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Evaluating crop management options for sorghum, pearl millet and peanut to minimize risk under the projected midcentury climate scenario for different locations in Senegal

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ABSTRACT

With the growth of population, climate change is a threat to global food security. Understanding and identifying appropriate options of cropping systems and management practices at spatial (locations) and temporal (climate change) scale is important and required. A simulation study was carried out on 13 different locations of Senegal with the objectives of (i) assessing impacts of midcentury climate change scenario across different spatial scales and (ii) evaluating effects of crop management strategies (date of planting, planting density, nitrogen fertilizer management, irrigation, and crop rotations) to reduce risk under current and midcentury climates. Simulation results showed that N fertilization, planting date, and irrigation greatly affected sorghum and millet yield, which can be considered as suitable crop management options to reduce risks under the projected midcentury climate in Senegal although the impact varied by location. The response to N was highly related to water availability or rainfall. In contrast, peanut yield was not sensitive to N application. Early planting (01 to 10-June) improved yield for all three crops across 9 of the locations whereas yield of the three crops in the northern Senegal (Podor, Dagan, Louga and Kanel) remains low and thus was not improved by change in planting date. The length of growing season during the midcentury period decreased at least by up to three weeks due to late onset of rain for some locations, implying that shorter and high-yielding cultivar will be more suitable under future climate. Climate change slightly decreased sorghum yield during the midcentury (likely due to increased temperature and decreased rainfall) although response varied by location while millet yield was either improved or unchanged for most locations. Peanut yields decreased on average by 16 to 20% during the midcentury period regardless of all factors tested. Yield decreases for peanut might be due to increased duration of elevated temperatures and late initiation and shorter duration of rainy season, which implied breeding for heat and drought tolerance, and shorter season varieties might be beneficial. Of all crops evaluated, millet

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performed well under future climate compared to sorghum or peanut in Senegal although this may be affected by varietals factors. Changes in production systems, particularly focusing on tolerant crops as millet and sorghum will be critical.

1. Introduction

Agriculture in Senegal is subsistence, low input, less mechanized, and sensitive to changes in climate factors, and hence the country is vulnerable to food insecurity. Resilient agriculture practices should be formulated to improve productivity and reduce food insecurity. Agriculture constitutes about 46% of the total land contributing about 15% of the Gross Domestic Product (GDP) and 70 – 75% of employment (CIAT/BFS/USAID, 2016; World Data Atlas, 2016). Crop production is limited by factors including climate change and variability, water stress and poor soil fertility, lack of access to improved seeds/varieties, inputs, credit, and markets (Akponikpe, 2008; Ganyo et al., 2019). In depth investigations are needed to develop agronomic management strategies under current and future climate change scenarios.

Sorghum (*Sorghum bicolor* L. Moench), pearl millet (*Pennisetum glaucum* L.) and groundnut or peanut (*Arachis hypogaea* L.) are among the major crops in Senegal (Leippert et al., 2020). In most cases, the distribution of crop types grown in Senegal is correlated with the distribution and timing of seasonal rainfall (IFPRI, 2013). Crop growth and development is influenced by changes in temperature and water stress, subsequently affecting yield. Most West African countries including Senegal depend primarily on rainfed agriculture. The rainfall and temperature patterns in West Africa are changing and is expected to change significantly by midcentury. Some studies have indicated rainfall may increase in the eastern/central and decrease in the western Sahel of West Africa during the midcentury period (Defrance et al., 2020; Monerie et al., 2020). Others indicated that under future climate, rainfall and water availability for agriculture is expected to decrease (Sylla et al., 2018). An increase in temperature by 1.0 – 1.4 °C during the midcentury (2040–2059) compared to the baseline (1986–2005) is projected for Senegal (Zermoglio et al., 2015). An increase of 2 °C could

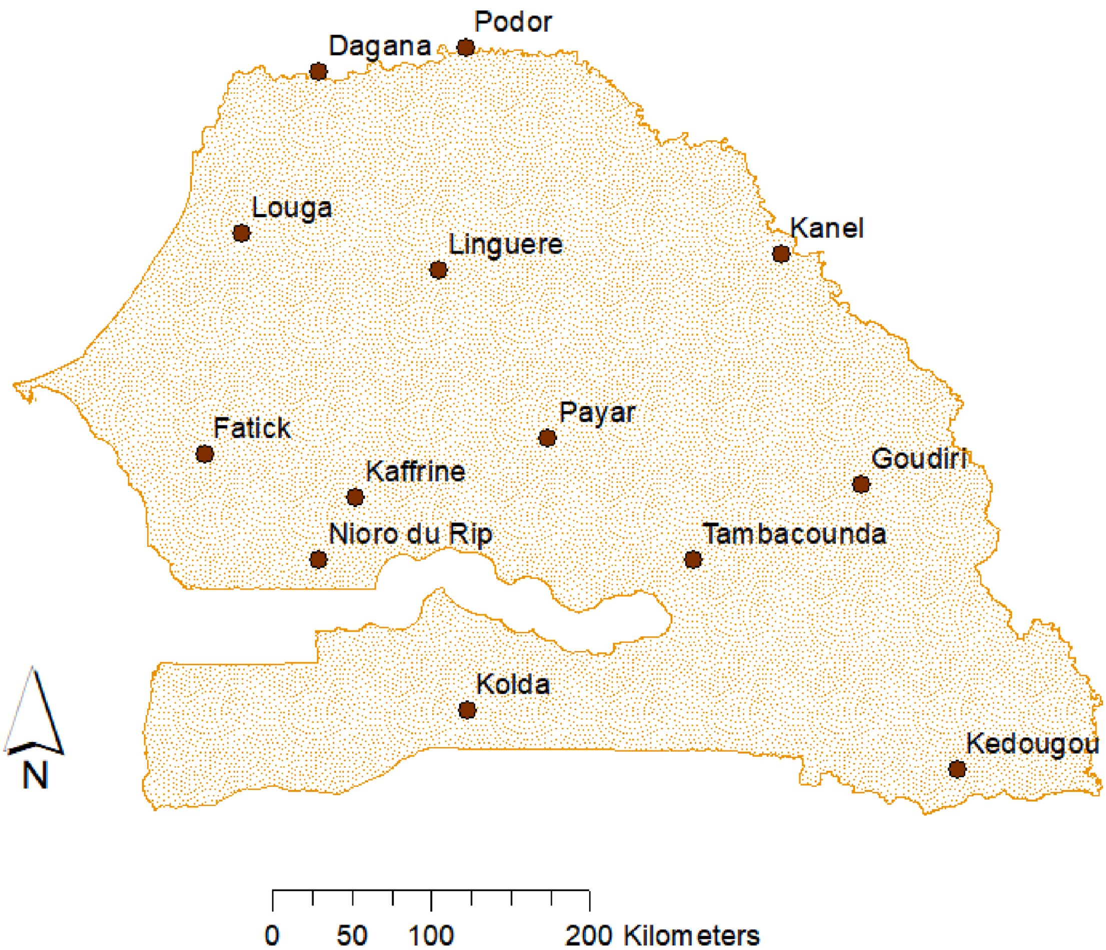

Fig. 1. Map of Senegal and selected locations (with 13 total locations) for simulations.

increase crop water demand and irrigation requirements, leading to substantially lower irrigation availability (Sylla et al., 2018). Climate change is expected to reduce crop yield in West African countries such as Senegal (Roudier et al., 2011; Ahmed et al., 2015; Defrance et al., 2020). Although, elevated carbon dioxide (CO_2) levels might have positive effect on yield due to increased photosynthesis and transpiration efficiency, but the associated increases in temperature and decreases in rainfall will have negative effects on yields (Jha et al., 2018; Defrance et al., 2020). The positive impact of elevated CO_2 will be greater in C_3 crops relative to C_4 crops (Ahmed et al., 2015). The benefits of elevated CO_2 is generally realized at below optimum temperatures, but not at above optimal temperatures in many crops, including sorghum (Prasad et al., 2006) and peanut (Prasad et al., 2003).

Evaluating management options for sorghum, pearl millet and peanut under midcentury climate scenario is necessary to enhance sustainable crop production practices and to reduce risk related to food insecurity. Therefore, understanding the impacts of climate change factors on the growing seasons and management practices at spatial and temporal scales could help to develop adaptation strategies in Senegal. Furthermore, at present producers do not have robust agronomic practices or strategies to reduce the negative impacts of climate change factors on crop yields (CIAT/BFS/USAID, 2016; Ganyo et al., 2019). For example, impacts of the interactions of different management practices (e.g., planting dates, nitrogen fertilizer rate, planting density, different crop rotation systems, and irrigation) under current and future climates have not been adequately studied for key crops such as sorghum, millet and peanut in different regions of Senegal. These interaction effects are hard to capture by conducting field experiments due to limitation of time, resources and confounding nature of multiple factors strategies.

Crop simulation models have been used to quantify impacts of current and future climate changes on crop yields (Asseng et al., 2011; Asseng et al., 2014) and evaluate different crop management strategies (Araya et al., 2020; Araya et al., 2021a; Araya et al., 2021b). The Decision Support Systems for Agrotechnology Transfer – Cropping System Model (DSSAT-CSM; Jones et al., 2003; Hoogenboom et al., 2017; 2019; termed DSSAT hereafter) has been rigorously tested across different regions and found to be useful tool for quantifying crop impacts and testing adaptation strategies (Asseng et al., 2011; Asseng et al., 2014; Araya et al., 2017). In this research, simulations were carried out in Senegal with the objectives of (i) assessing impacts of midcentury climate change scenario across different spatial scales and (ii) evaluating effects of crop management strategies (date of planting, planting density, nitrogen fertilizer management, irrigation, and crop rotations) under current and midcentury climates.

