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DOCTORATE THESIS

Domain: Agronomic sciences
Specialization: Climate Change and Agriculture

THEME:

Modeling Climate Risk and Adaptation Strategies for Pearl Millet (*Pennisetum glaucum* (L.) R. Br.) Production in Senegal Using DSSAT

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A THESIS
IN THE RURAL POLYTECHNIC INSTITUTE OF TRAINING AND APPLIED RESEARCH IN PARTNERSHIP WITH THE WEST AFRICAN SCIENCE SERVICE CENTRE ON CLIMATE CHANGE AND ADAPTED LAND USE (WASCAL), SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES, IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY IN CLIMATE CHANGE AND AGRICULTURE OF THE UNIVERSITY OF SCIENCES, TECHNIQUES AND TECHNOLOGIES OF BAMAKO (USTTB)

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DEDICATION

This work is dedicated to Almighty Allah for granting me the strength and health to complete this journey.

It is also dedicated to the memory of my beloved late parents, Salfo Zagre, my father, and Mariam Sana, my mother, whose unwavering guidance and tireless support shaped my life from childhood and continue to inspire me.

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List of acronyms and abbreviations

AEZ : Agroecological Zone

AGB : Aboveground Biomass

AICCRA : Accelerating Impacts of CGIAR Climate Research for Africa

BMBF : Bunderministerium fur Bildung und Fosrchung

CAM Climate Adaptation and Mitigation Cluster

CEC : Cation Exchange Capacity

CERAAS : Centre d'Étude Régional pour l'Amélioration de l'Adaptation à la Sécheresse

CERES : Crop Environment Resource Synthesis

CGIAR : Consultative Group on International Agricultural Research

CHIRPS : Climate Hazards Group InfraRed Precipitation with Station data

CMIP5 : Coupled Model Intercomparison Project Phase 5

CMIP6 : Coupled Model Intercomparison Project Phase 6

CNRA : Centre National de Recherche Agricole

CO_2 : Carbon dioxide

CSA : Climate-Smart Agriculture

CSI : Climate Service Information

CST : Climate-Smart Technology

DAP : Diammonium Phosphate

DSSAT : Decision Support System for Agrotechnology Transfer

DST : Decision Support Tool

DUL : Drained Upper Limit

EASM : Asian Summer Monsoon

ETC : Evapotranspiration Coefficient

ETO : Reference Evapotranspiration

EUC : Eastern and Upper Casamance

FAO : Food and Agriculture Organization of the United Nations

FAOSTAT : Food and Agriculture Organization Statistical Database

FMNR : Farmer-Managed Natural Regeneration

GC : Genetic Coefficient

GCM : Global Circulation Model

GHG : Greenhouse Gas

GSP Global Positioning System

HDR : Heavy Rain Day

HI : Harvest Index

ICRISAT : International Crops Research Institute for the Semi-Arid Tropics

EIR : Institut d'Economie Rurale

IFAD : International Fund for Agricultural Development

IFDC : International Fertilizer Development Center

IFRA : Formation et de Recherche Appliquée

ILRI : International Livestock Research Institute

INERA : Institut de l'Environnement et de Recherches Agricoles

IPCC : Intergovernmental Panel on Climate Change

IPR : Institut Polytechnique Rural

ISFM : Integrated Soil Fertility Management

ISRA : Institut Sénégalais de Recherche Agricole

K : Potassium

Kc : Crop coefficient

LAI : Leaf Area Index

LL : Lower Limit

MBE	: Mean Bias Error
N	: Nitrogen
NASA	: National Aeronautics and Space Administration
NPB	: New Peanut Basin
NRMSE	: Normalized Root Mean Square Error
OC	: Organic Carbon
OPB	: Old Peanut Basin
P	: Phosphorus
PAR	: Photosynthesis Active Radiation
PREA	: Participatory Research Extension Approach
RCP	: Representative Concentration Pathway
RMSE	: Root Mean Square Error
SAT	: Soil Saturation
SLPF	: Soil fertility determinant factor
SMS	: Short Message Service
SSA	: Sub-Sahara Africa
SSP	: Shared Socioeconomic Pathway
SVPZ	: Sylvopastoralism Zone
USTTB	: Université des Sciences, des Techniques et des Technologies de Bamako
WASCAL	: West African Science Service Centre on Climate Change and Adapted Land Use
WB	: World Bank
WUE	: Water Use Efficiency
ZALF	: Leibniz-Zentrum für Agrarlandschaftsforschung

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Abstract

This thesis explores how climate-smart technologies (CSTs) can enhance the resilience of dryland agricultural systems in Senegal, improving sustainability, productivity, and smallholder farmer incomes. It aims to generate science-based knowledge on climate-smart management practices for pearl millet production in Sub-Saharan Africa through experimentation, modeling, and participatory extension approaches (PREA). The study focuses on four key areas: first, examining the role of socioeconomic and institutional support in shaping community responses across three climate zones in Senegal; second, assessing the performance of micro-dosing fertilization strategies and plant populations on pearl millet production; third, evaluating the DSSAT model's ability to simulate the response of millet varieties to these strategies; and fourth, predicting millet yields under different fertilization and planting densities scenarios in Senegal's agroecological zones (AEZs) under current and future climate. Results show that most farmers recognize climate threats, with significant impacts from seasonal rainfall deficits (72%), delayed rainfall onset (88%), frequent dry spells (68%), and prolonged droughts (76%). Key drivers of CST adoption include access to credit, extension services, government subsidies, and advisor interactions, providing valuable insights for resilience-building strategies. The findings highlight that organo-mineral micro-dosing fertilizer (combining Senegal's recommended mineral rate with 2.5 tons of organic manure), improved plant populations (25,000 hills/ha), and dual-purpose millet varieties consistently enhance yields across study areas. Long-term simulations confirmed these parameters' effectiveness under both current and future climates. The CERES-Millet model accurately simulated four millet cultivars (Souna 3, SL 28, SL 423, and Thialack-2) with acceptable statistical index values. Future climate projection showed a decrease in rainfall across AEZs (up to 25%) and an increase in minimum and maximum temperatures for the mid-century. The results emphasized that using Senegal's recommended mineral fertilizer rate alone is more sensitive to future climate change, with yield declines ranging from 4% to 16% under SSP2–4.5 and from 8% to 33% under SSP5–8.5 by mid-century compared to organo-mineral doses. Higher planting densities were less sensitive to adverse climate impacts, demonstrating improved resource use efficiency and water retention compared to low-density practices, which exhibited a higher yield decline. Simulations indicate 6–17% yield increases compared to local varieties under various climate projections across AEZs. The effectiveness of interventions varies spatially, with northern regions showing higher vulnerability. Dual-purpose varieties, while effective under current conditions, are expected to decline by 1% to 13% under SSP2–4.5 and 6% to 27% under SSP5–8.5 in the future. These findings underscore the role of integrated soil fertility management (ISFM) and optimal plant density in mitigating climate effects. Smallholder farmers could adopt ISFM to enhance organic manure application combined with mineral fertilizers for sustainable productivity. This study highlights the importance of integrating high-resolution climate projections with agronomic modeling to guide adaptation strategies.

