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The potential impact of climate change on agriculture in West Africa: A bio-economic modeling approach

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Abstract

This paper investigates the impact of climate change on agriculture in the Economic Community of West African States (ECOWAS). To that end, a bio-economic model is built and calibrated on 2004 base year dataset and the potential impact is evaluated on land use and crop production under two representative concentration pathways (RCPs) coupled with three socio-economic scenarios (SSPs). The findings suggest that land use change may depend on crop types and prevailing future conditions. As of crop production, the results show that paddy rice, oilseeds, sugarcane, cocoa, coffee, and sesame production could experience a decline under both moderate and harsh climate conditions in most cases. Also, doubling crop yields by 2050 could overall mitigate the negative impact of moderate climate change. The magnitude and the direction of the impacts may vary in space and time.

Key words: Climate change mitigation; Socio-economic scenarios; Integrated assessment models

1. Introduction

Climate change is one of the serious threats recognized to hamper the ability to supply food in order to meet global growing demand and specifically the demand in sub-Saharan Africa (SSA) where food insecurity is prevalent (Parry et al., 2004; von Lampe et al., 2014). Climate change adds further pressure to the existing challenges in developing countries such as extreme poverty, inequality and hunger (Nelson et al., 2010; IPCC, 2014a, 2014b). Indeed, climate change is expected to hamper food production in the future. It is recognized that climate change is already reducing the productivity of major crops, and will greatly affect agricultural supply (Roudier et al., 2011; Di Falco et al., 2012). Agriculture in developing countries, which is mainly rain-fed, is predicted to be seriously impacted by climate change (Tol, 2002; Fischer et al., 2005; Mendelsohn et al., 2006). Unlike the net revenue from African crops that was predicted to likely fall with warming, the net revenue from African livestock was predicted to increase across scenarios (Seo and Mendelsohn, 2008a, 2008b; Seo et al., 2009).

Despite its negative dimensions, climate change is also expected to provide opportunities for improvements in certain aspects of farming systems (Gornall et al., 2010). For instance, Seo (2013) shows that it is possible for farmers to take upfront actions against climate change impacts even if there are only a few possibilities to avoid weather shocks. Therefore, there is a need to identify the most relevant adaptation strategies to help farmers adapt to climate shocks.

In order to identify these adaptation strategies, the magnitude of the climate change threats must first be estimated. There is a variety of economic models that have been developed to investigate the effects of climate change on agricultural production. These models span from large-scale (Butt et al., 2005; Medellin-Azuara et al., 2011) to small-scale bio-economic models (Pinky and Rayhan, 2013; Lokonon et al., 2015). In addition to impact evaluation, bio-economic models are used for policy simulations such as agricultural and adaptation policy simulations (Louhichi and y Paloma, 2014) and environmental policy simulations (Egbendewe-Mondzozo et al., 2011; Bamière et al., 2011; Egbendewe-Mondzozo et al., 2015).

Although earlier studies provide useful measures of the impact of climate change on agriculture at either a continental or national scale in Africa, there remains a question of how these effects vary across the landscapes (Seo et al., 2009). The effects of climate change will differ across agro-ecological (AEZs) and agro-climatic zones (ACZs) in Africa (Seo et al., 2009; van Wart et al., 2013). The Food and Agriculture Organization (FAO) of the United Nations defines AEZs as geographic units having similar climate and soils for agriculture, and ACZs as divisions of a region based on homogeneity in weather variables that have the greatest influence on crop growth and yield (van Wart et al., 2013). In other words, while AEZs help to broadly define environments where specific agricultural systems may thrive, ACZs seek to more adequately distinguish between the diversity of practices for similar agricultural systems within the larger agro-ecological zones, primarily in terms of different climates (van Wart et al., 2013).

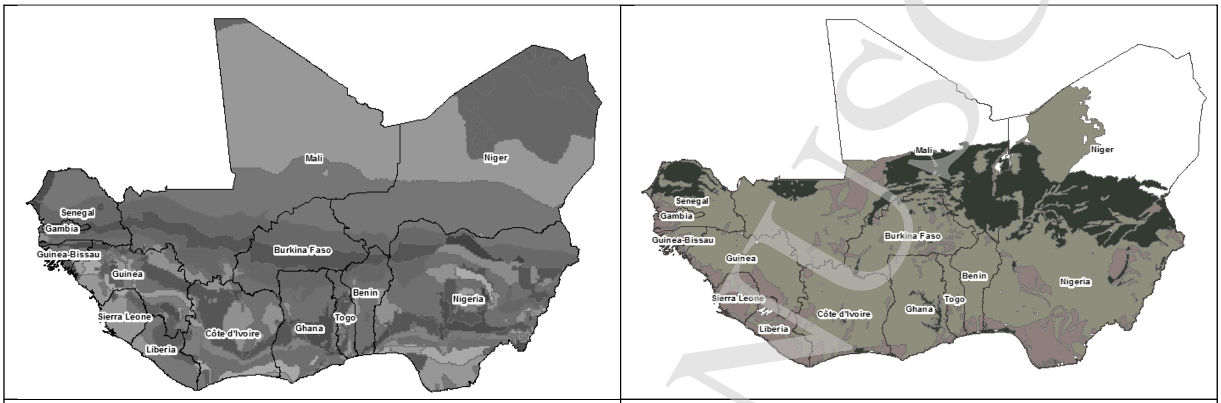
This paper aims at shedding light on the impacts of climate change on land allocation and crop production across ECOWAS through a bio-economic model built from ACZs perspective under different climate and socio-economic scenarios. Compared to previous studies on the impact of climate change on agricultural production in ECOWAS and in Africa in general, this paper innovates through an integration of socio-economic and climate scenarios into a regional bio-economic model with detailed time-space dimensions of climate and soil in West Africa. Therefore, it is possible to compare several geographic units in West Africa in terms of land allocations and agricultural production under various socio-economic and climate scenarios.

The remainder of the paper is organized as follows. Sections 2 and 3 describe the main components of the bio-economic model. The main results are presented in section 4. In section 5, we conclude with a discussion of key findings, policy implications as well as implications for future research.

2. Materials and methods

The ECOWAS regroups 15 countries, namely The Republic of Benin, Burkina Faso, Cape Verde, Cote d'Ivoire, The Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone, and Togo (Figure 1). It covers 5.1 million square kilometers of land area with about 339,860,900 inhabitants as of 2014. Agriculture is the major source of food supply in the sub-region and employs about 60 percent of the labor force, but contributes only on average about 35 percent to the Gross Domestic Product (GDP) of the States (Jalloh et al., 2013). Farmers in the ECOWAS produce mainly for subsistence due to poverty and face numerous constraints such as changing climate, soil acidity, nutrient depletion and soil degradation which negatively affect agricultural development in the sub-region (Jalloh et al., 2013). The main food crops grown and consumed in the ECOWAS are: cereals (maize, sorghum, millet, and rice), roots and tubers (cassava, sweet potatoes, and yams), and legumes (cowpeas and groundnuts), while the major cash crops are cocoa, coffee, and cotton (Jalloh et al., 2013). In this study, the sub-region is divided into 39 ACZs (Sebastian, 2014). Furthermore, soils are grouped into three types namely loam, clay and sand to obtain Agro-Climatic and Soil Zones (ACSZs) in order to account for soil characteristics in the yield estimation (see Figure 1).

Figure 1. Maps of ACZs and soils in ECOWAS



Agro-climatic zones
Source: van Wart et al. (2013)

Main soil types
Source: FAO (2015a)

2.1 The Structure of the Bio-economic Model

This research relies on a bio-economic modeling framework with a representative risk-neutral profit maximizing agent in an integrated assessment setting. The model integrates both biophysical and geographic information system (GIS) into a regional economic mathematical programming model. The model is built drawing on previous partial equilibrium regional bio-economic modeling framework (McCarl and Spreen, 1980; Chang, 2002; Spreen, 2006). For instance, the U.S Agricultural Sector Model (ASM), which is a spatial mathematical programming model, is used to simulate market equilibrium effects for resources (land, water and labor) and commodities such as primary and secondary or processed goods (Chang et al., 1992; Attwood et al., 2000). The Taiwan Agricultural Sector Model (TASM), which is a price-endogenous spatial equilibrium model, is used to assess the impact of crop yield changes on Taiwanese regional production, land use, welfare distribution, as well as the potentials for Taiwanese agriculture to adapt to climate change (Chang, 2002). In addition, Howitt et al. (2009)

used a Statewide Agricultural Production Model (SWAP), a price-endogenous optimization model calibrated with the Positive Mathematical Programming (PMP) approach, to estimate impacts of climate change on agricultural revenues in California. In this current paper, climatic factors such as temperature, precipitation, as well as non-climatic factors such as soil fertility, demography, output and input prices are exogenous in the model. Only land areas chosen under various cropping systems are endogenous. Crop yields are supplied to the bio-economic model by an econometric crop yields' simulator component. The GIS component supplies parameters related to the ACSZs such as crop and livestock land use. The economic mathematical programming model is a spatial optimization model that uses all the exogenous parameters to determine land allocation between cropping systems (maximization of the profit subject to resources constraints). The general structure of the bio-economic model is summarized in the Appendix 1.