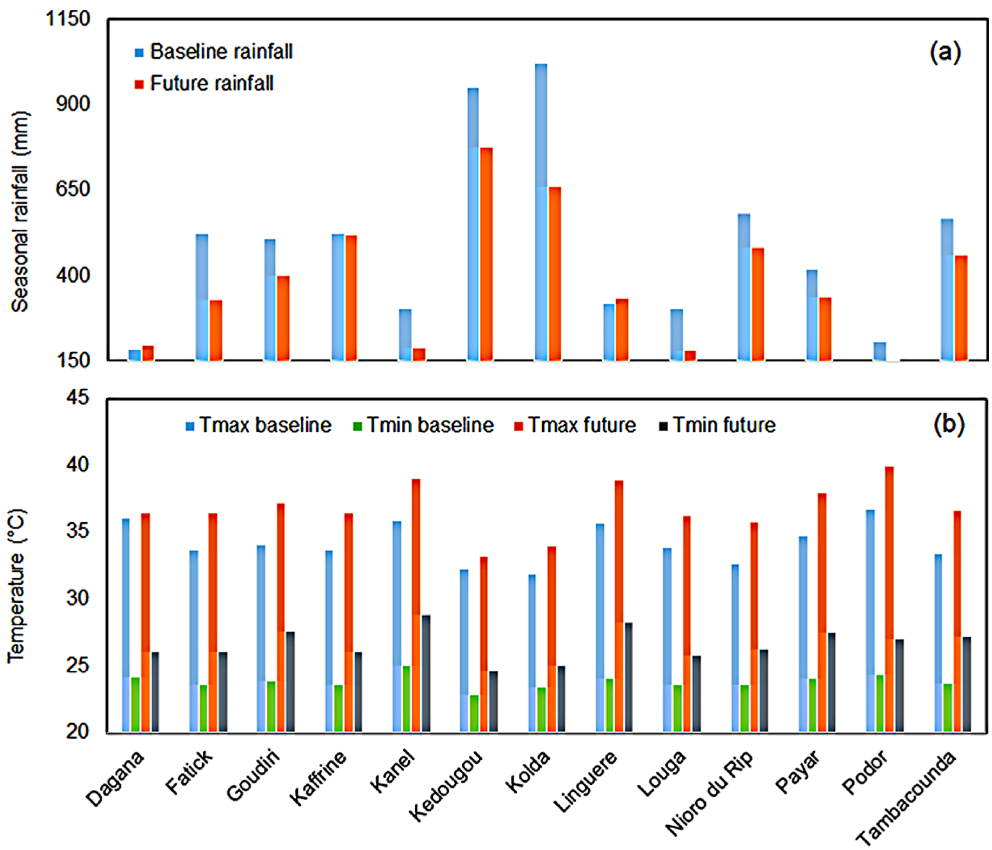

Fig. 2. Seasonal rainfall (planting to maturity) for the baseline (1980 – 2005) and midcentury (2040 – 2069) rainfall (a) and temperature (b) for selected locations in Senegal.

2. Material and methods

2.1. Locations

This research was conducted at 13 locations representing different agroecological conditions in Senegal (Fig. 1). The elevation of locations varied between 0 and 581 m above sea level with rainy season (growing season) ranging between May/June to October/November and dry season ranging between December to April/May. The north–south seasonal movement of the intertropical convergence zones influences the spatial distribution of rainfall or climate conditions in Senegal (Fall et al., 2006). The seasonal rainfall of the locations ranges from < 150 to >1000 mm. The southern Senegal have longer rainy season and higher rainfall compared to the northern Senegal. The main growing season average maximum and minimum temperatures for different study locations range from 32 to 36 °C and 23.3 to 25.7 °C, respectively (Fig. 2).

According to soil atlases of Africa, most Senegal soils are dominated by light textured soils and soil root zone plant available water corresponds from low to moderate (Jones et al., 2013; FAO, 1993), which is related to the sand - sandy loam soils. Consequently, most of the soils in Senegal has low water holding capacity (e.g., Ganyo et al., 2019; Gueye et al., 2015). Peanut and pearl millet are grown in red and light textured soils (sand or sandy loam) often locally termed as "Dior" soils. By considering sandy soils, we assumed the worst-case scenario, where crops are exposed to grow in soils that retain less water (sand). The crops grown on low water holding capacity soils suffer from limited water (drought) stress which could have several negative effects on crops such as nutrient uptake, photosynthesis and translocation, hampered growth and development and reproduction function (Prasad et al., 2008a). Thus, we assumed worst-case scenario for assessing the potential impacts of climate change on the performance of the crops under low soil water availability conditions and for evaluating the effectiveness of the available tested potential adaptation management options under baseline and future climate. For this study, one of the West African soil that correspond to the soil texture was adopted from the DSSAT soil database (profile IBML910001). typical sandy soils West African Accordingly, the soils used in this simulation study was sand soil with lower limit, drainage upper limit and water content at saturation of 0.031–0.037, 0.097–0.126 and 0.32–0.33 m^3/m^3, respectively.

In Senegal, there are three climate zones namely, the coastal (represent the Atlantic coastal areas), the Sahelian (north Senegal, representing warm and desert climate) and the Sudanic zones (southern half of Senegal characterized by hot and humid climate conditions). Peanut, millet and sorghum are among the dominant crops grown in the region. In addition, there are six agro-ecological zones based on socio-economic and physiographic characteristics of the country namely the River valley, Niayes valley, peanut basin, Silvo-pastoral zone, eastern Senegal and upper Casamance and lower Casamance (CIAT/BFS/USAID, 2016). Although some crops dominate over others due to difference in agro-ecologies, the selected crops are present in most regions. For example, the dominant crops in the peanut basin are peanut and millet while River valley is dominated by rainfed rice.

2.2. Model setup, calibration and evaluation

The DSSAT-CSM (version 4.75; Hoogenboom et al., 2019) used in this study was calibrated and validated for grain sorghum (CSM-335) and pearl millet (CIVT) genotypes by Singh et al. (2014) and Singh et al. (2017), respectively, and evaluated by Jha et al. (2021). Similarly, peanut cultivar Virginia 897 was calibrated and validated by Sarr and Camara (2018). Hereafter grain sorghum will be termed as sorghum, pearl millet as millet and groundnut as peanut. During the model evaluation process, average simulated yield for the period 1981 – 2005 for locations in the peanut basin was averaged and compared with yields from FAOSTAT (1980 – 2005). On average around the world, yield losses due to pest for maize (*Zea mays*), rice (*Oryza sativa*) and potato (*Solanum tuberosum*) range from 31 to 40% (Oerke, 2005). Some studies have indicated that estimated pre-harvest pest loss globally for soybean (*Glycine* max), wheat (*Triticum aestivum*) and maize could amount to an average of 26 to 29%, 24 to 34%, and 31 to 38%, respectively (Oerke, 2005; Popp et al., 2013). Since simulations did not account for impacts of pest, disease and weeds, we assumed at least that 30% yield losses occur at the country level due to pest, disease and weeds. The soil fertility factor was adjusted to account for these losses as well as other soil fertility constraints not simulated by the model, relative to the observed yields. After accounting for the impacts of biotic factors, simulated location average yield for the period 1981 – 2005 were used. However, 5-years (1998 – 1999, 1986 – 1987 and 2002) out of 25-years had more than 30% percent of deviation between the FAOSTAT data and model simulated yield. Since this difference might have been caused due to change in planting date or technology inputs, we have removed the outliers by conducting homogeneity test as presented by Raes et al. (2006). The simulated yield for each 20 growing seasons was compared against the corresponding season of the observed yield obtained from FAO. Then the model was evaluated statistically using Root Mean Square of Error (RM) (Eq. (1)), normalized root mean square of error (NRM) (Eq. (2)) and percent of deviation (P) (Eq. (3)).

$$RM = \sqrt{\frac{\sum_{i=1}^{n}(Si - Mi)^2}{n}} \tag{1}$$

$$NRM = \left[\frac{RM}{M}\right] \times 100 \tag{2}$$

$$P = \left[\frac{Si - Mi}{Mi}\right] \times \tag{3}$$

where, RM and NRM are root mean square of error and normalized root mean square of error, respectively. n, number of years of observation; *Si*, simulated; *Mi*, measured; *M*, average observed value; Σ is symbol used for summation of all variables; P, percent of deviation.

2.3. Model simulations with climate and crop management practices

The midcentury climate change impact assessment was carried out by comparing the simulated yield of three major crops (sorghum, millet and peanut) using the baseline climate data (1980 – 2005) against the simulated yield for the midcentury climate data (2040 – 2069) period. The baseline daily rainfall was obtained from high-resolution observational gridded dataset – Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) (Funk et al., 2014, 2015; Dinku et al., 2018). Whereas the baseline (1980 – 2005) daily maximum and minimum temperature and solar radiation data for the corresponding locations was obtained from the Coordinated Regional Climate Downscaling Experiment (CORDEX) (Endris et al., 2013; Mascaro et al., 2015). Similarly, the midcentury climate data including daily rainfall, maximum and minimum temperature and solar radiation was extracted from (CORDEX) under the pessimistic scenario (RCP8.5). Schwalma et al. (2020) reported that the RCP8.5 is suited to represent the midcentury scenario under the present policies for assessing climate risks and impacts.

Before running the model, the various treatments such as N fertilizer, planting date, irrigation, plant density, and crop rotation (peanut-sorghum-peanut-millet; peanut-sorghum-millet) scenarios were assigned in the model management files. In addition, major soils and measured weather conditions were used for the selected study locations (Fig. 1). There were six N application rates (0, 23, 45 68, 115 and 138 kg N/ha). Except for the treatment without fertilizer, 23 kg N/ha was applied at time of planting for all crops. In addition, for treatment with 45, 68, 115 and 138 kg N/ha, a second N application (23 kg N/ha) was carried out at 25 days after planting. For the 68, 115 and 138 kg N/ha, a third application (23 kg N/ha) was carried out at 45 days after planting and for the 115 and 138 kg/ha, 46 kg N/ha was applied at 60 days after planting and for the treatment 138 kg N/ha, another 23 kg N/ha was applied at 70 days after planting. For all treatments, 22 kg P and 22 kg K were applied at time of planting. N and P are the two most important