Keywords: Climate change, modeling, climate-smart practices, Pearl millet, micro-dosing, Sub-Saharan Africa, smallholder farmers

Résumé

Cette thèse explore le renforcement de la résilience des systèmes agricoles semi-arides du Sénégal face au changement climatique en améliorant la durabilité, la productivité et les revenus des petits exploitants grâce aux technologies climato-intelligentes. Elle vise à fournir des connaissances scientifiques sur les pratiques adaptées à la production de mil et aux systèmes d'utilisation des terres en Afrique subsaharienne, en combinant expérimentation, modélisation et vulgarisation participative. L'étude s'articule autour de quatre axes : (i) l'analyse du rôle du soutien socio-économique et institutionnel dans les réponses des communautés aux changements climatiques, (ii) l'évaluation de l'efficacité des stratégies de fertilisation par microdosage et des densités de plantation sur la production de mil, (iii) la calibration du modèle CERES-Millet de DSSAT pour simuler la réponse des variétés à ces stratégies, et (iv) la prédiction des rendements sous différents scénarios climatiques et pratiques culturales. Les résultats montrent que la majorité des agriculteurs perçoivent les menaces climatiques, avec des impacts majeurs tels que les déficits pluviométriques (72 %), le retard des pluies (88 %) et les sécheresses fréquentes (68 %) et prolongées (76 %). L'adoption des technologies intelligentes est facilitée par l'accès au crédit, les services de vulgarisation, les subventions et les interactions avec les agents agricoles, fournissant des pistes pour renforcer la résilience des communautés. La fertilisation organo-minérale combinant une dose minérale recommandée avec 2,5 t/ha de fumier organique, des densités optimales de 25 000 plants/ha et l'usage de variétés à double usage améliore systématiquement les rendements. Les simulations à long terme confirment l'efficacité de ces paramètres sous les climats actuels et futurs. Le modèle CERES-Millet simule avec précision les performances des variétés Souna 3, SL 28, SL 423 et Thialack 2. Les projections climatiques indiquent une baisse des précipitations pouvant atteindre 25 % et une hausse des températures d'ici 2069. L'utilisation seule de la fertilisation minérale est plus vulnérable aux changements climatiques, entraînant des pertes de rendement de 4 à 16 % sous SSP2-4.5 et de 8 à 33 % sous SSP5-8.5. En revanche, les stratégies organo-minérales offrent une meilleure résilience. Une densité de plantation élevée améliore l'efficacité de l'utilisation des ressources et la rétention d'eau, atténuant ainsi les effets du climat. Les variétés améliorées affichent des gains de rendement de 6 à 17 % selon les projections, mais leur efficacité varie selon les régions, le nord étant plus vulnérable. Les variétés à double usage pourraient voir leurs rendements diminuer de 1 à 13 % sous SSP2-4.5 et de 6 à 27 % sous SSP5-8.5. Ces résultats soulignent l'importance de la gestion intégrée de la fertilité des sols et des densités de plantation optimales pour atténuer les impacts climatiques. Enfin, cette étude met en évidence la nécessité d'intégrer des projections climatiques à haute résolution et la modélisation agronomique pour guider efficacement les stratégies d'adaptation.

Mots-clés : Changement climatique, modélisation, pratiques climato-intelligentes, mil, microdosage, Afrique subsaharienne, petits exploitants agricoles

CHAPTER ONE: INTRODUCTION

1.1. Problem or Justification

The effects of past climate trends on crop production are evident across several regions of the world (Freduah et al., 2019), with negative impacts being more prevalent than positive ones. Evidence shows that climate change has already adversely affected crop yields (Adiku et al., 2015; Akinseye et al., 2024), with many regions experiencing adverse effects such as rising temperatures, increased temperature variability, changes in precipitation patterns, more frequent dry spells and droughts, intensified extreme weather events, rising sea levels, and the salinization of arable land and freshwater (FAO, 2016; IPCC, 2021).

Building on this global perspective, Sub-Saharan Africa (SSA), including countries like Senegal, is particularly vulnerable (Sultan et al., 2023). Specifically, Senegal faces high climate variability and unpredictable rainfall patterns (Araya et al., 2022). The country's agricultural sector is heavily reliant on climate-sensitive activities, which, combined with frequent food shortages, water scarcity, rapid population growth, and limited resources for climate adaptation, exacerbate the challenges faced by farmers (Perez et al., 2015). Moreover, crop yields are expected to decline in areas already experiencing food insecurity (IPCC, 2014). This report presents projections of changes in crop yields due to climate change over the 21st century, emphasizing the detrimental impact on rural livelihoods.

In these regions, agriculture depends heavily on rainfed and smallholder farming systems with limited access to critical resources such as fertilizers, herbicides, machinery, and irrigation technologies (Haile, 2005; Hansen et al., 2019; Muzari et al., 2012; Namatsheve et al., 2020; Waongo et al., 2015). The adverse effects of climate change on agricultural production and livelihoods are anticipated to intensify and vary across different countries and regions (IPCC, 2021). In SSA, these climate-related impacts are further compounded by poor farming practices, low native soil fertility, inadequate access to improved crop varieties, pests and diseases, high input costs, ineffective extension services, market access issues, and storage risks (Diouf et al., 2019; Zagre et al., 2024).

To address low soil fertility and enhance crop yields, the Abuja Declaration 2006 targeted increasing nitrogen (N) fertilizer application from 8 kg/ha to 50 kg/ha. However, many countries have not achieved this target (IFDC, 2022). Consequently, research is needed to promote Integrated Soil Fertility Management (ISFM) practices tailored to specific environmental conditions. Such practices would enable farmers to maintain yields with fewer resources and implement climate-smart practices that increase resilience while reducing emissions.

Furthermore, in Senegal, millet is a crucial component of food and nutrition security (Diatta and Thomason, 2016; Faye et al., 2023; Tounkara et al., 2023; Vieira Junior et al., 2023). It is a staple crop extensively grown nationwide (Diatta and Thomason, 2016; Faye et al., 2023). It is valued for its resilience to dry conditions and its ability to maintain greenery with minimal moisture. Millet also provides both feed and grain, with its spacing allowing for a higher grain-fodder ratio, making it vital for agricultural practices (Faye et al., 2023; Pilloni et al., 2022). The high domestic demand for millet, whether for human consumption or livestock feed is a valuable income source for numerous smallholder farmers in Senegal and beyond (Pasternak et al., 2012). Certain millet varieties also serve as crucial forage in regions like the Sahel, especially under rainfed conditions (Faye et al., 2023).

Despite millet's importance, typical Pearl millet yields of 917 kg/ha (FAOSTAT, 2021) still fall short of the attainable yield of 3500 kg/ha due to challenges such as varying environmental conditions and high fertilizer costs (IFDC, 2016). Addressing these challenges necessitates more rigorous monitoring and evaluation of climate service projects, along with the adoption of smart practices, as rainfed agriculture systems are increasingly vulnerable to climate change impacts (Moutouama et al., 2022; Partey et al., 2018). Models assessing farm-level yields under different fertilizer strategies and contrasting environments have proven effective in aiding farmers' decision-making (Dodds, 2010; Sultan et al., 2019).

Climate and agricultural modeling tools are crucial for evaluating climate change implications and assisting stakeholders in making informed decisions to mitigate adverse effects (Araya et al., 2015; Jägermeyr et al., 2021; Lobell and Burke, 2010). These tools offer valuable insights for enhancing crop forecasting, developing climate variability indices, and supporting agricultural insurance programs (Jones and Thornton, 2003; Koo et al., 2016). Additionally, the Decision Support Systems for Agricultural Technology (DSSAT) has demonstrated its effectiveness in simulating crop growth and development in arid and semi-arid zones, especially when considering weather uncertainties, fertilization strategies, and optimal sowing windows on yield and profitability

(Adam et al., 2020; Akinseye et al., 2017; MacCarthy et al., 2010; Tovihoudji et al., 2019). DSSAT's capability to simulate both single cropping and intercropping systems (Jones et al., 2003) makes it well-suited for West African farming systems. Various studies have validated the accuracy of these models, highlighting their utility in optimizing agricultural practices and mitigating climate risks.

Nonetheless, calibrating these models with local data remains crucial, as this information is often unavailable. Hence, the latest generation of climate models, CMIP6, now incorporates socio-economic aspects alongside biophysical factors. This updated focus acknowledges integrating human activities and natural processes in climate modeling (IPCC, 2021; O'Neill et al., 2017). CMIP6 scenarios cover a broader range of greenhouse gas and air pollutant futures than previous RCPs (IPCC, 2021). It is important to note that some CMIP6 models exhibit high climate sensitivity, meaning they may produce different projections of future climate change compared to earlier models (Almazroui et al., 2020; Sang et al., 2021; Wehner, 2020). This underscores the need for continued research and adaptation strategies to address the climate impacts on crop production in Sub-Saharan Africa, a region particularly vulnerable to these changes, and to advance relevant, science-based knowledge.