2.1.1 Crop yield model

Crop yields are generated using climate data from two Representative Concentration Pathways (RCPs). Following Chang (2002), a regression approach is adopted to estimate crop yields. Average 2004 crop yields from the 39 ACZs under three soil types are collected and used in the econometric regressions. An econometric approach is used owing to the fact that the paper does not aims to estimate environmental outcomes such as agricultural runoffs and emissions. In addition, the model does not account for crop rotations and other management practices that may improve or deteriorate environmental conditions such as soil nutrient contents. Climate and non-climate variables are often used to estimate crop yield response models (Chang, 2002). This study assumes that crop yields are dependent only on climate and soil conditions. Actually, agriculture is mainly rain-fed in ECOWAS countries, and the use of technologies and fertilizers is not widespread and remains marginal. However, variations may arise in similar environmental conditions, due to technological change. Hence, in the study, we adjusted the result to account for technological change effects. The econometric crop yields' estimation model in its general form is given as:

$$yield = Z\left[f\left(climate, soils\right)\right] (1)$$

This model is used for each crop and group of crops included in the analyses at ACZ level. Long-run (1975-2004; 30 years) average temperature, and precipitation from May to November are assumed to be the major climatic factors prevailing during the phenological stages of crop development. Thus, climate data used are relative to the long-run average (30 years), not the weather in 2004. Soil types are included in the model to account for land characteristics. Based on this general form of the model where Z represents the effect of technological change, the following empirical model is used to estimate crop yield response:

$$yield_{ACZ} = Zf\left(temp_{ACZ}, temp^2_{ACZ}, vtemp_{ACZ}, precip_{ACZ}, precip^2_{ACZ}, vprecip_{ACZ}, clay_{ACZ}, loam_{ACZ}\right) (2)$$

where, *yield* is crop yield per ha *temp* is the average monthly temperature (in °C), *vtemp* is the monthly variability of the temperature captured by the variance from April to November, *precip* refers to total precipitation from April to November (in mm), *vprecip* is the monthly variability of rainfall captured by the variance, *clay*, and *loam* are dummy variables which help capture the effect of land characteristics on crop yields.

The non-linear effects of climate variables on crop yields are taken into account. Therefore, linear and quadratic terms of climate variables are included to be in line with the notion of the physiological optimum (Kaufmann & Snell, 1997; Chang, 2002; McCarl et al., 2008). Moreover, variables relative to rainfall and temperature variation are included in the model to capture the effects of variability in climate conditions and their omission may bias the analyses (Mendelsohn et al., 1996). The dynamic of the technological progress is captured by equation (3) to avoid non-stationary process and given as follows:

$$\log\left(Z_t\right)=0.06*\left(\frac{t}{1+t}\right)^{60}+0.98*\log\left(Z_{t-1}\right)+U_t;\, Z_0=1 \quad (3)$$

Where U_t is a positive white noise process with a truncated normal distribution $\aleph(0,0.005)$. The idea behind this technological progress formulation is to allow an average yield increase of 1% each year (Egbendewe et al., 2017). This total factor productivity growth rate of 1% implies doubling crop yields only after a century, and reflects the deceptive technical change rate observed in the West African region's agriculture in recent years (Nin-Pratt and Yu, 2008; Nin-Pratt et al., 2010). The results of the yield regression are presented in Appendix 2.

2.1.2 GIS component of the bio-economic model

GIS is used to design a consolidated map of ACZs, soils, land use, countries, river basins, and river sub-basins. Agricultural production decisions take place at the ACZ level. However, information about country, basin and sub-basin shares of ACZs are used to aggregate land allocation and agricultural production at country, sub-basin and basin levels. Five major basins in ECOWAS namely Niger basin, Volta basin, Gambia basin, Senegal basin, and Lake Chad basin are considered in the model. Cropland information per ACZs are obtained from land use map from previous research (van Wart, et al., 2013; Sebastian, 2014; FAO, 2015a) to compute land shares, which are used as aggregation coefficient for the modeling outputs.

2.1.3 Economic mathematical programming model

We consider a farming system characterized by seven crops and four livestock types. As in the Global Trade Analysis Project (GTAP), crops and crop groups such as paddy rice, cereals (maize, sorghum, and millet), vegetable and fruits (bananas, cassava, plantains, potatoes, sweet potatoes, and yam), oil seeds (beans, cashew nuts, cowpeas, groundnuts, and soybeans), sugarcane, cotton and other crops (cocoa, coffee, and sesame) are considered. The livestock types are cattle, sheep, chicken and others. This paper models economic behavior from the standpoint of a representative risk-neutral farmer endowed with land resources in each ACSZ described by resource vector B that chooses among a set of crop production activities X so as to maximize the farm's profit. Following Howitt (1995), the problem of the representative farmer can be captured by a positive mathematical programming (PMP) calibration technique which relies on decreasing marginal yields assumption, to replicate closely the observed mix of activities in the ECOWAS region. In its general form, the problem can be expressed as:

$$\underset{X}{Max} f(X) + a' X - \frac{1}{2} X' M X (4)$$

Subject to

$$A X \leq B (5)$$

where X is of dimension $I \times 1$, A is $m \times I$, and B is $m \times 1$. A is the matrix of crop yield coefficients. The set of land resource availability constraints is captured by constraint (5). The coefficient a refers to a $I \times 1$ vector of base yield constants and M is a $I \times I$ positive definite matrix of linear yield slopes that captures declining marginal product with expanding land use. The values of a and M are calculated from the land resource shadow prices, observed output market prices and the observed activity levels from an intermediate linear programming model constrained by actual observed activity levels. All other linear expressions not related to yields are included in the component $f(X)$ of the objective function. The resulting calibrated model is used to predict land use and food production responses to future socio-economic conditions under global climatic change.

3. The empirical bio-economic model

The empirical bio-economic model is built on the economic behavioral assumption that a representative farmer would select among a set of seven cropping systems to which the farmer allocates land resources to maximize returns over stated costs. As abovementioned, the modeling region is composed of the ECOWAS member countries. However, Cape Verde is not included in the modeling owing to data unavailability. Consequently, given average crop yields as well as production costs, the representative farmer allocates resources among various cropping systems to grow crops that maximize returns within each ACSZ. The mathematical statement of the empirical model is a quadratic program expressed as:

$$\underset{X_{zis},h_{zd}}{Max} \sum_{z=1}^{39} \sum_{i=1}^{7} \sum_{k=1}^{14} \sum_{s=1}^{3} \left[\rho_{kz} p_{ki} \left(\varphi_{zkis} X_{zis} - \delta_{zkis} X_{zis}^{2} \right) - \sum_{d=1}^{12} c_{zid} X_{zis} \right] (6)$$

Subject to

$$\sum_{i=1}^{7} X_{zis} \leq \beta_{zs}, \forall z=1¿39, s=1¿3 (7)$$

$$\sum_{s=1}^{3} \sum_{i=1}^{7} \alpha_{id} X_{zis} \leq f_{zd} + h_{zd}, \forall z=1¿39, d=1¿12 (8)$$

$$\sum_{i=1}^{7} \sum_{s=1}^{3} m_{zi} X_{zis} + \sum_{d=1}^{12} w_{zd} \frac{h_{zd}}{\mu} + \sum_{i=1}^{7} \sum_{s=1}^{3} q_{z} X_{zis} \leq \gamma_{z} \forall z=1¿39 (9)$$

The sets, parameters, and variables used in the model are defined in Table 1.

The objective function (6) contains two expressions. The first expression ($\sum_{z=1}^{39}\sum_{i=1}^{7}\sum_{k=1}^{14}\sum_{s=1}^{3}\rho_{kz}\,p_{ki}\left(\varphi_{zkis}X_{zis}-\delta_{zkis}X_{zis}^{2}\right)$) is the total crop production revenue from all crops and groups of crops. The term $\left(\varphi_{zkis}X_{zis}-\delta_{zkis}X_{zis}^{2}\right)$ defines the quadratic output level obtained by multiplication of the linear calibrated marginal yield expression $\left(\varphi_{zkis}-\delta_{zkis}X_{zis}\right)$ by the quantity of land X_{zis} allocated to the production of output. The second expression ($-\sum_{z=1}^{39}\sum_{i=1}^{7}\sum_{s=1}^{3}\sum_{d=1}^{12}c_{zid}X_{zis}$) represent the total variable costs across all cropping systems and land units. Equation (7) is the expression of crop land resource constraints. Equation (8) represents labor resource constraints, and equation (9) accounts for cash constraints. It should be noted that the yields in the production part of the profit function are supplied by the econometric simulations as depicted in Appendix 1. Labor supply and cash are exogenous, and they depend on the socio-economic scenarios.