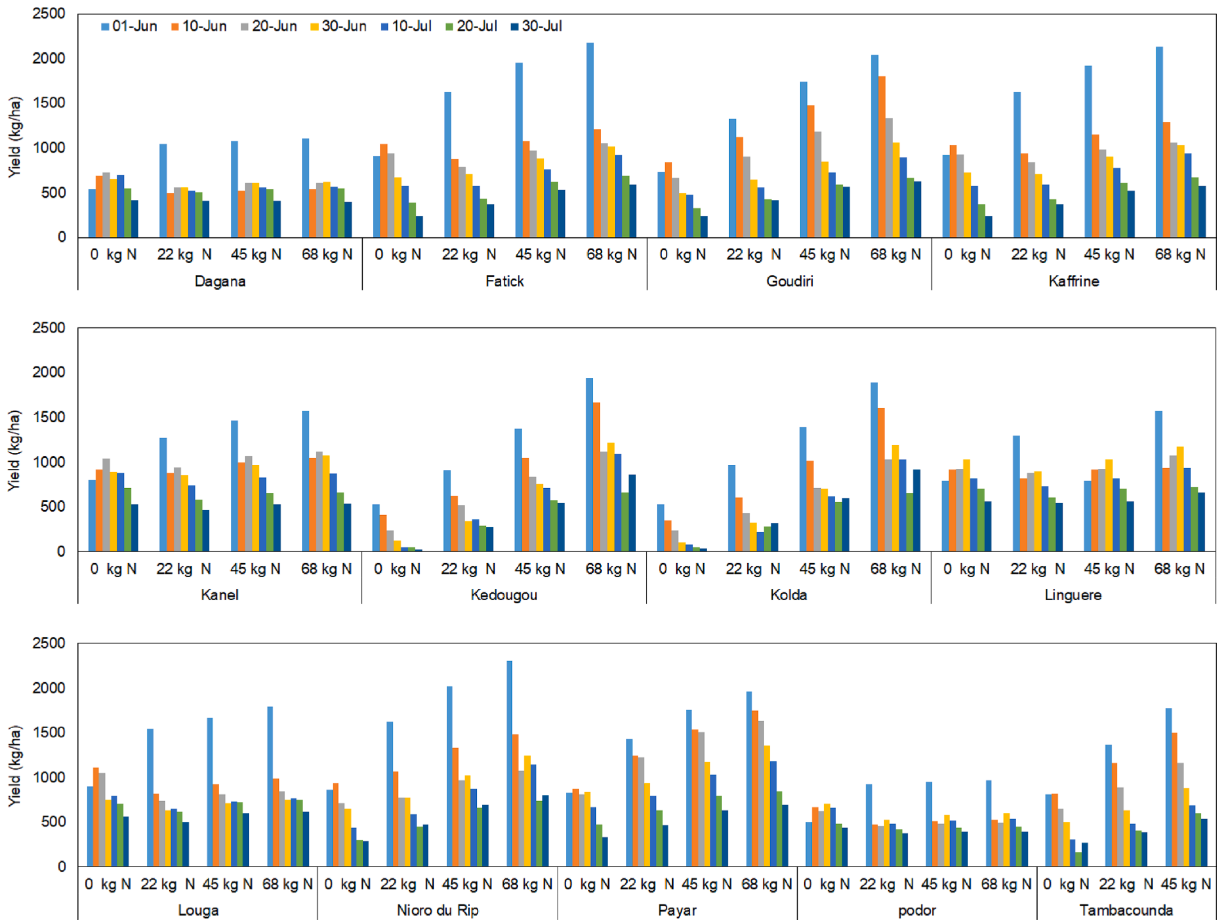

Fig. 3. Simulated sorghum yield under different planting dates and nitrogen fertilizer rates during the baseline period (1980 – 2005) for selected locations in Senegal.

fertilizer in the region (Akponikpe, 2008). Along with the fertilizer treatments, two water treatments were also evaluated (rainfed and full irrigation). Automatic irrigation was scheduled in the model to apply as required from planting to maturity. The application depth per irrigation event was set as 30 mm, which is the practiced irrigation depth per irrigation event for irrigated areas in Senegal. The start of planting and onset of rain for study locations in Senegal was evaluated for the baseline and midcentury period based on FAO (1980). According to FAO (1980), the week when long-term weekly rainfall exceeds or equals to the 50% of the weekly reference evapotranspiration is considered as start of planting or onset of rain. Following the evaluation of start of planting based on FAO (1980), the "optimal planting" date was screened using a simulation model considering yield and yield variabilities across seven different planting date treatments (01-Jun, 10-Jun, 20-Jun, 30-Jun, 10-Jul, 20-Jul and 30-Jul). "Optimal planting" date was defined as the planting date that result in high average long-term yield and low yield variability (Araya et al., 2021a). The impact of plant density was evaluated using a low (7 plants/m^2 for millet, sorghum and peanut) and high level (15 plants/m^2 for millet and sorghum and 13 plants/m^2 for peanut). Performance of continuous sorghum, millet and peanut as well as cropping systems rotation (peanut-sorghum-peanut-millet and peanut-sorghum-millet) under the various crop management strategies were evaluated in terms of yield differences by comparing the baseline yield against the corresponding future climate scenarios.

3. Results and discussion

3.1. Model performance

The model performance evaluation for sorghum and millet is presented in Jha et al. (2021). The RMs between simulated and observed sorghum and millet yields were 176 and 183 kg/ha, respectively (Jha et al., 2021). The NRM values for both sorghum and millet were in the range between 10 and 20%. Peanut yield was simulated with RM and NRM of 123 kg/ha and 14.8%, respectively for the long-term peanut yield data of Senegal. According to Soler et al. (2007), NRM is moderate if 10 – 20%, with this study presenting moderately good performance in simulating the observed values. In addition, the percent of deviation (P) between the long-term simulated and observed peanut yield was of 2%. This shows that the average simulated values deviated by only 2% when compared to the observed values, all indicating that the model was adequately calibrated.

3.2. Impacts of nitrogen and rainfall on yield of sorghum, millet, and peanut

Simulated yields of sorghum and millet responded positively to N for most of the locations with moderate to high seasonal rainfall (Figs. 3 and 4). For drier locations, application of N did not result in substantial increase in sorghum and millet yield relative to when N was not applied (Figs. 3 and 4) for example in locations Dagana, Kanel, Louga, Linguere and Podor (not shown). This was because the absorption and movement of nutrients from the root zone to roots and inside the plants depends on the availability of adequate water. This is particularly true for water-soluble nutrient such as N. In addition, drought has a two-fold effect on crop growth, direct reducing growth proportionally to transpiration, and an indirect mediated by a drought-induced crop N deficit (Kunrath et al., 2020). Lastly, adequate supply of water and nutrients enhances leaf area index and plant growth, improving light and carbon capture and ultimately increasing yield (Mandal et al., 2005; Kibe et al., 2006; Araya et al., 2019).

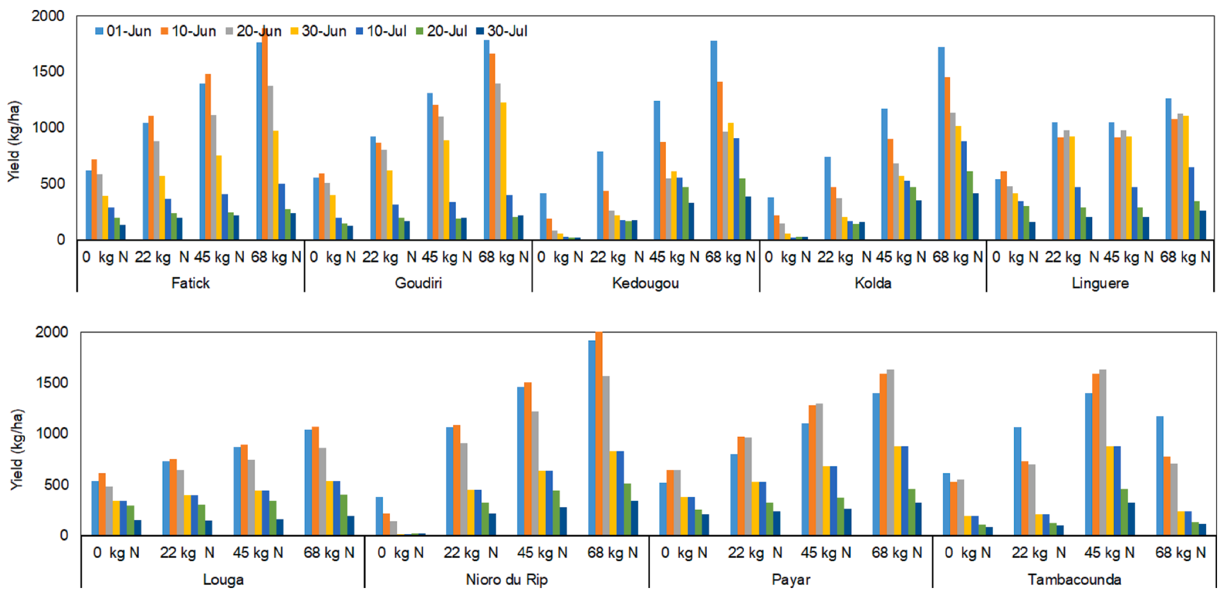

Fig. 4. Simulated millet yield under different planting dates and nitrogen fertilizer rates during the baseline period (1980 – 2005) for selected locations in Senegal. Some dry locations (Dagana, Podor & Kanel) are not included due to low yield and no change in yield from increased N.

For sorghum and millet, highest simulated yield corresponded to highest N application rate and greater rainfall. The relationship between yield and N for both sorghum and millet yield during the baseline and future period (at most locations) was more of curvilinear response although no relationship (flat) was obtained for some of the locations (Fig. 5 a-d). Buah and Mwinkaar (2009) reported a quadratic relationship between yield and N rate, where above 40 kg/ha did not substantially improve sorghum yield. Yield increased with the increase in N application rate compared to the control (Fig. 6 a and c). This study showed that there was substantial increase in yield up to 115 kg N/ha during the baseline period for locations with adequate seasonal rainfall (such as Tambacounda) after which yield increased at a diminishing rate for most locations. For some locations during the baseline period, there was linear increase up to 68 kg N/ha after which yield increase at decreasing rate (Fig. 6 a and c). While for dry locations such as Kanel, Dagana, and Louga yield did not respond appreciably to application of N (Fig. 6 a and c). The dry locations in the northern part of the country were reported to be more suitable for livestock production than for grain crop production systems (Fare et al., 2017). In contrast, sorghum and millet yield during the midcentury did not increase with an increase in N beyond 40 and 90 kg/ha, respectively (Fig. 5 b and d). The percent of yield increase for sorghum and millet due to addition of N (relative to that without application of N) was minimal for most of the locations (Fig. 6 b and d). Only two locations where precipitation is relatively high showed substantial increase with an increase in N application rate. This shows that crop's response to N under future climate was partly influenced by the amount of precipitation received. Reduced available soil water because of reduced amount of precipitation during the growing season (from shortening of growing season and increased daily evapotranspiration) could have reduced the N uptake. Some studies showed that increased CO_2 and rise in temperatures could decrease N uptake, which could limit yield (Jayawardena et al., 2017). Another plausible reason for these changes attribute to the impact of projected warming which could alter biogeochemical process in plants and soil, microbial respiration, and hence indirect negative impact on crop yields (Melillo et al., 2011).

