Chapter 2

Climate Change Impacts on West African Agriculture: An Integrated Regional Assessment (CIWARA)

Samuel G. K. Adiku[1], Dilys S. MacCarthy[1], Ibrahima Hathie[2],
Madina Diancoumba[3], Bright S. Freduah[1], Joseph Amikuzuno[4],
P. C. Sibiry Traore[3], Seydou Traore[5], Eric Koomson[1], Alhassane Agali[5],
Jon I. Lizaso[6], Dougbedji Fatondji[3], Myriam Adams[7], Lodoun Tigana[8],
Daouda Z. Diarra[9], Ousmane N'diaye[10], and Roberto O. Valdivia[11]

[1]*University of Ghana, Accra, Ghana*

[2]*Initiative Prospective Agricole et Rurale, Senegal*

[3]*International Crops Research Institute for the Semi-Arid Tropics, Patancheru, Mali*

[4]*University for Development Studies, Tamale, Ghana*

[5]*Centre Régional AGRHYMET, Niamey, Niger*

[6]*Technical University of Madrid, Madrid, Spain*

[7]*Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Burkina Faso*

[8]*Institut de l'Environnement et de Recherches Agricoles, Ouagadougou, Burkina Faso*

[9]*METEO, Mali*

[10]*Agence Nationale de l'Aviation Civile et de la Météorologie, Senegal*

[11]*Oregon State University, Corvallis, OR, USA*

Introduction

The West African Sub-Saharan region (Fig. 1) is home to some 300 million people, with at least 60% engaged in agricultural activity. Climate change is now recognized as a major constraint to development worldwide. While climate change primarily relates to the future, historical trends give evidence of climate change already occurring. Temperature increases of 1 to 1.5°C have been observed over the last 30 years

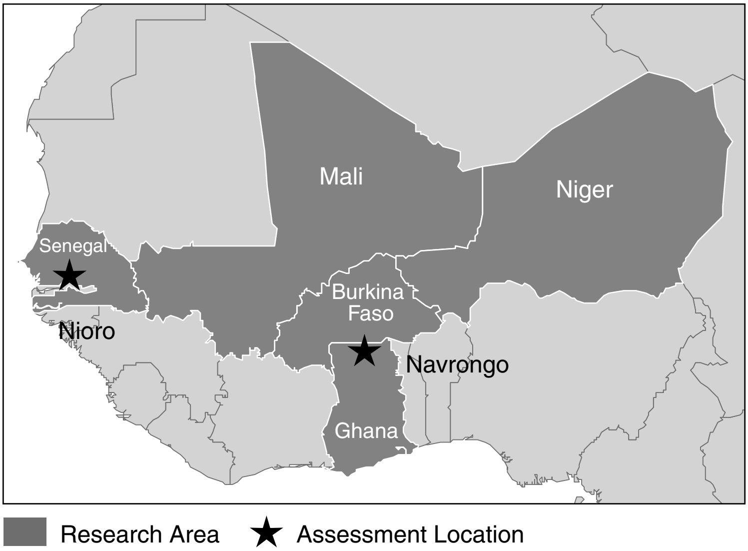


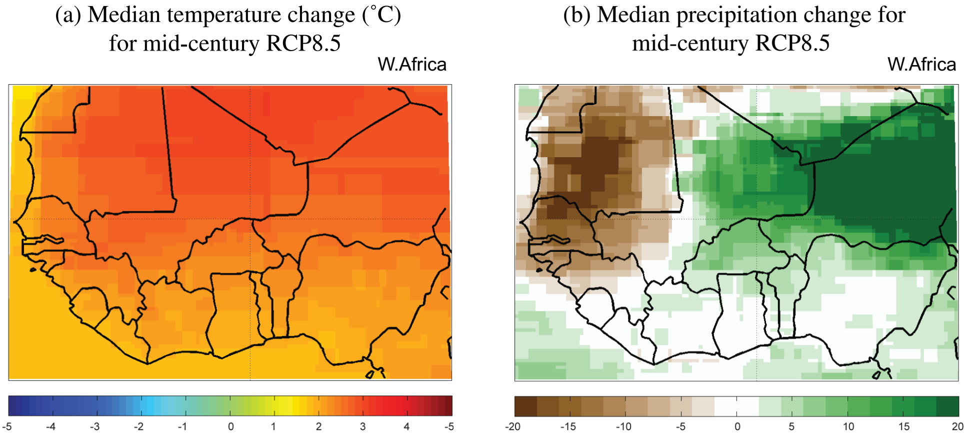
Fig. 1. Map of West Africa indicating the countries and sites included in the study.

in West Africa (EPA Ghana, 2001; IPCC, 2007) and there are projections of further warming of the West African region in the foreseeable future (2040–2069; Fig. 2a). The impact of climate change on West African rainfall is less clear. The analysis of historical data over the last 30 years shows that, whereas some zones experienced increased rainfall by as much as 20% to 40%, other locations experienced a decline in annual rainfall by about 15%. Future projections suggest a drier western Sahel (e.g., Senegal) but a wetter eastern Sahel (e.g., Mali, Niger; Fig. 2b). The southern locations of West Africa (e.g., Ghana) are projected to experience no change or slight increases in annual rainfall (Hulme *et al.*, 2001).

Irrespective of whether these zones will be dryer or not, there is historical evidence of shifts in rainfall patterns with extreme events (i.e., droughts and floods) becoming more frequent (Adiku and Stone, 1995) and it is probable that this trend may persist into the future.

Climate change impacts

The increased warming and shifts in rainfall patterns associated with climate change would adversely affect West African agriculture, which contributes between 40% and 60% of gross domestic product (GDP). Agriculture in West Africa is dominated by a large number of smallholder farmers, who cultivate a range of cereals (e.g., millet, maize, and sorghum) and legumes (e.g., peanut, cowpea, and soya).



(a) Median temperature change (˚C) for mid-century RCP8.5

(b) Median precipitation change for mid-century RCP8.5

Fig. 2. Projected changes in West Africa (median from 20 GCMs) of (a) median temperature change (°C) for mid-century RCP8.5 and (b) median precipitation change (%) for mid-century RCP8.5 in the study sites, Nioro, Senegal, and Navrongo, Ghana.

Crop farmers in West Africa rely largely on the soil's inherent fertilityfor production. The removal of crop residue after grain harvest for feed, fuel, and other purposes further impoverishes the soil, as this residue is the main source of soil organic matter (SOM). Studies by Adiku *et al.* (2009) showed that the regular removal of residue from an initially long-term fallowed cropland reduced the SOM by over 50% within a period of four years. Many previous studies such as that of Brams (1971) also observed a 50% decrease of organic matter within the top 0.2 m in the ferallitic soil of Sierra Leone after five years of land clearing and continuous cultivation. Crop and range productivity is thus generally very low in the region, often lower than 1500 kg/ha in the case of cereals and 1000 kg/ha for legumes.

Studies indicate that future climate change will adversely affect development and living standards in West Africa because of a number of independent factors: (1) high dependence of people and their livelihoods on natural resources, livestock, and cropping agriculture; (2) high rate of degradation of these natural resources, which renders them less resilient; (3) extreme poverty with *per capita* earnings as low as \$750/yr in Senegal (Khouma *et al.*, 2013) and \$1,000 in Ghana (Nutsukpo *et al.*, 2013); and (4) lack of social intervention schemes (e.g., agricultural insurance), which makes it difficult to respond to increased incidence of climate extremes.

The combination of these factors and the possible changes in future rainfall lead some researchers to project future declines in crop productivity in the region. For example, Nutsukpo *et al.* (2013) projected a future decline in maize yields in Ghana by the year 2050 of 25% below the 2005 base year. Even though the basis for such projections is not entirely clear (especially as they are based on single historical and future-year simulations without capturing the heterogeneity in the socio-economic dynamics of the farming community and uncertainties of the projection methodologies), they are often used as the basis for proposing adaptation strategies to minimize climate change impacts. However, with limited quantitative aspects and no defined framework within which to operationalize these interventions, their value for policy formulation and implementation is limited.

Given that agricultural production entails the interplay of socio-economic factors (e.g., households), biophysical factors (e.g., soil and climate), and management decisions (e.g., agronomic practices) as well as policy decisions (e.g., subsidies), an integrative assessment approach would be required for improved decision-making. This chapter demonstrates the AgMIP methodology in analyzing the impact of climate change on West African agriculture. The research questions posed relate to (1) the sensitivity of current agricultural production systems to climate change, (2) the impact of climate change on future agricultural production systems; and (3) the potential benefits of climate change adaptations.

Farming System Investigated

Settings and locations

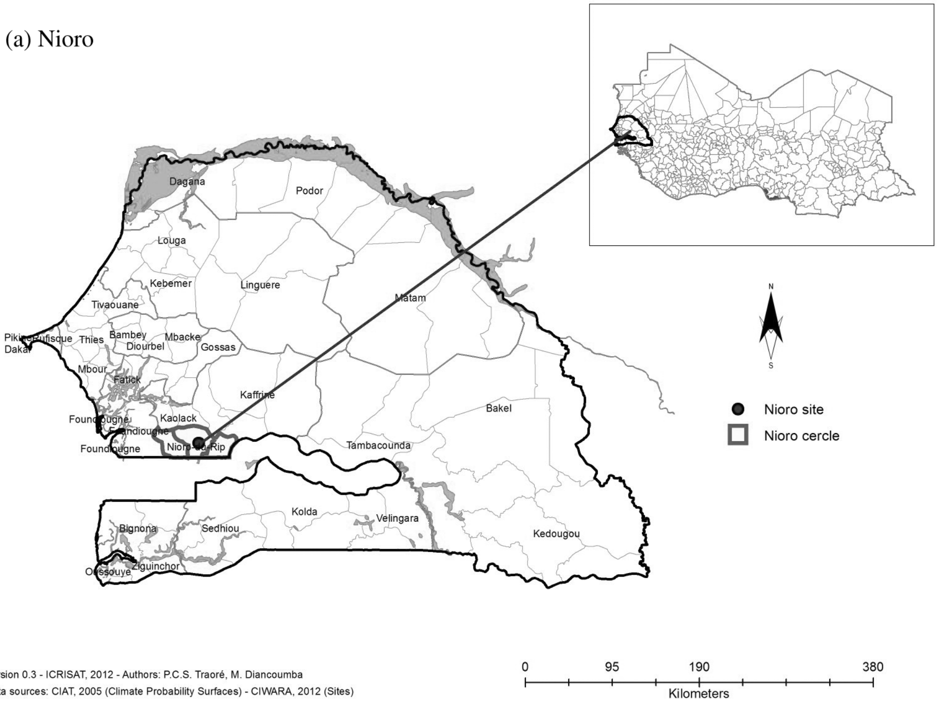
In this study, two sites are included to provide a comparative perspective. Figure 3 shows the two sites, Nioro in Senegal and Navrongo in Ghana. Nioro is located at latitude 13.7°N, longitude 34.4°W, and an elevation of 30 m. Navrongo is located at latitude 10.89°N, longitude -1.09°W, and an elevation of about 197 m above sea level. Economic analysis, however, was not done for the Navrongo site in this study.

Climate and soil data

Weather data for the survey year (2007), as well as the long-term baseline (1980–2010) climate records (e.g., solar radiation, maximum and minimum air temperatures, precipitation, wind speed, humidity, and vapor pressure) were obtained for Nioro du Rip City from the Senegal National Weather Agency. Additionally, rainfall data for the village locations were derived from the WorldClim database. For future projections (2040–2069), five general circulation models (GCMs) (namely CCSM4, GFDL-ESM2M, Had GEM2-ES, MIROC5, and MPI-ESM-MR (Rosenzweig *et al.*, 2013)) were used for the RCP 8.5 scenario, which assumes an elevated CO_2 concentration of 571 ppm compared with the current 390 ppm.

