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Research Application Summary

Modelling soybean yield response to nutrients applications under projected climate change scenarios in Benin

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Abstract

Climate and its variability is a major risk factor for the success of soybean cultivation in Benin. This aspect becomes even more important in the context of future climate scenarios, in which global warming is predicted and food security is under threat. This study evaluated the influence of future climate on soybean yield under fertilizer application considering the period (1980-2018) and future (2018-2079) climate scenario. The study applied DSSAT and the climate data projected from CORDEX to simulate the trends of crop yields for soybean in two agroecologicals zones in Benin by 2079 under different climate change circumstances (RCP 4.5 and RCP 8.5), based on a 2-years experiment established at Ouesse and Bembereke. Two fertilizers (NPKMgZn) practices were applied: 14-23.9-18.18-11.45-4.14 and 16.6-23.5-29-15.2-7.7. Our findings indicated that the CROPGRO model can accurately ($R^2 > 0.70$) simiulate soybean yields while NRSME values varied between 11.05 % and 22.8 %) in simulating soybean yields in both sites. This shows the ability of the CROPGRO model to simulate yields under a wide range of environmental conditions. Simulations carried out with different climate scenarios have shown that soybean yields will likely decrease from 9% to 19% for scenario RCP 4.5, and 22 % to 31%, respectively, by the middle of the century with the application of fertilizer doses. The study suggests that a readjustment of specific nutrient doses will be necessary by the end of the century to ensure good soybean production under future climatic conditions.

Key words: Benin, climate change, DSSAT, fertilizers, legume, simulation, soil fertility

Résumé

Le climat et sa variabilité constituent un facteur de risque majeur pour le succès de la culture du soja au Bénin. Cet aspect devient encore plus important dans le contexte des scénarios climatiques futurs, dans lesquels un réchauffement global est prévu et la sécurité alimentaire est menacée.

Cette étude a évalué l'influence du climat à venir sur le rendement du soja sous application d'engrais en considérant la période (1980-2018) et le scénario climatique futur (2018-2079). L'étude a appliqué le DSSAT et les données climatiques projetées à partir de CORDEX pour simuler les tendances des rendements des cultures de soja dans deux zones agro-écologiques du Bénin d'ici 2079 dans différentes circonstances de changement climatique (RCP 4.5 et RCP 8.5), sur base d'une expérience de deux ans conduite à Ouesse et Bembereke. Deux pratiques de fertilisation (NPKMgZn) ont été appliquées : 14-23,9-18,18-11,45-4,14 et 16,6-23,5-29-15,2-7,7. Nos résultats ont indiqué que le modèle CROPGRO peut simuler avec précision (R2 > 0,70) les rendements du soja alors que les valeurs NRSME variaient entre 11,05 % et 22,8 % dans la simulation des rendements du soja dans les deux sites. Cela montre la capacité du modèle CROPGRO à simuler les rendements dans une large gamme de conditions environnementales. Les simulations effectuées avec différents scénarios climatiques ont montré que les rendements du soja diminueront probablement de 19% à 9% et de 31% à 22% pour les scénarios RCP 4.5 et RCP 8.5, respectivement, d'ici le milieu du siècle avec l'application de doses d'engrais. L'étude suggère qu'un réajustement des doses d'éléments nutritifs spécifiques sera nécessaire d'ici la fin du siècle pour assurer une bonne production de soja dans les conditions climatiques futures.

Mots clés : Bénin, changement climatique, DSSAT, engrais, légumineuse, simulation, fertilité du sol

Introduction

Worldwide, soybean is one of the most cultivated crops due to its demand in several industries (Khojely *et al.,* 2018). In Africa, the main soybean producers include South Africa (787, 200 ha cultivated, Nigeria (780, 679 ha cultivated), and Uganda (480,000 ha cultivated) (Faostat, 2018). Soybean is part of the main annual crops in Benin, and serves as a cash crop for the producers and strategic crop for the country's food security (Chabi *et al.,* 2019). As a source of food, feed, and biofuel, soybean demand will continue to increase in the future.