The recommended fertilizer management practice for sorghum varies from applying 23 kg N, 10 kg P and 10 kg K/ha at time of planting followed by top dressing of 23 kg N/ha (IFDC, 2016) to applying 23 kg N, 23 kg P and 23 kg K /ha at time of planting and followed by 23 kg N/ha at time of tillering and 23 kg N/ha at around 45 to 60 days after planting (Ganyo et al., 2019). For millet in Senegal, the recommended fertilizer application is 150 kg NPK 15:10:10 at time of planting and 23 kg N/ha as dressing (IFDC, 2016). The recommended N rate for millet in Niger is 30 kg N/ha and 13 kg P/ha. In some areas of West Africa, millet yield could substantially improve, and yield variation could decrease with application of only 15 kg N/ha (Akponikpe, 2008). Furthermore, in Senegal, availability of subsidy programs influences the availability and use of fertilizers for crop production (Seck, 2016). On the contrary, peanut did not respond to N application, which could be due to adequate biological N fixation. A more formal investigation of the N fixation contribution for those environments is warranted to understand the N cycling on the peanut-based systems. This study showed substantial amount of N was fixed from growing peanut (Fig. 7). The lowest and highest correspond to Dagana and Kedougou,

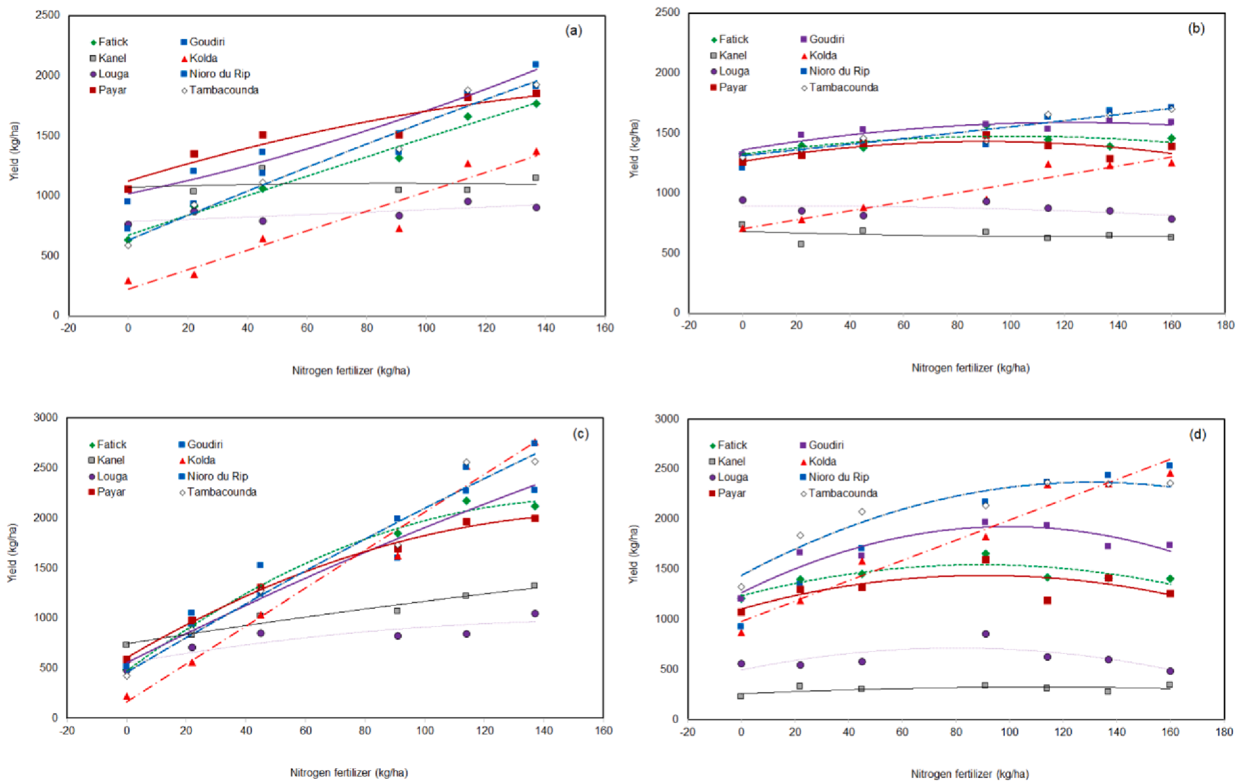

Fig. 5. The relationship between yield and nitrogen fertilizer rates for sorghum (a and b) and millet (c and d) for selected locations in Senegal during the baseline (a and c) and projected climate change scenario for midcentury (b and d) period.

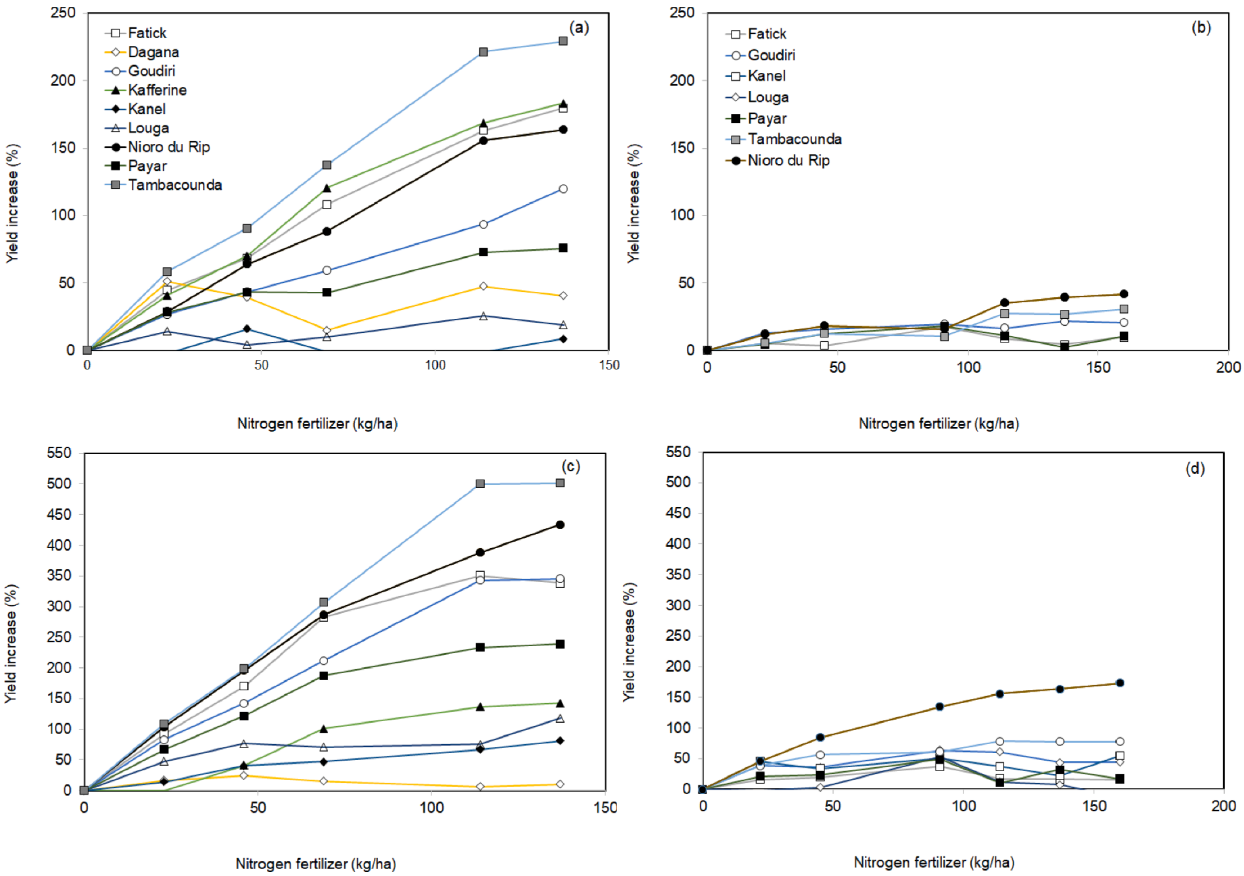

Fig. 6. The percent of yield increase due to application of nitrogen fertilizer when compared to the without nitrogen fertilizer of (a and b) sorghum (c and d) millet for selected locations in Senegal during the baseline (a and c) and projected climate change scenario for midcentury (b and d) period.

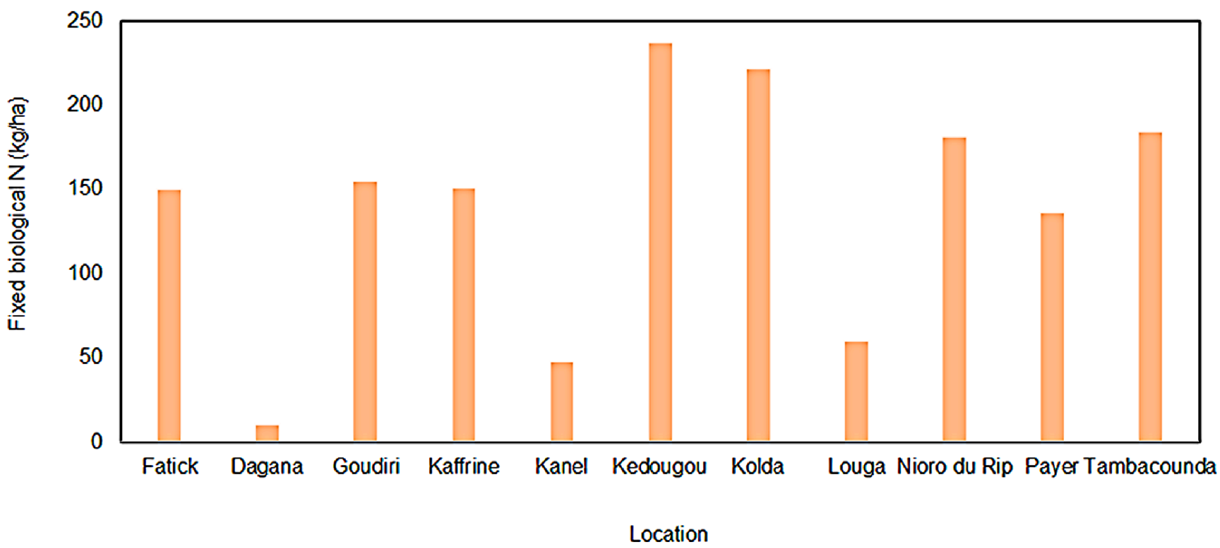

Fig. 7. Average seasonal biological nitrogen fixed from growing peanut at selected locations in Senegal during the baseline period.

respectively. The disparity might be due to difference in soil moisture conditions. Some studies showed about 32 – 120 kg N/ha, biological N fixed by peanut with the lowest and highest correspond to dry and moist soil condition (Peoples et al., 1992). Other studies also verified peanut could fix between 150 and 250 kg N/ha (Toomsan, et al., 1995).