Table 1. Model sets, parameters, and variables definitions

Sets, parameters, and variables	**Definition**
Sets	
i	Set of seven crops and groups of crops studied in the model
s	Set of three soil types
d	Set of 12 months of the year
t	Set of 5-year periods from 2010 to 2100 with 2004 as baseline
z	Set of 39 agro-climatic zones
k	Set of 14 countries included in the analyses
Parameters	
β_{zs}	Crop land per ACZ, and soil type (ha)
α_{id}	Labor requirement per crop and group of crops type, and per month (man-days)
p_{ki}	Crop prices per country (USD per ton)
m_{zi}	Technology costs of crop i, and per ACZ (USD)
w_{zd}	Hired labor wage per ACZ, per month (USD per man-day)
f_{zd}	Family labor per ACZ, per month (man-days)
q_z	Land costs per ACZ (USD)

γ_z	Working capital per ACZ (USD)
$\rho_{k,z}$	Crop land share of ACZs within countries
μ	Number of working days per month
Variables	
X_{zis}	Quantity of land in each ACZ allocated to crop or groups of crops i, and per soil type (ha)
h_{zd}	Hired labor to complement family labor per month in each ACZ (man-days)

3.1 Parameterization of the model

The parameters used in the bio-economic model are from several sources. In addition to crop yields, an intensive desk-survey was used to collect data on the remaining socio-economic parameters required to perform the optimization. Indeed, many socio-economic parameters used in the modeling are from previously published research (e.g., Kutcher and Scandizzo, 1981; Yilma, 2006; Paloma et al., 2012; Louhichi and Paloma, 2014; Lokonon et al., 2015). Other socio-economic parameters collected were from the World Development Indicators (WDI) (World Bank, 2015) and from the FAO database (FAO, 2015b). Some socio-economic parameters are projected from 2010 to 2100. The values and corresponding data sources of all parameters used in the baseline are given in Table 2.

Table 2. Parameters used in the empirical bio-economic model for the baseline

Parameters	Values	Units	Source
Crop prices			
Paddy rice	268.40	US$/ton	2004 average of countries from FAO (2015b)
Cereals	251.79	US$/ton	
Vegetable and fruits	247.32	US$/ton	
Oil seeds	350.03	US$/ton	
Sugarcane	15.20	US$/ton	
Cotton	353.81	US$/ton	
Other crops	679.07	US$/ton	
Land use validation parameters			
Paddy rice	350,203	ha	2004 average of countries from FAO (2015b)
Cereals	2,420,550	ha	
Vegetable and fruits	873,797	ha	
Oil seeds	1,061,422	ha	
Sugarcane	9,662	ha	
Cotton	223,339	ha	
Other crops	493,689	ha	

Mean yields			
Paddy rice	1.69	ton/ha	2004 average of countries from FAO (2015b)
Cereals	1.30	ton/ha	
Vegetable and fruits	8.92	ton/ha	
Oil seeds	0.82	ton/ha	
Sugarcane	46.98	ton/ha	
Cotton	0.90	ton/ha	
Other crops	0.44	ton/ha	
Cost parameters			
Crop labor requirement (paddy rice)	186.33	man-days/ha	Louhichi & y Paloma (2014), Lokonon et al. (2015)
Crop labor requirement (cereals)	53		
Crop labor requirement (vegetable and fruits)	71		
Crop labor requirement (oil seeds)	61		
Crop labor requirement (sugarcane)	75.96		
Crop labor requirement (cotton)	100		
Crop labor requirement (other crops)	100		
Technology costs (paddy rice)	16.85	US$/ha	Updated from Yilma (2006), Lokonon et al. (2015)
Technology costs (cereals)	22.73		
Technology costs (vegetable and fruits)	30		
Technology costs (oil seeds)	21.30		
Technology costs (sugarcane)	21.45		
Technology costs (cotton)	60.64		
Technology costs (other crops)	69.24		
Family reservation wage	16.84	US$/man-month	Updated from Yilma (2006), Lokonon et al. (2015)
Hired labor wage	84.20	US$/man-month	
Land costs	20.45	US$/ha	Updated from Louhichi & y Paloma (2014)
Other parameters			
Working capital	2.61E+10	US$/ACZ	Updated from Kutcher & Scandizo (1981)
Crop land share	15.36%		Average of countries within ACZs
Number of working days per month	25		Kutcher & Scandizo (1981)

This work relies on socio-economic scenarios to capture our uncertainty about future economic prospects of the region. Scenarios are not projections, predictions, or forecasts; rather they describe potential future conditions and how they came about (Wilkinson and Eidinow, 2008). Two axes of uncertainty structure the socio-economic scenarios: (i) short-term or long-term priorities dominate in regional governance and (ii) the state or non-state actors are the driving force of change in the region, though many other drivers play a key role in the scenario pathways (Palazzo et al., 2014). These other drivers (e.g., population, GDP, political stability) are assumed to occur in each socio-economic scenario to allow for comparisons to be made between them. This paper uses three out of the following four socio-economic scenarios (or Shared Socio-economic Pathways-SSPs) as developed by Palazzo et al. (2014):

- ✓ Cash, Control, and Calories: This scenario is about short-term priorities with state actors as the dominant force in West Africa (SSP1);
- ✓ Self-Determination: In this scenario, state actors are dominant and long-term priorities prevail in West Africa (SSP2);
- ✓ Civil Society to the Rescue?: In this scenario, non-state actors are dominant and long-term issues have priority (SSP3);
- ✓ Save Yourself: In this scenario, non-state actors are the driving force and short-term priorities dominate in West Africa (SSP4).

These three SSPs (SSP1, SSP2, and SSP4) are used to index prices and costs in the bio-economic model. Crop and livestock prices were projected based on annual inflation rates. The inflation rates differ across SSPs and across countries of the West African Economic and Monetary Union (WAEMU) and non-WAEMU countries; (i) SSP1: 6% for WAEMU countries and 12% for non WAEMU countries, (ii) SSP2: 2% for WAEMU countries and 8% for non WAEMU countries, (iii) SSP4: 8% for WAEMU countries and 15% for non-WAEMU countries.

Climate scenarios used in this study are based on a Regional Climate Model (RCM) developed in Sylla (2015). They are used to project future crop yields all else being equal. The RCP4.5, which is a mid-level future greenhouse gas (GHG) forcing and RCP8.5, which is a higher level GHG forcing are considered. Climate projections are mainly relative to precipitations and near surface temperature as well as evapotranspiration. RCP8.5 is combined with SSP4 as this RCP requires extraordinary emissions that only SSP4 can generate. RCP4.5 is combined with SSP1 and SSP2 based on the assumptions of these SSPs. Moreover, these combinations of climate and socio-economic scenarios are done drawing on previous literature such as Fischer et al. (2005) and Leclère et al. (2014).

3.2 The bio-economic model calibration

The economic-mathematical programming model was calibrated before being used for climate change impact simulation. The model calibration adopted consists of reproducing observed land use for the base year (2004). This means reproducing or obtaining the closest value of observed land use for various crops for 2004. For the calibration, we rely on the traditional PMP approach (Howitt, 1995), which is intensively used in the literature (e.g., Egbendewe-Mondzozo et al., 2011; Heckelei et al., 2012; Egbendewe-Mondzozo et al., 2015). This method is popular for calibrating regional bio-economic models (Howitt, 1995; Rohm and Dabbert, 2003). The strength of this approach is in the fact that the model's solution is close to the observed data (Kanellopoulos et al., 2010). The usual three steps of the PMP approach are followed during the calibration process. Firstly, a raw linear programming model is run to understand the model behavior. We found that only vegetable and fruits (bananas, cassava, plantains, potatoes, sweet potatoes, and yam) are grown in all ACZs. Secondly, we rerun the simulation model, in which land use is constrained by the observed countries cropland for the years 2004 in order to replicate the observed cropland for this years at the country level. Finally, the shadow prices from the second step are used to calculate the coefficients of the marginal yield functions, which are then used to calibrate the model as a nonlinear quadratic optimization model under the assumption of a decreasing linear marginal yield.

Following this calibration process, the model is able to predict cropland allocation at country level for the year 2004 with an average absolute percentage deviation of 13.9%, which is within the acceptable range in modeling farmer behavior (Hazell and Norton, 1986; Howitt, 1995). These predicted cropland allocations and crop productions are reported in Table 3. Land use, and productions differ across countries, showing the disparities in agricultural conditions. Three groups of crops are not produced by certain countries and these are sugarcane in The Gambia, cotton in Liberia and Sierra Leone and cocoa, coffee and sesame in Guinea Bissau and Niger.