Future climate scenarios were produced using the delta method (see Chapter 3 of Part 1 of this volume), which involves adjusting daily historical observations to match mean monthly climate changes in temperature and percentage changes in precipitation as determined by GCM simulations over the 1980–2009 baseline

(a) Nioro



Version 0.3 - ICRISAT, 2012 - Authors: P.C.S. Traoré, M. Diancoumba
Data sources: CIAT, 2005 (Climate Probability Surfaces) - CIWARA, 2012 (Sites)

(b) Navrongo

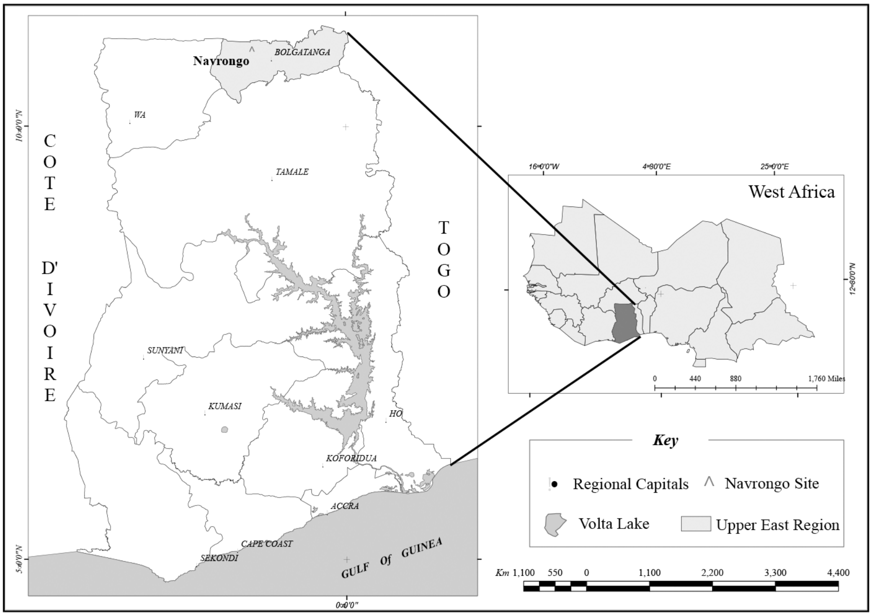


Fig. 3. Study sites: (a) Nioro, Senegal; (b) Navrongo, Ghana.

period. Solar radiation data and short gaps in temperature data were filled using the AgMERRA data set (Ruane *et al.*, 2014). In the case of Navrongo (2012), baseline climate data were obtained from the Ghana Meteorological Agency in Accra. Future projections were obtained using the same procedure as for Nioro. The soils in the Nioro basin are fairly deep, reaching depths of 100 cm (Table 1a). Four major soil types can be discerned in the basin, one of which is sandy with a clay content of less than 20%. The others have appreciable clay content, reaching 45% at greater depth. Unlike Nioro, the soils of Navrongo, which can be classified as Endoeutric-stagnic Plinthosol and Eutric Gleyic Regosols, are typically shallow, containing high proportions of coarse fractions (Table 1b).

Farming system

Agriculture in West Africa is dominated by a large number of smallholder farmers (with farms ranging from 1 to 2 ha), cultivating a range of cereals (millet, maize, and sorghum) and legumes (peanut, cowpea, and beans). Livestock plays a significant role in the functioning of the overall system through its dependence on crop residues

Table 1a. Soils of Nioro du Rip Basin and Navrongo (West Africa).

	L	LL	DUL	SAT	BD	OC	CLY	SIL	CF	pH	CEC
Soil ID	Cm	cm^3/cm^3	cm^3/cm^3	cm^3/cm^3	g/cm^3	%	%	%	%		cmol/kg
ITSN 840067	20	0.1	0.162	0.38	1.46	0.538	14	8	10	5.6	4.9
	40	0.12	0.188	0.373	1.48	0.64	18	9	10	5.1	5
	60	0.133	0.195	0.358	1.53	0.424	22	7	10	5.1	6
	80	0.143	0.2	0.375	1.48	0.28	25	5	10	5.1	5
	100	0.155	0.218	0.398	1.51	0.28	25	5	2	5.1	5
ITSN 840080	20	0.113	0.206	0.331	1.34	0.8	19	27	28	5.1	4
	40	0.089	0.165	0.278	1.46	0.715	18	27	34	5	4
	60	0.088	0.16	0.301	1.48	0.22	18	26	28	5.3	3.8
	80	0.08	0.151	0.293	1.51	0.2	16	26	28	5.4	3.5
	100	0.053	0.101	0.298	1.54	0.154	15	26	50	5.4	3
ITSN 840042	20	0.114	0.193	0.443	1.4	0.648	14	12	0	6.1	3
	40	0.167	0.253	0.452	1.38	0.42	26	14	0	5.1	4
	60	0.218	0.306	0.445	1.4	0.437	36	12	0	5	4
	80	0.261	0.35	0.42	1.47	0.362	45	11	0	5	4
	100	0.26	0.348	0.456	1.37	0.32	45	11	0	5	4
ITSN 840056	20	0.072	0.147	0.396	1.42	0.146	10	21	10	6.4	3
	40	0.12	0.197	0.376	1.48	0.26	20	18	10	6.4	2
	60	0.13	0.206	0.359	1.53	0.31	22	16	10	6.4	2
	80	0.13	0.206	0.375	1.48	0.31	22	16	10	6.4	2
	100	0.167	0.248	0.352	1.5	0.295	32	18	14	5.4	3

Table 1b. Soils of Navrongo, Ghana.

	L	LL	DUL	SAT	BD	OC	CLY	SIL	CF	pH	CEC
Soil ID	Cm	cm^3/cm^3	cm^3/cm^3	cm^3/cm^3	g/cm^3	%	%	%	%		cmol/kg
	15	0.15	0.203	0.352	1.56	0.39	12	16	71		
	30	0.11	0.209	0.321	1.58	0.36	17	21	62		
	50	0.11	0.205	0.32	1.56	0.32	12	16	71		
	15	0.12	0.203	0.352	1.56	0.39	12	16	71		
	30	0.09	0.209	0.321	1.58	0.36	17	21	62		
	50	0.11	0.205	0.32	1.56	0.32	12	16	71		
	15	0.1	0.203	0.352	1.56	0.58	12	16	71		
	30	0.09	0.209	0.321	1.58	0.56	17	21	62		
	50	0.11	0.205	0.32	1.56	0.45	12	16	71		

CLY=clay, SIL=silt, CF=coarse fraction, CEC=cation exchange capacity, LL=wilting point, DUL=field capacity

as feed, and provision of manure to the cropping system (Fig. 4). Agriculture is mainly rainfed. The use of manure for cereal farming is limited to the homestead. Agriculture in the study area is dominated by millet and peanuts grown in annual rotation. Maize is also cultivated, but to a lesser extent. Fallow durations tend to disappear under population pressure. Very few farmers apply mineral fertilizers. As a result, average yields of cereals and peanut are low.

Stakeholder Interactions, Meetings, and Representative Agricultural Pathways

The process of developing representative agricultural pathways (RAPs) began with consultations with appropriate personnel in government establishments that work in the sector responsible for agriculture. Additionally, non-governmental organizations (NGOs) working in the area of agriculture and climate change and scientists working in the subject area were engaged on the subject. The meetings were in the form of informal conversations, formal presentations of CIWARA's work at workshops to solicit informed discussions. These interactions helped in arriving at the RAPs that were developed. Additionally, a number of adaptation measures were discussed but only one of the adaptations was simulated in this study.

Representative Agricultural Pathways

An integrative assessment of climate change impacts on the future of agriculture in West Africa must of necessity consider the development policies and the

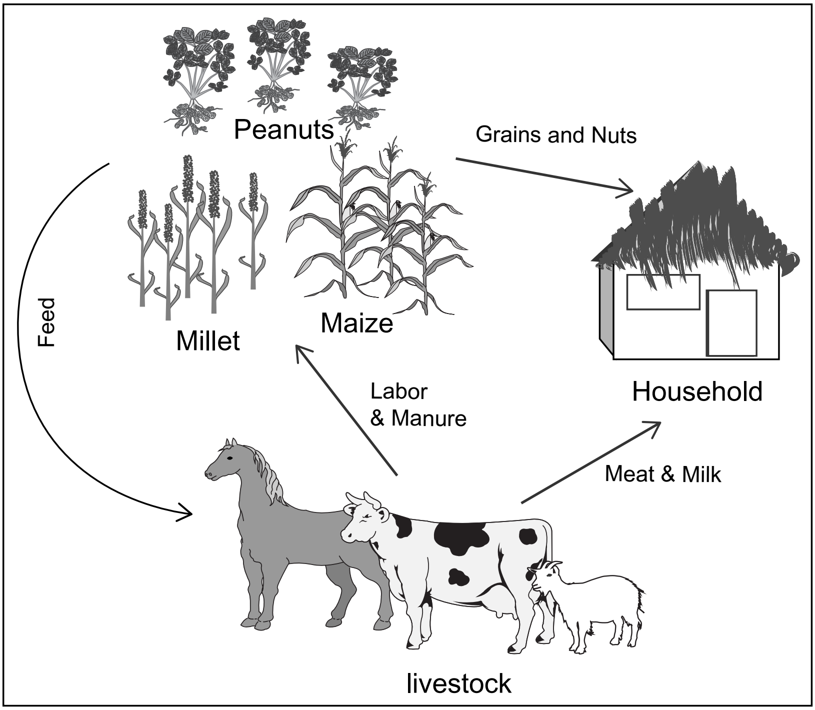


Fig. 4. Farming systems diagram for Nioro and Navrongo.

socio-economic pathways that are currently in place and projected for the future. By following a number of stakeholder interactions and surveys by the research program on Climate Change, Agriculture, and Food Security (CCAFS), and AgMIP, a two-pronged development pathway can be described.

First, short-term RAPs foresee the continual dominance of state actors in the agricultural development agenda with the view of bringing in fast short-term gains in food security outcomes for the population. Within this short term, several changes are expected in the agricultural sector. On the biophysical front, small and fast-growing animal (e.g., poultry) production would increase as there is pressure to meet the protein demands of a rapidly increasing urban population. The use of high-yielding crop varieties and application of agrochemicals would also increase. On the policy front, there would be a drive to facilitate agricultural extension and agro-processing. However, infrastructure improvement would concentrate in the urban centers. On the socio-economic front, rural household sizes would decrease due to the high rural-to-urban migration, increased efforts to enhance women's literacy, and the quest to improve living standards by rural communities. As a result, the main interventions are likely to include state support for the agricultural service sector, fertilizer subsidies, and preference for importing cheaper food over an apparently more expensive domestic production.

Second, long-term RAPs for many West African countries foresee the situation whereby the role of the private sector would become more relevant in agriculture. Organized civil society demand for higher food quality must also be factored in. This transformative path could lead to an emerging agricultural powerhouse in West Africa with reliance on strong private agrobusinesses that deliver healthy food choices to meet consumer preferences, improved climate information delivery services to farmers, improved soil management, and development of seed technologies that would address climate change effects. On this study, adaptation strategies examined are limited to the performance of new crop varieties that can withstand projected temperature increases and increased rainfall variability under climate change.

Data and Methods of Study

Climate

Observed trends in temperature and precipitation

In Nioro, the minimum temperature during the crop growing season (May to October) ranged between 13.1 and 20.5°C, with a mean of 18.2°C over the baseline period. As for maximum temperature, this ranged from 41.8 to 46.3°C with a mean of 43.8°C. Annual rainfall ranged between 418 and 1035 mm with a mean of 725 mm over the 30-year period (1980–2009). The observed trends show a sharp increase in maximum temperature, and slight increases in annual rainfall and minimum temperatures (Fig. 5).

In the case of Navrongo, minimum temperature ranged between 15.6 and 20.6°C, with an average of 19.2°C. As for maximum temperature, it ranged from 38.0 and 42.8°C, with an average of 40.4°C. Annual rainfall amounts ranged between 688 and 1365 mm, with an average of 969 mm over the 30-year period. The observed trends are not significant for maximum temperature and annual rainfall, but minimum temperatures show some slight increase.

Climate projections and significance tests for delta method changes

A significance test was done for the projected change in the total rainfall and the average maximum temperature for the growing period (from May to October at all sites). The (Δs) criterion, which serves as the significance threshold, is equal to the standard deviation for the 30-year baseline period (1981–2010) multiplied by a factor of 0.36 (see Part 1, Chapter 3 in this volume). For maximum temperature, this corresponded to 0.14°C at the two sites, a threshold which is largely expected to be

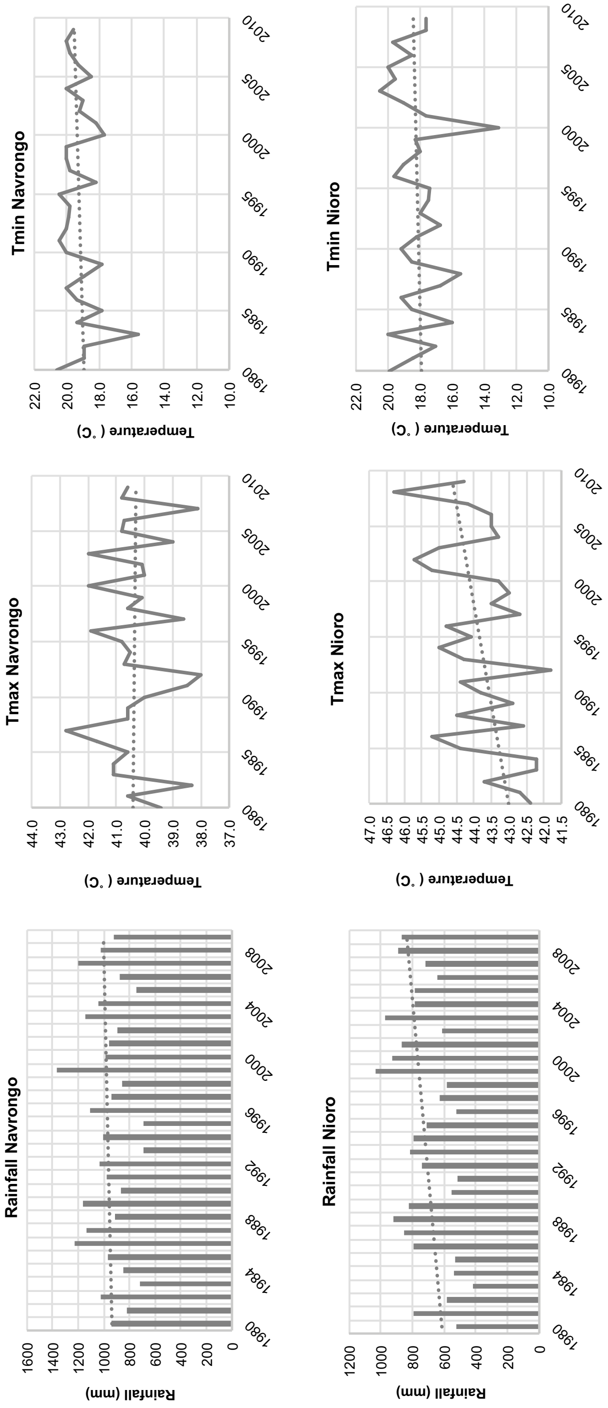
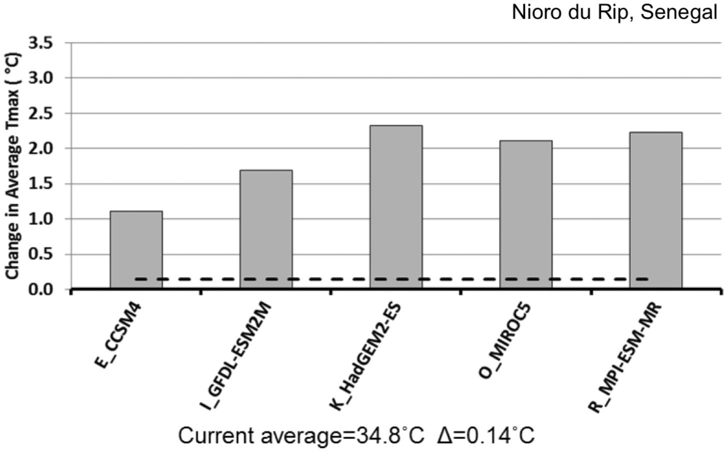


Fig. 5. Historical (1980–2009) crop growing season (May–October): cumulative rainfall amounts, absolute minimum, and absolute maximum temperatures for Nioro, Senegal, and Navrongo, Ghana.