3.3. Impact of planting dates on yield of sorghum, millet, and peanut

As presented in sections above, the planting date evaluation was carried out for the baseline and midcentury period based on FAO (1980) method (i.e., relationship between rainfall versus reference evapotranspiration) (Fig. 8) and (ii) based on relationship between long-term simulated average yield and inter seasonal yield variability (Table 1). The relationship between rainfall and reference evapotranspiration indicated that the start of planting date for most of the sites varied between week 22 and 26 (late May to late June). Onset of rain in the southern regions such as Kolda is around late May to mid-June, while in the northern region's onset is relatively late (around late June). This indicates that the start of planting in the south could be at least one to three weeks earlier than the northern Senegal (Fig. 8). According to FAO (1980), the first cross point between the long-term weekly 50% reference evapotranspiration (ETc) and corresponding rainfall is the onset of rain (start of planting date) while the cessation of rain is the end cross point between weekly 50% ETc and rainfall (FAO, 1980; Araya et al., 2012). The length of growing season, which is the period between the onset and cessation of rain, is longer for the southern locations than those in the central and northern Senegal (Fig. 8). One main reason for this rainfall pattern in Senegal is that it is influenced by the movement of the Inter Tropical Convergence Zone with northward movement in early June and southward movement around September which results in a shorter rainy duration of main rain season to the north while longer rainy duration for the south (Fall et al., 2006). The onset of rain for the baseline period (1980 – 2005) (Fig. 8) is at least one to three weeks earlier than the onset of rain for the midcentury climate period (2040 – 2060) (Fig. 9). However, there was no significant change for the time of cessation of rainfall or end of growing season between the baseline and midcentury climate period. This implies the length of growing season for the midcentury (future) scenario is one to three weeks shorter than the baseline. Improved understanding of changes in the growing season is important for adaptation strategies (such as crop choice and management practices) under future climate scenarios. The "optimal planting" date (the date of planting that result into relatively high yield with low inter seasonal yield variabilities) for sorghum, millet and peanut during the baseline period is presented in Table 1. The optimal

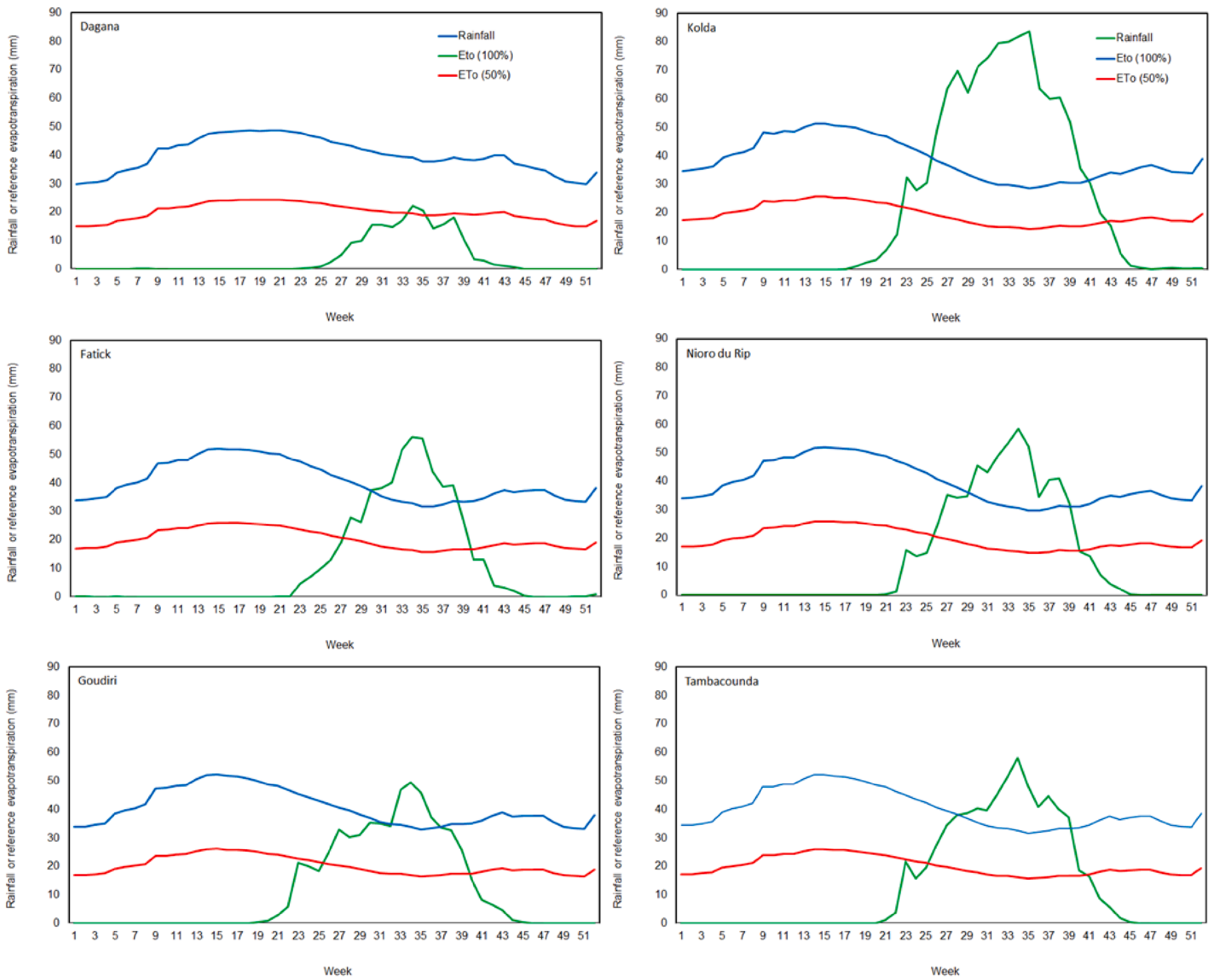

Fig. 8. Long-term baseline (1980 – 2005) weekly rainfall versus weekly reference evapotranspiration (ETc) (100% and 50%) for six selected locations in Senegal. The first time at which the long-term weekly rainfall crosses the 50% ETc is considered as time of planting for many cereals.

Table 1
Optimal planting date (early June) for sorghum, millet and peanut based on yield and inter seasonal variabilities for locations in Senegal during the bassline period.

Location	Sorghum BM (kg/ha)	Y (kg/ha)	CV_BM (%)	CV_Y (%)	Millet BM (kg/ha)	Y (kg/ha)	CV_BM (%)	CV_Y (%)	Peanut BM (kg/ha)	Y (kg/ha)	CV_BM (%)	CV_Y (%)
Dagana	5821	1101	32	41	3500	490	54	56	2700	378	56	57
Fatick	10,577	2179	17	24	9565	1765	11	18	6187	1534	18	19
Goudiri	11,245	2043	13	15	10,151	1783	9	18	6175	1438	16	20
Kaffarin	10,436	2129	17	23	7120	1020	10	12	6730	989	23	25
Keudogo	10,105	1944	11	12	9675	1782	12	17	8669	2480	7	10
Kolda	9698	1892	10	12	8954	1720	8	11	7913	2182	7	10
Linuere	8761	1571	24	28	7985	1263	28	44	4150	818	34	39
Louga	8236	1795	28	32	8001	1043	15	47	3919	915	37	36
Nioro du Rip	11,625	2302	8	12	10,058	1920	6	16	6828	1750	15	21
Payar	10,289	1959	12	14	9042	1395	18	35	5185	1043	20	27
Podor	5238	972	38	46	3100	320	59	57	2534	623	44	46
Tambacounda	11,375	2100	11	14	5955	1572	17	14	6540	1530	13	11

BM, biomass; Y, yield; CV_BM & CV_Y, coefficient of variation for biomass and yield, respectively. Note that optimal planting might vary by crop variety.