1.2. State of the knowledge

Research on climate change impacts and adaptation strategies in Sub-Saharan Africa (SSA) has gained significant attention recently. Several studies have documented the adverse effects of climate change on agriculture in SSA countries, including Senegal (Adiku et al., 2015; Akinseye et al., 2012, 2013; Araya et al., 2022; Berg et al., 2013; Falconnier et al., 2020; Sultan et al., 2013, 2019, 2023). Changes in temperature and precipitation patterns directly affect crop yields, soil health, and water availability (Berg et al., 2013; Thornton and Cramer, 2012). Pearl millet, renowned for its resilience to drought and poor soil conditions, is vital to food security in semi-arid regions (Singh et al., 2017; Ullah et al., 2017; Yadav et al., 2017). Furthermore, studies have explored farmers' coping mechanisms and adaptation strategies in SSA (Diouf et al., 2020; Nyadzi et al., 2018; Ouedraogo et al., 2018; Totin et al., 2018; Zagre et al., 2024).

Among these, climate-smart management practices, particularly micro-dosing technologies, have proven effective in improving crop production in arid and semi-arid zones (Akinseye et al., 2023; Fatondji et al., 2012; Tabo et al., 2007). Given the rising costs of fertilizers, there is growing interest in exploring smart agricultural practices that minimize fertilizer loss in farming systems. Micro-dosing technology is crucial in this regard (IFDC, 2016). Developed to address low mineral fertilizer availability and optimize crop uptake, micro-dosing involves point application techniques that offer multiple benefits (Bagayoko et al., 2011). These include reduced phosphorus fixation, enhanced early-season growth, and increased infection with vesicular-arbuscular mycorrhiza, leading to improved nutrient uptake and higher yields of grain and stover (Choudhary et al., 2016; Olson et al., 2014; Saidia and Kahimba, 2019). Despite its promise, research on integrating micro-dosing with combined applications of organic and mineral fertilizers remains limited, particularly in West Africa.

Recent studies have also shown that dual-purpose millet varieties, when combined with optimal planting densities, can significantly boost yields (Faye et al., 2023; Pilloni et al., 2022). However, it is worth assessing their adaptability under changing environmental conditions for more adoption at the farm scale. Furthermore, there is a lack of crop model simulations that evaluate micro-dosing and fertilization strategies under changing conditions. This study seeks to address these gaps by assessing the optimal combination of micro-dosing technology with organo-mineral fertilizers under different millet varieties.

The research aims to generate new insights into the effectiveness of climate-smart agricultural practices while examining farmers' perceptions and adaptive responses to climate change. To do this, crop simulation models were used to evaluate the technologies under elevated atmospheric CO_2 and variable seasonal conditions. This modeling approach supports the development of adaptive management strategies suited to diverse agroecological contexts.

While previous studies have examined climate change impacts on staple crops in SSA, there remains a paucity of research specifically focusing on pearl millet in Senegal (Akinseye et al., 2024; Araya et al., 2022). Moreover, most earlier studies relied on projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5). This study instead uses the more recent CMIP6 projections (Eyring et al., 2016), which provide refined assessments of 21st-century climate scenarios. By doing so, it offers critical insights into the potential effects of climate change on pearl millet and evaluates adaptation strategies such as improved varieties, soil fertility management, and optimized planting density.

Although integrated soil fertility management is recognized as an essential strategy for sustainable intensification, little research has assessed its effectiveness under projected climate conditions for pearl millet. This study incorporates organo-mineral micro-dosing, improved plant densities, and newly released dual-purpose varieties to fill this knowledge gap. Additionally, there is a strong need for policy-relevant research. This study aims to support evidence-based decision-making by generating practical recommendations for enhancing the resilience of millet-based systems in Senegal.

By synthesizing existing knowledge and addressing current gaps, this study contributes to understanding how micro-dosing and organo-mineral fertilization can enhance adaptation to climate change. The findings will offer actionable insights for farmers, researchers, and policymakers, helping guide the implementation of robust and locally appropriate climate-smart agriculture strategies.

Crop models such as DSSAT have proven valuable for simulating crop responses to climate change (Feleke et al., 2021). These models incorporate climate, soil, and crop management data to predict future crop performance under various scenarios (Hoogenboom et al., 2019; Jones et al., 2003). Studies using such models have provided valuable insights into potential yield changes and adaptation strategies (Garba et al., 2024; Tovihoudji et al., 2019; Wimalasiri et al., 2023). Adaptation strategies like drought-resistant varieties, soil fertility management, and optimized planting dates have been proposed to mitigate climate change impacts on pearl millet production (Akinseye et al., 2023). Research has shown that combining improved millet varieties with appropriate soil and water conservation practices can significantly enhance resilience and productivity (Akponikpe et al., 2014; Ibrahim et al., 2016).

Despite these advances, challenges persist in technology adoption, especially due to limited access to inorganic fertilizers and underutilization of organic inputs (Raes et al., 2021; Waongo et al., 2015). With a wide yield gap between farmers' current production and the potential of improved varieties, this study evaluates the performance of dual-purpose millet varieties under improved population densities and micro-dosing across Senegal's agroecological zones. Employing a Participatory Research and Extension Approach (PREA), this research aims to accelerate the adoption of climate-smart practices (Ajeigbe and Dashiell, 2010), raise awareness of integrated soil fertility management, and enhance millet cultivation under increasingly variable climatic conditions.

In summary, this study will contribute new knowledge on the performance of micro-dosing combined with organo-mineral fertilizers. It will also enhance understanding of farmers' adaptive strategies to climate change, ultimately providing practical insights for implementing effective climate-smart agricultural practices in SSA.

1.3. Research hypothesis

- ✓ Farmers in the three cluster zones of Senegal have distinct perceptions of climate variability and its environmental impacts, which influence their coping and adaptation strategies.
- ✓ Micro-dosing fertilization and optimal plant population densities significantly enhance pearl millet yields at the smallholder level in Senegal.
- ✓ The DSSAT CERES-Millet model can effectively simulate the yield response of pearl millet to micro-dosing and plant density under current and future climate scenarios.
- ✓ Climate-smart technologies such as improved varieties, optimal density, and fertilization strategies can sustain millet yields under projected climate change in Senegal’s agroecological zones.

1.4. OBJECTIVES

1.4.1. Overall objective

To assess the impact of climate-smart management practices on the resilience of pearl millet production in Sub-Saharan Africa using Integrated Soil Fertility Management, crop modeling, and socio-economic factors to develop practical recommendations for improving productivity under changing climatic conditions.

1.4.2. Specific objectives

1. To analyze farmers’ perceptions of climate variability and change, their environmental impacts, and local adaptation strategies in three cluster zones of Senegal.

2. To evaluate the performance of micro-dosing fertilization and plant population density on pearl millet yields at the smallholder scale.

3. To calibrate and validate the CERES-Millet model of DSSAT for simulating the response of pearl millet varieties to plant density and fertilization strategies
4. To simulate and project pearl millet yields under current and future climate scenarios using DSSAT, considering adaptation strategies across agroecological zones in Senegal.

CHAPTER TWO: LITERATURE REVIEW

2.1. Trend and climate change and variability over Sub-Saharan Africa

Sub-Saharan Africa (SSA) is considered to be one of the most vulnerable regions to climate variability and change (Almazroui et al., 2020; IPCC, 2021; Kouman et al., 2024), which poses major challenges to agricultural development (Fisher et al., 2015; Stewart et al., 2020; Van Ittersum et al., 2016). Gaetani and Mohino (2013) observed significant interannual variability in precipitation in West Africa, with droughts from the 1960s to the 1980s and partial recovery in recent years. Several studies have highlighted precipitation's uncertainty, temporal and spatial variability (Akinseye et al., 2013, 2016; Lodoun et al., 2013; Salack et al., 2011; Sultan et al., 2013). Strong variations in precipitation characteristics, such as the number of rainy days, precipitation, mean precipitation per rainy day, and the start and end dates of the growing seasons in the Sahel from 1941 to 2000, were noted by Lodoun et al. (2013). According to Traore et al. (2014) , between 1961 and 2010, fewer continuous rainy days and more consecutive dry days occurred. De Longueville et al. (2016) emphasized that between 1950 and 2013, the Sahel region's annual precipitation reduced noticeably, the number of maximum consecutive dry days rose, and the number of maximum consecutive rainy days fell. In the southern region of Mali, Traore et al. (2013) discovered that the number of dry days dramatically increased throughout the growing season, indicating a change in the distribution of precipitation. Modeling approaches to assess climate change scenarios show contrasting effects on crop yields, although the downward trend is more pronounced. Projections suggest that the growing season for crops and livestock in SSA could be shortened by an average of 20% by 2050 (IPCC, 2013), which could significantly affect the productivity of agriculture. In Senegal, where this study was conducted, vulnerability to climate change is escalating due to unpredictable rainfall patterns, recurrent droughts, floods, dry spells, shortened growing periods, and deteriorating conditions for farmers (Chiputwa et al., 2020; Salack et al., 2011). The climate change prediction done by Adiku et al. (2015) in West Africa for mid-century RCP8.5 of median precipitation change showed that Senegal ranks between -20 and -5%. In that case, the rainfall amount is predicted to decrease significantly in this country having considered the worst scenario. For temperature, this prediction revealed that there is a uniform increase in minimum and maximum temperature between 1 and 4% throughout West Africa. The

