International Journal of Applied Agricultural Sciences
2024, Vol. 10, No. 6, pp. 289-296
https://doi.org/10.11648/j.ijaas.20241006.13

SciencePG Science Publishing Group

Research Article

Impact of Climate Change on Millet and Maize Yields in the Agroecological Zones of Senegal

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Abstract

Climate change poses a major threat to agricultural productivity, especially in regions where crops are vulnerable to climate variations. This article examines the impact of climate change on millet and corn yields in Senegal by focusing on various agro-ecological zones and using a multiple regression model. The study analyzes the influence of specific climate variables – evapotranspiration, soil temperature, precipitation, and solar radiation – on crop yields. Results show that the model is effective for corn in eastern Senegal, where the coefficients of determination are significant, indicating predictive reliability. However, for millet, coefficients are low across all zones, reflecting limited model quality for this crop. Furthermore, findings reveal that evapotranspiration and soil temperature negatively affect corn yields in eastern Senegal, highlighting the crop's sensitivity to heat and drought conditions. These findings contrast with some previous research that, by not disaggregating crops, arrives at less specific conclusions. This study advocates for a disaggregated approach in analyzing climate impacts, enabling a more nuanced understanding of effects by crop and zone. It also emphasizes the need to adapt agricultural practices and public policies to mitigate the adverse impacts of climate change, ensuring the resilience of Senegal's agricultural sector. This research ultimately recommends tailored agricultural practices and policies to mitigate negative climate effects on yields and bolster the sustainability of Senegalese agriculture.

Keywords

Climate Change, Multiple Regression Model, Agricultural Yields, Agro-ecological Zones, Cereals, Senegal

1. Introduction

Climate change is currently the most severe crisis our planet has faced in decades. In sub-Saharan Africa, rural populations are particularly vulnerable, as they largely depend on rain-fed agriculture, which covers nearly 93% of cultivated land [12]. According to these researchers, 80% of the cereal consumed in the region come from this traditional agriculture, and the agricultural sector employs about 70% of the workforce, contributing between 15 and 20% of the GDP [5]. The worsening socio-economic impacts linked to climate in sub-Saharan Africa are exacerbated by rapid population growth and poverty, limiting access to adaptation technologies such as mechanization, fertilizers, and irrigation [10].

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Received: 23 October 2024; **Accepted:** 19 November 2024; **Published:** 28 November 2024

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The study [8] highlighted that between 2000 and 2009, temperatures in West Africa rose by 1 ℃, accompanied by more frequent storms and heatwaves. These adverse climatic conditions caused a decrease in millet yields by 10 to 20% and sorghum yields by 5 to 15%. From a macroeconomic perspective, the study estimates that losses for producing countries amount to $2 to $4 billion for millet and $1 to $2 billion for sorghum, creating an emergency threatening food security and local economies. Moreover, the yields of durum wheat, soft wheat, and barley in Tunisia are influenced by climatic variables such as rainfall and temperatures [2]. Climate projections from the HadCM3 model predict a decline in yields by 2030, particularly for soft wheat. Adaptation strategies include adopting new agricultural techniques and disseminating drought-resistant and early maturing varieties.

The study [11] studied the impact of climate change on agricultural yields in West Africa, evaluating the effects of climate variability on crops. This research used climate and agricultural data to model future yields and propose recommendations to strengthen the resilience of agricultural systems to climate change. Specifically concerning millet production in West Africa, it was observed that rising temperatures and changing rainfall patterns lead to a significant reduction in yields. Projections indicate that these yields could decrease by 10 to 20% by 2050 without adaptation measures. The use of seasonal forecasts is also highlighted as a way to help farmers better organize their agricultural activities, allowing them to adjust planting and harvesting schedules to mitigate negative impacts.

It is also essential to examine farmers' perceptions of the impact of climate change on production. In the Sahelian and Sudanian-Sahelian regions of Burkina Faso, millet producers reported indicators such as rising temperatures, irregular rainfall, and shifting planting dates as the most notable [1]. These changes harm millet cultivation, leading to lower yields and the disappearance of certain varieties.