(a) Change in average maximum temperature



(b) Change in average maximum temperature

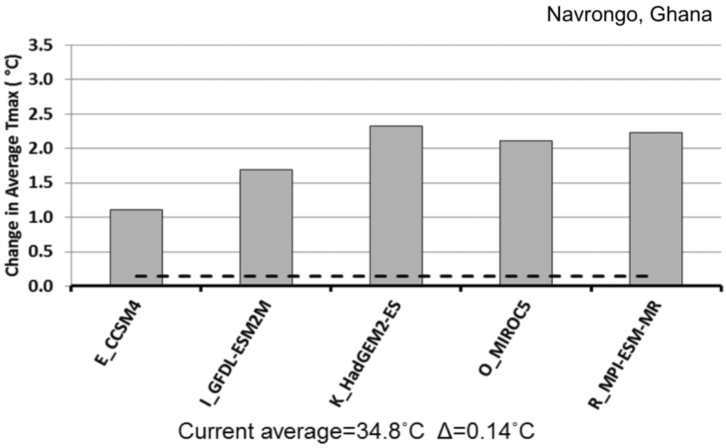
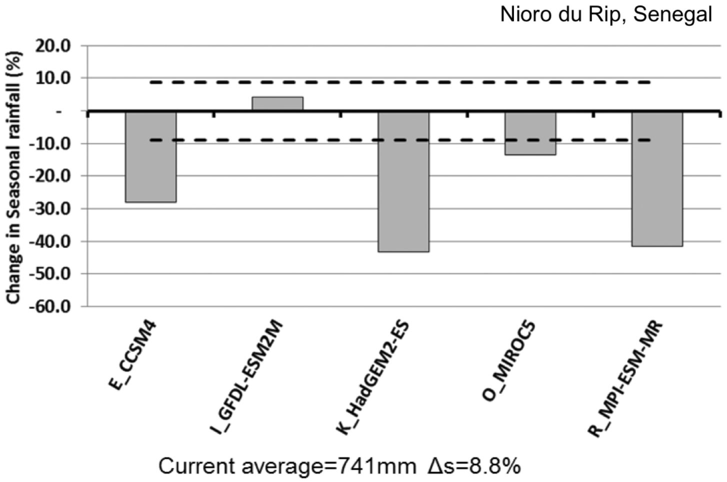


Fig. 6a. Comparison of projected maximum temperature with that of baseline climate in the growing season (May to October) for Nioro, Senegal, and Navrongo, Ghana. Dashed lines represent the (Δs) threshold for statistically significant changes relatively to the 30-year baseline period (1981–2010).

exceeded everywhere and according to all five GCMs tested. Indeed, the expected increases in temperature range from 1.7 to 2.3°C in Nioro, and from 1.8 to 2.8°C in Navrongo (Fig. 6a). The greatest warming is projected by HadGEM2-ES and the least warming is projected by CCSM8 at both sites.

Regarding cumulative rainfall, the expected changes are not uniform across the GCMs and the sites. The value of the (Δs) criteria is equal to 8.8% in Nioro and 6.8% in Navrongo. Both sites are likely to experience both positive and negative changes, depending on the GCM relative to the threshold. In the case of Nioro, four

(a) Change in seasonal rainfall



(b) Change in seasonal rainfall

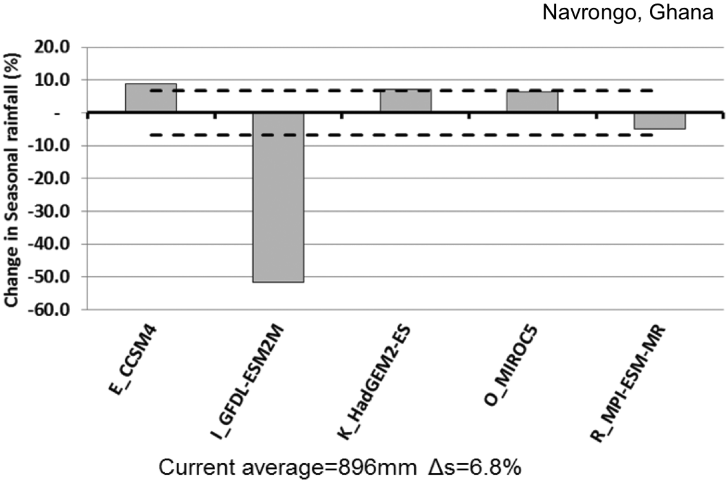


Fig. 6b. Projected changes in growing season (May to October): cumulative rainfall at Nioro, Senegal and Navrongo, Ghana. Dashed lines represent the Δs threshold for statistically significant changes relative to the 30-year baseline period (1981–2010).

out of the five GCMs predict a decreased seasonal rainfall by 13.5 to 43.3%. Only GFDL-ESM2M predicts a slight, not significant increase in seasonal rainfall at this site (Fig. 6b). As for Navrongo, while GFDL-ESM2M predicts a dramatic decrease (−51.7%) in seasonal rainfall, the other GCMs predict barely significant but positive changes (Fig. 6b). The projected changes in average monthly mean temperature and rainfall, as well as the scatter of the 20 CMIP5 GCM projected values relatively to the baseline period (1981–2010) for the two locations are given in Fig. 7a and

Fig. 7b. From these graphs, it is evident that while all GCMs agree on a temperature increase, there are differences in the magnitude and direction of the changes in precipitation. Indeed, while a median decrease in precipitation is foreseen during the rainiest months in Nioro, no change is expected in the early part (April, May, June, July) of the season, but some increases are expected in the latter part (August, September and October) in Navrongo.

Crops

Crop model calibration (*DSSAT and APSIM*)

Two crop models were used in this study, namely (1) Decision Support System for Agrotechnology Transfer (DSSAT v. 4.5) (Jones *et al.*, 2003), and (2) Agricultural Production Systems Simulator (APSIM v. 7.5) (Keating *et al.*, 2003). The DSSAT model was previously used in simulation studies in Ghana (Adiku *et al.*, 2007; MacCarthy *et al.*, 2010; MacCarthy *et al.*, 2013) and in the Sahel (Traore *et al.*, 2007). The APSIM model was also used in previous studies in West Africa (Akponikpe *et al.*, 2010; MacCarthy *et al.*, 2009). However, the models were re-calibrated as shown in Table 2 for the crop varieties grown at Nioro, Senegal, and Navrongo, Ghana. For Nioro, the selected millet variety was *CIVT* and the calibration dataset was from Akponikpe (2008) and Akponikpe *et al.* (2010). For maize, *TZEY-SRBC5* was selected for Nioro and the calibration data were from Dzotsi *et al.* (2003). In the case of Navrongo, the maize variety was *Obatanpa* with calibration from Dzotsi *et al.* (2010). For peanut, the *Chinese* variety was selected for all sites with Naab *et al.* (2004) as the calibration dataset. In the current study, the DSSAT and APSIM models were used to simulate all three crops (millet, maize, and peanut).

Additional model parameterization and validation

Following the calibration of the crop models, they were validated for 226 farms at Nioro and 250 at Navrongo, with derived model input data from the household survey information. The parameterization of the models using household data brought with it many challenges. First, given the frequently low crop yields reported in the survey, it was necessary to re-examine the soil data, which were based on the National Soil Survey Manual rather than actual soil surveys. In situations where the reported soil organic carbon (SOC) was high, SOC values were re-adjusted so that their contribution to soil fertility was reduced by increasing the proportion of the stable fraction, which is the inert carbon. A previous study by Bostick *et al.* (2006) lends support to this approach. For DSSAT simulations of millet and peanut, the stable carbon proportion was gradually adjusted from 0.7 to 1 from the top to the bottom of the soil profile. In APSIM, the stable carbon fraction was similarly varied from

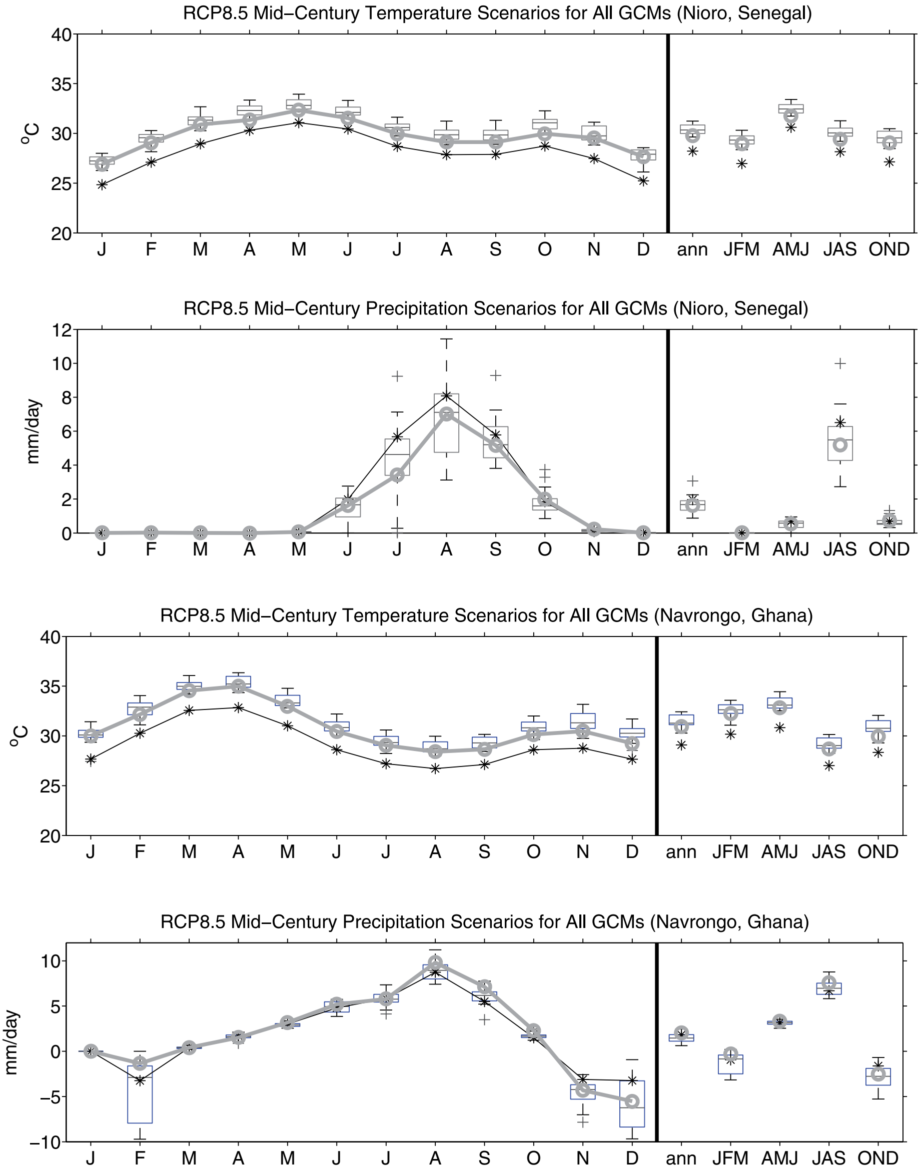


Fig. 7a. Projected changes in average monthly mean temperature and rainfall at Nioro, Senegal, and Navrongo, Ghana. The black line represents the average values for the 30-year baseline period (1981–2010) and the gray line represents the median of the projected values by 20 CMIP5 GCMs.