Table 3. Land use and production in 2004

	Land use (1000 ha)							**Production (1000 tons)**						
	Paddy rice	**Cereals**	**Vegetable & fruits**	**Oil seeds**	**Sugarcane**	**Cotton**	**Cocoa, coffee, & sesame**	**Paddy rice**	**Cereals**	**Vegetable & fruits**	**Oil seeds**	**Sugarcane**	**Cotton**	**Cocoa, coffee, & sesame**
Benin	24.8	940.2	412.9	473.0	1.9	116.1	14.6	41.8	1014.0	4131.3	373.1	53.7	103.5	7.1
Burkina Faso	49.5	2959.8	19.9	336.6	3.6	14.1	1.5	86.0	2859.3	184.6	247.0	307.4	12.9	0.7
Cote d'Ivoire	341.0	383.7	1290.5	499.2	23.0	257.6	1063.1	552.5	556.1	11094.5	419.5	1372.3	199.6	504.2
Gambia	5.2	173.4	2.7	47.4		1.4	0.7	11.7	165.1	25.4	42.8		1.2	0.3
Ghana	119.4	767.2	1457.7	476.7	5.5	25.0	850.0	185.8	935.5	13000.8	414.6	408.3	20.3	399.5
Guinea	691.1	83.6	342.9	191.2	5.2	31.9	64.7	1040.7	110.4	2554.4	170.2	295.8	32.5	31.8
Guinea Bissau	65.0	61.9	16.3	154.3	0.2	4.1		107.5	83.6	158.5	133.4	7.8	3.6	
Liberia	47.1	6.9	109.6	5.5	0.1		10.0	62.5	8.7	717.8	4.7	7.3		4.5
Mali	96.7	2800.0	10.9	550.6	4.5	38.7	0.6	170.4	2681.0	110.1	350.3	373.8	35.0	0.3
Niger	23.4	7364.2	10.7	3090.1	3.8	10.0		43.7	6503.1	210.9	1834.3	325.0	9.7	
Nigeria	2348.0	12772.1	8008.0	6962.0	43.0	632.0	1230.6	3734.9	14608.6	73628.7	5971.7	4746.8	505.6	581.1
Senegal	81.5	890.9	62.1	589.0	7.1	43.6	1.2	184.4	807.0	551.9	367.2	662.9	39.2	0.6
Sierra Leone	452.8	67.5	312.7	120.0	1.0		47.4	556.0	84.7	2189.9	99.3	51.1		22.5
Togo	32.3	321.3	176.1	219.4	0.9	117.7	69.9	51.2	361.7	1594.2	194.0	49.2	94.2	34.3

Drawing on Egbendewe-Mondzozo et al. (2015), this study assumes a land penetration rate of plus and minus 1% each year to constrain cropland allocation dynamically in the simulations and taking into account the fact that the total crop land use cannot be greater than the available arable land. This allows us to adapt the static nature of the traditional PMP approach into a dynamic context with more realistic levels of land use over time, using a discount rate of 3% (Nordhaus, 2007) for the objective function. It is worth noting that this approach does not allow the model to capture extreme climatic events in the short run. As many farmers in ECOWAS semi-subsistence growers (Seo et al., 2009), there may not be a significant shift in land use patterns in the short run. Therefore, our calibration approach is consistent with observed rigidity in land use expansion in the short run. A similar calibration approach is used for livestock production in ECOWAS. It should be mentioned that the projected values of the model are constrained within 12% absolute deviation vis-à-vis the actual 2010 and 2015 data (land use) as suggested by the theory (Hazell and Norton, 1986).

4. Results and discussion

In this section, the underlying rationale for crop supply in response to climate change is presented. Given the long time horizon, from 2004 to 2100, for climate change impact assessments, the findings should not be interpreted as a projection or forecast rather as a probable outcome of an interaction between several uncertain driving forces (Medellin-Azuara et al., 2011).

4.1 The baseline: cropland allocation and production without climate change

Simulations without climate change are conducted to understand agricultural production paths under different socio-economic scenarios in the absence of climate change in ECOWAS, thereby defining baseline scenarios against which the impact of climate change are assessed. The scenarios without climate change are constructed using the yield levels of 2004, adjusted with respect to technological change defined above. The parameters that need to be adjusted over years are predicted under the three SSPs, therefore there are three scenarios without climate change with respect to each SSP. The findings show that cropland and production have an increasing trend over years for all crops.[1] Paddy rice land use and production follow the same patterns across all SSPs. However, they are almost 39% and 43% lower during the second half of the century than the first half in Senegal under SSP2 for land use and production, respectively. Unlike paddy rice, cereals land use and production exhibit heterogeneities across SSPs. As an illustration, land use and production are lower under SSP2 than other SSPs for Burkina Faso, Mali, Niger, Nigeria, and Senegal during the century. This pattern is also observed for Republic of Benin, The Gambia, Ghana, and Togo from 2090 to 2100. Vegetable, fruits, sugarcane, cocoa, coffee, and sesame land use and production do not exhibit any heterogeneity across SSPs, except for Senegal where they are lower under SSP2 from 2080 to 2100 for sugar cane. Although oilseeds, and cotton land use and production follow the same patterns for all countries under SSPs 1, and 4, they differ substantially under SSP2. Indeed, oilseeds, and cotton land use and production are lower under SSP2 than SSP1 for Burkina Faso, Mali, Niger, Nigeria, and Senegal.

4.2 Impact of climate change on land use

The impacts of climate change on crop land allocations are assessed with respect to the baseline without climate change for each climate scenario combined with the appropriate SSPs (Tables 4, and 5) for each crop type. The distribution of paddy rice land use varies in some extent across SSPs 1, and 2 under RCP4.5. In general, the moderate climate change impacts negatively paddy rice land use in most of the countries from 2080 to 2095, while this land use remains unchanged for the remaining years. Countries such as Benin, The Gambia, Mali (under SSP1), Niger (under

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[1] The results are not reported, but are available upon request.

SSP1), and Togo. Paddy rice land use will decrease due to moderate climate change from 2020 to 2040 under the two SSPs and from 2080 to 2085 under SSP2. Guinea Bissau will experience an increase in paddy rice during the century irrespective to the socioeconomic scenario. The impact of climate change on paddy rice land use is also unevenly distributed among countries under the harsh climate change conditions. Most of the countries experience no change in paddy land use under the harsh climate change until 2080, and from 2080 to the end of the century the impact is negative (it is at least 95% in Niger). However, The Gambia and Liberia will not experience any change in paddy rice land use, while in Guinea Bissau, Sierra Leone, Guinea (from 2020 to 2075), and Nigeria (from 2020 to 2070) this land use will increase under RCP8.5. It is worth mentioning that the negative impacts of climate change on paddy rice land use are higher under harsh climate change compared to the moderate climate change. It is important also to note that climate change impacts on paddy rice land use vary across ACZs within countries.

The impact of climate change on maize, sorghum, and millet land use does not follow the same patterns across the two SSPs under RCP4.5. Most of the countries are expected to experience both positive and negative effects of climate change, depending on the years regardless of socio-economic scenarios under the moderate climate change, except Burkina Faso under SSP2. However, Guinea Bissau and Liberia will only experience positive impact of climate change; from 2020 to the end of the century for Guinea Bissau, and from 2055 to 2065. The findings further show that under the harsh climate change, the negative effects will be less pronounced in all countries, except countries such as Guinea Bissau, and Liberia in the same years as aforementioned. On average, maize, sorghum, and millet land use is slightly higher under harsh climate change compared with the moderate climate change. In general, the negative impacts outweigh the positive ones under SSP1 for the RCP4.5. Land under maize, sorghum, and millet production is differently impacted by climate change across ACZs. Indeed, a positive impact is observed in some ACSZs (e.g., in ACZ24 for sandy soils, and ACZ38 for clay soils), whilst negative impact is found in another ACZs (e.g., in ACZ22 for loamy soils and in ACZ34 for clay soils) under moderate climate change coupled with SSP1.

For most of the countries, both moderate and harsh climate change do not affect vegetable and fruits land use in most of the countries. However, moderate climate change leads to a decrease in cropland allocated to vegetable and fruits in Senegal from 2020 to 2080 under SSP2 and for the years 2020 and 2055 under SSP1. Harsh climate change leads to a decrease in cropland allocated to vegetable and fruits in Burkina Faso (0.5), Mali (6.8%) and Niger (92.3%) by the end of the century, and in Senegal from 2090 to 2100 (ranging from 0.2% to 2%). These findings depict the fact that generally, cropland allocated to vegetable and fruits does not change due to climate change under the socio-economic scenarios.

Both moderate and harsh climate change will affect oilseeds land use positively or negatively depending on countries and the years. Under moderate climate change countries such as Burkina Faso, The Gambia, Ghana, Mali, Niger, and Senegal will experience a decrease in land allocated to oilseeds production under SSP1, while under SSP2 we have The Republic of Benin, Burkina Faso, The Gambia, Niger, and Senegal. With harsh climate change, The Republic of Benin, Burkina Faso, The Gambia, Liberia, Mali, Niger, Senegal, and Togo will experience only drop in oilseed land use. The remaining countries will experience both increase and decrease in oilseeds land use. These findings show that, on average, the negative effect of climate change will be higher under harsh climate change compared with moderate climate change. The impact of climate change on oilseeds land use in countries in ECOWAS will vary between -85.4% and 259.3% for RCP8.5. It is worth mentioning that the impacts of climate change differ also across ACZs. For example, we observe positive impacts of climate change on oilseeds land use in ACZ26 for clay soils (from 2030 to 2045), while these impacts are negative in ACZs 28 and 30 for sandy soils under moderate climate change coupled with socio-economic scenario SSP1.

Climate change does not have any significant impact on the sugarcane land use in the countries in the ECOWAS region during the period of the study. However, Guinea, Guinea Bissau, and Sierra Leone will experience an increase in sugarcane land use between 0.1%, and 73.8% irrespective to the climate scenarios. This increase in cropland allocated to sugarcane in these three countries is due to the rise in loamy soils in ACZ38. In the other ACZs, sugarcane land use will keep the same trend from 2020 to 2100 irrespective of the climate scenarios.