In Senegal, rain-fed agriculture employs nearly 60% of the active population [14]. In 2020, cereal crops represented 47% of cultivated areas, with millet and maize accounting for 58.3% and 16.9% of the areas, respectively [4]. Total cereal production reached 3,640,545 tons, with millet at 1,144,855 tons and maize at 761,883 tons [6] forming an essential food base for many rural households.

However, the harmful effects of climate change are manifesting through disrupted rainfall, extreme events, and rising temperatures [3]. Temperature variations have direct consequences on crop health, altering growth cycles and harvest quality while increasing pressures on agricultural systems. Extreme temperatures, notably prolonged heatwaves, compromise crop resilience and jeopardize food security in an already vulnerable country, particularly due to famine in some regions. This is partly explained by the short rainy season (three to four months according to [7] and heavy reliance on rain-fed agriculture [13].

This research also explores other factors influencing agricultural yields. It aims to examine the impact of climate change on cereal crop (millet and maize) yields in different agroecological zones of Senegal, excluding the Niayes zone, which specializes in fruit and vegetable production through artisanal market gardening and agribusiness. For this purpose, a multiple regression method was applied to a sample of 310 farming households, taking into account climate variables such as evapotranspiration, precipitation, air temperature, soil temperature, and solar radiation. The results of this study will provide insights for strengthening the resilience of agricultural systems in the face of climate challenges.

2. Matériels and Methods

2.1. Presentation of the Study Area

Agroecological zoning defines homogeneous areas based on the interaction of soil characteristics, their agricultural suitability, geomorphology, the availability of water resources, and climate. In this research, all agroecological zones of Senegal (map 1) are included except the Niayes zone, which is more specialized in vegetable production. These zones include, among others, the Senegal River Valley, the Agro-Sylvo-Pastoral Zone, the Northern Groundnut Basin, the Southern Groundnut Basin, Eastern Senegal and Casamance.

2.2. Data Source

The household data used in this study come from the agricultural survey conducted by the Directorate of Analysis, Forecasting, and Agricultural Statistics (DAPSA) for the 2017/2018 agricultural season. Data collection was carried out using a structured questionnaire divided into three main sections: the Household Questionnaire (HQ), the Producer Questionnaire (PQ), and the Income Questionnaire (IQ). This information was then combined with climate data related to crop yields, as well as data from the Energy and Water Balance Monitoring System (EWMBS).

The EWMBS data include agro-meteorological information obtained via satellite through Meteosat, downloaded from the Agrymeth server. This system provides data fields derived from Meteosat, including hourly measurements of temperature, radiation, evapotranspiration, cloud cover, and precipitation. These climate data are essential for generating early warnings on drought and yields.

The data extraction process aims to gather all the annual information from EWMBS concerning Senegal's departments. These data will be used to develop an equation model and mainly include air temperature, soil temperature, precipitation, evapotranspiration, and solar radiation.

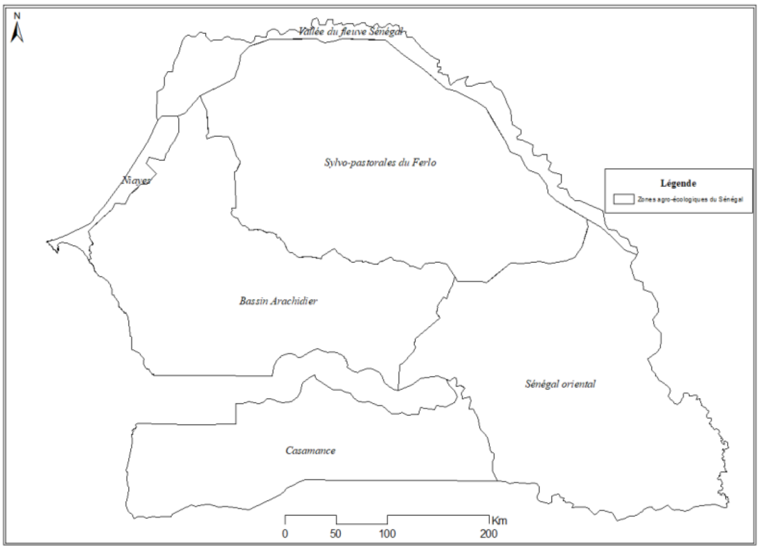

Figure 1. *Map of agroecological zones of Senegal.*

2.3. Analysis Model

The analytical method used in this research is the multiple regression model. It represents a generalization of the simple regression model (simple linear model) when the explanatory variables are finite in number. The theoretical model, formulated in terms of random variables, takes the form:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots\ldots + \beta_P X_{ip} + \varepsilon_i, \quad i=1,\ldots, n \qquad (1)$$