IPCC's global scenarios (IPCC, 2013) predict that SSA will see a temperature increase that is 1.5 times greater than the global average. The worst-case scenarios predict a temperature increase of 2.0°C to 4.8°C over pre-industrial levels by the end of the century. The prevalence of drought and mean annual temperature rise are the most significant climate variables, posing a high risk to rain-fed crop production systems and the livelihoods of subsistence farmers in SSA, according to several studies (Bossa and Diekkrüger, 2014; Hansen et al., 2019; Sultan and Gaetani, 2016). The region is experiencing an increase in the frequency of climate disasters like droughts and floods, which pose serious difficulties for impoverished farmers.

2.2. Effect of climate change and variability on crops across the West African Sahel

2.2.1. Rainfall variability and associated risk for crop production

In the absence of adaptive measures, a study by Bello and Maman (2015) found a positive correlation between precipitation increase and crop receipts, with an increase of 1 mm/month resulting in a gain in crop receipts of up to USD 1,227.26. However, the crop receipts grew even more to USD 3,164.47 after adaptation techniques were put into place. This study emphasized that rainfall variability in the Sahelian zone is a crucial factor influencing crop yield loss. In countries like Senegal located in the Sahel zone, rainfall plays a major role in determining crop production. Different varieties of crops grown in the Sahelian zones, such as cereals and leguminous plants, have varying maturity cycles, making it challenging for farmers to determine the optimal sowing windows (Akinseye et al., 2023; Joseph et al., 2023). Climate change and variability pose significant challenges to crop productivity and resource use efficiency in West Africa. The most substantial overall resource efficiency and yield loss is projected under the RCP 8.5 scenario (Amouzou et al., 2019). Various studies have indicated that missing the optimal planting windows negatively impacts crop yield (Akinseye et al., 2016; 2023; Egbebiyi et al., 2020; Soler et al., 2007, 2008). Mohamed et al. (2023) predicted that the impacts of sowing dates on production could lead to millet yield reductions of up to 50% in the Sahel zone. Reliable determination of the rainy season onset and the optimal sowing time is crucial for sustainable food production. Since the mid-1980s, a progressively delayed onset of the rainy season has been observed in Sub-Sahara Africa (Laux et al., 2008). Considering the regional onset of the monsoon appears to improve the relationship between water availability and plant water use, potentially leading to increased crop water utilization (Sultan et al., 2005). Sufficient water availability is essential for nutrient absorption and movement from roots to other parts of the plants (Araya et al., 2022). Studies have projected a delayed onset of the rainy season by one to three weeks for the midcentury climate period compared to the baseline period. Ibrahim et al., (2012) projected a decrease in the number of low rainfall events (0.1-5 mm/d) by 3% and an increase in the number of strong rainfall events (>50 mm/d) by 15% on average. In this study, they emphasized that the onset of the rainy season is consistently projected to be delayed by one week on average, and there is a consensus among models regarding the lengthening of dry spells by about 20% for the period 1971-2000 to 2021-2050. On the same hand, Hess et al. (1995) observed a consistent decrease in annual rainfall of 8 mm/year across four stations in Nigeria, with the majority of the reduction occurring in August or September. According to them, this reduction in rainfall was primarily due to a decrease of 25 days in the number of rainy days during the rainy season, resulting in longer dry spells of up to 1.5 days. This variability over the Sahelian region which led to a delay in the onset of the rainy season explained above caused the real impact on the cropping system. Indeed, Joseph et al. (2023) discussed the influence of the onset of the rainy season on rainfall distribution and maize yield, emphasizing its inter-variability in Senegal. Furthermore, the decrease in the amount of rainfall combined with the temperature increase which has been proven by several studies cited above for Sahelian zones has an impact visible on crop production. For instance, Akinseye et al. (2020) conducted a simulation study to assess the impact of increased temperatures (2°C, 4°C, and 6°C) and decreased rainfall (25% and 50%) on varying N fertilizer application rates on sorghum and maize. Their findings revealed a highly significant risk of low maize yield associated with decreased rainfall compared to increased rainfall. According to their results, a decrease in rainfall by 25% and 50% led to yield declines ranging between 5% and 37%, respectively. Similarly, Sultan et al. (2013) found that most scenarios negatively impacted sorghum and millet yields, with reductions of up to 41% when rainfall decreased by 20% and temperature increased by 6°C. Knox et al. (2012) estimated mean yield changes across West Africa, resulting in reductions of 17% for wheat, 5% for maize, 15% for sorghum, and 10% for millet. Rezaei et al. (2014) simulated the projected climate change impacts on millet yields in Niger and found yield declines ranging from 11% to 62%, depending on the scenario and period. Roudier et al. (2011) also conducted a study in tropical regions. They concluded that Pearl millet, one of the major crops in the area, would decrease by an average of 6% across all models and scenarios, with individual model projections ranging from a decrease of 29% to an increase of 11%. These impacts of weather anomalies over West Africa emphasized by several studies mentioned above are not homogenous from one side to another. For that, Graef and Haigis (2001) conducted research in Niger and found that rainfall can vary considerably even within a few kilometers and across different time scales. This variability leads to unpredictable crop yields in the Sahel region.

2.2.2. Increased temperature and associated risk for crop production

With temperature increases of 2°C or higher beyond late-20th-century levels, the IPCC predicts that major crops in tropical regions may experience negative effects; however, the signal may differ for specific locations. Several studies in the Sahel regions (Adiku et al., 2015; Akinseye et al., 2020; Silungwe et al., 2019; Sultan et al., 2013) have demonstrated that rising temperatures affect agricultural and livestock systems. Temperature increases during the rainy season can immediately result in decreased yields for the majority of food crops, which will lower food output (IPCC, 2014). Crop water stress during the growth season is typically caused by high evapotranspiration and an increase in water demand under high temperatures (Amouzou et al., 2019; Fatondji et al., 2012). Consequently, it is predicted that throughout Senegal, temperatures will rise by 2.5°C by the middle of the century (Parkes et al., 2018; Sultan et al., 2019). Despite being one of the most resilient crops to harsh climate events like drought and dry spells, Silungwe et al. (2019) showed that temperature increases of 1.5°C and 2°C harmed millet yields in Semi-Arid Central Tanzania. Then, Bello and Maman (2015) reported a decline in income as a result of rising temperatures in Niger. They demonstrated that yearly crop net sales fell by up to USD 989.69 for the model without adaptation methods and up to USD 2.24 for the model with adaptation strategies, with a rise in annual temperature of 1°C. Consequently, the region's food security is significantly impacted by climate change, which also presents considerable concerns. Araya et al. (2022) further indicated that temperature increases in Senegal by 1.5-2°C during the mid-century under RCP8.5 resulted in a yield decline of approximately 12% for sorghum and 6% for millet. According to Sultan et al. (2013), this yield decline due to climate change is expected to be higher for early-duration genotypes. Sultan and Gaetani (2016) discovered that yield losses are mostly caused by an increase in mean temperature, with potential modifications from wetter or drier circumstances as well as increasing CO2 concentrations.