All countries except Senegal exhibit a constant trend in cotton land use changes under moderate climate change coupled with SSP1. Under SSP1, Senegal will experience a decline in cotton land use. Under SSP2 coupled with RCP4.5, the Republic of Benin, Burkina Faso, Ghana, Mali, Niger, Nigeria, Senegal, and Togo are expected to see their cropland allocated to cotton production to decrease. Under the RCP8.5 the countries will experience an increase in cotton land use, except Burkina Faso, Mali, Niger, and Senegal. Indeed, harsh climate change will lead to an inverted U-shape form effect in countries such as Burkina Faso, and Mali. In general, the increase in land allocated to cotton production may reach 283.5% (in Guinea Bissau) under RCP4.5, whilst it may reach 686.6% (in Nigeria) under RCP8.5. Land under cotton production also exhibited different patterns across ACZs for the two climate scenarios. Indeed, the negative impact is observed in ACZ17 for sandy soils all over the century.

The findings indicate that both moderate and harsh climate changes do not affect land under cocoa, coffee, and sesame production.

Table 4. Impact of climate change on land use from baseline under RCP4.5 in % (SSPs 1 and 2)

	SSP1: Cash, Control & Calories																				
	Paddy rice			**Cereals**			**Vegetable & fruits**			**Oil seeds**			**Sugarcane**			**Cotton**			**Cocoa, coffee & sesame**		
	2020	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**
Benin	0.0	0.0	0.0	-10.4	0.0	0.4	0.0	0.0	0.0	-0.6	0.0	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Burkina Faso	0.0	0.0	0.0	-15.6	-0.3	1.5	0.0	0.0	0.0	-13.0	0.0	-9.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cote d'Ivoire	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gambia	0.0	0.0	0.0	-19.4	0.0	0.1	0.0	0.0	0.0	-0.9	0.0	-0.8				0.0	0.0	0.0	0.0	0.0	0.0
Ghana	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Guinea	0.1	0.2	0.4	5.7	6.4	36.3	0.0	0.0	0.0	1.0	2.3	10.8	0.1	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Guinea Bissau	5.0	9.5	24.4	40.6	64.1	141.9	0.0	0.0	0.0	9.2	25.3	42.8	25.8	57.5	73.8	0.0	0.0	0.0			
Liberia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				0.0	0.0	0.0
Mali	0.0	0.0	0.0	-13.6	-1.9	11.0	0.0	0.0	0.0	-33.7	0.0	-51.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Niger	0.0	0.0	0.0	-25.2	-2.1	131.3	0.0	0.0	0.0	-10.0	0.0	-85.4	0.0	0.0	0.0	0.0	0.0	0.0			
Nigeria	0.6	1.2	2.5	-4.6	-0.1	9.5	0.0	0.0	0.0	-10.6	0.0	-19.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Senegal	-11.2	0.0	0.0	-25.6	-10.5	24.9	-3.2	0.0	0.0	-46.1	-0.5	-38.3	0.0	0.0	0.0	-26.6	-35.7	-11.6	0.0	0.0	0.0
Sierra Leone	0.0	0.1	0.2	1.5	1.5	14.6	0.0	0.0	0.0	6.6	14.0	259.3	2.4	4.3	5.1				0.0	0.0	0.0
Togo	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	SSP2: Self-determination																				
	Paddy rice			**Cereals**			**Vegetable & fruits**			**Oil seeds**			**Sugarcane**			**Cotton**			**Cocoa, coffee & sesame**		
	2020	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**
Benin	0.0	0.0	0.0	-14.7	-12.3	-19.4	0.0	0.0	0.0	-23.4	-0.9	0.0	0.0	0.0	0.0	-11.4	0.0	0.0	0.0	0.0	0.0
Burkina Faso	0.0	0.0	0.0	-28.1	-27.2	-8.0	0.0	0.0	0.0	-46.6	-23.6	0.0	0.0	0.0	0.0	-9.5	-54.2	-65.1	0.0	0.0	0.0
Cote d'Ivoire	0.0	0.0	0.0	0.0	21.1	0.0	0.0	0.0	0.0	0.0	-8.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gambia	0.0	0.0	0.0	-31.8	-31.9	-13.7	0.0	0.0	0.0	-13.0	-2.0	0.0				0.0	0.0	0.0	0.0	0.0	0.0
Ghana	0.0	0.0	0.0	-5.1	7.9	0.1	0.0	0.0	0.0	-3.8	-11.6	0.0	0.0	0.0	0.0	-14.5	0.0	0.0	0.0	0.0	0.0
Guinea	0.1	0.2	0.4	5.7	8.3	36.3	0.0	0.0	0.0	1.0	1.4	10.8	0.1	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Guinea Bissau	5.0	9.5	24.4	40.6	109.2	141.9	0.0	0.0	0.0	9.2	17.7	42.8	25.8	57.5	73.8	0.0	0.0	0.0			
Liberia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				0.0	0.0	0.0
Mali	0.0	0.0	0.0	-20.6	-25.0	-15.6	0.0	0.0	0.0	-44.8	-75.4	0.0	0.0	0.0	0.0	-8.0	-57.7	-70.5	0.0	0.0	0.0
Niger	0.0	0.0	0.0	-0.3	-52.3	-80.9	0.0	0.0	0.0	-47.3	-71.1	0.0	0.0	0.0	0.0	0.0	-84.1	-97.9			
Nigeria	0.6	1.2	2.5	-14.7	-7.7	-11.8	0.0	0.0	0.0	-15.7	-29.1	0.0	0.0	0.0	0.0	-2.4	-12.5	-32.3	0.0	0.0	0.0
Senegal	-11.2	0.0	0.0	-12.4	-51.1	-42.8	-3.2	-14.8	0.0	-46.7	-82.6	0.0	0.0	0.0	0.0	-27.2	-39.6	-62.3	0.0	0.0	0.0
Sierra Leone	0.0	0.1	0.2	1.5	10.6	14.6	0.0	0.0	0.0	6.6	7.8	259.3	2.4	4.3	5.1				0.0	0.0	0.0

Togo	0.0	0.0	0.0	-24.2	0.0	0.0	0.0	0.0	0.0	-0.3	0.0	0.0	0.0	0.0	0.0	-9.8	0.0	0.0	0.0	0.0	0.0

Table 5. Impact of climate change on land use from baseline under RCP8.5 (SSP 4)

	SSP4: Save Yourself																				
	Paddy rice			**Cereals**			**Vegetable & fruits**			**Oil seeds**			**Sugarcane**			**Cotton**			**Cocoa, coffee & sesame**		
	2020	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**
Benin	0.0	0.0	-11.7	0.0	0.0	0.4	0.0	0.0	0.0	0.0	-0.4	-13.4	0.0	0.0	0.0	0.0	1.9	91.2	0.0	0.0	0.0
Burkina Faso	0.0	0.0	-41.4	-0.1	-0.3	3.1	0.0	0.0	-0.5	0.0	-0.7	-9.2	0.0	0.0	0.0	0.0	18.8	-45.6	0.0	0.0	0.0
Cote d'Ivoire	0.0	0.0	-70.7	0.0	-1.9	0.0	0.0	0.0	0.0	0.0	-41.8	0.0	0.0	0.0	0.0	0.0	170.3	369.9	0.0	0.0	0.0
Gambia	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	-0.8				0.0	0.0	0.0	0.0	0.0	0.0
Ghana	0.0	0.0	-8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.5	-0.9	0.0	0.0	0.0	0.0	26.0	37.7	0.0	0.0	0.0
Guinea	0.1	0.2	-2.8	5.7	6.0	36.3	0.0	0.0	0.0	1.0	-5.9	10.8	0.1	0.2	0.2	0.0	65.2	161.5	0.0	0.0	0.0
Guinea Bissau	5.0	9.5	24.4	40.6	64.1	141.9	0.0	0.0	0.0	9.2	25.3	34.2	25.8	57.5	73.8	0.0	0.0	405.1			
Liberia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				0.0	0.0	0.0
Mali	0.0	0.0	-58.4	-1.0	-1.9	16.4	0.0	0.0	-6.8	0.0	-1.6	-51.5	0.0	0.0	0.0	0.0	29.0	-39.9	0.0	0.0	0.0
Niger	0.0	0.0	-97.9	-0.6	-2.1	135.2	0.0	0.0	-92.3	0.0	0.0	-85.4	0.0	0.0	0.0	0.0	0.0	-97.9			
Nigeria	0.6	1.2	-43.7	0.3	-0.2	11.6	0.0	0.0	0.0	0.0	-9.9	-20.0	0.0	0.0	0.0	0.0	303.8	651.7	0.0	0.0	0.0
Senegal	0.0	0.0	-39.4	-5.5	-10.5	32.1	0.0	0.0	-2.0	-0.3	0.0	-38.3	0.0	0.0	7.1	0.0	0.0	-30.1	0.0	0.0	0.0
Sierra Leone	0.0	0.1	0.2	1.5	1.5	14.6	0.0	0.0	0.0	6.6	14.0	259.3	2.4	4.3	5.1				0.0	0.0	0.0
Togo	0.0	0.0	-17.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-2.4	-8.4	0.0	0.0	0.0	0.0	4.3	16.0	0.0	0.0	0.0

4.3 Impact of climate change on crop production

The impacts of climate change on crop production are assessed with respect to the baseline without climate change. Except for rice, sugarcane and cotton, crop production should be interpreted as an indicator of production because it refers to a group of crops (Tables 6, and 7). Except for Cote d'Ivoire, Ghana, Guinea, Guinea Bissau, Liberia, Nigeria, Sierra Leone, and Togo (under RCP4.5), Guinea, Guinea Bissau, Liberia, and Sierra Leone (under RCP8.5), that may experience increase in paddy rice production, the production of this crop decreases in many years for all countries in ECOWAS. The decrease ranges between 0.5-99.0% with an average of 6.2% under RCP4.5, and between 2.3-99.7% percent with an average of 13.9% under RCP8.5. However, the yearly distribution of these impacts will depend significantly on climate scenarios. For instance, the effects of climate change on paddy rice production is similar across socio-economic scenarios for RCP4.5, and the negative impact is higher under the harsh climate change. Similar to the paddy rice land use, the impact of climate change on paddy rice production also exhibits heterogeneities across ACZs.

