting, planting depth - 5 cm, fertilizer application - NPK (37.5 kg/ha, 16 kg/ha and 31 kg/ha), urea - 58.4 kg/ha, irrigation - continuous flooding. There were nine treatments used these are F0B0 (no fertilizer no biochar); F100B0 (full fertilizer application rate without biochar - the full rate of fertilizer is NPK (37.5 kg/ha, 16 kg/ha and 31 kg/ha and urea - 58.4 kg/ha); F0B20 (no fertilizer, 20 t/ha of biochar); F25B0 (25% of the full fertilizer application rate plus no biochar; F25B20 (25% of the full fertilizer application rate plus 20 t/ha of biochar); F25B30 (25% of the full fertilizer application rate plus 30 t/ha of biochar); F50B20 (50% of the full fertilizer application rate plus 20 t/ha of biochar); F50B30 (50% of the full fertilizer application rate plus 30 t/ha of biochar); and F75B20 (75% of the full fertilizer application rate plus 20 t/ha of biochar).

The treatment used for the standard scenario is F100B0. The rice variety used for the modelling is IR 52, which is close to the AGRA rice in terms of its phenology and genetics. Yields were simulated under localized conditions for the nine (9) treatments using the weather data for the year 2018. The environmental modifications section of the XBuild file in the CERES-rice model was used to simulate climate change scenarios.

2.4.1. Calibration and validation of model

The XBuild programme within the CERES - rice model was used to into parameters of climate, soil and cultivar. The XBuild programme provides an effective tool to access all the functionalities of the crop model. It enables modelers various combinations of management options for simulation and validation.

2.4.2. Yield simulations

The XBuild was used to create an experimental data file containing the details of the field experiment (i.e soil data, initial field conditions, planting information, irrigation, fertilizer and residue application, environmental modification, harvest information, etc). These data were saved in the XBuild experimental file and recalled for simulation. The different treatments and climatic conditions were used to run the simulations. The simulated yields were then compared with the actual yields for validation purposes.

2.4.3. Yield estimations under climate change scenarios

The environmental modifications tool in the CERES-Rice model was used to input various changes in climatic data. Carbon dioxide was increased and decreased by 2 ppm, maximum temperature were increased and decreased by 2.6 °C, minimum temperature was increased and decreased by 2.2 °C, solar radiation was increased and decreased by 0.5 MJm^{2}d^{-1} and rainfall was increased and decreased by 4 mm. These increases and decreases were based on the average changes in the weather parameters over five years. These climatic variations were then used to simulate the yield of rice.

3. Results and discussion

3.1. Simulated verses actual yield

Fig. 1 shows the actual and simulated yields of rice cultivated with various combinations of soil amendments during the major season. The yield of rice from the simulations were sensitive to the soil amendments especially the biochar. Treatments with no biochar had relatively low rice yields compared with those with biochar. The average simulated yields were 1.5 t/ha, 5.6 t/ha and 5.5 t/ha for treatments with 0 t/ha, 20 t/ha and 30 t/ha of biochar respectively.

The overall average yield of rice from the simulations was 4.2 t/ha, which was higher than the 3.6 t/ha from the actual yields as indicated in Table 1. The differences between the simulated and actual yields can be as a result of unsustainable agronomic practices on the land over the past years. Also in the simulation, provision was not made for yield losses so the differences between the simulated and actual yields can be said to account for the yield losses. The losses can be due to post harvest handling or picking by birds prior to harvesting.

The treatments F100B0, F25B20 and F25B30 had a relative difference less than 30%, which according to Ref. [10], indicates that the model is efficient in predicting the yield of rice under these treatment combinations. The other treatments combinations had relative differences higher than 30%, with that of F0B0, F0B20 and F25B0 being very high.

The treatment F0B0 has a very low simulated yield compared with the actual yield and hence a very high relative difference because the model's interpretation of F0B0 is that there is absolutely no nutrient added for plant uptake. Though no nutrient was added, the actual yield is higher than the simulated yield because the soil's inherent nutrients were enough to result in a yield of 2.7 t/ha.

The very high relative difference for F0B20 can be attributed to the immobilization of native soil nitrogen upon the addition of organic materials such as biochar. With the addition of 20 t/ha of biochar (B20)