0.8 to 1 from the top to the bottom of the soil profile. In the case of maize, the soil fertility parameter factor (SLPF) in DSSAT was used to adjust soil productivity.

Second, the household survey for the base years provided information for sowing windows only, rather than actual sowing dates. For realistic simulation at the study

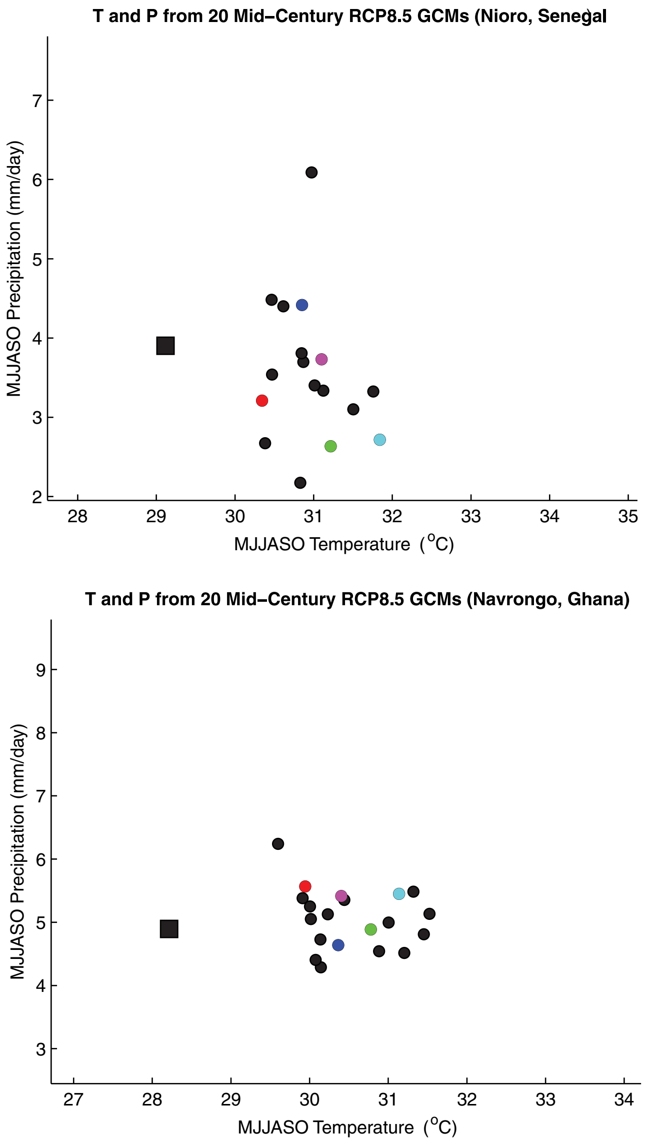


Fig. 7b. CMIP5 GCM projections for temperature and precipitations during the crop growing season (May to October) at Nioro, Senegal, and Navrongo, Ghana. The black square represents the current (1981–2010 baseline) situation, and the colored dots represent the five GCMs considered in the study.

sites, sowing date distributions were constructed from previous studies. Third, fertilizer application rates were derived from application costs, and the application dates were assumed to follow extension advice (i.e., 14 and 42 days after sowing). The main consequence of these assumptions was that it was difficult to match simulated and observed yields directly.

Table 2. Calibration of maize, millet, and peanut cultivars for grain yields.

	APSIM		DSSAT	
	RMSE (kg/ha)	R^2	RMSE (kg/ha)	R^2
Maize (*obatanpa*)	476	0.90	474	0.89
Millet (*CIVT*)	206	0.75	433	0.90
Peanut (*Chinese*)	272	0.90	633	0.95

Crop model results (*DSSAT and APSIM*)

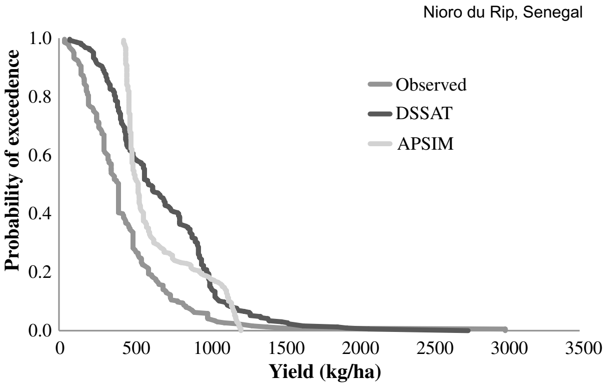
All crop models were successfully calibrated for the test locations. The calibrations showed strong relationships between simulated and observed yields for both APSIM and DSSAT (Table 2). The results confirm that the genetic coefficients are sufficiently accurate to reliably simulate growth and yield of the cultivars in response to the soil and climate environments of West Africa.

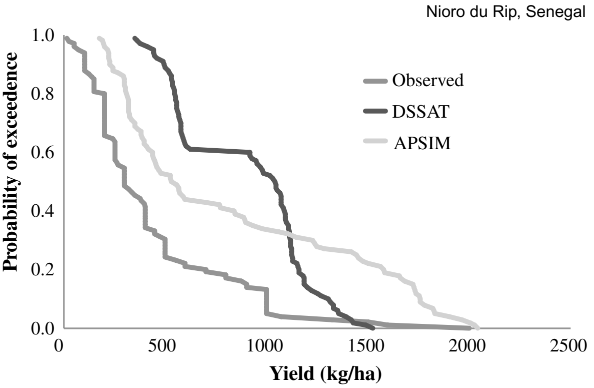
The validations of the crop models for Nioro for the base year (2007) are shown in Fig. 8. The coarse level of the input information prevented a direct matching of simulated and observed yields. For the low yield range of millet, APSIM overestimated the yields, whereas DSSAT captured the distribution well. In the case of maize, APSIM matched the observed distribution well except at the high yield ranges. For peanut, DSSAT underestimated yields while APSIM overestimated yields. However, the probability distributions of observed and simulated yields were similar. Reliable validations were also obtained for Navrongo, Ghana.

Economics

Survey data

A household survey conducted in 2007 at six villages — Djiguimar, Medina Sabakh, Ndiba, Ngayene, Paoskoto, and Porokhane — documented their geo-referenced locations, household size, farm size, stratified cropping systems, cost of manure and fertilizer applications, and crop yields, among other variables. The sowing period spans almost two months from mid-May to mid-July. The total number of farms surveyed was 226, of which 100 cultivated maize (9.6% by area), 223 cultivated peanuts (53% by area), and 226 cultivated millet (37% by area). Socio-economic information for Navrongo was obtained from a survey carried out in 2012 in 16 communities. The same information was collected as in the case of Nioro. The sowing period spans from mid-May to end of July. The total number of households surveyed was 276, of which 74 cultivated maize (16 % by area), 156 cultivated millet (42 % by area), and 237 cultivated peanuts (42 % by area). Information on farm management practices were used as input data for crop modeling in both sides.


(a) Probability of exceedance for millet yield


(b) Probability of exceedance for maize yield

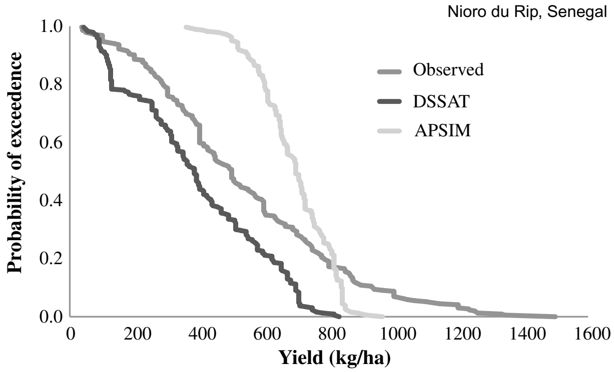

(c) Probability of exceedance for peanut yield

Fig. 8. Validation of crop models at Nioro, Senegal, 2007.

Strata

A major task of this study was to assess the impacts of climate change on agricultural productivity in West Africa. New methodologies and tools were required. First, two subsystems (strata) of farms are considered in both sites. In Nioro, the two strata are non-maize farms (Strata 1) and maize-based farms (Strata 2). Second, the yields for each farm were simulated for the 30 baseline years and the 30 future years for each of the five GCMs, assuming that farmers continue their current practices (base cultivar). Thereafter, future yields were again simulated assuming that farmers adopted new technology (i.e., an adapted cultivar that is heat- and drought-tolerant) as an adaptation strategy to minimize climate change impacts.

The AgMIP methodology is schematically shown in Fig. 9. The ability to simulate multiple farms, management regimes, and years was enabled by the development of innovative AgMIP tools. QuadUI (v1.2.1- Beta24-hf1) is a utility that extracts relevant crop model input data from socio-economic data (i.e., raw survey data) and stores them in Data Overlay Multi-model Export (DOME) files. QuadUI was used to translate survey and DOME files into model-ready formats (i.e., APSIM and DSSAT), which enables multiple model simulations. This resulted in a spatial simulation of crop yields beyond single farms for baseline climate and climate change scenarios. These serve as inputs for the socio-economic model (Tradeoff

Fig. 9. Schematic representation of the integrated assessment framework.

Analysis Model for Multi-dimensional Impact Assessment; TOA-MD; Antle and Stoorvogel, 2006) to determine changes in the behavior of the farm households under climate change conditions.

To evaluate the ability of the crop models to simulate observed data the root-mean-square error (RMSE), modified coefficient of model efficiency, and correlation coefficient were used. Baseline and projected simulated grain yield data were analyzed by using analysis of variance (ANOVA). Analyses were carried out to compare the performance of base technology with changed technology for the various climate scenarios. A randomized complete block design (RCBD) approach was used to analyze data and the least significant differences were determined at 5% probability to separate means of treatments. Farms were considered as replications and years taken as blocks, as yields under each treatment in a given year were not affected by another year.

RAP narrative and development

RAP 1 assumes that crop production in Nioro will be characterized by short-term agricultural policy intervention/short-term, state-led, urban driven (negative). This RAP 1 assumes dominance of state actors in the agricultural development agenda with the view of bringing in fast short-term gains with food security outcomes to the population. Main interventions will include support for the agricultural service sector, fertilizer subsidies, and feeder roads (slow), trading land and human resources to foreign investors who will in turn develop infrastructure (Table 3).

For Navrongo, crop production will be farmer-led with the adoption of intensive and expanded (I&E) irrigation technology using hand-dug, shallow wells. The RAP 1 for Navrongo assumes that farms located within the WVB with access to irrigation will be better-off following reduced precipitation and increased temperature under future climate. This is because irrigation mutes the negative impacts of climate change on farm systems. Details of parameters used are indicated in Table 3.

Adaptation package

We assumed that farmers in the future will adopt improved technology to adapt cropping systems to the new environment. The development of the changed technology was done within the context of the RAPs, with a focus on new varieties that are heat- and drought-tolerant. Virtual varieties of the crops were simulated by changing the genetic coefficients (for cereals), root distribution parameters, and root-water extraction potentials. Heat tolerance was simulated for the cereals by increasing thermal time from silking to physiological maturity (P5 in DSSAT) by

Table 3. Summary of RAP 1 for Nioro, Senegal with main parameters.

Variables	Direction of change	Magnitude of change	Rationale for direction and magnitude of change	Percent change over the period	Rationale for percent change over period
Household size	Decrease	Medium	Internal migration of young people to the cities, split in households and education (younger people having smaller family sizes).	50%	Education, higher literacy rate of women and migration.
Farm size	Increase	Large	People migrate and the few that stay have more available land to mechanize and increase farm sizes. As farm sizes increase (family size decreasing), farmers have to rely on mechanization and not human labor hence they have to increase farm size.	100%	Minimum farm size for farm hiring labor and machinery.
Non-agricultural income	Increase	Medium	Service sector is developed, farm consolidation (causing people to find alternatives sources of income outside farming).	30%	Development of new labor opportunities, farm labor will shrink.
Production cost	Increase	Small	Increased input cost due to high fuel prices and greater concentration of input providers (e.g., seed providers).	10%	Amount and cost of inputs considering some subsidies, fertilizer being subsidized by the government
Livestock numbers	Increase	Medium	Increased demand, increasing incomes and purchasing power.	55%	Sedentarization trends as cropland extends.
Livestock yield	Increase	Medium	Animal breeding programs, improved animal health programs.	30%	Research development programs, government policies.

10% to restore the lifecycle of the original cultivar under climate change conditions. In APSIM, the percentage increase applied to P5 in DSSAT was calculated on the thermal time from the start of grain-filling to maturity and the increase was added to the thermal time from flowering to maturity. The density of the root distribution of the base cultivars was increased beneath the 20-cm depth. This was done to enable the plant roots to explore more of the soil profile for the uptake of water and nutrient resources as pertains to drought and/or nutrient-stress conditions.

$$\mathrm{WR} = \left(1 - \left(\frac{Z}{1000}\right)\right)^{6}$$

where z is depth of soil layer and WR is root distribution. The water extraction potential was increased by adjusting the crop-specific lower limit such that total water availability increased by 20%, as described by the following equation (Singh *et al.*, 2013):

$$\mathrm{LL}\left(\mathrm{adapt}\right) = \mathrm{LL} - 0.2(\mathrm{DUL} - \mathrm{LL})$$

where LL(adapt) is the lower limit of soil moisture under adaptation conditions, LL is the original lower limit of the soil, and DUL is the original, drained upper limit of the soil moisture.