Y_i: Represents the model error that expresses or summarizes the missing information in the linear explanation of the values of Y_i;

X_{i1}, …. X_{ip}; β_0, β_1,….., β_{ip} Are the parameters to be estimated.

$$\text{In matrix form, we have: } Y=X\beta+\varepsilon \qquad (2)$$

The dependent variable Y_i is the yield in kg/ha.

The X_i are represented by the following climatic variables:

X_1: Air température;

X_2: Soil température;

X_3: Rainfall;

X_4: evapotranspiration and

X_5: Solar radiation

The equation of the model becomes:

$$Y_i = \beta_0 + \beta_1\, Air\ température + \beta_2\, Soil\ température + \beta_3 Rainfall + \beta_4 évapotranspiration + \beta_5\, Solar\ radiation + \varepsilon_i \qquad (3)$$

2.4. Steps of the Modeling Process

1. Estimate the values of the coefficients (β_0, β_{i1},..., β_{ip}) from a sample of data (ordinary least squares estimator);
2. Assess the accuracy of these estimates (bias, variance of the estimators);
3. Measure the explanatory power of the model as a whole (analysis of variance table, coefficient of determination);
4. Test the validity of the relationship between Y and the exogenous variables X_{ij} ((global significance test of the regression);
5. Test the marginal contribution of each explanatory variable in explaining Y (significance test for each coefficient);
6. For a new individual i, calculate the predicted value and the prediction interval.

2.5. Estimation of Régression Coefficients

Conditioned on knowing the values of X_j, the unknown parameters of the mode: the vector β and σ, are estimated by minimizing the least squares criterion (LS) or, alternatively, by maximizing the likelihood (ML) assumption.

The expression to minimize with respect to β is written by:

$$\Sigma(y_i - \beta_0 - \beta_1 X_{i1} - \beta_2 X_{i2} - \cdots - \beta_P X_{ip})^2 = \|y - X\beta\|^2$$

$$= (y - X\beta)'(y - X\beta) \qquad (4)$$

$$= y'y - 2\beta' X' y + \beta' X' X\beta$$

By taking the matrix derivative of the last equation, we obtain:

$$X'y = X'X\beta \qquad (5)$$

Since $X'X$ is assumed to be invertible, the estimation of the parameters βj is given by:

$$\hat{\beta} = (X'X)^{-1} X'y \qquad (6)$$

where y is a vector of observed data and the fitted (or estimated, predicted) values of y are expressed as:

$$\hat{y}=Xb=X(X'X)^{-1}X'y=Hy \quad (7)$$

$$H = X(X'X)^{-1}X' \text{ is called the "hat matrix.} \quad (8)$$

Geometrically, it is the orthogonal projection matrix in R^n onto the subspace spanned by the column vectors of X. We denote:

$$\hat{\varepsilon}=y-\hat{y}=y-X\beta=(I-H)y \quad (9)$$

2.6. Coefficient of Determination

The coefficient of determinationR^2which ranges from 0 to 1, allows us to determine the quality of the model. It represents the proportion of variance in the dependent variable that is explained by the model. It indicates how well a statistical model predicts an outcome. The result is represented by the dependent variable of the model. The closer R^2 is to 1, the better the model's predictive capacity.

3. Results

3.1. Caractéristiques Des Ménages

Households are primarily composed of men, with women representing only 2.5% of the sample. They cultivate millet and maize, with a predominance of millet cultivation. Most of them practice rainfed agriculture, which relies heavily on rainfall (see Table 1).