Climate change will have an important impact on agricultural production and sustainable development of the environment (Yan *et al.,* 2020) especially in West Africa (Sultan and Gateani, 2016). Climate change is likely to affect the profitability of soybean farming system in the future in West Africa (Sultan and Gaetani, 2016). It has already caused significant impacts on water resources, food security and health system (Wei *et al.,* 2014). Indeed, climate variability is one of the most significant factors influencing year to year crop production, even in high yield and high-technology agricultural areas. Improving agricultural production around the world in the context of climate change is a challenge that must be met through increasing crop yields to meet the demand for food and energy especially as the sustainability of farming systems in countries like Benin whose economy relies primarily on agriculture in the future depends on adaptation to climate change (Dingkuhn *et al.,* 2006). Consequently, a better knowledge of how climate will change in West Africa and how such changes will impact crop productivity is crucial to inform policy making (Sultan and Gaetani, 2016).

Soil fertility is key in maintaining agricultural sustainability (Yan *et al.,* 2020). Unfortunately, frequent and extreme precipitation accompanied by soil nutrient loss are expected from climate change and will intensify the impact of long-term cultivation on soil degradation (Yan *et al.,* 2020). Therefore, investigating the impact of climate change on crop yield and soil fertility is needed to improve agricultural management measures, improve crop adaptability to climate change, ensure food production safety, reduce the risk of continuous farming and climate change on land degradation, and maintain the sustainable development of agriculture (Sultan and Gaetani, 2016). The risks of climate change and soil degradation for the agricultural environment and crop production are increasingly. Based on the limitations of land resources, it is important to explore a sustainable and effective fertilization strategy to reduce risks and ensure there is a high grain yield and sustainable development of agricultural ecosystems.

Crop growth models may simulate crop development and yield by integrating environmental factors and crop management practices (Jing *et al.,* 2017). Crop models have been extensively used to predict crop response to different environmental conditions (do Rio *et al.,* 2015; Teixeira *et al.,* 2018; Battisti *et al.,* 2019). The crop growth simulation model is capable of analyzing the effects of various climatic factors on crop growth and soil condition in the context of interactions with fertilizer, soil, cultivar, and agronomic factors. Despite advances in African agriculture in recent years, the use of crop models for planning agriculture activities and estimating yield is still limited in Benin (Saïdou *et al.,* 2018; Tovihoudji *et al.,* 2019).Thus, modeling soybean responses to future growing conditions under projected climatic change is warranted, so that stakeholders may adapt to meet the expected demand (Jing *et al.,* 2017). In Benin, adjustment in soybean fertilization practices as a strategy for adapting to climate variability is not yet documented. Similarly, the use of climate scenarios to assess the sustainability of adaptation strategies to climate risks is also not well documented. The objectives of this study were to develop a CROPGRO model to estimate soybean yield cultivars in Southern Borgou and the cotton zone of the centre in Benin and to evaluate the influence of climate change on soybean yield in Southern Borgou and the cotton zone of the centre under fertilizer application.

Materials and Methods

Study area and field management. The simulations carried out in this study concerned two agro-ecological zones of Benin namely Southern Borgou (AEZ 3) and the cotton zone of the centre (AEZ 5). The experimental site in the AEZ 3 was in Bembèrèkè district, whereas that of the AEZ5 was in the district of Ouessè. The AEZ 3 is located between 1 10-3 45 E and 9 45-12 25 N and is part of the Sudanian phytogeographical region of Benin. The AEZ 5 is located between 1 45'- 2 24' E and 6 25'- 7 30' N and belongs to the sudano-guinean phytogeographical region also known as transitional zone of Benin. The soybean variety used was TGX 1448-2E (105 days of growth cycle and an achievable yield of 1.8 $t.ha^{-1}$). Flat ploughing was carried out with the plough using animal traction at a depth of about 15 cm in AEZ3, while in AEZ5 the ploughing was carried out with hoe. Spacings were 50 cm between rows and 20 cm between plants, i.e., a density of 100,000 $plants.ha^{-1}$. Sowing was done at a depth of 5 cm at a rate of two seeds per seedbed. Nutrients were applied as urea (46% N), TSP (46% P_2O_5), KCl (60% K_2O), kieserite (23.5% MgO) and sulphate of zinc (35% Zn2+). The different nutrient doses simulated for the two crops are NPKMgZn combinations of 14-23.92-18.18-11.45-4.14 and 16.6-23.5-29-15.2-7.7.