2.3. Future Climate Prediction over West African Sahel

According to IPCC (2014), global warming and more extreme weather events are expected to increase more frequently. Therefore, to feed approximately 9.6 billion people by 2050, global food production must increase by 60-70% (El Bilali et al., 2020; Raes et al., 2021). However, the climate prediction made recently over West African regions (Ruane and McDermid, 2017; Sultan and Gaetani, 2016; Sylla et al., 2018) highlighted that intra-seasonal dry spells are common and may occur at any moment during the cropping season as well as considerable spatial variation of dry spells exists. This scenario involves providing more scientific knowledge at the local level for different crops and cultivars to anticipate climate risk and yield loss. As stated by several future climate predictions in West Africa, biomass and grain yields will decrease in the future under the Representative Concentration Partway (RCPs) given by IPCC (2013). The Coupled Model Intercomparison Project Phase 5 (CMIP5) model output is frequently used to forecast future climatic conditions (Hempel et al., 2013). The use of coupled models, which combine multiple climate components, offers a more robust and comprehensive prediction compared to using a single model (Fotso-Nguemo et al., 2018). These models are based on well-established physics principles and are designed to simulate the complex interactions within the climate system (Hempel et al., 2013). Global Circulation Models (GCMs) are a key component of CMIP5 and are constructed using established climate physics. They play a crucial role in climate projections by taking into account the emissions of greenhouse gases into the atmosphere. These models integrate the biophysical aspects of the climate system, allowing for an assessment of the impact of increasing CO_2 levels on the climate. In that case, previous studies frequently used the intermediary scenario RCP 4.5 which involves environmental protection emphasized and the world population increases at a relatively low speed (IPCC, 2013) by the end of the 21st century. In this scenario, the atmospheric CO_2 concentrations are predicted to be stabilized at 550 ppm by the end of the century. Then, the temperature will likely increase by 1.1- 2.9 °C. So, about RCP 8.5, which is the worst-case scenario, as a result of continuously increasing global population and limited technological change, CO_2 emissions in the period 2000–2099 will multiply 4-5 times and the atmospheric CO_2 concentrations will likely rise to 850 ppm. The temperature will likely increase by 2.0- 5.4 °C (IPCC, 2013). According to various authors, these two scenarios are pertinent and give a useful overview to help decision-makers and policy with climate action mainstreaming. In reality, mainstreaming fair and effective climate action would not only lessen losses and harms to people and nature but will also have broader positive effects, according to the IPCC's sixth assessment.

Thereby, in West Africa, several studies (Adiku et al., 2015; Akinseye et al., 2013; Toure et al., 2018; Traore et al., 2014) have been done using CMIP5 for climate-impacted assessments in the Sahelian countries. Among them, Akinseye et al. (2013), found that under climate change scenarios using Representative Concentration Pathway (RCP) 8.5, there are projected yield losses for an early-maturing variety of crops over West Sahelian zones. These findings suggest that climate change, as represented by the RCP 8.5 scenario, could harm crop yields, leading to potential losses in both the near-future and midcentury periods for the early-maturing variety. These projections highlight the importance of considering climate change impacts on agriculture and implementing adaptation strategies to mitigate potential yield losses. Furthermore, Toure et al. (2018) indicated that all climate change scenarios underestimated millet crop yield compared to the baseline, regardless of the treatment and variety considered. This suggests that the climate change scenarios used in the study resulted in lower simulated millet grain yields compared to the historical weather data. These findings highlight the potential negative impacts of climate change on millet grain yields and suggest that the simulations used in the study underestimated the actual yield reductions. Beyond West Africa, Msongaleli et al. (2014) revealed that the Representative Concentration Pathway (RCP) 4.5 scenario predicts a 2 to 9% decline in sorghum output in Semi-Arid Central Tanzania by the middle of the century (2040–2069). This shows that semi-arid and arid regions are more susceptible to changes in the climate in the future, which could harm crop production. Despite the relevance of CMIP5 to predict change based on the biophysical aspects, the new generation was developed CMIP6 includes the socio-economic aspects. In CMIP6, there was an added focus on integrating socio-economic and biophysical aspects, recognizing the importance of considering human activities and natural processes in climate modeling (IPCC, 2021; O'Neill et al., 2017). The Shared Socio-economic Pathways (SSP) cover a broader range of GHG and air pollutant futures than the RCPs (IPCC, 2021). They are similar but not identical, with different concentration trajectories for different GHGs. It should be noted that some models in CMIP6 exhibit high climate sensitivity, which refers to the response of simulated temperature to increases in greenhouse gas forcing (Almazroui et al., 2020; Sang et al., 2021; Wehner, 2020). This means that these models may produce different projections of future climate change compared to CMIP5 models. These differences in climate sensitivity can potentially lead to varying multi-model projections of future climate at specific time points between CMIP5 and CMIP6. However, some studies (Tian and Dong, 2020; Wehner, 2020) using both generations of coupled models found that at their standard resolutions, there were no significant differences in their projections of extreme daily temperature and precipitation at specific global warming targets. Unlike these results, several authors (Fernandez-Granja et al., 2021; Zamani et al., 2020) revealed that CMIP6 is more sensitive than CMIP5. Xin et al. (2020) found that CMIP6 demonstrates improvements compared to the previous CMIP5 models in reproducing the interannual anomalous rainfall pattern over Asian Summer Monsoon (EASM). These improvements imply that the CMIP6 models offer a better representation of the complex dynamics involved in the EASM and its impact on regional rainfall patterns. On the same hand, Kim et al. (2020) revealed that CMIP6 models are better overall in simulating heat waves in Korea and the associated diagnostic indices. Regarding rainfall, Bağçaci et al. (2021) have shown that CMIP6 products outperform CMIP5 in terms of accuracy statistics. Furthermore, Almazroui et al. (2020), the CMIP6 multi-model ensemble predicts that the mean annual temperature will rise consistently and noticeably throughout Africa and its eight sub-regions over the 21st century. These projections indicate a clear trend of increasing temperatures across Africa under various greenhouse gas emissions and socioeconomic development pathways. The mean annual temperature over Africa is projected to rise by 1.2 °C to 1.8 °C in the near-term period and by 1.4 °C to 4.4 °C in the long-term period. This indicates that the CMIP6 models show enhanced consistency in their projections compared to the CMIP5 models. Furthermore, these findings suggest that the CMIP6 models exhibit improved performance in capturing the variability and teleconnections related to heatwaves compared to the CMIP5 models, thus providing more reliable projections for studying heatwave events and their impacts in the region (Kim et al., 2020). Recent studies (Almazroui et al., 2020; Berhanu et al., 2023; Wada et al., 2023) have further highlighted the improved performance of CMIP6 models in projecting climate change in Sub-Saharan and East Africa, emphasizing their utility for regional climate adaptation and planning. All these results showed by the previous studies emphasize the need for continued research and adaptation strategies to address the challenges posed by climate change and its potential effects on crop production. It also highlighted the importance of using the new generation of coupled models in crop simulation to assess climate impact on crop production over Sub-Sahara Africa which is one of the more vulnerable regions to bring up relevant scientific based-knowledge.

2.4. Importance of millet over West African Sahel food security

In arid and semi-arid regions of Asia and Africa, pearl millet is a crucial crop that provides food security for millions of people living in hard and ecologically delicate environments (Yadav et al., 2017). Indeed, there are several reasons why millet is frequently seen as a superior smart crop when compared to other cereals like rice, sorghum, and maize. Firstly, millet requires less fertilizer, pesticides, and irrigation inputs compared to mainstream cereals (Anuradha et al., 2018). This makes it a more sustainable and environmentally friendly option for cultivation. Pearl millet is known for its exceptional water use efficiency, making it a suitable crop for regions with limited water availability or under drought conditions. It also utilizes C4 photosynthesis, which is a more efficient photosynthetic pathway compared to C3 plants. C4 plants typically have higher water use efficiency due to their specialized carbon fixation mechanism (Uppal et al., 2015; Yadav et al., 2017). Moreover, Pearl millet has fewer pest and disease problems compared to other cereals and is suited to different cropping systems (Michels and Bielders, 2006)