Climate change may negatively affect the production of maize, sorghum, and millet regardless of climate scenarios for most countries in ECOWAS. Although the negative impact of climate change on cereal production is significantly different between RCPs, it exhibits almost similar pattern under SSPs in the case of moderate climate change. Indeed, cereal production may decrease by 14.4-97.8% (with an average of -10.8%, and -12.5%, respectively for SSP1, and SSP2) under RCP4.5, whilst it will decrease by 9.7-90.3% (with an average of -0.3%) under RCP8.5. These findings indicate that cereal production will be higher under harsh climate change compared to moderate climate change. During the first half of the century, most of the countries seem to be mostly positively affected by climate change, although they experience also a drop in cereal production during some years. However, the Republic of Benin, Burkina Faso, the Gambia, Mali, Nigeria, and Senegal may experience only a drop in cereal production from 2020 to 2100 under moderate climate change coupled with SSP1, the Republic of Benin, Burkina Faso, The Gambia, Mali, Niger, and Senegal under SSP2, and the Republic of Benin under harsh climate change.

The disparity in climate change impacts on cereal production is also observed across ACZs. Under SSP1, the production of maize, sorghum, and millet may decrease under moderate climate change on clay soils in ACZ38 from 2020 to 2100. It should be noted that the impacts on cereal production do not depict the actual impacts on each crop under this category (maize, sorghum, and millet). Therefore, it is not possible to indicate which crops between these three are going to be mostly affected. However, maize that needs more water during its growing period than sorghum, and millet may be more affected than the others.

Vegetable and fruits production may increase for almost all countries in ECOWAS, except Niger under the moderate and harsh climate change. It should be noted that the positive effects of climate change vary across the countries. Indeed, Niger may experience from 2020 to the end of the century a drop in vegetable and fruits production of on average 58.7% under RCP4.5 regardless of socio-economic scenarios, and 66.9% under RCP8.5. The positive impact of climate change on vegetable and fruits production is slightly higher under moderate climate change. The observed disparities of the impact of climate change on production of vegetable and fruits at the country level also hold at the ACZ level. Indeed, there are ACZs experiencing an increase in vegetable and fruit production under both moderate, and harsh climate change.

Both moderate, and harsh climate change hamper oil seeds production in all countries at least for some years. Under the moderate climate change, countries like Benin, Burkina Faso, The Gambia, Mali, Niger, Nigeria, Senegal, and Togo may experience a decrease in oilseeds all over the study period ranging between 8.2-98.8%, and 9.4-98.0% for SSPs 1, and 2. For these countries, a similar trend is observed for the harsh climate change, except that the impact is now ranged between 8.2-97.5%. Other countries such as Cote d'Ivoire, Ghana, Guinea, and Liberia exhibit a climate change impact on oilseeds production having an inverted U-shape form regardless of climate scenarios. Indeed, these countries may first experience an increase in oilseeds production, and then a decrease. Moderate and harsh climate change may also have differentiated impacts at ACZ level. For example, oilseeds production rises on loamy soils in some ACZs from 2020 to 2035, and from 2080 until the end of the century under RCP4.5 coupled with SSP1.

Sugarcane production may decrease during the century under both moderate and harsh climate change for all countries except Guinea Bissau, and Benin (under RCP4.5). This trend exhibits similar patterns across socio-economic scenarios under moderate climate change. Actually, except for Guinea Bissau, and Benin, the decrease in sugarcane production ranges between 0.5-68.0% (with an average of 8.4%) under RCP4.5, and between 8.2-97.5% (with an average of 22.0%) under RCP8.5. Guinea Bissau will exhibit an increase in sugarcane production all over the study period ranging from 140.3% to 210.7% under moderate climate change irrespective of socio-economic scenarios. Under the harsh climate change, sugarcane production may decrease in Guinea Bissau from 2085 to 2100 (an average decrease of 51.8%). The heterogeneity of climate change impacts on sugarcane production is also observed at ACZ level. For example, sugarcane production may decrease in all years on loamy soils in some ACZs under moderate climate change.

The effect of climate change in cotton production is mixed under moderate climate change, with negative effect more pronounced in the case of SSP2. Therefore, the beneficial effect of climate change on cotton production is higher under the prevailing socio-economic conditions of SSP1. It will range between 0.5-358.9% under both RCPs. The simulation suggest that most of the countries may experience an increase in cotton production under RCP8.5. However, cotton production may decrease in Burkina Faso and in Mali from 2085 to 2100, in Niger from 2080 to 2100, and in Senegal from 2070 to 2100 under harsh climate change. The direction of the impacts also varies across ACZs. For example, loamy soils in some ACZs experience a decrease in cotton production from 2020 to the end of the century under moderate climate change coupled with SSP1.

Under moderate climate change, Cote d'Ivoire, The Gambia, and Nigeria may exhibit an increase in production of cocoa, coffee, and sesame in all years, regardless of socio-economic scenarios. In the remaining countries, under moderate climate change irrespective to the socio-economic scenarios, cocoa, coffee, and sesame production may decrease all over the study period. Under the harsh climate change, none of these countries exhibits only an increase in cocoa, coffee, and sesame production in all years. Cote d'Ivoire, Ghana, Guinea, Liberia, Nigeria, Sierra Leone, and Togo are expected to experience drop in the production in some years. Cocoa, coffee, and sesame production may only decrease in the other countries under the harsh climate change from 2020 to the end of the century. So, under harsh climate change, all countries experience decline in cocoa, coffee, and sesame production for some years. It appears that the negative impact of climate change on cocoa, coffee, and sesame production is lower under the moderate climate than under the harsh climate change. The impacts of climate change on cocoa, coffee, and sesame production also vary across ACZs. Overall, the impacts of climate change vary across countries or across geographic units as predicted by a previous study (Mendelsohn et al., 2006; Seo et al., 2009; Medellin-Azuara et al., 2011). Moreover, climate change impacts do differ not only in terms of the direction of the impacts, but also in terms of the magnitude of the impacts.

Table 6. Impact of climate change on production from baseline under RCP4.5 (SSPs 1 and 2)

SSP1: Cash, Control & Calories

	Paddy rice			**Cereals**			**Vegetable & fruits**			**Oil seeds**			**Sugarcane**			**Cotton**			**Cocoa, coffee & sesame**		
	2020	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**
Benin	7.9	19.1	-13.2	-10.5	-4.8	-53.7	11.3	7.9	7.4	-8.2	-20.9	-34.6	54.4	88.4	57.8	6.5	7.4	-3.1	-11.2	0.1	-22.3
Burkina Faso	-8.2	-0.5	-35.2	-16.8	-13.1	-73.5	29.0	25.2	23.8	-28.4	-39.3	-59.1	-51.2	-41.5	-48.9	0.0	-9.8	-27.6	-14.6	-5.8	-22.8
Cote d'Ivoire	11.6	33.3	6.6	3.3	8.3	-17.1	25.8	28.3	37.9	15.0	13.3	0.6	-35.2	-16.0	-23.3	37.3	36.6	23.4	12.6	25.0	1.0
Gambia	-39.8	-23.5	-45.6	-22.4	-15.3	-77.1	16.1	18.7	25.2	-17.5	-24.8	-43.2				11.4	16.0	7.5	-11.2	0.1	-22.3
Ghana	4.9	22.1	-11.1	8.0	8.6	-31.0	23.8	26.4	35.6	12.1	9.1	-24.6	-51.2	-37.3	-47.3	18.6	15.7	0.7	14.1	26.6	3.6
Guinea	-1.4	31.4	9.4	14.1	27.8	30.8	26.6	36.6	49.2	13.5	13.1	9.2	-19.1	2.9	-9.8	-4.6	-13.5	-17.4	-0.7	13.2	-9.2
Guinea Bissau	11.7	24.6	-0.6	170.2	125.8	169.6	8.5	9.2	13.9	20.3	22.3	27.5	146.6	200.0	150.6	12.0	14.1	22.9			
Liberia	12.2	43.3	17.3	5.6	24.3	5.9	20.2	33.6	48.8	10.1	9.1	7.7	-18.3	3.4	-11.2				-4.0	13.0	-11.5
Mali	-13.1	-5.8	-40.9	-17.9	-17.4	-66.1	17.2	15.2	12.6	-51.9	-53.8	-93.4	-43.3	-36.5	-45.4	2.6	-10.3	-29.4	-11.2	0.1	-22.3
Niger	-31.9	-29.9	-66.9	-61.3	-59.2	-9.2	-49.5	-55.7	-61.6	-27.5	-44.7	-98.8	-50.6	-43.9	-52.5	-11.9	-17.4	-36.3			
Nigeria	5.3	30.8	0.2	-1.9	-0.9	-53.1	13.1	18.7	25.8	-17.0	-24.0	-59.8	-68.0	-56.1	-58.4	34.6	19.6	-14.7	14.6	27.2	4.6
Senegal	-52.0	-48.0	-71.5	-41.3	-37.8	-68.2	5.5	1.1	-5.4	-66.5	-61.6	-94.1	-50.7	-44.7	-51.5	-46.8	-49.2	-55.3	-12.9	-2.8	-22.4
Sierra Leone	24.3	52.7	22.7	18.4	29.8	18.4	25.3	34.4	44.5	27.8	28.8	343.6	-13.9	8.7	-6.7				-4.4	12.8	-12.0
Togo	5.8	27.0	-3.4	1.0	0.7	-44.0	14.0	14.7	24.7	-12.0	-12.8	-17.3	-23.7	-4.0	-19.2	18.2	20.9	7.9	-4.3	8.9	-13.5