Weather data, climate scenarios and crop simulation. For calibration and validation, the data of historic weather beetween 1980 to 2017 were used for the initial fertilizer dose simulation and daily data of 2018 and 2019 were used for the on-farm validation of the fertilizer recommendation. These data included precipitation (mm), minimum and maximum temperatures (C) and solar radiation (WJ m^{-2}). The data were collected from ASECNA (Agence pour la Sécurité de la Navigation Aérienne en Afrique et à Madagascar) synoptic station of Savè and Parakou close to the research area.

The future climate data used were obtained from the CORDEX database. The CORDEX was established by the World Climate Research Program (WCRP), aiming to develop a coordinated international framework for generating Regional Climate Model projections (RCM). CORDEX used a new set of Global Climate Model (GCM) simulations published by the Intergovernmental Panel on Climate Change (IPCC) in its fifth assessment report, referred to as the fifth Coupled Model Intercomparison Project (CMIP5). The CORDEX uses emission scenarios (Reference Concentration Pathways-RCPs) known as RCP 4.5 and RCP 8.5, which closely correspond to the IPCC emissions scenarios SRES (Special Report on Emissions Scenarios) B1 and A1B, respectively. The controls of the scenario and technological options are detailed in Clarke *et al.* (2007). Additional details about the simulation of land use and carbon emissions are given by Wise *et al.* (2009). Ideally, all simulations of regional models should cover the period 1951-2100. For this study, however, future simulations covered the period from 2018 to 2079. In this study, the weather of future climate events started in 2018. We used two periods that are 2018-2048 and 2049-2079. The simulations were conducted by CROPGRO modules in DSSAT v4.7. Input data, including daily weather data, crop management, cultivar coefficients, and initial soil conditions, were required by the model. For all simulations, the seasonal analysis of DSSAT was performed.

Parameterization and evaluation of the model. The model results were evaluated by computing three parameters including the root mean square error (RMSE), the normalized root mean square error (NRMSE) and the determination coefficient (R). The genetic coefficients (Table 1) used in this study are defined based on those reported by Nyambane *et al.* (2012) and Narh *et al.* (2015) for the same variety. These genetic coefficients were established for the two varieties that we used in the field trials. The reported coefficients were tested and fitted in the model. The values of the coefficients' genetic references were set and compared with the observed values for each treatment to verify their adjustment. The adjustment was made by increasing or decreasing the value of the coefficient determined by the trial process until concordance between the estimated and observed was achieved.

Table 1. Genetic coefficients used for modeling the soybean and groundnut variety in CROPGRO model at the two sites

Cultivars	CSDL	EM-FL	FL-SH	FL-SD	SD-PM	FL-LF	LFMAX	XFRT	PODUR	SFDUR	THRSH
TGX 1448-2E	11.88	28.9	7	13.5	31.5	15	1.09	1.00	7.5	24.5	77.0

In Table 1, CSDL represents Critical Short Day Length below where reproductive development progresses with no day length effect, EM-FL Time between plant emergence and flower appearance, FL-SH Time between first flower and first pod, FL-SD Time between first flower and first seed, SD-PM Time between first seed and physiological maturity, FL-LF Time between first flower and end of leaf expansion; LFMAX, light-saturated leaf photosynthesis rate; XFRT, maximum fraction of daily growth partitioned to seed + shell; PODUR, photothermal days required for cultivar to reach final pod load; SFDUR, seed-filling duration (photothermal days) for seed cohort under good growth conditions; THRSH, maximum ratio of seed/(seed + shell) at maturity.