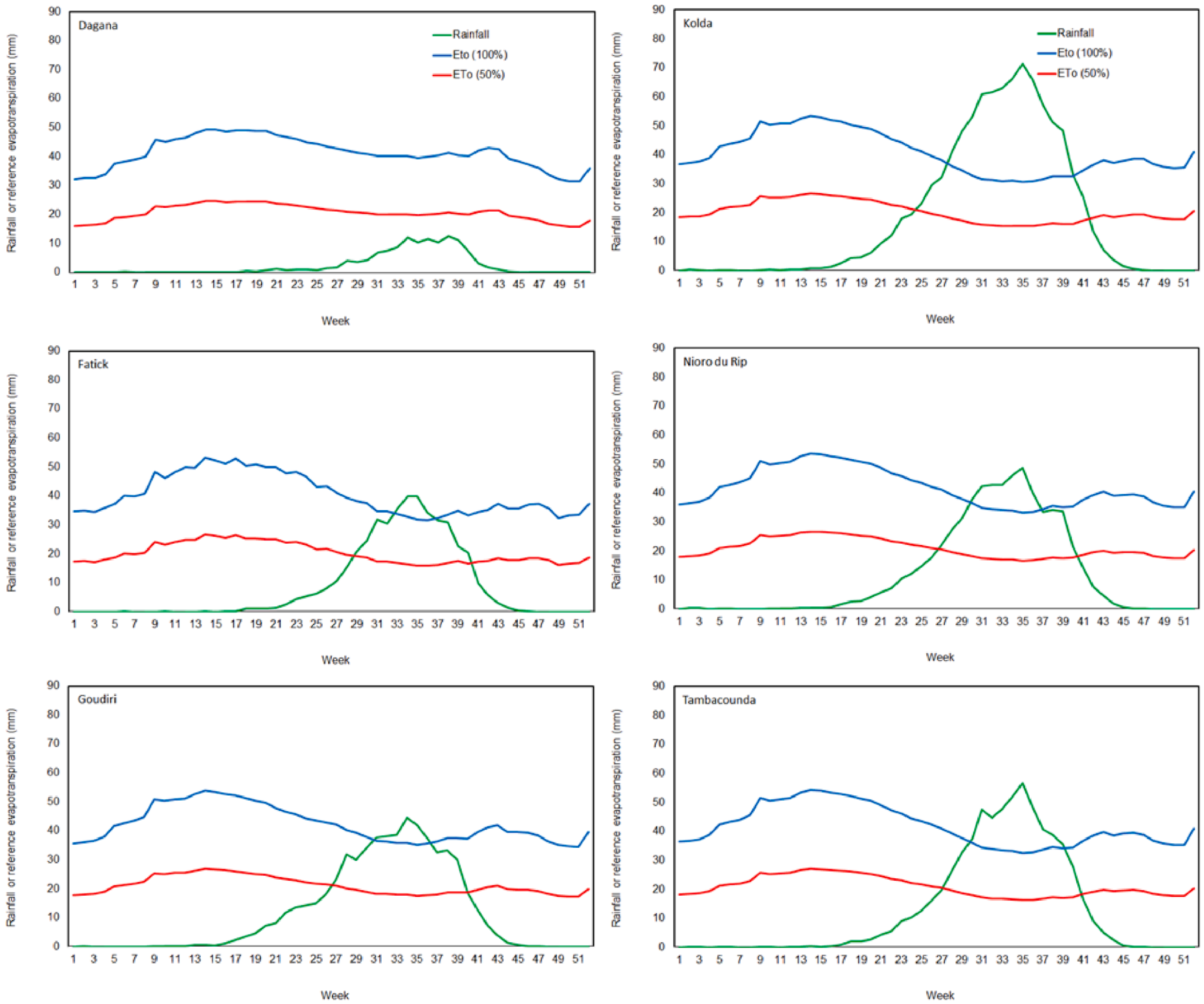

Fig. 9. Long-term future (2040 – 2069) weekly rainfall versus weekly reference evapotranspiration (ETc) (100% and 50%) for six selected locations in Senegal based on ensemble CORDEX. The first week at which the long-term weekly rainfall crosses the 50% ETc is considered as time of planting for many cereals.

planting date matches planting date presented based on FAO (1980). However, the "optimal planting" date could vary by crop varietal characteristics (not shown). For example, late maturing variety might produce better yield with less inter seasonal yield variability under early planting due to matching of the rainy season with the length of growing period of the variety (Araya et al., 2010).

Simulation results showed all crops were highly responsive to planting date for almost all locations. A change by 10 day in planting date showed substantial impact on yields of sorghum, millet and peanut, and most of the locations showed substantial increase in yield with early planting of 01 to 10-June for sorghum (Fig. 10). For example, those planted in early June in Goudiri, Kedougou, Kolda, Payar, Tambacounda resulted in relatively higher yield to those planted before or after these dates (Fig. 10). However, in some dry locations such as Dagana, the growing season was too short and change in planting date did not result in changes on yield (Figs. 8 and 10). This implies that locations in northern Senegal are vulnerable to extended dry period and it is difficult to grow crops without supplementary irrigation. FAO/WEP (2002) reported the optimal planting dates for sorghum, millet and peanut is between 1 and 15 June for southern Senegal such as Kolda, center-south (such as Fatick), southeast and east (such as Kédougou, Tambacounda). Their findings for the above-mentioned locations agree with our study (Figs. 8 and 10). Similarly, Roudier et al. (2014) reported planting period extending from early June to late July, whereas Gueye et al. (2015) observed July 15 to be suitable planting date for millet in southeastern Senegal. The differences in planting dates might be caused due to differences in the length of observational climate seasons. As described in sections above, varietal characteristics could determine the time of planting. Besides, the selected planting date should consider not only the high mean yield but also the inter-seasonal yield variability.

3.4. Impact of future climate change scenario

3.4.1. Sorghum

Midcentury climate change scenario reduced simulated sorghum yield for some of the warm and dry locations in northern Senegal (Fig. 11) and could decrease yields by 5% under both continuous (Fig. 11a) and rotation cropping systems (Fig. 11 d) for many of the study locations. Whereas some of the study locations showed an increase by 5 to 30% or no change in yield compared to the baseline (Fig. 11 a and d). Sorghum in rotation with peanut did not result in significant yield change compared to continuous sorghum (Fig. 11 a and d).

Changes in simulated sorghum yields slightly improved when plant density increased from 7 to 15 plants m^{-2} (Fig. 12 a and b), but they were not significantly different. Buah and Mwinkaar (2009) reported that plant density did not have significant effect on sorghum

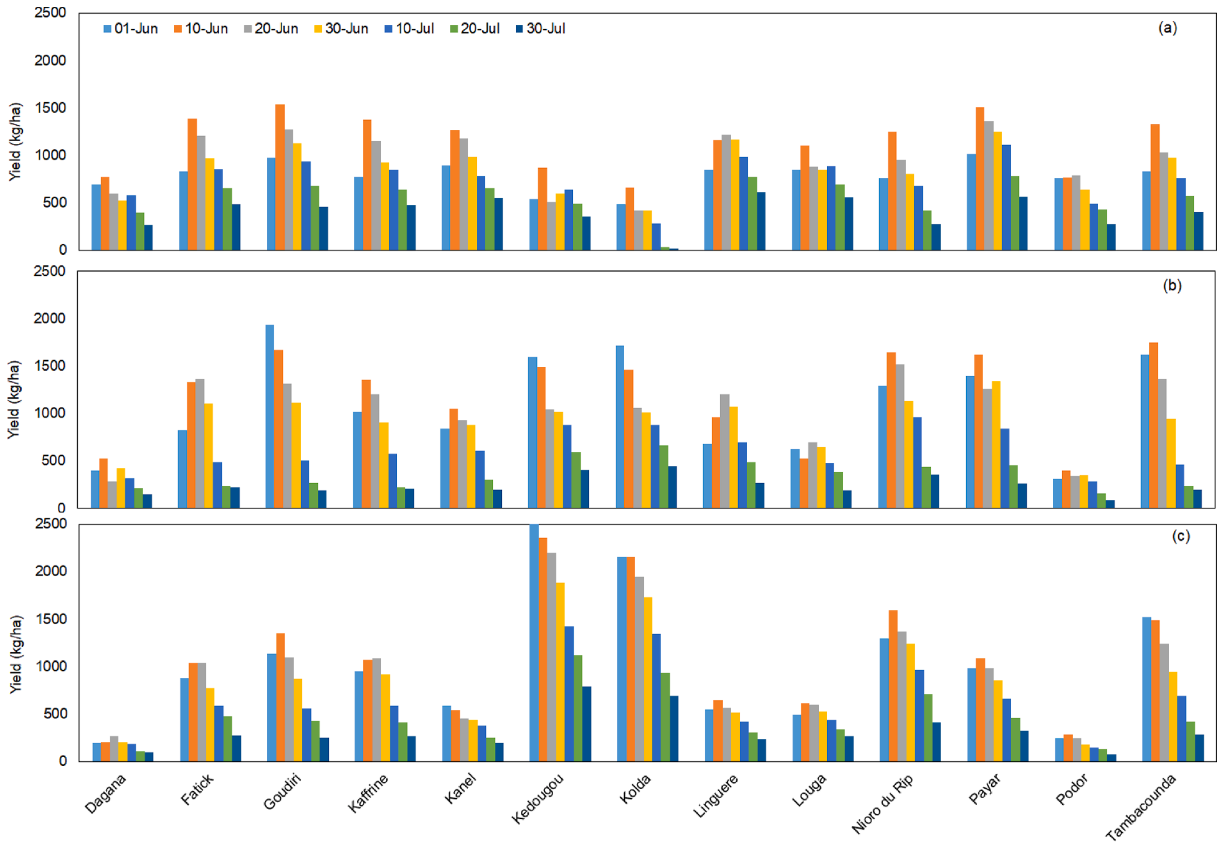

Fig. 10. Yield of sorghum (a), millet (b) and peanut (c) under different planting dates during the baseline period (1980 – 2005) for selected locations in Senegal.

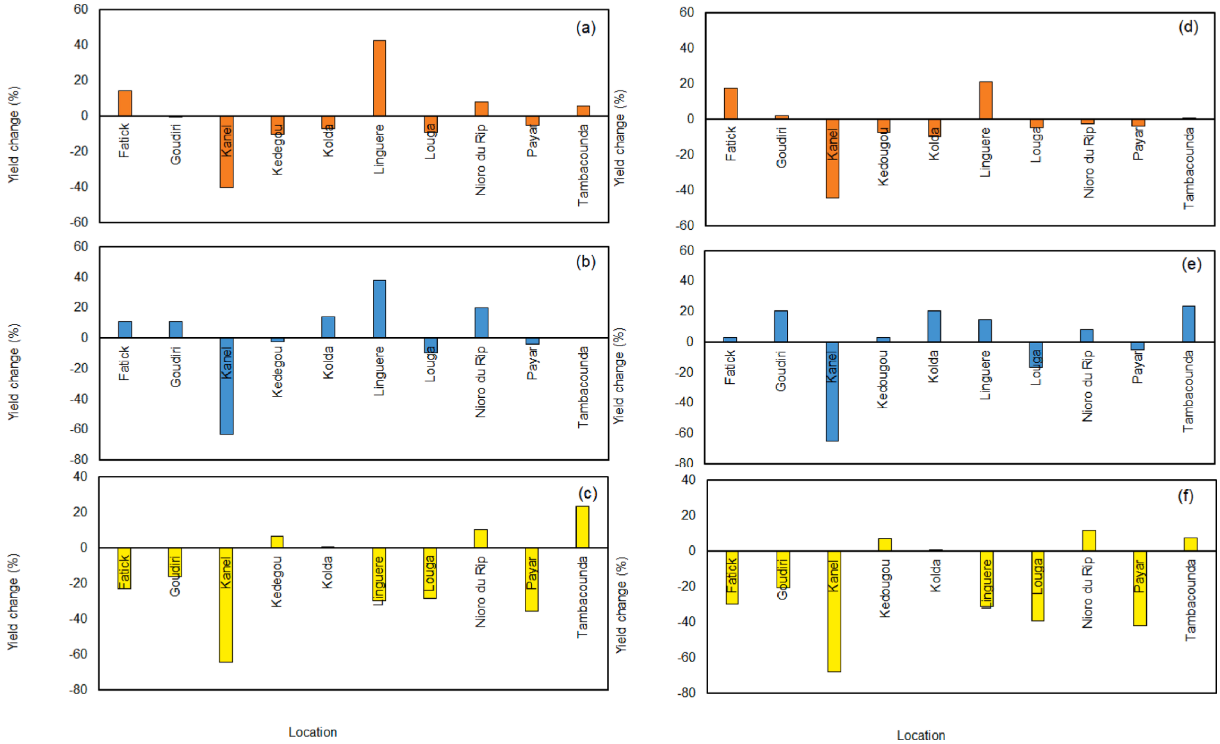

Fig. 11. Yield change of the future projected climate change scenario for midcentury in continuous cropping system compared to their corresponding continuous baseline climate under rainfed condition for sorghum (a), millet (b) and peanut (c). Yield change of the future in rotation cropping system (under peanut-sorghum-peanut-millet) compared to their corresponding rotation system (peanut-sorghum-peanut-millet) for baseline period rainfed condition for sorghum (d), millet (e) and peanut (f).