Core Question 1: What Is the Sensitivity of Current Agricultural Production Systems to Climate Change?

Impact of climate change on crop production

Maize

Simulated maize yields using DSSAT for the baseline climate were 889 kg/ha and 994 kg/ha for Nioro and Navrongo, respectively. For Nioro, the maize yields simulated for the 2050s under the five GCMs were significantly lower than those of the baseline and ranged from 344 kg/ha for HadGEM2-ES to 600 kg/ha for CCSM. In Navrongo, simulated future yields under all GCMs were significantly ($p < 0.05$) lower than that of the baseline climate (Table 4), with the lowest yield simulated under HadGEM2-ES and the highest under CCSM4. Climate change resulted in yield reductions between 32% and 62% in Nioro and 18% and 35% in Navrongo. Variability in yields simulated under baseline climate in Nioro was 36% while those for the GCMs ranged between 34 and 42% across GCMs. The variability in the simulated baseline climate yields was 50% while those for the GCMs ranged between 48% and 49% across the GCMs in Navrongo.

Table 4. Simulated mean yields of maize, millet, and peanut by DSSAT and APSIM under baseline and current production systems with climate change scenarios without adaptation for Nioro, Senegal, and Navrongo, Ghana.

Nioro	Maize (kg/ha/ha)		Millet (kg/ha)		Peanut (kg/ha)	
Climate scenario	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
BASELINE	889	891	286	758	273	550
GFDL-ESM2M_I	596	800	412	728	258	621
CCSM4_E	600	766	292	697	290	643
MIROC5_O	536	802	304	703	254	601
MPI-ESM-MR_R	390	688	184	630	229	591
HadGEM2-ES_K	344	709	231	653	218	609
LSD (0.05)	61	121	38	31	26	28

Navrongo	Maize (kg/ha/ha)		Millet (kg/ha)		Peanut (kg/ha)	
Climate scenario	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
BASELINE	994	941	433	324	281	432
GFDL-ESM2M _I	701	947	319	325	349	557
CCSM4 _E	804	925	338	295	330	599
MIROC5_O	747	925	313	292	319	556
MPI-ESM-MR_R	698	929	299	381	320	636
HadGEM2-ES_K	641	902	272	286	292	581
LSD (0.05)	123	197	63	23	16	43

For APSIM, simulated maize yield under the baseline climate in Nioro was 891 kg/ha and was significantly higher than those from HadGEM2-ES and MPI-ESM-MR. The other GCMs — GFDL-ESM2M, CCSM4, and MICROC5 — produced lower yields in the 2050s relative to the baseline yields, but the differences were not significant. In Navrongo, simulated baseline grain yield was 941 kg/ha and 2050s yields simulated for the five GCMs ranged between 902 and 947 kg/ha. Grain yields for the GCMs ranged from 688 kg/ha for MPI-ESM-MR to 802 kg/ha for MIROC5 in Nioro. In Navrongo, HadGEM2-ES produced the least yield while GFDL-ESM2M produced the highest yield. Reduction in yield due to climate change was between 9% to 23% for all GCMs in Nioro and between 1% and 4% in Navrongo for all GCMs, except for MIROC5 and MPI-ESM-MR, which produced a yield increment of 1%. Differences observed among GCMs and baselines were, however, not statistically significant. Variability in simulated baseline climate yield was 56%, while those for the GCMs ranged between 50% to 58% in Nioro. In Navrongo, variability in baseline yield was 67% as against between 63% and 66% across GCMs.

Millet

In Nioro, simulated mean yield of millet was 286 kg/ha under baseline conditions. Yields produced under MPI-ESM-MR and HADGEM2-ES for the 2050s were significantly ($p < 0.05$) lower than the baseline yields while those from the other GCMs were higher than baseline yields. Differences between baseline yields and those obtained from CCSM4 and MIROC5 were not significant. Yields varied across GCMs (Table 4). Yields from GFDL-ESM2M were significantly higher than those from the other GCMs and the baseline. Percentage increment in grain yield was observed in three GCMs and ranged from 4% (MIROC5) to 49% (GFDL-ESM2M) while percentage reductions were observed in two GCMs from 19% (HADGEM2) to 35% (MPI-ESM-MR) in Nioro.

For Navrongo, simulated mean grain under baseline climate was 433 kg/ha and was significantly higher than the yield produced under the five GCMs for the 2050s. Yield reductions simulated under the GCMs ranged between 25% (CCSM4) and 42% (HadGEM2-ES). Variability in yields was very high, ranging from 66% to 75% across GCMs with baseline climate variability of 74% when the DSSAT crop model was used in Nioro. For Navrongo, variability in baseline climate yield was 71% compared with a range of 83% to 95% across the five GCMs.

For APSIM, the mean baseline yield obtained in Nioro was 758 kg/ha, while those obtained under the five GCMs ranged from 630 to 728 kg/ha and were lower than those obtained from the baseline climate except for GFDL-ESM2M which was not significantly different. Simulated reduction in yields ranged from 4% (GFDL-ESM2M) to 16% (MPI-ESM-MR) in Nioro. In Navrongo, simulated mean grain yield under baseline climate was 324 kg/ha and higher than those under CCSM4, HadGEM2-ES, and MIROC5, while GFDL-ESM2M was similar to baseline yields and MPI-ESM-MR produced higher yields. Simulated future yields ranged from 286 kg/ha (HADGEM2-ES) to 381 kg/ha for (MPI-ESM-MR). GFDL-ESM2M and MPI-ESM-MR produced yield increments of 3 and 19% respectively, while yield reductions of between 9 to 12% were simulated for CCSM4, HadGEM2-ES, and MIROC5. Variability in yield in Nioro ranged from 20 to 27% across GCMs compared with a baseline climate variability of 25% for APSIM. In Navrongo, variability in the baseline climate yields was 34%, compared with a range of 26% to 37% across GCMs.

Peanut

In Nioro, peanut yield simulated by DSSAT under baseline climate was 273 kg/ha while simulated yield for the future (2050s) under the five GCMs ranged from 218 (HadGEM2-ES) to 290 kg/ha (CCSM4). This translates into yield reductions ranging from 2% to 17% across GCMs except for CCSM4, which recorded yield increase of 10%. In Navrongo, simulated mean yield of peanut under baseline climate was 281 kg/ha, while mean simulated future yields ranged from 292 (HadGEM2-ES) to 349 kg/ha (GFDL-ESM2M). All the five GCMs showed yield increments of between 5% and 19% over the baseline. Variability in peanut yield was between 53% and 56% across GCMs, compared with the baseline yield variability of 58% in Nioro. In Navrongo, variability in yield ranged between 27% and 28% across GCMs and 33% in the baseline climate.

For APSIM, simulated yield under baseline climate was 550 kg/ha and was significantly lower than those obtained under each of the GCMs in Nioro, ranging from 591 (MPI-ESM-MR) to 643 kg/ha (CCSM4). Yield increments of between 7% and 17% were obtained across GCMs relative to the baseline climate. In Navrongo, simulated baseline climate yield was 432 kg/ha, compared with yields of 556 (MIROC5) to 636 kg/ha (MPI-ESM-MR) across the five GCMs. This translates into yield increments of between 28% and 47%. Variability in yields obtained under the five GCMs was between 23% and 26%, compared with 23% for baseline yields in Nioro. In Navrongo, variability in yields under the baseline climate was 43%, whereas those across the GCMs were between 39% and 45%.

Discussion

The effects of climate change on yields relative to baseline climates were generally negative for the cereal crops (i.e., millet and maize), irrespective of the crop simulation model. This can be attributed to increases in temperature during the growing period and differences in the total rainfall amounts relative to those of the baseline climate. However, yield reductions simulated for maize by APSIM in Navrongo were not significantly different from that of the baseline. Similarly, both models simulated similar yields to the baseline yields under some GCMs. In the case of peanut, yield increases were simulated at both sites by both models except for CCSM4, under which DSSAT simulated a yield increase which was not significantly different from that of the baseline. Even though CCSM4 projected lower future rainfall amounts relative to that of the baseline in Nioro, it had the lowest temperature increase; hence, lower reductions in yields were simulated by both models. Similar observations were made for Navrongo. Of all the five GCMs, MPI-ESM-MR and HadGEM2-ES resulted in the lowest yield projections for all three crops. This may be due to the lower total rainfall amounts, low daily intensity recorded during the growing season in the case of MPI-ESM-MR, coupled with a higher temperature regime that characterized these GCMs (Figs. 6a and 6b). The effect of temperature in reducing crop yield has been reported by several studies (Mearns *et al.*, 1984; Moriondo *et al.*, 2011) and has been described as having the most adverse effect on crop yield among all weather parameters. Certain stages of crop growth are particularly sensitive to temperature change. Increased temperatures above certain thresholds for most crops during the reproductive stage can result in significant yield loss through its effect on grain-filling, grain numbers, and even sterility. It also exerts stress on the crop through high evapotranspiration and energy demands that otherwise would result in crop production but are instead used to manage the stress.

The extent of the changes in crop yield due to projected future climate did vary between the crops models. For instance with millet, the impact of climate change on grain yield varied from 11% to 44% for DSSAT and from 5% to 19% for APSIM. Similar observations can be made in the case of maize and peanut. The extent to which the two models respond to temperature and increased rainfall varied, which also resulted in differences in model outcomes. The effect of climate change was higher in Nioro than Navrongo using both crop simulation models. Additionally, the effect of climate change on grain yield was generally higher with DSSAT than with APSIM.

Differences in the extent of climate change impact predictions on yield by the crop models may be attributed to the different approaches they employ in simulating yield. For instance, DSSAT uses two main genetic coefficients (P1 and P5) to describe maize phenology, whereas APSIM uses as many as seven genetic coefficients. Further, APSIM simulation of millet considers each tiller as a separate plant, which thus complicates the calibration procedure since such detailed data are not available in the calibration datasets used in this study. Also, the life-cycle description of cereals in DSSAT is independent of environmental stresses such as water and nutrient deficiencies, but these are captured by APSIM. Given that a shift in phenology may result in sensitive stages in crop growth coinciding with favorable or less favorable weather conditions, these differences in approach could explain the outcomes of the two crop models. Both models, however, agree on the direction of impacts under future climate change scenarios with baseline technology. In spite of the lower impact of climate change on crop production in Navrongo, variability in yields was much higher than for Nioro. This could be attributed in part to the poorer soils in Navrongo compared to those in Nioro.

Economic impact of climate change on current production systems

The economic part of this assessment first explores how the current climate affects selected economic outcomes in Nioro without adaptation. Due to the lower future yields simulated by DSSAT and APSIM, most economic indicators would decline under climate change without adaptation. Whereas APSIM seems to project less variability in net returns irrespective of stratum, DSSAT shows considerable variations in net returns. In Nioro the aggregate results show that estimated mean net returns per farm, using simulated yields, decrease from the DSSAT model between 10% and 38% (Table 5). The impact of climate change is greater for maize-based farms (Stratum 2) as their estimated mean net returns per farm decrease between 13% (reduction from \$2376 to \$2075) to 41% (decrease from \$2376 to \$1411) for the same climate scenarios.

In the case of APSIM, the results are similar although there is less variability. In the aggregate, the impact of climate change on net returns is negative, varying between 10 and 19%.

By considering two climate scenarios (GCM CCSM4 and GCM HadGEM2-ES), with DSSAT, as an illustration, we notice the following: For GCM CCSM4, gains per farm amount to \$40 while losses reach \$323, which results in net losses per farm of \$283; for GCM HadGEM2-ES, gains per farm are only \$7 whereas losses amount to \$636 for a net loss per farm of \$629. Figures 10a and 10b show the gains, losses, and net impacts as a percent of mean net farm returns.

Assuming no adaptation, the impacts of climate change on *per capita* income and poverty rates in Nioro are also largely negative.

The GCMs, MPI-ESM-MR and HadGEM2-ES display the greatest negative values. With DSSAT, *per capita* income decreases on average by 15%, i.e. \$45 with a minimum of \$19 and a maximum of \$69 (Fig. 11). Without climate change, the poverty rate reaches about 73% on aggregate, with 82% displayed in Stratum 1 (non-maize farms) and 64% in Stratum 2 (maize-based farms). Climate change without adaptation results in a higher level of poverty under both models for maize-based farms. Non maize farms, however, experience a smaller impact under both DSSAT and APSIM.

Table 5. Climate sensitivity of current agricultural production systems for Nioro, Senegal.