Table 1*. Household Characteristics.*

Agroecological situation of the household	Gender		Types of cereal crops		Economic activity	
	Masculine	Feminine	Maize	Miller	Rainfed Agriculture	Other agricultural activities
Northern groundnut basin	63	0	15	48	56	7
Southern groundnut basin	65	1	32	34	58	8
Silvo-pastoral zone	24	0	2	22	18	6
Senegal River Valley	51	2	15	38	41	12
Eastern Senegal	50	1	23	28	40	11
Casamance	49	4	25	28	46	7
Total	302	8	112	198	259	51

Source: DAPSA 2018, Authors' calculations

Households face climate risks such as prolonged dry spells/droughts, flooding, and insufficient rainfall. The latter, in particular, constitutes the most recurring risk and is common in Eastern Senegal and the Southern groundnut basin (see Table 2).

Table 2*. Agro-climatic risks experienced in the plot.*

Agroecological situation of the household	Agro-climatic risks experienced in the plot			
	No risk	Prolonged dry spell/drought	Flooding	Insufficient rainfall
Northern groundnut basin	12	13	10	28
Southern groundnut basin	9	3	7	47
Silvo-pastoral zone	0	0	1	23
Senegal River Valley	33	5	7	8
Eastern Senegal	2	1	3	45

Agroecological situation of the household	Agro-climatic risks experienced in the plot			
	No risk	Prolonged dry spell/drought	Flooding	Insufficient rainfall
Casamance	9	2	4	38
Total	65	24	32	189

Source: DAPSA,2018 Authors' calculations

3.2. Impact of Climate Change on Millet and Maize Yields

To assess the impact of climate change on millet and maize yields in the different agroecological zones, we will proceed in two steps:

1. The first step aims to determine, for millet and maize, the coefficients of determination in the various agroecological zones. This coefficient helps to assess the quality of the model.
2. The second step involves identifying the zones where not only is the model quality good, but the coefficients of the variables are significant at 5%. These two conditions allow us to select the zone(s) where climate change impacts yields.

3.2.1. Estimation of the Coefficient of Determination R^2

To assess the overall quality of the model, it is necessary to determine the value of R^2 for millet and maize in each agroecological zone. The closer the coefficient of determination is to zero, the better the model. For maize, the coefficient of determination is closer to 1 in the groundnut basin (0.532) and in Eastern Senegal (0.578) (see Table 3). This indicates that the model is of better quality for these two zones.

Table 3. Coefficient of determination by agroecological zone for maize.

Agroecological situation of the household	Type of cereal	R^2
Northern groundnut basin	Maize	0.532
Southern groundnut basin	Maize	0.265
Silvo-pastoral zone	Maize	-
Senegal River Valley	Maize	0.384
Eastern Senegal	Maize	0.578
Casamance	Maize	0.121

Source: DAPSA, Authors' calculations

However, for millet, the values of the coefficient of determination are low (below 0.5) in all agroecological zones (see Table 4). The model is not globally significant for the different zones.

Table 4. Coefficient of determination by agroecological zone for millet.

Agroecological situation of the household	Type of cereal	R^2
Northern groundnut basin	Mil	0.086
Southern groundnut basin	Mil	0.272
Silvo-pastoral zone	Mil	0.450
Senegal River Valley	Mil	0.384
Eastern Senegal	Mil	0.306

Agroecological situation of the household	Type of cereal	R^2
Casamance	Mil	0.235

Source: DAPSA, Authors' calculations

3.2.2. Estimates of the Coefficients of Climatic Variables for Maize in Eastern Senegal and the Groundnut Basin

The analysis of the impact of different climatic variables on maize yields in Eastern Senegal and the Northern groundnut basin reveals that in the latter zone, no variable impacts maize yields because the coefficients are not significant at 5%. However, in Eastern Senegal, the coefficients are significant for the variables of evapotranspiration (0.038) and soil temperature (0.028) (see Table 5).