Results

Model calibration and validation. Table 2 summarize the statistical parameters used to validate the CROPGRO model. Results of the t-test for paired sample analysis showed that the difference between the observed and simulated average yields is significant ($p<0.05$ and $p<0.001$) between the two agro-ecological zones during both growing seasons (2018 and 2019). The model has slightly underestimated soybean yields at Bembereke and Ouesse (growing season of 2019) and Bembereke (growing season of 2018) while the yield predicted by the model matches well with that of Ouesse during the growing season of 2018 (Table 2). Furthermore, it was noticed that the observed soybean yields (Table 2) were highly correlated with estimated values by the model. The R^2 values varied between 0.76 and 0.96 overall for both sites. The NRSME values between the observed and simulated soybean grain yields varied between 11.05 and 15.18 % (for the growing season of 2018) and between 14.01 and 22.8% (growing season of 2018).

Influence of climate change on soybean yield. Figure 1 shows the changes in average annual yields of soybean for different fertilizer treatments in the cultural system under the climate scenarios, between 2018 and 2079. Yield declines are observed for both scenarios with a more drastic yield decline for the scenario RCP 8.5. Compared to baseline (1980 to 2018), yield decreases for soybean will be greater. Figure 1 indicates a 9% (T1) to 19% (T2) decrease in soybean yield when we consider the optimistic scenario and yield decreases of 38% when we consider the pessimistic scenario, and this for the cotton zone in the center following the two doses of fertilizer. For the food-producing zone in southern Borgou, the climate projections show

Table 2. Comparison between the observed and simulated soybean yield (kg ha-1) in 2018 and 2019 in Bembereke and Ouesse

Variables	2018		2019	
	Bembereke	Ouesse	Bembereke	Ouesse
Observed (kg ha^{-1})	2200	2076	1980	1883
Simulated (kg ha^{-1})	2051	1986	1772	1731
MD	-149**	-90**	-208***	-152*
Ratio	0.93	0.95	0.89	0.91
R^2	0.86	0.94	0.96	0.76
RMSE (%)	243.16	315.23	452.6	263.9
NRMSE (%)	11.05	15.18	22.8	14.01

MD: mean difference, RMSE: root mean square error; NRMSE: normalized root mean square error a drop in soybean yields of 14% to 18% (RCP 4.5 scenario) and 41% (T1) to 49% (T2) when we consider the alarmist scenario. Therefore, the future influence of climate change on soybean will be more pronounced. Tracking the changes in projected annual soybean yields for both sites (Figures 2 and 3), declines in soybean grain yields will be more accelerated by mid-century and this trend will continue as we move toward the end of the century. Similarly, the regressive trend is more pronounced for the RCP 8.5 scenario, especially for the Bembèrèkè site (Figure 3). This general trend will be observed for both fertilizer rates. The projected variations in climatic factors will have a negative effect on soybean yields with long-term application of the micronutrient and macronutrient doses.