SSP2: Self-determination

	Paddy rice			**Cereals**			**Vegetable & fruits**			**Oil seeds**			**Sugarcane**			**Cotton**			**Cocoa, coffee & sesame**		
	2020	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**
Benin	7.9	19.1	-13.2	-18.9	-9.6	-53.7	11.3	7.9	7.4	-27.0	-21.1	-34.4	54.4	88.4	57.8	-4.7	7.4	-3.1	-11.2	0.1	-22.3
Burkina Faso	-8.2	-0.5	-35.2	-33.0	-28.0	-56.3	29.0	25.2	23.8	-57.8	-47.1	-52.3	-51.2	-41.5	-48.9	-9.2	-56.4	-70.5	-14.6	-5.8	-22.8
Cote d'Ivoire	11.6	33.3	6.6	3.3	31.1	-17.1	25.8	28.3	37.9	15.0	3.2	0.6	-35.2	-16.0	-23.3	37.3	36.6	23.4	12.6	25.0	1.0
Gambia	-39.8	-23.5	-45.6	-40.9	-34.4	-66.2	16.1	18.7	25.2	-26.2	-25.4	-42.4				11.4	16.0	7.5	-11.2	0.1	-22.3
Ghana	4.9	22.1	-11.1	3.7	19.2	-29.7	23.8	26.4	35.6	9.2	-3.0	-24.6	-51.2	-37.3	-47.3	2.9	15.7	0.7	14.1	26.6	3.6
Guinea	-1.4	31.4	9.4	14.1	30.4	30.8	26.6	36.6	49.2	13.5	12.3	9.2	-19.1	2.9	-9.8	-4.6	-13.5	-17.4	-0.7	13.2	-9.2
Guinea Bissau	11.7	24.6	-0.6	170.2	221.2	169.6	8.5	9.2	13.9	20.3	15.1	27.5	146.6	200.0	150.6	12.0	14.1	22.9			
Liberia	12.2	43.3	17.3	5.6	24.3	5.9	20.2	33.6	48.8	10.1	9.1	7.7	-18.3	3.4	-11.2				-4.0	13.0	-11.5
Mali	-13.1	-5.8	-40.9	-28.6	-26.2	-55.7	17.2	15.2	12.6	-60.7	-84.7	-61.4	-43.3	-36.5	-45.4	-5.2	-59.7	-75.5	-11.2	0.1	-22.3
Niger	-31.9	-29.9	-66.9	-47.2	-81.4	-92.4	-49.5	-55.7	-61.6	-58.4	-84.3	-88.0	-50.6	-43.9	-52.5	-11.9	-86.9	-98.6			
Nigeria	5.3	30.8	0.2	-11.0	-1.8	-43.0	13.1	18.7	25.8	-20.8	-34.2	-40.5	-68.0	-56.1	-58.4	32.0	7.8	-36.6	14.6	27.2	4.6
Senegal	-52.0	-34.0	-60.2	-36.4	-59.3	-77.8	5.5	-0.8	16.7	-67.0	-92.6	-77.1	-50.7	-44.7	-53.1	-47.4	-49.6	-65.6	-12.9	-2.8	-22.4
Sierra Leone	24.3	52.7	22.7	18.4	43.6	18.4	25.3	34.4	44.5	27.8	21.7	343.6	-13.9	8.7	-6.7				-4.4	12.8	-12.0
Togo	5.8	27.0	-3.4	-20.7	0.7	-44.0	14.0	14.7	24.7	-12.2	-12.8	-17.3	-23.7	-4.0	-19.2	7.4	20.9	7.9	-4.3	8.9	-13.5

Table 7. Impact of climate change on production from baseline under RCP8.5 (SSP 4)

	SSP4: Save Yourself																				
	Paddy rice			**Cereals**			**Vegetable & fruits**			**Oil seeds**			**Sugarcane**			**Cotton**			**Cocoa, coffee & sesame**		
	2020	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**
Benin	7.7	18.0	-67.4	-5.5	-9.7	-18.5	11.5	7.2	-11.6	-8.2	-25.4	-69.9	53.6	93.1	66.2	71.9	75.8	168.0	-12.0	-0.5	-54.0
Burkina Faso	-7.5	-3.6	-80.2	-5.9	-20.9	26.9	29.3	24.2	-4.4	-21.4	-46.1	-67.5	-51.1	-40.9	-53.0	59.5	79.0	-32.6	-15.3	-7.1	-54.7
Cote d'Ivoire	11.0	35.4	-71.9	2.4	6.0	-59.2	26.3	29.3	32.9	14.7	-33.0	-20.4	-35.5	-13.4	-14.4	109.9	489.3	755.4	11.8	25.4	-20.6
Gambia	-38.7	-26.0	-67.3	-8.3	-23.1	25.8	15.7	19.7	8.8	-17.2	-27.6	-67.9				78.5	82.4	48.0	-12.0	-0.5	-54.0
Ghana	5.1	24.1	-46.9	7.6	5.0	-62.3	24.2	27.4	31.1	12.0	6.4	-45.0	-51.3	-35.8	-44.2	88.0	137.3	98.5	13.3	26.6	-20.4
Guinea	-2.3	38.3	9.1	14.1	30.6	-15.2	27.4	39.8	52.9	13.4	4.2	-12.2	-19.7	6.8	1.9	50.8	131.3	213.8	-1.8	16.6	-20.5
Guinea Bissau	9.9	28.0	-18.1	168.2	127.6	55.7	8.9	9.7	4.4	20.0	19.4	-21.9	145.6	209.5	171.5	81.0	83.9	771.5			
Liberia	12.9	48.5	17.7	6.3	27.7	-10.1	21.9	38.1	59.5	10.4	8.5	-10.1	-18.4	5.3	0.9				-3.3	16.2	-21.5
Mali	-12.3	-9.3	-85.9	-10.9	-25.8	56.8	17.4	14.9	-9.5	-31.3	-64.0	-47.5	-43.0	-36.7	-54.9	62.7	96.4	-23.2	-12.0	-0.5	-54.0
Niger	-30.5	-35.3	-99.3	-46.6	-71.2	358.8	-49.4	-57.4	-98.6	-20.5	-53.8	-82.8	-50.2	-44.1	-61.8	42.8	34.1	-98.6			
Nigeria	5.1	33.5	-59.9	0.6	-5.7	10.8	13.3	19.8	13.3	-12.3	-38.7	-56.9	-68.7	-52.9	-51.6	104.2	683.5	1033.4	13.8	27.2	-20.0
Senegal	-48.7	-49.8	-82.2	-26.4	-47.3	122.1	5.4	0.5	6.5	-38.3	-69.8	-26.9	-50.7	-42.9	-55.5	23.8	18.1	-65.9	-13.6	-3.7	-54.1
Sierra Leone	26.0	57.1	15.8	19.9	32.0	-9.7	26.8	37.2	48.2	28.0	27.9	242.8	-13.9	10.8	5.9				-3.7	16.2	-20.9
Togo	5.7	29.1	-47.5	0.9	-4.3	-59.4	14.4	15.0	14.7	-12.2	-16.0	-48.9	-24.0	-1.5	-12.7	89.9	101.6	75.1	-5.6	12.1	-27.6

4.4 Sensitivity of crop production to yield increase

In this paper we also run the simulation assuming 2% of annual yield growth to due technological progress. Indeed, the evidence showed that crop production have tripled in Asia and Latin America between 1960 and 2000 (Sanchez, 2010), and food quantity and quality can also be improved in Africa according to several scientists (Sanchez and Swaminathan, 2005). Assuming 2% of annual yield growth means doubling crop yields by 2050. The results indicate that overall the negative impact of moderate climate change, in percentage, is slightly lower, while the positive impact is slightly higher under 2% annual yield growth compared to 1%. Under the harsh climate change, the impact seems to be the same, with a slight difference (higher negative impact and lower positive impact for 2% annual yield growth) which is less pronounced compared with the moderate climate change.