Table 5. *Impact of climate change on maize yields.*

Variables	Sénégal oriental		Bassin arachidier nord	
	Coefficients	Significativités	Coefficients	Significativités
Constante	28909.585	0.007	-1009.749	0.895
Évapotranspiration (mm/jours)	-2467.210**	0.038	-460.892	0.335
Pluviométrie	-0.561	0.635	3.236	0.075
Température du sol	-446.828**	0.028	-111.246	0.520
Température de l'air	-172.906	0.266	109.246	0.753
Radiation solaire	-0.057	0.996	7.488	0.439

Source: Authors' calculations ** Significance at 5% level

It is important to note that maize is a crop that, although tolerant to some heat, is sensitive to high temperatures beyond a certain threshold. Its heat resistance varies depending on the varieties and growing conditions. It thrives at moderate temperatures, generally between 20 ℃ and 30 ℃. High temperatures, around 35 ℃ or more, can have detrimental effects on maize growth. In fact, this area of Eastern Senegal—one of the hottest regions in Senegal—experiences primarily two seasonal variations: from November to May and from June to October. During the first period, soil temperatures can be extremely high due to the intensity of solar radiation and low cloud cover. Surface soil temperatures can reach up to 60 ℃, especially during the hottest months (March to May). In the second period, temperatures are more moderate, although they range between 30 ℃ and 40 ℃.

By analogy, maize cannot withstand a continuous climate change scenario, particularly with rising temperatures, which will lead to irreversible negative impacts. Additionally, this situation of high soil temperatures, combined with evapotranspiration, results in water loss from the soil and water bodies in the form of vapor and plant transpiration—negatively affects maize yields concerning this climatic variable.

4. Discussion

Studies on the impact of climate change or climate variability on agricultural yields or production in Senegal focus on the entire agroecological zones taken as a whole. This part of the discussion will take this shortcoming into account since the results of the article are produced in a disaggregated manner.

Thus, [6] showed in their study that climate change, manifested by levels of temperature and precipitation, has positive effects on the yields of major cereal crops (wheat, rice, maize, and millet) and that the impact of temperature variation on yield is greater than that of precipitation variation. This result is at odds with those of our article, although the interpretations only concern maize. The limitation of [6] research lies in the aggregation of cereal crops, which does not allow for a real measurement of the expected impact.

In contrast, the results of [9] in their study on the Southern groundnut basin partly corroborate those of our study. They found that average temperatures negatively impact millet and peanut yields at the 1% threshold and maize yields at the 5% threshold. Moreover, their predictive calculations showed that by the dawn of 2031, the Southern ground nut basin could experience agricultural yield losses of around 21.95%, 19.68%, 05.08%, 05.88%, and 03.01%, respectively, for peanuts, millet, sorghum, maize, and cowpeas.

Outside Senegal, [2] also illustrated that maximum temperatures have a significant and negative impact on soft wheat in the Béja region of Tunisia. Indeed, soft wheat and maize exhibit similarities; both are affected by high temperatures, especially during critical growth periods.

Similarly, [15] revealed that among the impacts of climate change in northern Benin, yield decline occupied the most significant position ahead of disruption of planting dates, which is generally consistent with the results of this study.

5. Conclusion

This study focused on the impact of climate change on millet and maize yields in different agroecological zones of Senegal, through a methodology based on the estimation of regression coefficients and the calculation of the coefficient of determination. By relying on empirical data, the relationships between climatic variables and millet and maize yields were identified.

The results reveal that the coefficient of determination for maize is highest in the groundnut basin and Eastern Senegal. This indicates that these models offer better predictive capacity in these areas. In contrast, the values of the coefficient of determination for millet are low in all zones, highlighting a lack of overall significance of the model. The analysis also highlighted that factors such as evapotranspiration and soil temperature exert a negative impact on maize yields in Eastern Senegal, while these variables did not show significance in the Northern groundnut basin.

In summary, this research contributes to the existing literature on the effects of climate change on agriculture, while underscoring the importance of a disaggregated approach to better understand local dynamics. It highlights the necessity of adapting agricultural practices and public policies to mitigate the adverse effects of climatic conditions on agricultural yields, particularly in the most vulnerable areas.