Non-maize Farms	GCM E = CCSM4		GCM I = GFDL-ESM2M		GCM K = HadGEM2-ES		GCM O = MIROC5		GCM R = MPI-ESM-MR	
	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
Observed mean yield (millet) (kg/ha)	786	786	786	786	786	786	786	786	786	786
Mean yield change (millet) (%)	8	8	49	3	−18	−4	4	3	−34	−7
Observed mean yield (penaut) (kg/ha)	956	956	956	956	956	956	956	956	956	956
Mean yield change (peanut) (%)	13	15	0	11	−15	9	−2	7	−11	5
Observed mean yield (maize) (kg/ha)	—	—	—	—	—	—	—	—	—	—
Mean yield change (maize) (%)	—	—	—	—	—	—	—	—	—	—
Losers (%)	71	69	58	74	92	78	83	77	94	82
Gains (% mean net returns)	4.0	4.2	6.3	3.3	0.7	2.6	1.8	2.9	0.5	2.2
Losses (% mean net returns)	−16.6	−15.0	−10.7	−17.2	−31.2	−19.5	−20.6	−18.5	−34.6	−21.5
Net impact (% mean net returns)	−12.6	−10.8	−4.5	−13.9	−30.5	−16.8	−18.8	−15.5	−34.0	−19.3
Projected net returns without climate change (US$)	1308	1308	1308	1308	1308	1308	1308	1308	1308	1308
Projected net returns with climate change (US$)	1143	1167	1250	1127	909	1088	1062	1105	863	1055
Change in mean net returns	−13%	−11%	−4%	−14%	−30%	−17%	−19%	−16%	−34%	−19%
Projected *per capita* income without climate change (US$)	249	249	249	249	249	249	249	249	249	249

(*Continued*)

Table 5. (*Continued*)

Non-maize Farms	GCM E = CCSM4		GCM I = GFDL-ESM2M		GCM K = HadGEM2-ES		GCM O = MIROC5		GCM R = MPI-ESM-MR	
	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
Projected *per capita* income with climate change (US$)	232	234	243	230	207	226	223	228	202	222
Percent change in *per capita* income	−7%	−6%	−2%	−8%	−17%	−9%	−10%	−9%	−19%	−11%
Observed poverty rate without climate change (%)	82.6	82.6	82.6	82.3	82.6	82.3	82.6	82.3	82.6	82.3
Projected poverty rate with climate change (%)	85.0	84.8	83.5	85.7	90.0	86.4	87.2	86.1	90.7	87.1
Change in poverty rate	2.4	2.2	0.9	3.4	7.4	4.2	4.5	3.8	8.1	4.8
Maize farms										
Observed mean yield (millet) (kg/ha)	857	857	857	857	857	857	857	857	857	857
Mean yield change (millet) (%)	6	11	52	7	−22	−8	5	2	−38	−10
Observed mean yield (penaut) (kg/ha)	894	894	894	894	894	894	894	894	894	894
Mean yield change (peanut) (%)	6	17	−5	13	−20	11	−7	10	−16	8
Observed mean yield (maize) (kg/ha)	2025	2025	2025	2025	2025	2025	2025	2025	2025	2025
Mean yield change (maize) (%)	−32	−15	−34	−10	−62	−18	−41	−9	−57	−23
Losers (%)	88	72	78	68	98	77	96	71	98	80

(*Continued*)

Table 5. (*Continued*)

Non-maize Farms	GCM E = CCSM4		GCM I = GFDL-ESM2M		GCM K = HadGEM2-ES		GCM O = MIROC5		GCM R = MPI-ESM-MR	
	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
Gains (% mean net returns)	0.9	3.0	2.2	4.2	0.2	2.9	0.3	3.9	0.2	2.5
Losses (% mean net returns)	−19.7	−12.7	−14.9	−14.3	−40.0	−19.1	−28.6	−15.8	−40.8	−21.6
Net impact (% mean net returns)	−18.8	−9.8	−12.7	−10.0	−39.9	−16.1	−28.3	−11.9	−40.6	−19.2
Observed net returns without climate change (US$)	2376	2376	2376	2376	2376	2376	2376	2376	2376	2376
Projected net returns with climate change (US$)	1931	2144	2075	2138	1429	1993	1703	2093	1411	1921
Change in mean net returns	−19%	−10%	−13%	−10%	−40%	−16%	−28%	−12%	−41%	−19%
Observed *per capita* income without climate change (US$)	341	341	341	341	341	341	341	341	341	341
Projected *per capita* income with climate change (US$)	299	319	313	319	252	305	278	315	250	298
Percent change in *per capita* income	−12%	−6%	−8%	−7%	−26%	−11%	−19%	−8%	−27%	−13%
Observed poverty rate without climate change (%)	63.9	64.0	64.0	63.2	64.0	63.2	64.0	63.2	64.0	63.2
Projected poverty rate with climate change (%)	73.2	68.4	69.8	68.6	84.3	71.8	78.1	69.6	84.7	73.3
Change in poverty rate	9.3	4.4	5.8	5.4	20.4	8.6	14.2	6.5	20.8	10.2

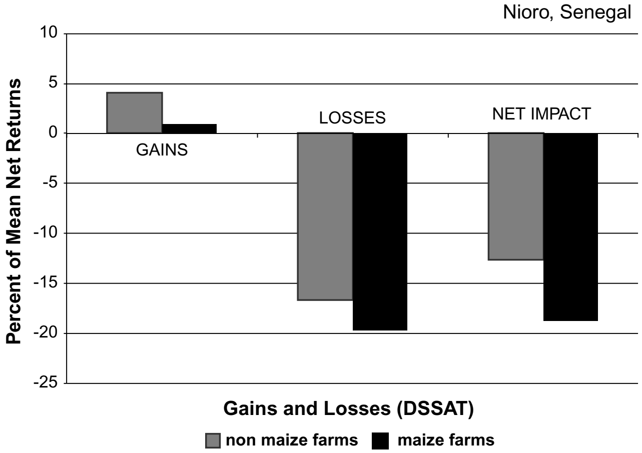
(*Continued*)

Table 5. (*Continued*)

Non-maize Farms	GCM E = CCSM4		GCM I = GFDL-ESM2M		GCM K = HadGEM2-ES		GCM O = MIROC5		GCM R = MPI-ESM-MR	
	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
All farms										
Losers (%)	80	71	68	71	95	78	90	74	96	81
Gains (% mean net returns)	2.3	3.5	4.0	3.9	0.4	2.8	0.9	3.5	0.3	2.3
Losses (% mean net returns)	−18.4	−13.7	−13.1	−15.5	−36.2	−19.2	−25.2	−16.9	−38.1	−21.6
Net impact (% mean net returns)	−16.1	−10.2	−9.1	−11.7	−35.8	−16.4	−24.2	−13.5	−37.8	−19.2
Observed net returns without climate change (US$)	1757	1757	1772	1757	1757	1757	1757	1757	1757	1757
Projected net returns with climate change (US$)	1474	1578	1597	1552	1128	1468	1331	1520	1093	1419
Change in mean net returns	−16%	−10%	−10%	−12%	−36%	−16%	−24%	−13%	−38%	−19%
Observed *per capita* income without climate change (US$)	295	295	297	295	295	295	295	295	295	295
Projected *per capita* income with climate change (US$)	265	277	278	274	230	265	250	271	226	260
Percent change in *per capita* income	−10%	−6%	−6%	−7%	−22%	−10%	−15%	−8%	−23%	−12%
Observed poverty rate without climate change (%)	73.3	73.3	73.3	72.7	73.3	72.7	73.3	72.7	73.3	72.7
Projected poverty rate with climate change (%)	79.1	76.6	76.6	77.1	87.2	79.1	82.6	77.9	87.7	80.2
Change in poverty rate	5.8	3.3	3.3	4.4	13.9	6.4	9.4	5.1	14.4	7.5

NB: Poverty line is equal to FCFA204845, i.e., US$ 409.69 (1$=500 FCFA).

(a) GCM CCSM4



(b) GCM HadGEM2-ES

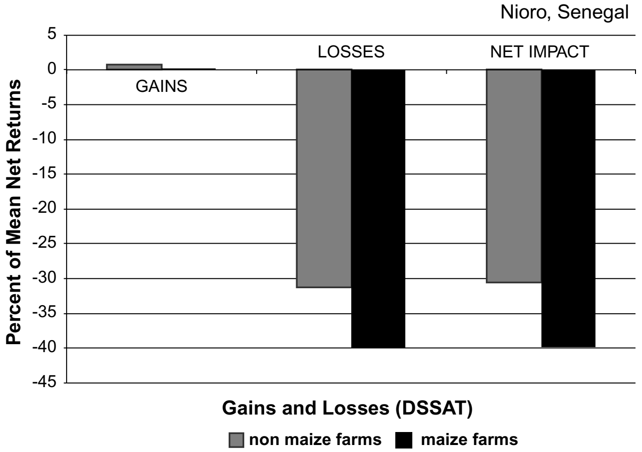


Fig. 10. Gains, losses, and net impact on farmers' livelihoods in Nioro, Senegal with CCSM4 and HadGEM2-ES climate change scenarios.

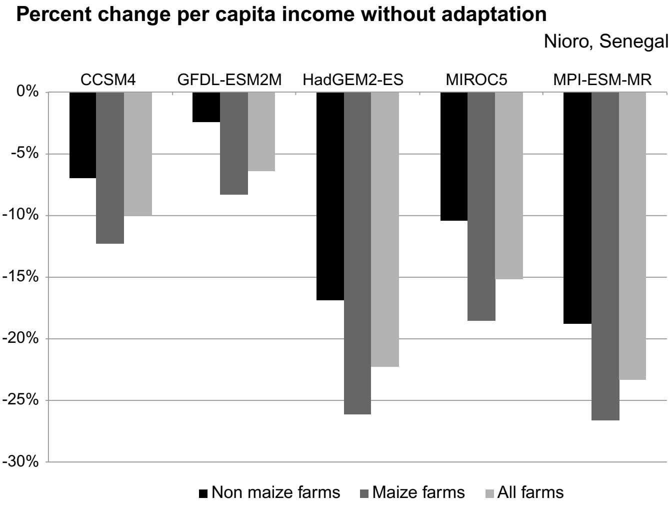


Fig. 11. Effect of climate change without adaptation on the percentage change of *per capita* income of farmers in Nioro, Senegal.

Core Question 2: What Is the Impact of Climate Change on Future Agricultural Production Systems?

Results and discussion

Our interest in this question is to assess the economic impact of climate change on farms in Nioro when autonomous yield and price trends are accounted for as the current production system continues. We use IFPRI IMPACT model data to estimate the percent changes from 2005–2050 for the no climate change yield trend. We also use these simulated Impact data to project trends in prices. Table 6 gives the yield growth trend factor and the price trend for the three crops used in the estimation. Note that, in the absence of millet in the impact data, sorghum trends are used instead. In the RAP 1 for Nioro, we assumed a 30% increase in non-agricultural income, 100% increase in farm size, 50% decrease in household size, and 10% increase in costs of production. These factors combine to increase net farm returns substantially and decrease poverty rates.

Under these assumptions, the results of the TOA-MD simulations assuming autonomous trends in crop yield, price, and production cost show an overall better picture than the case of climate change effects on current productions systems without adaptation for Nioro. With DSSAT, farmers still witness declines in their returns with two climate models (HadGEM2-ES and MPI-ESM-MR). Improvements are dramatic with APSIM. Specifically, we note a decrease in the percentage of farms that lose from climate change (between 68% and 96% under current productions

Table 6. Trend factors for yields and prices for selected crops in Senegal.

	Senegal	
Crop	Yield	Price
Maize	1.905	2.218
Peanut	1.164	1.222
Sorghum	1.417	1.578

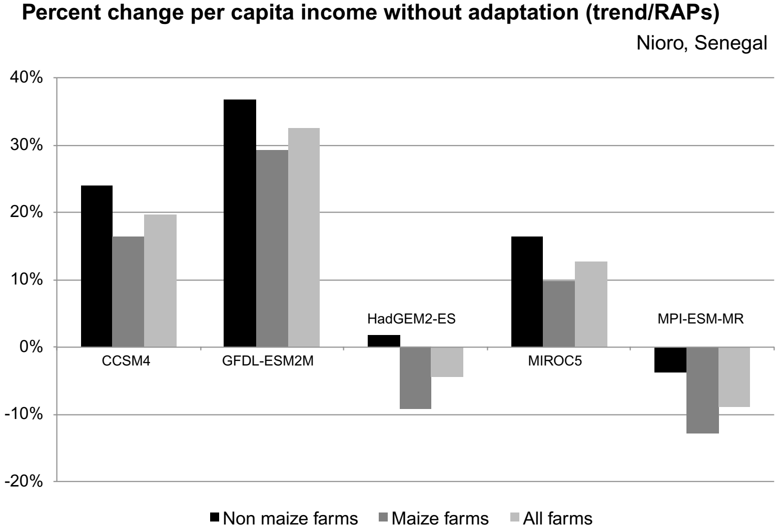


Fig. 12. Effect of climate change without adaptation but with trends and RAPs on the percentage *per capita* income of farmers in Nioro, Senegal.

systems to between 14% and 70% under future production systems with DSSAT; between 71 and 81% to 10 to 15% with the APSIM model).

Additionally, net impacts as a percent of mean net farm returns are mostly positive (between 5% and 44% for DSSAT, while under APSIM net gains vary from 1% to 12%). Shifting from current to future agricultural systems, it appears that trend factors will have significant positive impacts which may offset some of the impact of climate change. For instance, poverty rates drop dramatically by more than 60 points for non-maize-based farms, while the decrease is about 52 points for maize-based farms. *Per capita* income increases between 17% and 47% for all GCMs under APSIM when effects of climate change and trend factors are projected for the future agricultural system. The data for the DSSAT model show similar results for HadGEM2-ES, GFDL-ESM2M, and MIROC5. In contrast, the results for CCSM4 and MPI-ESM-MR are slightly lower and negative (Fig. 12 and Table 7).