yield. One of the reasons for sorghum not responding to planting density is related to tillering nature of this crop. Although some studies indicated tilleres could contribute to about 5 – 78% of soghum yield (Lafarge et al., 2002), but tillers may not improve yield when plant density is beyond 12.5 plants/m^2 (Greik and Neely, 1987; Ciampitti et al., 2019). Emergence of sorghum tillers depend on assimilate availablity and radiation use efficiency at the time of tillering and its contribution to yield could be affected by assimilate availablity at early stages of tiller development (Lafarge et al., 2002). Other studies showed that sorghum optimal density for high yield and water use efficiency could vary from 2 to 12.5 plant/m^2 depending on the variety (Tabo et al., 2002).

The yield response of sorghum to climate change under high and low plant densities in peanut-sorghum-millet (PN-GS-ML) rotation system slightly differed by location. Half of the locations showed a small decrease (~5%) while others shown slight increase (5 – 30%) (Fig. 12 a and b) with location average of no yield change compared to the baseline. Studies reported that sorghum yield in Senegal can decrease by the midcentury climate (Sultan et al., 2013). In Senegal, sorghum yield is expected to decrease by 12% under an elevated CO_2 scenario during the midcentury (Defrance et al., 2020). Locations in Senegal, crop variety and models used for the study might have contributed to the small disparity in the impacts on yields in different studies.

Impacts of irrigation on sorghum yield slightly differed by locations. Sorghum yield decreased and increased by 5 to 50% and 15 to 35%, respectively under the simulated future climate scenario, when compared to the corresponding irrigated baseline yield depending on the locations (Fig. 13 a and d). Numerous studies have reported that areas in the southern Senegal are influenced more by temperature changes than water stress (Sultan et al., 2013). In contrast, crop grown in the northern Senegal are more affected by water stress than temperature changes (Sultan et al., 2013). Our research indicated that for most locations in Senegal, the seasonal rainfall decreased substantially under the future climate scenario, which could contribute to the relative decrease in yield when compared to the baseline. In addition, increased temperatures above 2 °C could worsens the situation (Sultan et al., 2013).

Studies indicated that increased temperatures influence crop growth and development, reproductive, photosynthesis, yield and dry matter production (Prasad et al. 2006; Prasad et al., 2008a; Prasad et al., 2008b; Djanaguiraman et al., 2014). Prasad et al. (2019) reviewed and summarized that the mean optimal temperature for sorghum seed germination, vegetative growth, panicle initiation and reproductive stage is 21 to 35, 27 to 34, 26 to 27 and 25 to 28 °C, respectively. Many of the study area in Senegal already experience above optimum temperatures. An increase in temperatures by 2–3 °C in already warm locations could have adverse impacts on sorghum yield. Above optimum temperatures decreased simulated grain set, grain number, grain size, grain filling duration, grain yield and total dry weight (Prasad et al., 2006; Prasad et al., 2008b) when compared to that 32/22 °C. For Senegal, a moderate projected increase in average temperature by 2 °C could result in reduced precipitation, which could affect water availability by up to 30% (Sylla et al., 2018). Assuming an increased temperature by 6 °C and decrease in precipitation by 20%, cereals like sorghum yield are expected

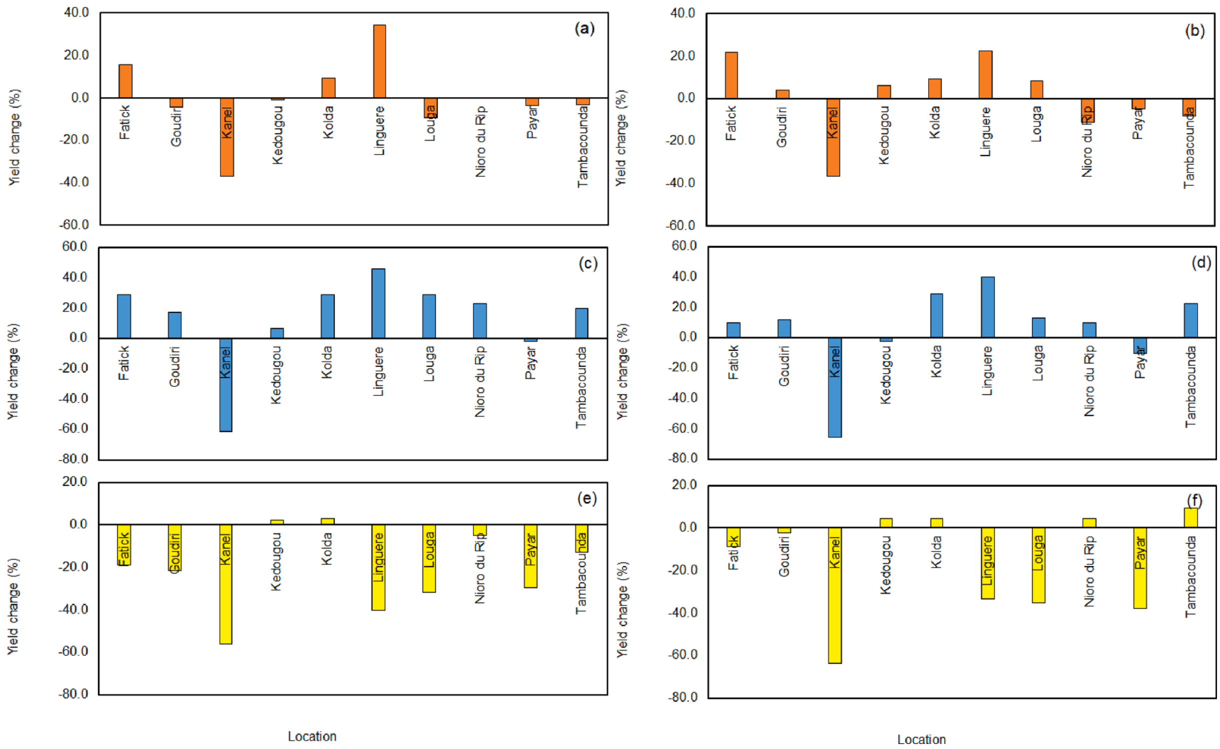

Fig. 12. Yield change of crop under the projected climate change scenario for midcentury in rotation peanut-sorghum-millet (PN-GS-ML) relative to their corresponding rotation during the baseline period for (a and b) sorghum, (c and d) millet and (e and f) peanut. The yield change in a, c, e is under relatively lower and b, d and f are under higher plant population.

to decrease by about 41% (Sultan et al., 2013). In sub-Saharan Africa, sorghum, millet and peanut yield could decline by 17 – 18% during the midcentury scenario (Schlenker and Lobell, 2010).

One of the major reasons for lower sorghum yields under high temperatures and drought stress was due to reduced seed numbers caused by decreased floret fertility (Prasad et al., 2008b; Djanaguiraman et al., 2014; Prasad et al., 2015). High temperature stress or drought occurring during critical and sensitive stages of gamete development results in significant reductions in seed numbers and seed yield (Prasad et al., 2008a). However, sorghum genotypes differ in their response to heat stress in which case higher percent of seed set was obtained for heat tolerant sorghum genotypes (Djanaguiraman et al., 2014).

3.4.2. Millet

Millet yield was slightly improved or remained the same compared to the baseline for most of the locations both under continuous and rotation cropping systems with an average increase by 6% (Fig. 11 b and e). However, one of the study locations, Kanel, showed substantial decrease (~60%) in yield regardless of irrigation, high nitrogen, higher plant density or optimal plant time (Fig. 11 b and e). Millet yield showed better performance under relatively low plant density (Fig. 12 c) (more positive with an increase by 5 to 50%) compared to the high plant density level (Fig. 12 d) (increased by 5 to 40%) with location average increase by 13%. All locations, except Kanel, showed substantial increase in yield relative to the baseline both under relatively low and high plant density scenarios (Fig. 12 c and d). Defrance et al. (2020) reviewed climate change in Africa could reduce yield of millet by 10% by 2050. However, as shown by our study depending on location, millet yield may even improve under midcentury climate conditions.