5. Conclusion

This paper investigates the impacts of climate change on land allocation and crop production in ECOWAS zone. It relies on the mapping of ECOWAS region into Agro-Climatic and Soil Zones (ACSZs) to predict the impacts of climate change across countries in ECOWAS. Following Chang (2002), the methodology adopted involves a two-step procedure. In the first step, data on crop yields, climate, and soil characteristics were used to estimate yield response functions to environmental and climate conditions. These yield functions were then used to simulate future crop yields following two RCPs (RCP4.5 and RCP8.5). In the second step, the predicted yields were then incorporated into a mathematical programming model for agricultural production with exogenous prices, to assess climate change impact on the agricultural land use and agricultural production in ECOWAS. The optimization model is calibrated using the traditional PMP approach to ensure that the model is able to replicate the observed cropland for 2004, the base year.

The findings suggest that the impact of climate change on cropland may be lower, higher, or remains the same depending on crop types and future conditions (combinations of climate and socio-economic scenarios). As of crop production, negative as well as positive impacts, are observed. However, overall paddy rice, oilseeds, sugarcane, cocoa, coffee, and sesame production may experience a decline in production under both moderate and harsh climate change. In addition, the model sensitivity to yield increase suggests that doubling crop yields by 2050 could overall mitigate the negative effect of moderate climate change on crop production. Thus, crop land use and crop production in ECOWAS countries are sensitive to climate change. The findings are not uniform across countries, and ACZs, highlighting disparities across geographical units. Thus, the findings are in line with previous ones, which found that the effects of climate change on agricultural production will be quite different across Africa (e.g., Seo et al., 2009). For farmers seeking to maximize the profit of their farm activities, climate change may lead to a shift in land use for agricultural production within and among countries as a rational response to its impact on crop yields. A structural transformation of the agricultural sector is, therefore, inevitable to offset the negative impacts of climate change and take advantage of the positive ones, thereby fostering a better level of livelihoods for the population.

Although the paper brings more lights on the spatial, negative and positive impacts of climate change on agricultural land use and agricultural production in ECOWAS countries, taking into account inefficiencies in crop production, it does not investigate possible adaptation strategies to alleviate the negative impacts and take advantage of the positive ones. The findings call for more efforts in terms of adequate adaptation strategies to offset the negative impacts of climate change on agricultural production in West Africa. Moreover, our modeling approach does not account for water scarcity as well as climate-induced price changes. Including these factors could more or less affect the results of this paper. This could be investigated in future research. Furthermore, the model does not take into account the fact that the boundaries of the ACZs may move as climate changes. Price are exogenous in the model, so aggregate supply-demand (price) feedbacks are not captured in the analyses.

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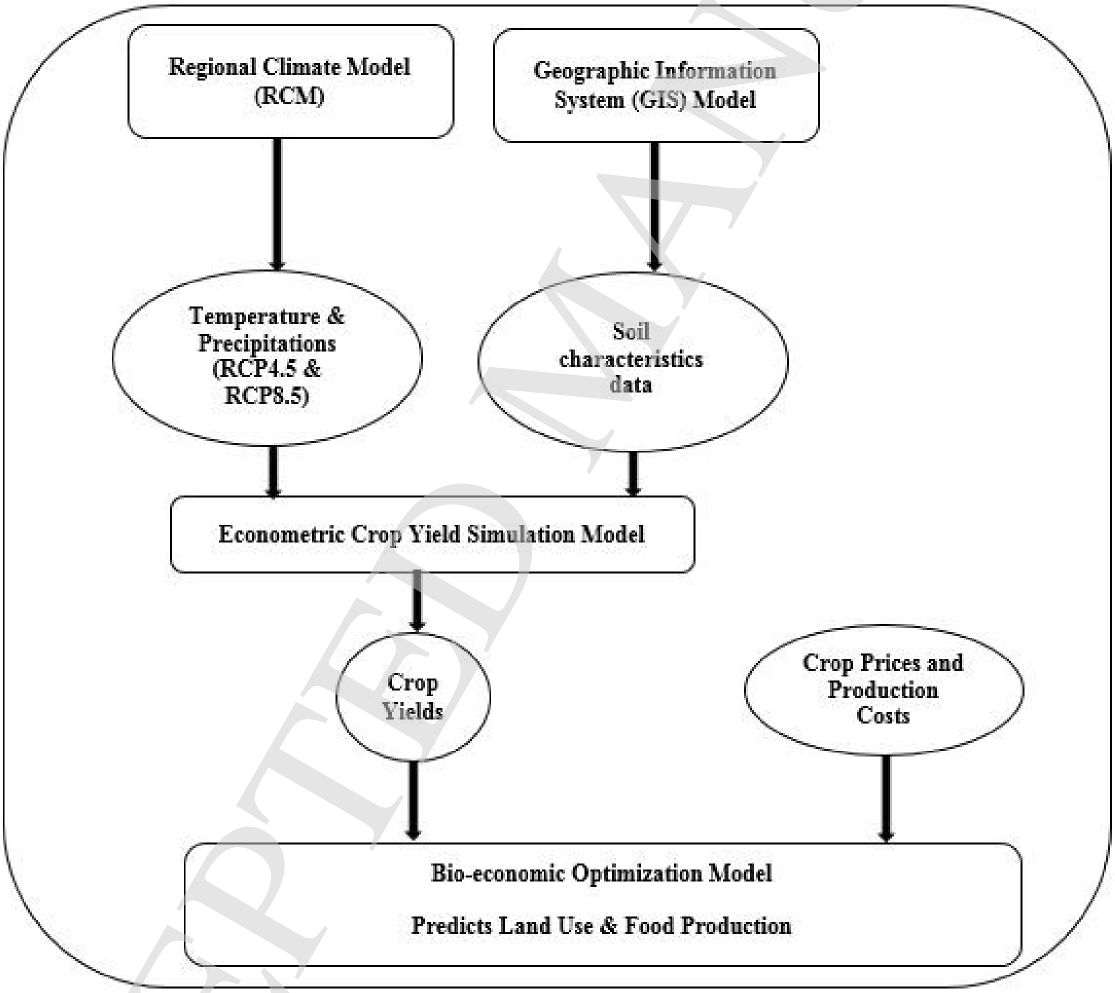
Appendix 1. The structure of the bio-economic model



Appendix 2. Yield function's parameters

VARIABLES	Paddy Rice	Cereals	Vegetable & Fruits	Oil Seeds	Sugarcane	Cotton	Cocoa, Coffee & Sesame
Ln(temperature)	198.8**	191.4***	935.7*	89.11**	2,946	71.72*	53.13***
	(81.22)	(46.64)	(477.4)	(36.46)	(3,478)	(36.31)	(18.89)
Ln(temperature)^2	-30.50**	-29.72***	-143.0*	-13.89**	-438.3	-11.01*	-8.191***
	(12.94)	(7.365)	(75.95)	(5.774)	(556.5)	(5.778)	(3.007)
Ln(variance_temperature)	-0.153	-0.0556	0.738	0.00733	-6.752	-0.0219	-0.0329
	(0.128)	(0.0506)	(0.560)	(0.0439)	(6.163)	(0.0535)	(0.0295)
Ln(rainfall)	2.561***	1.283***	18.53***	0.749***	61.57**	0.446	0.481***
	(0.645)	(0.359)	(3.490)	(0.283)	(30.01)	(0.282)	(0.149)
Ln(rainfall)^2	-0.132**	-0.0217	-1.221***	-0.0370	-4.694	-0.00416	-0.0194
	(0.0655)	(0.0326)	(0.321)	(0.0262)	(3.101)	(0.0269)	(0.0149)
Ln(variance_rainfall)	-0.482	-0.427***	-0.403	-0.0436	-4.051	-0.0939	-0.108
	(0.298)	(0.148)	(1.254)	(0.112)	(14.32)	(0.122)	(0.0694)
Clay	0.464***	0.313***	2.209***	0.300***	18.35***	0.332***	0.132***
	(0.159)	(0.103)	(0.756)	(0.0742)	(6.719)	(0.0712)	(0.0389)
Loam	0.115	0.107	1.018	0.122*	5.465	0.156**	0.0448
	(0.143)	(0.0970)	(0.723)	(0.0722)	(6.123)	(0.0709)	(0.0359)
Constant	-329.9**	-311.4***	-1,588**	-145.3**	-5,071	-118.1**	-87.28***
	(127.9)	(74.25)	(750.1)	(57.87)	(5,452)	(57.24)	(29.80)
Observations	114	114	114	114	114	114	114
R-squared	0.420	0.579	0.533	0.424	0.221	0.486	0.458

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1