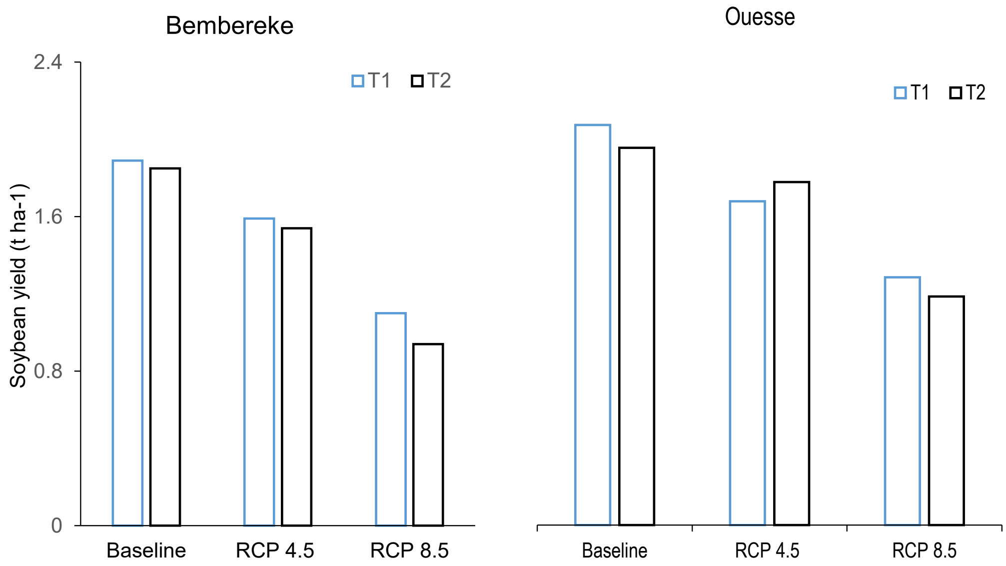

Figure 1. Average of soybean yields under the baseline and the climate scenarios between 2018 and 2078 at the Ouesse and Bembereke site (T1=$N_{14}P2_{3.92}K1_{8.18}Mg1_{1.45}Zn_{4.14}$; T2= $N_{16.6}P_{23.5}K_{29}Mg_{15.2}Zn_{7.7}$)

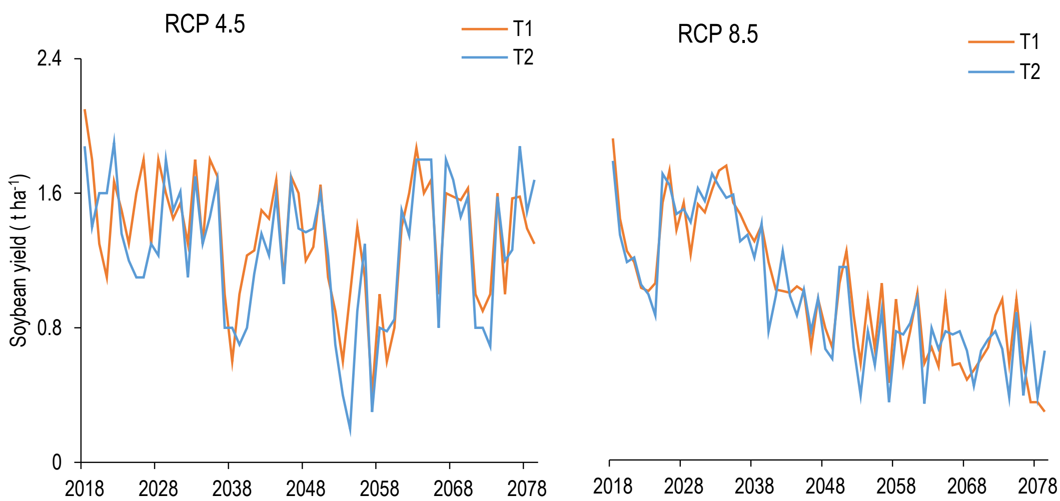

Figure 2. Annual grain yields of soybean under the climate scenarios between 2018 and 2078 at Ouesse site