Table 7. Impact of climate in future without adaptation for the Nioro, Senegal cropping system.

Non-maize Farms	GCM E = CCSM4		GCM I = GFDL-ESM2M		GCM K = HadGEM2-ES		GCM O = MIROC5		GCM R = MPI-ESM-MR	
	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
Projected mean yield (millet) (kg/ha)	1114	1114	1114	1114	1114	1114	1114	1114	1114	1114
Mean yield change (millet) (%)	8	8	49	3	−18	−4	4	3	−34	−7
Projected mean yield (peanut) (kg/ha)	1103	1103	1103	1103	1103	1103	1103	1103	1103	1103
Mean yield change (peanut) (%)	14	16	1	12	−14	10	−1	8	−10	6
Projected mean yield (maize) (kg/ha)	—	—	—	—	—	—	—	—	—	—
Mean yield change (maize) (%)	—	—	—	—	—	—	—	—	—	—
Losers (%)	15	2	9	2	45	20	20	2	60	3
Gains (% mean net returns)	35.8	100.3	52.6	93.0	9.8	27.3	25.8	89.3	5.8	78.7
Losses (% mean net returns)	−2.5	−0.4	−1.7	−0.4	−7.3	−3.3	−3.1	−0.4	−11.0	−0.4
Net impact (% mean net returns)	33.3	99.9	50.9	92.6	2.5	24.0	22.7	88.8	−5.2	78.3
Projected net returns without climate change (US$)	3560	2396	3560	2396	3560	3560	3560	2396	3560	2396
Projected net returns with climate change (US$)	4747	4791	5373	4617	3649	4416	4369	4525	3376	4272
Change in mean net returns	33%	100%	51%	93%	2%	24%	23%	89%	−5%	78%
Projected *per capita* income without climate change (US$)	1039	794	1039	794	1039	1039	1039	794	1039	794

(*Continued*)

Table 7. (*Continued*)

Non-maize Farms	GCM E = CCSM4		GCM I = GFDL-ESM2M		GCM K = HadGEM2-ES		GCM O = MIROC5		GCM R = MPI-ESM-MR	
	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
Projected *per capita* income with climate change (US$)	1289	1298	1421	1261	1058	1219	1209	1242	1000	1189
Percent change in *per capita* income	24%	64%	37%	59%	2%	17%	16%	56%	−4%	50%
Projected poverty rate without climate change (%)	16.4	25.9	16.4	25.9	16.4	16.4	16.4	25.9	16.4	25.9
Projected poverty rate with climate change (%)	13.3	13.2	11.8	13.6	16.5	14.2	16.4	14.0	17.7	14.6
Change in poverty rate	−3.1	−12.6	−4.6	−12.2	0.1	−2.2	0.0	−11.9	1.3	−11.3
Maize farms										
Projected mean yield (millet) (kg/ha)	1214	1214	1214	1214	1214	1214	1214	1214	1214	1214
Mean yield change (millet) (%)	6	11	52	7	−22	−8	5	2	−38	−10
Projected mean yield (peanut) (kg/ha)	1041	1041	1041	1041	1041	1041	1041	1041	1041	1041
Mean yield change (peanut) (%)	6	17	−5	13	−20	11	−7	10	−16	8
Projected mean yield (maize) (kg/ha)	3858	3858	3858	3858	3858	3858	3858	3858	3858	3858
Mean yield change (maize) (%)	−32	−15	−34	−10	−62	−18	−41	−9	−57	−23
Losers (%)	22	18	17	19	72	24	30	20	79	27
Gains (% mean net returns)	24.7	36.8	41.9	35.3	3.4	24.9	17.3	31.4	2.5	21.1

(*Continued*)

Table 7. (*Continued*)

Non-maize Farms	GCM E = CCSM4		GCM I = GFDL-ESM2M		GCM K = HadGEM2-ES		GCM O = MIROC5		GCM R = MPI-ESM-MR	
	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
Losses (% mean net returns)	−3.5	−3.5	−3.8	−3.7	−15.3	−4.0	−4.7	−3.6	−19.0	−4.6
Net impact (% mean net returns)	21.3	33.3	38.1	31.6	−11.9	20.9	12.6	27.8	−16.5	16.5
Projected net returns without climate change (US$)	5482	5482	5482	5482	5482	5482	5482	5482	5482	5482
Projected net returns with climate change (US$)	6648	7310	7568	7214	4829	6628	6173	9608	4576	6389
Change in mean net returns	21%	33%	38%	32%	−12%	21%	13%	75%	−17%	17%
Projected *per capita* income without climate change (US$)	1338	1338	1338	1338	1338	1338	1338	1338	1338	1338
Projected *per capita* income with climate change (US$)	1557	1682	1731	1664	1215	1554	1468	2114	1167	1509
Percent change in *per capita* income	16%	26%	29%	24%	−9%	16%	10%	58%	−13%	13%
Projected poverty rate without climate change (%)	11.9	11.9	11.9	11.9	11.9	11.9	11.9	11.9	11.9	11.9
Projected poverty rate with climate change (%)	11.0	10.9	11.0	11.1	12.9	11.4	11.6	11.1	13.6	11.7
Change in poverty rate	−0.9	−1.0	−0.9	−0.8	1.0	−0.5	−0.3	−0.8	1.7	−0.2

(*Continued*)

Table 7. (*Continued*)

Non-maize Farms	GCM E = CCSM4		GCM I = GFDL-ESM2M		GCM K = HadGEM2-ES		GCM O = MIROC5		GCM R = MPI-ESM-MR	
	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
All farms										
Losers (%)	19	10	14	11	59	12	25	11	70	15
Gains (% mean net returns)	30.0	60.7	47.0	57.0	6.4	26.0	21.3	53.2	4.0	42.8
Losses (% mean net returns)	−3.0	−2.3	−2.8	−2.4	−11.5	−3.6	−4.0	−2.4	−15.2	−3.0
Net impact (% mean net returns)	27.0	58.4	44.1	54.5	−5.1	22.4	17.4	50.7	−11.2	39.8
Projected net returns without climate change (US$)	4368	3694	4368	3694	4368	4368	4368	3694	4368	3694
Projected net returns with climate change (US$)	5546	5850	6296	5708	4145	5346	5127	5568	3880	5162
Change in mean net returns	27%	58%	44%	55%	−5%	22%	17%	51%	−11%	40%
Projected *per capita* income without climate change (US$)	1188	1066	1188	1066	1188	1188	1188	1066	1188	1066
Projected *per capita* income with climate change (US$)	1423	1490	1576	1463	1136	1386	1339	1433	1084	1349
Percent change in *per capita* income	20%	40%	33%	37%	−4%	17%	13%	34%	−9%	27%
Projected poverty rate without climate change (%)	14.2	18.9	14.2	18.9	14.2	14.2	14.2	18.9	14.2	18.9
Projected poverty rate with climate change (%)	12.1	12.1	11.4	12.4	14.7	12.8	12.9	12.5	15.6	13.1
Change in poverty rate	−2.0	−6.8	−2.7	−6.5	0.5	−1.4	−1.3	−6.3	1.5	−5.8

NB: The poverty line is equal to FCFA204845, i.e., US$ 409.69 (1$=500 FCFA).

Core Question 3: What Are the Benefits of Climate Change Adaptations?

Impact of adaptation on crop productivity

Maize

Maize yields simulated by DSSAT based on the use of adapted cultivar ranged from 433 kg/ha for HadGEM2-ES to 766 kg/ha for CCSM4 in Nioro, and from 791 kg/ha for HadGEM2-ES to 995 kg/ha for CCSM4 for Navrongo (Table 8). Comparison between grain yields with and without the use of adapted cultivar indicates yield increments of between 29% and 30% in Nioro, which are different from those obtained for Navrongo (33% and 34%). In Nioro, the statistical analysis indicated that maize yields with the adapted cultivar under the five GCMs were significantly lower ($p < 0.05$) than the yields under the baseline climate and baseline cultivar. The variability in the yield of adapted cultivar was between 29% and 37% in the case of Nioro and between 41% and 43% in Navrongo.

For APSIM, the simulated yields based on the use of adapted cultivar in Nioro ranged from 948 to 1123 kg/ha, while those of Navrongo ranged from 988 kg/ha to

Table 8. Simulated mean yield of maize, millet, and peanut by DSSAT and APSIM under future climate scenarios with the use of adaptation technology for Nioro, Senegal and Navrongo, Ghana.

Nioro	Maize (kg/ha)		Millet (kg/ha)		Peanut (kg/ha)	
Climate scenario	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
GFDL-ESM2M_I	751	1123	587	907	291	691
CCSM4_E	766	1049	393	882	327	716
MIROC5_O	673	1123	424	924	288	672
MPI-ESM-MR_R	493	968	241	858	259	663
HadGEM2-ES_K	433	948	291	848	246	683
LSD (0.05)	66	134	48	31	28.1	29

Navrongo	Maize (kg/ha)		Millet (kg/ha)		Peanut (kg/ha)	
Climate scenario	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
GFDL-ESM2M_I	865	1030	446	409	388	643
CCSM4_E	995	1006	484	393	368	604
MIROC5_O	924	995	450	393	357	598
MPI-ESM-MR_R	860	1017	418	469	357	681
HadGEM2-ES_K	791	988	385	383	328	624
LSD (0.05)	130	213	77	19	16	26

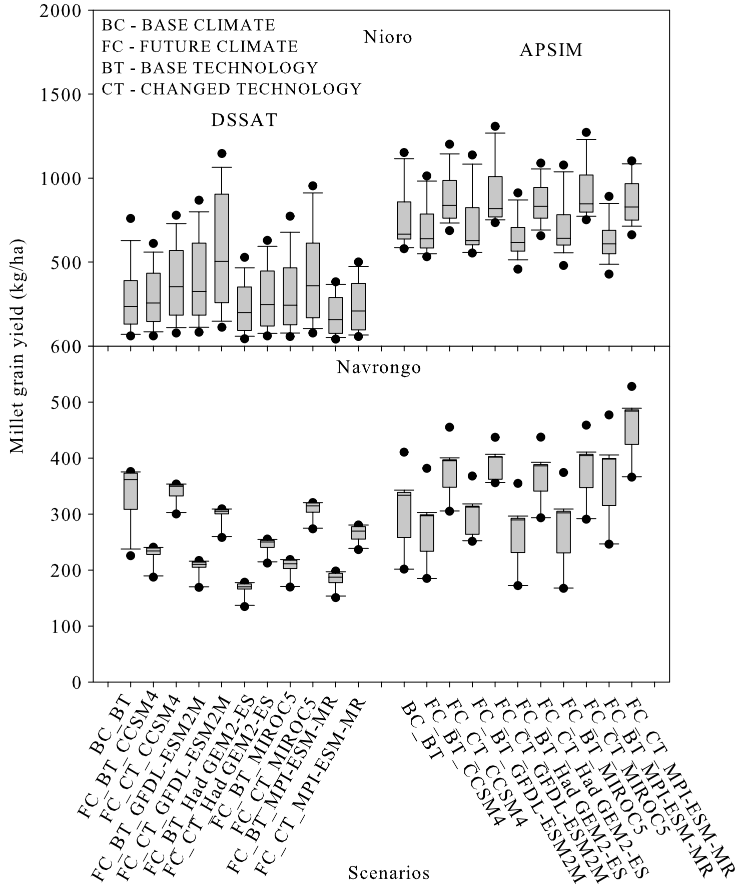


Fig. 13. Simulated variability in millet yields with current base technology (BT) compared to adapted future changed technology (CT) under climate change scenarios for Nioro, Senegal and Navrongo, Ghana.

1030 kg/ha. These translate into yield increments of between 48% (HadGEM2-ES) to 50% (GFDL-ESM2M) in Nioro and from 9% (MIROC5) to 12% (HadGEM2-ES) in Navrongo. HadGEM2-ES produced the lowest grain yields while GFDL-ESM2M and MIROC5 produced the highest grain yields in Nioro. Simulated yield variability of the adapted cultivar was higher (64% to 66%) in Navrongo than in Nioro (44% to 48%). The magnitude of the impact of the adaptation package varied across sites and crop models.

Millet

In Nioro, the yield of millet with the adapted cultivar simulated by DSSAT ranged from 241 kg/ha to 587 kg/ha while those for Navrongo ranged between 385 to

484 kg/ha. The lowest and highest yields were obtained from MPI-ESM-MR and GFDL-ESM2M, respectively, for Nioro, whereas at Navrongo, HadGEM2-ES and MIROC5 showed the lowest and highest yields respectively. The direction of impact of the adapted cultivar was the same between sites, whereas the magnitude of the impact differed (Fig. 13). Comparison between yields for current system with climate change scenario with and without adaptation indicates a yield increase of between 28% and 44% in Nioro and from 32% to 34% in Navrongo. Variability in yields with adapted cultivar was high for Nioro, ranging from 63% to 73% and from 41% to 43% for Navrongo.

Simulated millet yields for APSIM using adapted cultivar ranged from 848 to 924 kg/ha in Nioro and between 383 and 469 kg/ha in Navrongo. The least and the highest yields were obtained with HadGEM2-ES and MIROC5, respectively, for Nioro and HadGEM2-ES and MPI-ESM-MR, respectively, for Navrongo. Using future climate projections with and without adaption resulted in yield increases of between 26% and 39% in Nioro and between 10% and 11% in Navrongo. Variability in simulated yields with the adapted cultivar ranged from 16% to 21% for Nioro and from 64% to 66 % for Navrongo. Simulated yields for all GCMs with the use of adapted cultivar were significantly higher than those with the base cultivar for both sites and models.