Furthermore, the study by Traore et al. (2014) highlights the adaptability of millet to a late planting date. They found that late planting had significant yield decreases for maize, sorghum, and cotton, but not for millet. This suggests that millet can tolerate and perform well even when planted later in the growing season. Additionally, they mention that a short-duration variety of millet was particularly well-suited for late planting in Mali. This indicates that specific millet varieties have been developed and adapted to maximize their yield potential even under less favorable planting conditions. Second, millet-based foods can significantly improve food security and offer several nutritional benefits, especially for the world's expanding population (Couturon et al., 2003). As a highly nutritious crop with unique nutritional properties and climate resilience, pearl millet has the potential to increase the country's food and nutritional security (Singh et al., 2018). Millets are resistant to climate change and can be grown on parched fields with little assistance. Since pearl millet has special qualities and can adapt to harsh agroclimatic conditions, it is regarded as a climate-resilient crop (Ullah et al., 2019). It can withstand high temperatures, low soil fertility, and repeated droughts thanks to its great photosynthetic efficiency and dry matter production (Anuradha et al., 2018; Yadav et al., 2017). It is a hardy cereal crop with short growth periods (60-100 days) in semi-arid to arid zones where soils predominately have sandy textures, low organic matter, and nutrient levels; rainfall is limited and erratic (annual precipitation as low as 300 mm), air and soil temperatures are high; and the growing season length varies greatly across years

(Mason et al., 2015; Michels and Bielders, 2006; Vieira Junior et al., 2023; Yadav et al., 2017). Due to its low transpiration rate and capacity to fix carbon even in high temperatures and low nitrogen environments, pearl millet is usually grown in the most difficult agro-climatic conditions, where other crops find it difficult to produce viable yields (Ekwangu et al., 2020; Ibrahim et al., 2015; Sanoussi et al., 2020). Nevertheless, pearl millet has an amazing capacity to adapt to favorable conditions because of its quick developmental stages and fast growth rate (Yadav et al., 2017). Thus, pearl millet can cope with climate variability due to its high buffering capacity, specific adaptation traits such as resistance to drought, high temperature, and flooding, and its genetic variability (Eyshi Rezaei et al., 2014; Vieira et al., 2023). They are therefore the perfect answer for countries looking to boost their level of independence and decrease their reliance on imported grains and cereals. In Senegal, millet is a crop crucial to achieving food and nutrition security since it is one of the staple crops and is usually cultivated as a mono-crop throughout the country (Diatta and Thomason, 2016; Faye et al., 2023; Faye et al., 2018). Millet withstands dry conditions of 300 mm annual rainfall and remains green at very low moisture levels. It provides the farmers with feed and grain and requires suitable spacing which allows for a higher grain-fodder ratio (Faye et al., 2023; Pilloni et al., 2022). The high domestic demand for millet as food for humans or as livestock feed makes it a valuable source of income for a large community of smallholder farmers in this country. In that case, Pasternak et al. (2012) demonstrated that varieties of pearl millet can become an important source of forage in the Sahel under rainfed conditions. Therefore, in low-production areas, pearl millet can play a major role in climate-resilient agriculture when handled with enhanced agronomic practices (Uppal et al., 2015). However, yields are low due to inappropriate management and erratic rainfall. In that case, improving crop yields is a key pathway to reducing poverty for smallholders. Our study aims to provide a chance to increase awareness of millet management and its suitability for cultivation under challenging and changing climatic conditions, as well as to focus policy attention in these areas. To assist in decision-making and guide investments in the sustainable intensification of millet production, this study set out to scale up climate-smart management practices under yield production and to arrive at potential interventions for closing the millet yield gap.

2.5. Soils fertility and cereals fertilization

2.5.1. Concept of Integrated Soil Fertility Management (ISFM)

Poor and highly variable soil physical and chemical characteristics in West Africa combined with climate effects led to yield spatial and temporal variability (Bationo and Buerkert, 2001). SSA has been affected by land degradation, making it one of the most area urgent development issues with significant costs(Jones et al., 2012; Nyamekye et al., 2018). The fundamental biophysical reason for SSA's declining per capita food production over the past three to five decades is soil infertility (Stewart et al., 2020). This is evident from the huge gap between actual and potential crop yields. As a consequence of declining soil fertility and low use of fertilizers, has been identified as a future hotspot for food shortage due to low agriculture yields. Several West African countries are food insecure and have persistently been unable to feed their populations. Senegal is not left out of this reality and remains vulnerable to several constraints that affect agricultural development in a changing climate. The primary obstacles to arable agriculture are crop growth on primarily sandy soils with low soil fertility, especially in terms of nitrogen (N) and phosphorus (P) and low levels of organic matter (Bationo et al., 2006). In addition, arable land across agroecological zones is being gradually reduced due to the southward creep of the 400 mm isohyet or less with a significant erratic pattern within the season limiting the water availability to support crop growth (Akinseye et al., 2020). Fundamental improvements in soil and plant nutrition will be required to meet the challenge of sustainably feeding an increasing number of people by 2050. To address the task of building a more environmentally sustainable and food-secure future, significant adjustments in agricultural systems will be needed (Bationo et al., 2018). Integrated Soil Fertility Management (ISFM) is a method designed to assist farmers in managing their farms more effectively to reduce yield loss due to soil quality, particularly in West Africa. The term Integrated Soil Fertility Management (ISFM) pertains to the application of tailored soil fertility management strategies that are intended to optimize the efficiency of organic matter and fertilizers in agricultural crop production (Bekunda et al., 1997). It also includes understanding their local adaptation in soil fertility management practices, as well as the use of organic inputs, enhanced germplasm, and mineral fertilizer. The nutrients required for plant growth are mostly provided by inorganic fertilizers, whereas organic fertilizers improve the soil's overall organic matter status, soil structure, and buffering ability (Bagayoko et al., 2011; Tounkara et al., 2020). It has been demonstrated that the use of both organic and inorganic fertilizers produces a synergistic effect that increases the efficiency of water and nutrient utilization (Fatondji et al., 2012). In actuality, chemical fertilizers and organic sources like manure are the main sources of nitrogen (N) and phosphorus (P) inputs to the soil for agricultural purposes; nevertheless, the application of these nutrients is severely neglected because of their high cost and lack of technical know-how. Then, micro-dose technology which is suited to West African soil is appropriate for improving nitrogen uptake and reducing fertilizer loss (Bationo and Waswa, 2011). It involves the strategic application of small doses of fertilizer and enables farmers to overcome the risks associated with fertilizer use under conditions of low soil moisture(Vanlauwe et al., 2023). The combination of strategic hill application of fertilizer with a complimentary organic fertilizer in a micro-dosing technology has been demonstrated to boost yield productivity close to the cultivar's yield potential resulting in economic gain (Akinseye et al., 2023). When organic and inorganic inputs are mixed, the effects of nutrients are prolonged and the physical qualities of the soil are improved compared to when either source is used separately (Wood et al., 2015). The soil fertility enhancement technologies developed over the years for the main staple food crops in West Africa, such as sorghum and millet remain one of the climate-smart technology practices against climatic risks for better farm-level interventions. Thus, the technology adoption remains low due to limited access to inorganic fertilizers due to high market prices and inadequate use of manure amendments. The technological foundation of integrated soil fertility management (ISFM) was the integration of organic resources and mineral fertilizer as inputs, especially when micro-dose application methodologies were used. The farmers who opt for the technology experience a higher benefit/cost ratio, net positive gains, and little environmental risk (Tabo et al., 2007). The benefits of integrated soil fertility management include enhanced resilience, higher productivity, and mitigation benefits. It is a strategy to ensure nutrient availability while at the same time building the natural nutrient reserve through soil organic matter build-up (Waswa et al., 2013). ISFM entails using a range of methods for smallholder farms, such as crop management, fertilizer application, utilization of organic resources, and other amendments. Largely to support an African Green Revolution focused on intensifying higher production per unit of land area, the strategy was designed in Africa, for Africa. The effective use of applied nutrients is the main driving force behind ISFM, which seeks to maximize fertilizer value while reducing nutrient loss to the environment. This approach emphasizes the responsible and sustainable management of nutrients for agricultural production

(Vanlauwe et al., 2023). Werede et al. (2018) claim that it is both financially practical and possible to reduce long-term soil deterioration by incorporating soil fertility management into crop management.