This study showed that millet yield was substantially improved by irrigation relative to rainfed yield. Location such as Kanel was positively affected by irrigation implying that water stress contributed significantly on yield of millet in Senegal (Fig. 13 b and f). We found that the length of growing period and seasonal rainfall (planting to maturity) decreased by 2040 – 2069. Similarly, to our study, Defrance et al. (2020) reviewed rainfall in western Sahel Africa is expected to decrease by 20% by 2050. Increased millet yield due to irrigation is likely to occur if temperatures are within the optimum range beyond which floret fertility and seed set could decrease and/or panicle emergence could be delayed (Gupta et al., 2015; Djanaguiraman, et al., 2018). Temperature during the midcentury across Senegal could increase by 2.5 °C while the seasonal average baseline temperature for all study locations is 29.1 °C with a range of 27.9–31 °C. The average temperature during the midcentury across the study locations could reach 31.6 °C with a range of 28.7 – 33.8 °C (with a location average increase of 2.5 °C). Studies showed that temperature increases in Senegal by 1.5 – 2 °C during the midcentury under RCP8.5 resulting in yield decline for sorghum and millet of about 12 and 6%, respectively (Defrance et al., 2020). Yield reduction due to climate change is expected to be high for early duration genotypes (Sultan et al., 2013). Djanaguiraman et al. (2018) found that temperatures above 36/26 °C could decrease grain number, individual grain weight, and grain yield. Furthermore,

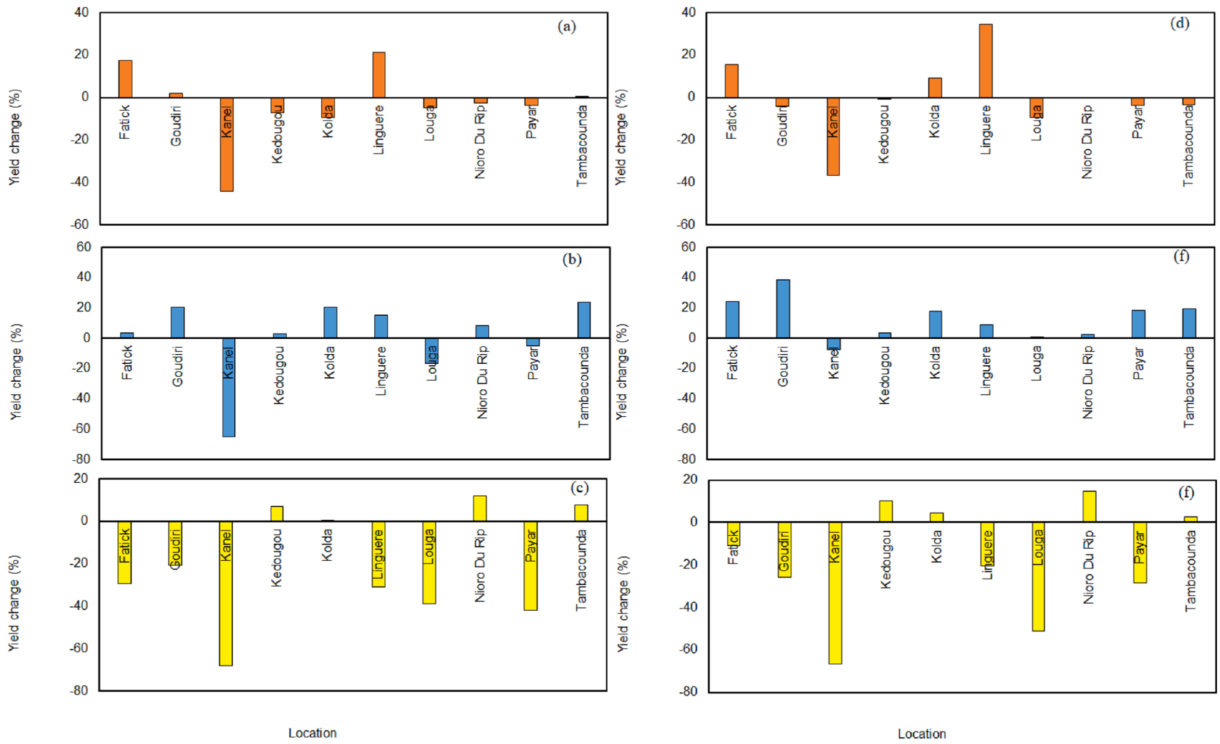

Fig. 13. Yield change of crop under the projected climate change scenario for midcentury in continuous cropping system under rainfed condition (a-c) compared to their corresponding continuous baseline for sorghum (a), millet (b) and peanut (c); and yield change of the future under irrigated condition compared to their corresponding irrigated baseline for sorghum (d), millet (e) and peanut (f).

genotypes varied in their response to temperature stress, and heat tolerant genotypes had higher pollen germination (Djanaguiraman et al., 2018). However, millet will remain as an important and promising crop under future climate change (Djanaguiraman et al., 2018) as it has higher ceiling temperature compared to other cereal crops (Prasad et al., 2017). This was evident in this study where millet performed better than sorghum in future midcentury climate scenario both under rainfed and irrigated conditions.

3.4.3. Peanut

For peanut, there was a substantial decrease in yield with a location average of 16 to 20% under midcentury (future) compared to the baseline climate change scenario (Fig. 11 c and f). There was neither any substantial difference between peanut in rotation and continuous cropping (Fig. 11 c and f) nor between peanut with lower and higher plant population (Fig. 12 e and f). On the other hand, irrigation slightly narrowed the deviation of the future peanut yield when compared to the baseline but was not that substantial. For example, for locations such as Payar and Fatick, the irrigated yield (Fig. 13 f) was slightly improved when compared to the corresponding rainfed yield (Fig. 13 c). However, irrigation did not substantially improve peanut yield when all locations were considered. Peanut is expected to decrease by up to 25% while millet and sorghum are expected to slightly increase or stay unchanged during the period 2040 – 2060 (CIAT/BFS/USAID, 2016). The reason for the decrease in peanut yield could be mainly due to increased temperatures. The optimal temperature for peanut is in the range between 25 and 30 °C (Williams and Boote, 1995; Prasad et al., 2000). However, many of the locations have already reached 30 °C during the baseline period. Increased temperature above the optimal limit could decrease fruit-set, seed numbers and yield of peanut (Prasad et al., 1999; Prasad et al., 2000; Prasad et al., 2001). Prasad et al. (2003) reported that increasing of CO_2 from 350 to 700 μmol/mol significantly increases leaf photosynthesis and seed yield, particularly at optimum temperatures. However, at super-optimal temperatures, doubling of CO_2 may not improve peanut yield despite the substantially higher vegetative growth and increased photosynthesis rate (Prasad et al., 2003). For C_3 plants, elevated CO_2 may enhance yield by increasing net assimilation, while conserving water by reducing stomatal conductance during drought years (Leakey et al., 2006; Leakey et al., 2009). Whereas C_4 plants comparatively less influenced by elevated CO_2 under both irrigated and water stress conditions.

3.5. Assumptions and limitations

In our simulations, pests, diseases and weeds are assumed managed. The simulation study was conducted on a dominant soil type (sand) in Senegal, which may not represent all specific locations. Crops grown on sandy soils are sensitive to long-dry spells as the soils have low water holding capacity. We assumed that considering sand soil as worst-case scenario could help explore the potential impacts of climate change and adaptation management strategies. Some studies also showed that considering worst scenario is important for developing adaptation strategy (Araya et al., 2021a). The simulations of future climate change do not account for temperature extremes that will have greater negative impacts if they occur during sensitive stages of crop development. In our simulation, peanut yield was not substantially changed due to application of N (under both the baseline and future climate) albeit to biological N fixation and is expected, however, there was limited impact on yield of cereal crop in rotation. This indicates that the simulation on the total biological N fixation may not be accurate and may be limited by deficiencies of other macro or micronutrients. The model does not account for other nutrients (e.g., P and K) except nitrogen which can limit crop yields. Another limitation is that the response to management options by crops in Senegal could vary by crop varietal characteristics which changes with region, especially as farmers may or may not have access to new varieties.

4. Conclusions

This simulation study showed that N fertilization, planting date, and irrigation were identified as suitable crop management options to reduce risks for sorghum and millet under the projected midcentury climate in Senegal. However, the response to these management options could vary by location and varietal characteristics. A curvilinear relationship for yield and N application was documented for both sorghum and millet crops under the baseline climate scenario. Sorghum and millet yield increased with N up to 68 kg N/ha for most of the locations, while some locations simulated increase up to 115 kg/ha, and for dry locations did not show any response in the baseline period. As expected, the response to N was influenced by quantity and distribution of seasonal rainfall. There was no clear relationship between sorghum yield and N application under midcentury climate. In contrast, for millet crop, N application substantially improved yields (following a curvilinear response) under midcentury climate. Unlike millet and sorghum, peanut yield was not substantially changed due to application of N (both under the baseline and future climate), which might be due to the N contribution to plant nutrient demand derived from the biological N fixation process. Early planting around the first and second week of June improved yield for all crops across most of the locations. Locations in southern Senegal tend to have early onset of rain, while locations in the northern part of the country tend to have late onset of rain (by at least one to three weeks). Under midcentury climate change scenario, the length of rainy season in most of the locations was shortened by one to three weeks compared to the baseline, which may have substantial influence on varietal or crop choice. The projected midcentury climate will slightly decrease sorghum yield, but results may vary with location. While millet yield was relatively less impacted by projected climate change compared to other crops. In contrast, peanut yield substantially decreased on average by 16 to 20% during the midcentury period regardless of the tested factors. Decreases in peanut yield might be due to increased intensity or duration of high temperatures and late initiation and shorter duration of the rainy season, which implied breeding for heat and drought tolerance might be beneficial. Of all crops evaluated, millet performed the best under the projected midcentury climate scenario relative to both sorghum and peanut in Senegal. Thus, crop management and breeding programs should target development of suitable genotypes and best soil, crop, nutrient and water management practices enhancing or protecting yields under diverse climate change scenarios.

Author contributions

AA: Conceptualization, Investigation, Formal analysis, Visualization, Writing – original draft. PVVP: Conceptualization, Methodology, Funding acquisition, Resources, Project administration, Visualization, Writing – review & editing. PK: Formal analysis, Visualization. ZZ: Formal analysis, Visualization; AF: Writing – review & editing; IAC: Formal analysis, Writing – review & editing. DM: Writing – review & editing; PHG: Formal analysis, Writing – review & editing. US: Formal analysis, Writing – review & editing. All authors contributed to writing and approve the content of manuscript.

CRediT authorship contribution statement

A. Araya: Conceptualization, Investigation, Formal analysis, Visualization, Writing – original draft. **P.K. Jha:** Formal analysis, Visualization. **Z. Zambreski:** Formal analysis, Visualization. **A. Faye:** Writing – review & editing. **I.A. Ciampitti:** Formal analysis, Writing – review & editing. **D. Min:** Writing – review & editing. **P.H. Gowda:** Formal analysis, Writing – review & editing. **U. Singh:** Formal analysis, Writing – review & editing. **P.V.V. Prasad:** Conceptualization, Methodology, Funding acquisition, Resources, Project administration, Visualization, Writing – review & editing.

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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