Peanut

Simulated yields of peanut using DSSAT for both sites ranged between 246 to 327 kg/ha across GCMs for Nioro and 328 kg/ha to 388 kg/ha for Navrongo. A comparison between yields obtained for current production system with climate change scenarios with and without adaptation indicates yield increments of 18% for Nioro and between 12 and 13% for Navrongo. The lowest yield was produced by HadGEM2-ES at both sites while the highest yields were from CCSM4 and GFDL-ESM2M for Nioro and Navrongo, respectively. Variability in the yields was lower in Navrongo with values between 23% and 25 % across the GCMs while it ranged from 51% to 54% in Nioro.

For APSIM, simulated yields ranged from 663 to 716 kg/ha across GCMs for Nioro and between 598 kg/ha and 681 kg/ha for Navrongo. Comparisons of yields obtained with and without the use of adapted cultivars indicate yield increases of 7% to 8% at both sites. Variability in yields of adapted cultivar was similar on both sites (22% to 24% in Nioro and 39% to 45% in Navrongo). The highest yield was attained under CCSM4 and MPI-ESM-MR while the lowest yields were simulated under MPI-ESM-MR and MIROC5 for Nioro and Navrongo, respectively. Variability in the yield of adapted cultivar was higher with for APSIM compared to DSSAT. While the impact of adaptation was positive in both models, the magnitudes of the effects

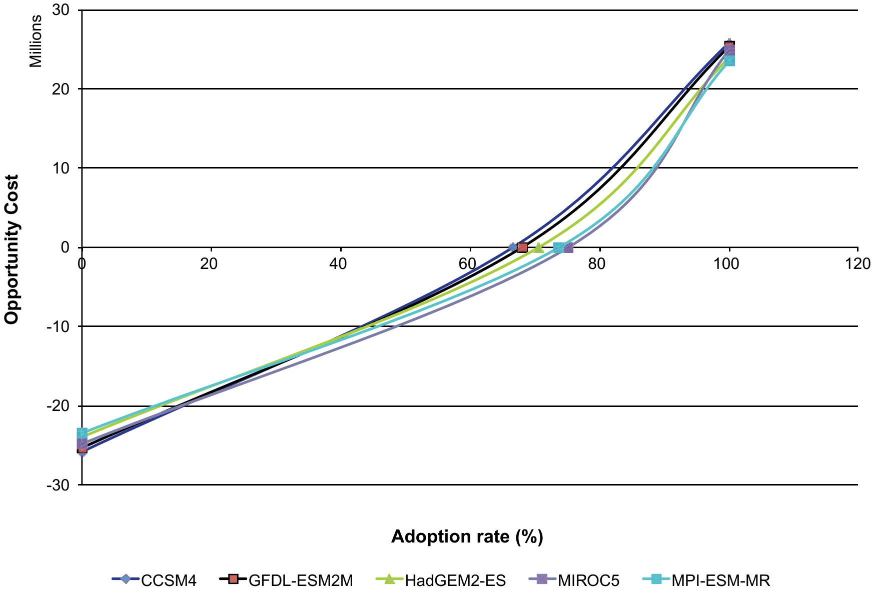


Fig. 14. Opportunity cost and adoption rate for adaptation package simulated with DSSAT under climate change scenarios for Nioro, Senegal.

varied between sites and were not consistent among the crops simulated. Both crop models simulated a general increase in yield and also positive effects of adaptation strategies under future systems (use of adapted cultivars).

Impact of adaptation on farmers' livelihoods

When adaptation to climate change is possible, we notice a dramatic positive change in all the economic indicators in Nioro. A majority of farmers are now better off in all the economic indicators examined. For Nioro, under DSSAT, the adaptation process results in at least 68% of farms that adopt the adaptation package. Adoption rates vary between 68% and 78% (Table 9 and Fig. 14).

Mean net returns per farm increase between 12% and 22% with DSSAT and between 10% and 19% with APSIM. Under the APSIM model, *per capita* income increases on average by $163 (i.e., 11%) and reaches a maximum increase of $217 (i.e., 15%; Fig. 15). There is more dispersion with inputs from DSSAT simulations. *Per capita* income increases 13% on average. Poverty rates display record low levels, between 11% and 14%. This is because poverty drops by large proportions with both crop models.

Table 9. The benefits of climate change adaptations for the Nioro, Senegal cropping system.

Non-maize Farms	GCM E = CCSM4		GCM I = GFDL-ESM2M		GCM K = HadGEM2-ES		GCM O = MIROC5		GCM R = MPI-ESM-MR	
	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
Projected mean yield without adaptation (millet) (kg/ha)	1202	1199	1656	1150	915	1071	1159	1143	736	1032
Mean yield change (millet) (%)	36	22	44	25	29	29	40	31	35	35
Projected mean yield without adaptation (peanut) (kg/ha)	1253	1282	1113	1239	948	1210	1088	1195	991	1173
Mean yield change (peanut) (%)	19	12	18	12	18	13	19	12	18	13
Projected mean yield without adaptation (maize) (kg/ha)	—	—	—	—	—	—	–	—	—	—
Mean yield change (maize) (%)	—	—	—	—	—	—	—	—	—	—
% adoption rate	80	66	75	68	68	71	74	72	69	74
Projected net returns without adaptation (US$)	4778	4822	5404	4647	3680	4446	4400	4556	3406	4303
Projected net returns with adaptation (US$)	5900	5269	6524	5142	4152	5020	5207	5174	3910	4965
Change in mean net returns	23%	9%	21%	11%	13%	13%	18%	14%	15%	15%
Projected *per capita* income without adaptation (US$)	1295	1305	1427	1268	1064	1226	1216	1249	1007	1195

(*Continued*)

Table 9. (*Continued*)

Non-maize Farms	GCM E = CCSM4		GCM I = GFDL-ESM2M		GCM K = HadGEM2-ES		GCM O = MIROC5		GCM R = MPI-ESM-MR	
	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
Projected *per capita* income with adaptation (US$)	1532	1399	1663	1372	1164	1346	1386	1379	1113	1335
Percent change in *per capita* income	18%	7%	17%	8%	9%	10%	14%	10%	11%	12%
Projected poverty rate without adaptation (%)	13.2	13.1	11.7	13.5	16.3	14.1	14.0	13.8	17.5	14.4
Projected poverty rate with adaptation (%)	11.7	12.3	10.4	12.5	15.0	12.8	12.5	12.5	16.0	12.8
Change in poverty rate	−1.4	−0.8	−1.3	−1.0	−1.3	−1.3	−1.5	−1.4	−1.5	−1.6
Maize farms										
Projected mean yield without adaptation (millet) (kg/ha)	1290	1352	1845	1301	953	1123	1269	1235	752	1087
Mean yield change (millet) (%)	35	17	44	15	27	28	40	30	32	35
Projected mean yield without adaptation (peanut) (kg/ha)	1107	1219	985	1177	830	1154	967	1140	872	1121
Mean yield change (peanut) (%)	14	12	14	12	14	13	14	12	14	13
Projected mean yield without adaptation (maize) (kg/ha)	2632	3274	2545	3479	1462	3148	2289	3511	1669	2954

(*Continued*)

Table 9. (*Continued*)

Non-maize Farms	GCM E = CCSM4		GCM I = GFDL-ESM2M		GCM K = HadGEM2-ES		GCM O = MIROC5		GCM R = MPI-ESM-MR	
	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
Mean yield change (maize) (%)	26	44	36	47	30	38	30	47	31	48
% adoption rate	77	67	73	68	67	70	72	78	69	73
Projected net returns without adaptation (US$)	6713	7438	7694	7340	4938	6751	6291	6753	4683	6510
Projected net returns with adaptation (US$)	8094	8284	9297	8216	5465	7724	7378	8368	5280	7706
Change in mean net returns	21%	11%	21%	12%	11%	14%	17%	24%	13%	18%
Projected *per capita* income without adaptation (US$)	1570	1706	1754	1688	1235	1577	1490	1577	1187	1531
Projected *per capita* income with adaptation (US$)	1829	1865	2056	1852	1335	1760	1695	1881	1300	1756
Percent change in *per capita* income	17%	9%	17%	10%	8%	12%	14%	19%	9%	15%
Projected poverty rate without adaptation (%)	10.9	10.7	10.8	10.8	12.5	11.1	11.3	11.8	13.2	11.4
Projected poverty rate with adaptation (%)	10.4	11.0	11.4	11.0	12.4	11.3	11.5	11.0	13.0	11.4
Change in poverty rate	−0.5	0.3	0.6	0.2	−0.1	0.2	0.2	−0.8	−0.2	0.0

(*Continued*)

Table 9. (*Continued*)

Non-maize Farms	GCM E = CCSM4		GCM I = GFDL-ESM2M		GCM K = HadGEM2-ES		GCM O = MIROC5		GCM R = MPI-ESM-MR	
	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM
All farms										
Adoption rate (%)	78	67	74	68	68	71	73	75	69	74
Projected net returns without adaptation (US$)	5591	5922	6367	5779	4209	5415	5195	5479	3943	5231
Projected net returns with adaptation (US$)	6822	6536	7690	6434	4704	6157	6120	6517	4486	6117
Change in mean net returns	22%	10%	21%	11%	12%	14%	18%	19%	14%	17%
Projected *per capita* income without adaptation (US$)	1432	1505	1591	1478	1150	1401	1353	1413	1097	1363
Projected *per capita* income with adaptation (US$)	1681	1632	1860	1612	1249	1553	1540	1630	1206	1546
Percent change in *per capita* income	17%	8%	17%	9%	9%	11%	14%	15%	10%	13%
Projected poverty rate without adaptation (%)	12.0	11.9	11.2	12.2	14.4	12.6	12.7	12.8	15.4	12.9
Projected poverty rate with adaptation (%)	11.1	11.6	10.9	11.7	13.7	12.0	12.0	11.7	14.5	12.1
Change in poverty rate	−1.0	−0.3	−0.3	−0.4	−0.7	−0.6	−0.7	−1.1	−0.9	−0.8

NB: The poverty line is equal to FCFA204845, i.e., US$ 409.69 (1$=500 FCFA).

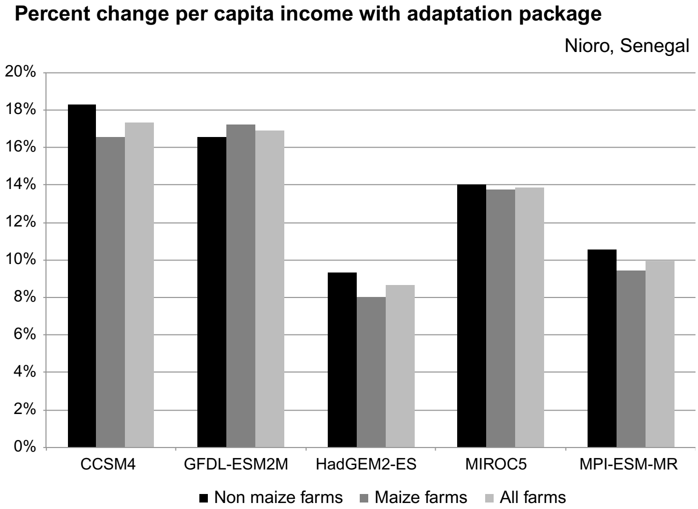


Fig. 15. Effect of climate change with adaptation on the percentage change in *per capita* income of farmers in Nioro, Senegal.

Conclusions and Next Steps

This study has shown that projected climate change as shown by the five GCMs would adversely affect the productivity of cereals in Nioro, Senegal and Navrongo, Ghana under the current production system. Simulated impacts of climate change without adaptation were severe in the Nioro and Navrongo, given that climate projections and crop yield simulations in the two areas show similar dynamics, despite slight differences in projected yield, temperature, and rainfall levels. The simulated impact of climate change was also higher with DSSAT than APSIM. The use of base technology (i.e., current crop varieties) most often resulted in lower yield under future climate scenarios.

This study has shown that farmers in Nioro du Rip, Senegal may witness varying levels of negative impacts in their net per farm revenues and *per capita* income, and increases in poverty rates under hypothesis of climate change without adaptation. Using current crop varieties in the context of projected future rainfall regimes will result in lower productivity (based on DSSAT and APSIM models), and thus lower returns.

Taking into account the RAPs, farmers may experience significant gains in their net revenues; *per capita* income and declines in poverty levels in the future even under climate change in Nioro. When we account for adaptation, as well as future increases in agricultural development, most farmers in Nioro may gain from climate change. The adoption rate of the adaptation package reaches a minimum of 64% for Nioro on aggregate. Adaptation strategies may offset some of the negative impacts of climate change on agriculture in SSA. In some circumstances, the net impact of climate change may be positive. Thus, it is critical to design the right measures and incentives and to ensure that climate-resilient strategies are adopted. Further consultations with stakeholders will be intensified in future studies to enable them to apply the outcome of study. This will also facilitate the process of dissemination of the results. More of the adaptation packages that were identified with stakeholders will be explored in future studies.

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