2.5.2. Pearl millet fertilization and improved variety

Threats from climate change and low soil fertility limit the production of cereal crops in the Sahelian region (Akponikpè et al., 2010). Given the extreme age of the continent's soil and the lack of volcanic rejuvenation, Africa has seen multiple cycles of weathering, erosion, and leaching, which has left the continent's soil severely lacking in nutrients. Inappropriate land use, poor management of soil fertility, and a lack of inputs have all contributed to a drop in productivity. Compared to the global average of 100 kg/ha, farmers in Sub-Saharan Africa apply only 13 kg/ha of NPK fertilizer to their croplands (Bationo et al., 2006). This average is also so far with the Abuja agreement recommendation to raise it to 50kg/ha to get food security. Therefore, to minimize the effect of low fertilizer, many investments are made in agricultural research to generate improved varieties as well as new techniques in main crops to close the yield gap. Previous studies noted that the adoption of improved pearl millet varieties has a positive impact on yields. Diatta and Thomason (2016) indicate that investments are needed to increase adoption and promote good practices in using improved pearl millet varieties to achieve food security. Fertilizer is a crucial input for farmers since it gives plants nutrients that aren't easily available in the soil, promoting plant development and boosting yields. Akponipke (2008) further highlighted that manure and inorganic fertilizer increased millet yields in the Sahel zone on sandy soil. Similar to this, Bagayoko et al. (2011) suggest that to maximize pearl millet grain and stover output in the Sahel zone and meet farmers' needs for food and soil improvement, micro-dosing in conjunction with 20 kg ha-1 P2O5 and 30 kg ha-1 N fertilizer application is necessary. In fact, in areas where water is scarce, N fertilizer could boost the overall dry matter and water usage efficiency of pearl millet. On the other hand, (Singh et al., 2003) precise that combinations of low input systems of integrated nutrient management could be most beneficial to obtain relatively good yields of pearl millet hybrids by resource-poor farmers of semi-arid tropical environments. Maintaining long-term soil fertility and consistently high productivity levels can be achieved by the judicious application of an organic and inorganic fertilizer combination (Singh et al., 2003; Tounkara et al., 2020). Ibrahim et al. (2015) demonstrate in Niger that fertilizer application can optimize the yield of pearl millet stover and grain. Additionally, Upadhyaya et al. (2007) showed that applying a balanced nutrient use to the crops by the integration of organic manures and fertilizers can preserve the production of the wheat and pearl millet crop. In the semiarid regions of Senegal, Diangar et al. (2004) observed that the use of compost enhanced the yield of six millet cultivars by over 40% when compared to the control. Tounkara et al. (2023) also highlighted how the use of micro-dosing technology increased grain yield in Senegal by 62% when compared to farmers' practices and by 148% when compared to the control group. Badiane et al. (2001) underlined that in Senegal's semi-arid agroecological zone, millet output significantly increased when farmers applied both mineral and organic fertilizers. They further highlighted that the efficiency of the fertilizer applied was better with the micro-dosing technology than with the research-recommended rate. Indeed, organic manure application has a beneficial effect on crops due to the improvement of P nutrition by both increases in P mobility in the soil and enhancement of root growth (Kretzschmar et al., 1991). Moreover, Jamil et al. (2014), found that low doses of DAP fertilizer are a promising strategy to lower the destructive effect of Striga on pearl millet. Phosphorus, for example, causes crops to grow hardier and mature earlier, reducing damage from exposure to drought. Nitrogen is one of the most important elements that has a central impact on plant growth and yield. The plant needs it to survive and thrive. N is also widely involved in plant stress responses. The main issues facing Senegal's agricultural sector include improper fertilizer formulas, lack of quality control standards, and limited adoption of new fertilizer products and technology (IFDC, 2016). Furthermore, the fertilizer recommended rates are homogenous over the country which is not suitable in the context of climate change. The recommended rate must be adapted for each agroclimatic zone taking into account the specificity of environmental conditions.

2.6. Impacts of Micro-dosing technology on crop production

Climate-smart management practices such as micro-dosing as an approach, promise a more sustainable and resilient future for food systems by minimizing damage to natural resources, reducing the use of chemical inputs, and increasing yield and social inclusion (Tabo et al.,2007). The strategic application of fertilizer, also known as fertilizer “micro-dosing”, which consists of applying small doses of fertilizer in the planting hills has proven a good opportunity to improve crop productivity and farmers’ incomes (Tabo et al., 2007; Tounkara et al., 2023). Also, according to IFDC (2016), instead of broadcasting fertilizer over the entire field, micro-dosing includes applying small amounts to the target crop's hills at planting time or as a top dressing 4 to 5 weeks following emergence. Microdosing increases crop yields while giving crops an early start and faster maturity to prevent early and late-season droughts. Micro-dosing technology was developed to help farmers minimize environmental concerns related to agriculture while maximizing economic benefits(Hayashi et al., 2008; Saidia and Kahimba, 2019; Tabo et al., 2007). Micro-dose can also be done by combining organic and inorganic fertilizers or with organic fertilizer alone. Using fertilizer micro-dosing, Tabo et al. (2007) found that grain yields of millet and sorghum improved by 43–120% in three West African countries (Burkina Faso, Mali, and Niger). In East Africa, Dunjana et al. (2012) and Rusinamhodzi et al. (2013) also noted that the combination of animal manure 5 t ha^{-1} with inorganic fertilizers 40 kg N ha^{-1} statistically increases yield than sole manure treatment. For smallholder farmers who cannot afford to purchase and apply fertilizers at the recommended rate, these responses are helpful. Nowadays, in the context of the rising cost of fertilizer, it is worth finding in the research framework the smart practices to reduce fertilizer loss on the farm. The micro-dosing technology has been proven to be affordable to the smallholder farming system because of the reduced investment cost. Micro-dosing application can reduce P fixation, promote early season shoot and root growth, and enhance infection with vesicular-arbuscular mycorrhizae leading to increased nutrient uptake of grain and stover yields(Choudhary et al., 2016; Olson et al., 2014; Saidia and Kahimba, 2019). In Senegal, several studies noted that under micro-dosing technology (Laminou et al., 2020; Tounkara et al., 2023), which nevertheless uses less fertilizer (less than 25% NPK and less than 67% urea compared to the research recommendation) gives an average yield (908.28 kg/ha) close to the research recommendation's (1,043.28 kg/ha). It also gives the crop a quick start and earlier maturity, avoiding early and late-season drought while increasing crop yields (IFDC, 2016). This result suggests that micro-dosing increases crop yield minimizes loss from runoff or leaching, assures that plants use fertilizer efficiently, and mitigates the impact of fertilizer in drought-prone locations. They highlighted that INERA's most recent results in Burkina Faso using micro-dosing technology revealed yield improvements of 85–174% as compared to not using fertilizer. Thus, using this technology in combination with manure is beneficial to farmers (Blessing et al., 2017; Ibrahim et al., 2015). Furthermore, it has been demonstrated that using both organic and inorganic fertilizers produces a synergistic effect that increases the efficiency of water and nutrient usage (Sabaï et al., 2020). Indeed, Hayashi et al. (2008) noted that the application of micro-dosing alone increases millet yield by 56% above the control. But combining with crop residue or manure increased millet grain yield to 140% over the control. These results can explain the importance of combining organic and inorganic fertilizers in micro-dosing technology. Sorghum grain yields increased significantly by 100% and 186%, respectively, when micro-dosing fertilizer was applied to local and improved seed varieties compared to the control. In that case, micro-dosing can play a crucial role in achieving the United Nations Sustainable Development Goals.