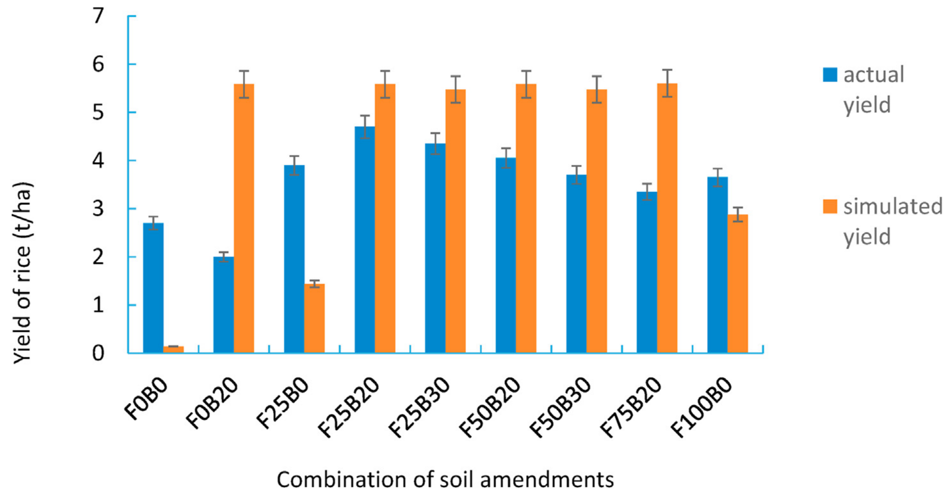

Fig. 1. Actual and simulated yields of rice from various combinations of soil amendments.

Table 1
Actual yield, simulated yield and relative difference of various treatment combinations.

Treatment	Actual Yield (t/ha)	Simulated Yield (t/ha)	Relative Difference (%)
F0B0	2.7	0.14	−94.89
F0B20	2.0	5.6	179.30
F25B0	3.9	1.4	−63.13
F25B20	4.7	5.6	18.85
F25B30	4.4	5.5	25.89
F50B20	4.1	5.6	37.95
F50B30	3.7	5.5	48.00
F75B20	3.4	5.6	67.31
F100B0	3.7	2.9	−21.12

without any addition of inorganic fertilizer (F0), the soil microbes immobilize the nitrogen already in the soil, hence the relatively low yield observed as compared with the simulated yield and thus the very high relative difference.

The absence of biochar in F25B0 resulted in a simulated yield of rice lower than the actual yield. This is because combining the biochar with inorganic fertilizer produces a synergetic effect which results in an improvement in yield. However, this synergy was absent due to the absence of biochar on this treatment. Thus, resulting in a low simulated yield and a very high relative difference.

The treatment combination that gave the highest yield in both the actual and simulated is the F25B20 (i.e 25 % percent of fertilizer application rate plus 20 t/ha of biochar).

3.2. Yield estimations under climate change scenarios

The effect of changes in temperature on the simulated yields of rice is shown in Table 2. It was observed that increasing temperature resulted in a reduction in the yield of rice for the various treatments. The reduction in the yield of rice ranged from 11% to 34.67%. The reduction in yield associated with the increase in temperature is as a result of a decrease in pollen viability at high temperatures [11]. Decreasing the temperature however resulted in an increase in the yield of rice for the various treatments. Yield increases ranged from 1.39% to 37.41%. These findings corroborates with findings by Refs. [7,12].

Table 3 shows the effect of changes in solar radiation on the simulated yields of rice. Increasing solar radiation resulted in increased yields from 1.04% to 291.67% and decreasing solar radiation caused decrease in the yield of rice between 1.39% 7.14%. These variations in yield are as a result of the fact that solar radiation serves as source of energy for photosynthesis [13], so as the amount of solar radiation received by the plants increase, it leads to an increase in photosynthesis and hence increase in yield. This trend ties in with the findings of [12,14].

Table 2
Effect of changes in temperature on the simulated yields of rice.

Treatment	Yield (t/ha)		
	No changes in temperature	Increase in temperature	Decrease in temperature
F0B0	0.14	0.15 (7.14%)	0.08 (-42.86%)
F0B20	5.59	3.70 (-33.81%)	7.09 (26.83%)
F25B0	1.44	1.33 (-7.64%)	1.46 (1.39%)
F25B20	5.59	3.70 (-33.81%)	7.15 (27.91%)
F25B30	5.48	3.58 (-34.67%)	7.53 (37.41%)
F50B20	5.59	3.70 (-33.81%)	7.61 (36.14%)
F50B30	5.48	3.58 (-34.67%)	7.53 (37.41%)
F75B20	5.61	3.70 (-34.05%)	7.65 (36.36%)
F100B0	2.88	2.56 (-11.11%)	3.59 (24.65%)

Table 3
Effect of changes in solar radiation on the simulated yields of rice.