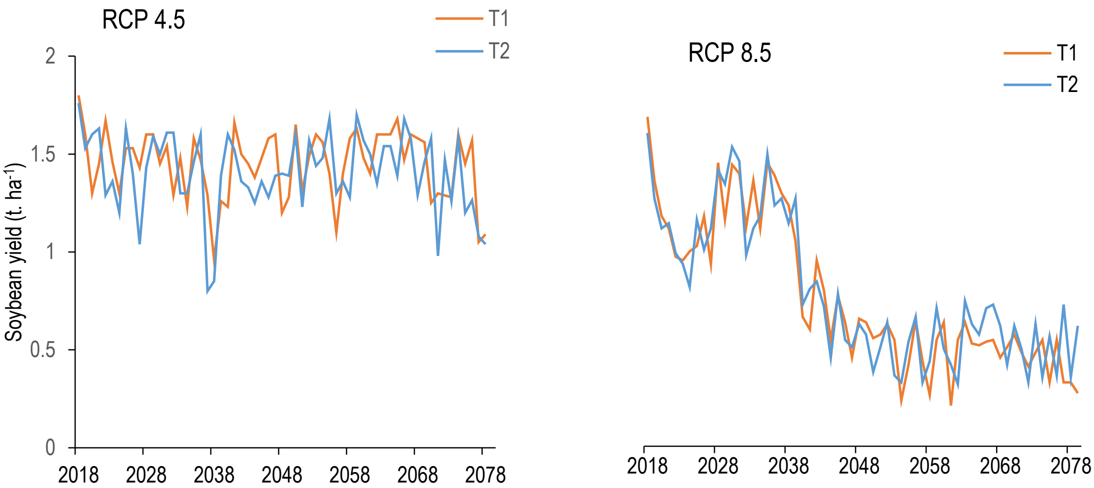

Figure 3. Annual grain yields of soybean under the climate scenarios between 2018 and 2078 at Bembereke site (T1=$N_{14}P_{23.9}K_{18.18}Mg_{11.45}Zn_{4.14}$; T2=$N_{16.6}P_{23.5}K_{29}Mg_{15.2}Zn_{7.7}$)

Discussions

Soybean yield simulated by CROPGRO model match well data observed in the field during the two growing seasons (2018 and 2019) for all of the experimental sites. The R value range between 0.76 and 0.97 which indicates a strong correlation between the simulated and observed yields. Same findings were also reported by Yan *et al.* (2020) who found R values of 0.80 for soybean. The ability of the CROPGRO model to well simulate soybean grain yields was also reported by Walikar *et al.* (2018). These authors concluded that a good agreement existed between the observed soybean grain yield and the simulated one. Standardized mean prediction error (NRMSE) value between the observed and simulated results varied between 11.05 and 15.18 % for the 2018 growing season and between 14.01 and 22.8% for the 2019 growing season. This reveals that DSSAT model performed well in simulating soybean grain yields as the NRMSE values calculated were within the acceptable range (Loague and Green, 1991). Our results showed that the model performed well as reported by several authors (Talacuece *et al.,* 2016; Yan *et al.,* 2020) using the NRMSE value. This shows that the model can therefore be used to recommend optimal agronomic parameters for soybean production in regions exhibiting similar climatic conditions with those of the current study (do Rio *et al.,* 2016; Jing *et al.,* 2017; Yan *et al.,* 2020).

Our results showed that the future impact of climate change will be severe on soybean production. Yield reductions will be drastic for soybean especialy in the case of CO_2 emission scenario, even when fertilization is carried out. This raises the possibility that high emission levels may have adverse effects on overall agricultural productivity and ultimately on global food security (Bhattarai *et al.,* 2017). The results found in this study differ from those of Bhattarai *et al.* (2017) who reported that the influence of high carbon dioxide emissions will, on the contrary, favor an increase in soybean yields. Nevertheless these authors used atmospheric CO_2 concentration as the only factor influencing soybean yield. But the work of Yan *et al.* (2020) showed that under mineral fertilization conditions, the future impact of climate change will lead to a drop in soybean yields. Rising temperature was generally considered as a negative factor for soybean production in tropical regions (Bao *et al.,* 2015) and an advantage for soybean production in temperate regions

(Wolf, 2002; Jing *et al.,* 2017). It would therefore be judicious to carry out these simulations while keeping the fertilizer doses on other soybean cultivars in order to prevent the harmful effects of climate change (Talacuece *et al.,* 2016). Also, the projections carried out within the framework of this study show that in the middle and towards the end of the century, yields decrease will be observed in both agro-ecological zones, with a higher potential prominence in the case of higher greenhouse gas emissions (scenario 8.5). This implies that the effect of these climate changes will be observed on the soils of legumes farming system and it would therefore be important to think about a readjustment of fertilizer doses in these agro-ecological zones.

Conclusion

In the present study the CSM-CROPGRO model was found to be satisfactory in simulating soybean yield under nutrients applications and the model was able to simulate soybean yield under different climate conditions in cotton zone of central Benin and food-producing zone of south Borgou. Yields predicted by the model were very good (R^2 values more or less close to 1) . The results of our simulations showed that future climatic conditions between now and 2079 will lead to a decrease in soybean yields in both agro-ecological zones. This decline will be greater for the scenario RCP 8.5. The different nutrient combinations will be affected by the effects of climate change and yield declines will be observed towards the end of the century. This calls for the implementation of adaptation strategies to ensure good soybean production in these areas with the application of fertilizers.

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