Abbreviations

EWMBS	Energy and Water Balance Monitoring System
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross domestic product
DAPSA	Direction de l'Analyse, de la Prévision et des Statistiques Agricoles

Author Contributions

Mame Asta Gueye: Conceptualization and Project administration

Amadou Tandjigora, Thierno Bachir Sy : Formal Analysis and discussions, Presentation of the Study Area

Elhadj Mamadou D Ngom: Methodology

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Bougma, L. A., Ouédraogo, M. H., Sawadogo, N., Sawadogo, M., Balma, D., & Vernooy, R. (2018). Perceptions paysannes de l'impact du changement climatique sur le mil dans les zones sahélienne et soudanosahélienne du Burkina Faso. *Afrique Sciences*, *14*(4), 264-275.

[2] Chebil, A., Mtimet, N., & Tizaoui, H. (2011). Impact du changement climatique sur la productivité des cultures céréalières dans la région de Béja (Tunisie). African Journal of Agricultural and Resource Economics, 6(2). https://doi.org/10.22004/ag.econ.156981

[3] Cissé, A. B., & Diop, Khalifa. (2022). Perception du changement climatique et stratégies d'adaptation paysannes à Louga. Espace Géographique et Société Marocaine, 1(60). https://doi.org/10.34874/IMIST.PRSM/EGSM/32321

[4] Direction de l'Analyse, de la Prévision et des Statistiques Agricoles, 2021. Rapport de l'Enquête Agricole Annuelle (EAA) 2020-2021, 149p.

[5] FAO (2003). The state of food insecurity in the world. Rome, Food and Agricultural Organisation.

[6] Faye, A., Ndiaye, M., & Ndiaye, A. (2018). L'impact des changements climatiques sur les rendements des principales cultures céréalières au Sénégal. Revue Internationale des Economistes de Langue Française, 3, 291-306. https://doi.org/10.18559/rielf.2018.2.17

[7] Garcia, L. (2015). Impact du changement climatique sur les rendements du mil et de l'arachide au Sénégal: Approche par expérimentation virtuelle (Doctoral dissertation, Montpellier SupAgro).

[8] IRD (2019). Réchauffement climatique: une situation d'urgence pour les céréales africaines. IRD le mag' https://lemag.ird.fr/fr/rechauffement-climatique-une-situation-durgence-pour-les-cereales-africaines Consulté le 22 septembre 2024.

[9] Kadet, A., & Fall, N. (2024). Impact du changement climatique sur le rendement agricole dans le sud du bassin arachidier. Economics and Management Review, 2(2).

[10] PNUD (2004). Reducing disaster risk: A challenge for development. UNDP global report, ed. M. Pelling.

[11] Roudier, P. (2012). *Climat et agriculture en Afrique de l'Ouest: Quantification de l'impact du changement climatique sur les rendements et évaluation de l'utilité des prévisions saisonnières* (Doctoral dissertation, Ecole des Hautes Etudes en Sciences Sociales (EHESS)).

[12] Sultan, B., Lalou, R., Kergoat, L., Gastineau, B., & Vischel, T. (2021). Changements climatiques et agriculture: impacts et adaptation en Afrique de l'Ouest. Milieux extrêmes et critiques face au changement climatique: climats, territoires, environnement, 139-154.

[13] Sultan, B., Roudier, P., & Traoré, S. (2015). Les impacts du changement climatique sur les rendements agricoles en Afrique de l'Ouest. Les sociétés rurales face aux changements climatiques et environnementaux en Afrique de l'Ouest », Ed. IRD, 209-224.

[14] Tandjigora, A., & Sy, T. B. (2021). Economie rurale non agricole, levier de réduction de la pauvreté dans le Bassin arachidier du Sénégal. International Journal of Financial Accountability, Economics, Management, and Auditing (IJFAEMA), 3(4), 611-619. https://doi.org/10.52502/ijfaema.v3i4.133

[15] Vodounou, J. B. K., & Onibon Doubogan, Y. (2016). Agriculture paysanne et stratégies d'adaptation au changement climatique au Nord-Bénin. Cybergeo: European Journal of Geography. https://doi.org/10.4000/cybergeo.27836