Treatment	Yield (t/ha)		
	No change in solar radiation	Increase in solar radiation	Decrease in solar radiation
F0B0	0.14	0.15 (7.14%)	0.13 (-7.14%)
F0B20	5.59	5.75 (2.86%)	5.41 (-3.22%)
F25B0	1.44	5.64 (291.67%)	1.42 (-1.39%)
F25B20	5.59	5.75 (2.86%)	5.43 (-2.86%)
F25B30	5.48	5.64 (2.92%)	5.31 (-3.10%)
F50B20	5.59	5.75 (2.86%)	5.43 (-2.86%)
F50B30	5.48	5.64 (2.92%)	5.31 (-3.10%)
F75B20	5.61	5.77 (2.85%)	5.44 (-3.03%)
F100B0	2.88	2.91 (1.04%)	2.84 (-1.39%)

The effect of changes in rainfall and carbon dioxide concentrations on the simulated yields of rice is are shown in Tables 4 and 5 respectively. Increasing or decreasing rainfall resulted in reduction in the yield of rice, similar to what was observed by Ref. [15]. Increasing carbon dioxide concentrations generally led to an increase in the simulated yields of rice, between 0 and 0.18%. On the other hand, decreasing the carbon dioxide concentrations resulted in decreased simulated rice yields from 0 to 0.36%. The reason being that carbon dioxide is a major input in photosynthesis, so as its concentration is increased, it enhances photosynthesis and hence yield [11]. observed an interactive effect whereby high temperature and elevated carbon dioxide concentrations resulted in a decline in yield.

Table 4
Effect of changes in rainfall on the simulated yields of rice.

Treatment	Yield (t/ha)		
	No change in rainfall	Increase in rainfall	Decrease in rainfall
F0B0	0.14	0.09 (-35.71%)	0.15 (7.14%)
F0B20	5.59	5.21 (-6.79%)	5.40 (-3.39%)
F25B0	1.44	1.00 (-30.56%)	1.54 (6.94%)
F25B20	5.59	5.22 (-6.62%)	5.43 (-2.86%)
F25B30	5.48	5.48 (0.00%)	5.39 (-1.64%)
F50B20	5.59	5.23 (-6.44%)	5.45 (-2.50%)
F50B30	5.48	5.49 (0.18%)	5.41 (-1.28%)
F75B20	5.61	5.23 (-6.77%)	5.46 (-2.67%)
F100B0	2.88	3.09 (7.29%)	2.99 (3.82%)

Table 5
Effect of changes in carbon dioxide on the simulated yields of rice.

Treatment	Yield (t/ha)		
	No change in carbon dioxide	Increase in carbon dioxide	Decrease in carbon dioxide
F0B0	0.14	0.14 (0.00%)	0.14 (0.00%)
F0B20	5.59	5.59 (0.00%)	5.57 (-0.36%)
F25B0	1.44	1.44 (0.00%)	1.44 (0.00%)
F25B20	5.59	5.59 (0.00%)	5.57 (-0.36%)
F25B30	5.48	5.49 (0.18%)	5.47 (-0.18%)
F50B20	5.59	5.60 (0.17%)	5.58 (-0.18%)
F50B30	5.48	5.49 (0.18%)	5.47 (-0.18%)
F75B20	5.61	5.62 (0.17%)	5.59 (-0.36%)
F100B0	2.88	2.88 (0.00%)	2.87 (-0.35%)

Table 6
Effect of changes in all the climatic parameters on the simulated yields of rice.

Treatment	Yield (t/ha)		
	No change in climatic parameters	Increase in climatic parameters	Decrease in climatic parameters
F0B0	0.14	0.11 (-21.43%)	0.13 (-7.14%)
F0B20	5.59	4.09 (-26.83%)	5.41 (-3.22%)
F25B0	1.44	0.96 (-33.33%)	1.42 (-1.39%)
F25B20	5.59	4.09 (-26.83%)	5.43 (-2.86%)
F25B30	5.48	3.73 (-31.93%)	5.31 (-3.10%)
F50B20	5.59	4.09 (-26.83%)	5.43 (-2.86%)
F50B30	5.48	3.73 (-31.93%)	5.31 (-3.10%)
F75B20	5.61	4.10 (-26.92%)	5.45 (-2.85%)
F100B0	2.88	2.51 (-12.85%)	2.84 (-1.39%)

Table 6 shows the effect of changes in all the climatic parameters. There was a decline in the simulated yields for both an increase and a decrease in all the climatic parameters. The percentage decrease in yield was much greater with the increase in the climatic parameters than the decrease in the climatic parameters. This shows the interactive effect of the various climatic parameters on the simulated yields of rice [11]. observed an interactive effect whereby high temperature and elevated carbon dioxide concentrations resulted in a decline in yield.

4. Conclusion

Addition of biochar in combination with inorganic fertilizer positively affected rice yield. The model predicted accurately, the yields of rice upon the addition of the biochar-inorganic fertilizer with the treatment having 25% of the recommended rate of inorganic fertilizer and 20 t/ha of biochar (F25B20) giving the best yield. Increases in temperature resulted in a decrease in the yield of rice with the reverse giving an increase in yield. Increases in solar radiation and carbon dioxide generally caused an increase in yield whilst reducing these two climatic parameters cause a decline in rice yield. Increases or decreases in all the parameters (temperature, carbon dioxide, solar radiation and rainfall) resulted in a decline in the yield of rice.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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