2.7. Micro-dosing technology and climate change

Water stress and decreasing soil fertility are two of the primary causes of low crop productivity worldwide (Saidia and Kahimba, 2019). Crop productivity in semi-arid regions receiving more than 300 mm of rainfall annually is mostly restricted by nutrients, particularly nitrogen and phosphorus, rather than water or unfavorable biophysical conditions. In light of the changing climate conditions, these components' magnitudes are increasing. Consequently, there is a rise in food, nutrition, and income instability in smallholder agricultural systems. Climate change mitigation in these drought-prone Sahelian countries will involve the application of proven affordable technologies like micro-dosing (Tabo et al., 2007) for low-income farmers and greatly boosts output and revenue is a more effective strategy to deal with the consequences of climate change and variability. Integrated soil, water, and nutrient management that is acceptable locally and advantageous for smallholder farmers is necessary as crop production intensifies (Liang et al., 2019). Murendo and Wollni (2015) noted that this approach is more sustainable than conventional fertilization practices, which may contribute to reducing climate change linked to agricultural activity. Rezaei et al. (2014) further concluded that nutrient fertilization and other crop yield-limiting factors need to be considered when analyzing and assessing the impact of climate variability and change on crop yields. Because of this, an earlier study (Murendo and Wollni, 2015) showed that micro-dosing sustainability boosts food output, which affects Climate-Smart Agriculture's first pillar (CSA). The Food and Agriculture Organization of the United Nations (FAO, 2010) defines CSA as agriculture that sustainably increases productivity, increases resilience, reduces GHG where possible, and improves the achievement of national food security and development goals. Ibrahim et al. (2015) claim that micro-dosing is extremely resilient and helps minimize greenhouse gas emissions by significantly reducing fertilizer loss, which is one of the drivers of GHG emissions. Murendo and Wollni (2015) further emphasized the contribution of micro-dosing to the first pillar of CSA. Therefore, concerning the definition of CSA, it can also contribute more to the achievement of the two remaining pillars. In sum, all three pillars of CSA are targeted following the micro-dosing approach. Figure 1 is designed to give a clear overview of the achievement of pillars and food security purposes.

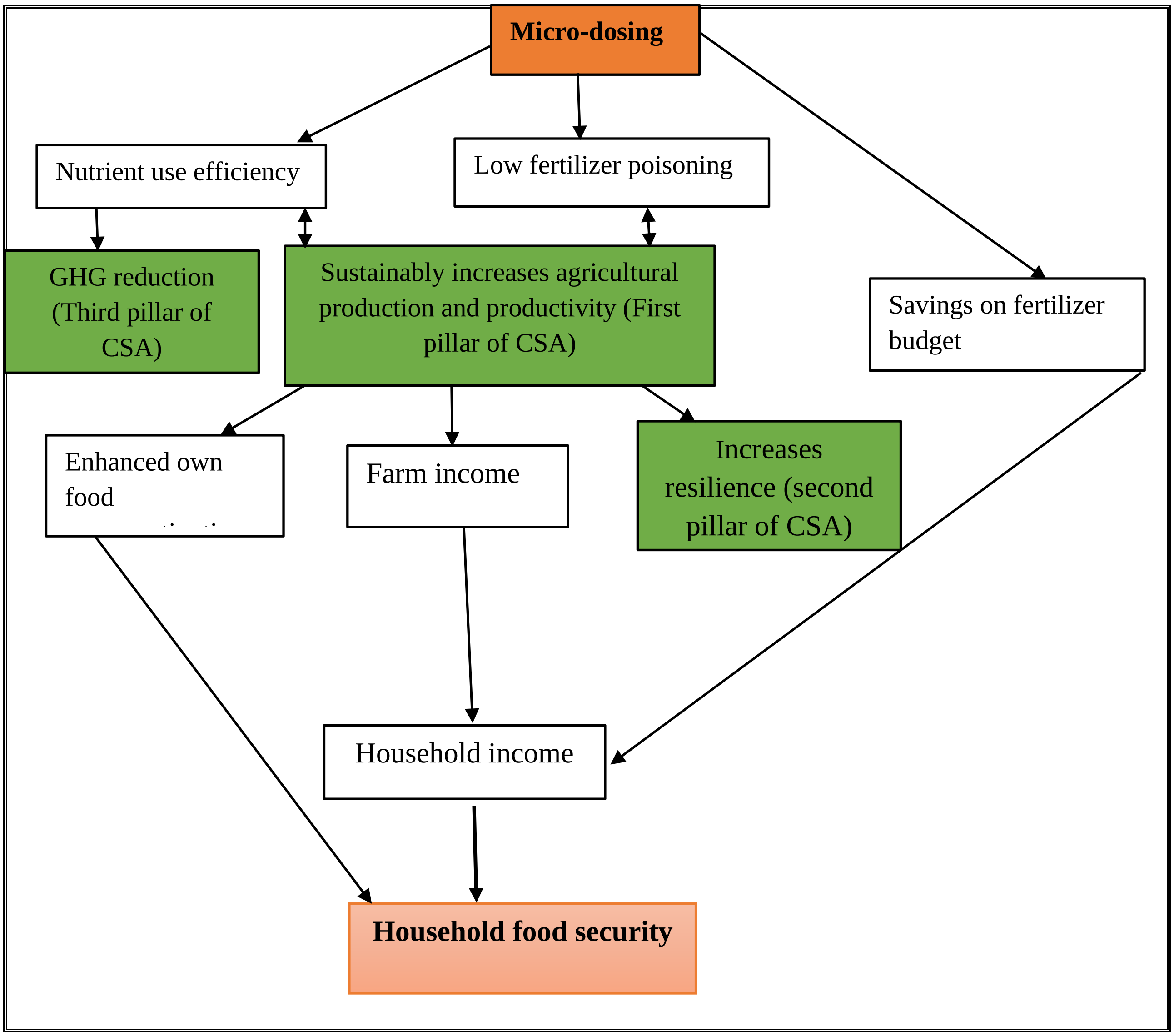


Figure 1: Framework of micro-dosing contribution to food security at the household scale and the achievement of CSA's three pillars

2.8. Crop modeling

2.8.1 Crop Model Overview in the Sub-Sahara Africa

In both developed and developing countries, models are increasingly being employed as research tools to forecast agricultural system outcomes under various climatic, soil, and management situations (Jones et al., 2012). Numerous research in SSA (Adiku et al., 2015; Akinseye et al., 2020;2023; Beah et al., 2021; Toure et al., 2018; Traore et al., 2014) have significantly advanced the understanding of the interactions between crops and their local environment. They further support the understanding of multi-dimensional spatial variability inherent in farming landscapes throughout the Sub-Sahara Africa region (Koo et al., 2016). Understanding and developing practical solutions for the agricultural system depends on the modeling approach, which enables farmers to become more resilient and deal with the more severe effects of climate change. This is particularly true in Sub-Sahara Africa where (1) soils are low in fertility and hold very little water, (2) where farmers typically do not apply fertilizer or irrigate, (3) there is considerable annual variability in climate, (4) weeds, insects, and diseases may cause considerable damage to the crop, and (5) farming practices are mainly subsistence with low input (Faye et al., 2018; Roudier et al., 2011; Zougmoré et al., 2014). The impacts of and adaptations to climate change have been extensively studied using crop models. These models are now increasingly employed to simulate near- and long-term changes affecting the sustainability of production across diverse environments under various IPCC scenarios. Predictive analytics is used in precision agriculture to forecast future results by using both historical and current data, enabling farmers to make well-informed decisions based on data-driven forecasts. Model developers routinely emphasize the importance of obtaining accurate cultivar coefficients to apply cropping system models in local studies, which suggests that without reliable values for these parameters, the models will not adequately simulate the responses to climate and management (Jones et al., 2003; Keating et al., 2003). Various statistical and mathematical models, including linear regression, time-series analysis, and spatial interpolation, have been employed in this context. In the real-time precision agricultural context, these models facilitate the analysis of patterns, trends, and linkages in the data, enabling precise forecasts and well-informed decision-making (Ritchie et al., 1998). Crop simulation models are widely used in precision agriculture. Research conducted in West Africa used several crop modeling systems to estimate crop growth, yield, and resource usage efficiency under various environmental and management conditions. These models are essential for assessing and forecasting how various elements, including soil properties, crop management techniques, and environmental conditions, affect crop production. Farmers may make well-informed decisions about the best way to allocate resources, choose crops, and implement management techniques to optimize productivity and sustainability in precision agriculture by combining historical and current data with these simulation models (Hoogenboom et al., 2019). Crop simulation models allow farmers to assess how different management approaches could affect crop yield and resource use. By offering insights into how various practices, such as irrigation scheduling, fertilizer use, and planting dates, can affect crop production, these models facilitate data-driven decision-making (Akinseye et al., 2020; Chen et al., 2010; Soler et al., 2008). Through the simulation of crop growth and development in various scenarios, farmers can evaluate the possible consequences and adjust their management tactics accordingly (Araya et al., 2015; Van Oosterom et al., 2002; White et al., 2011). In precision agriculture, this modeling technique helps to reduce risks, optimize resource efficiency, and eventually enhance total crop productivity.

2.8.2. Importance of crop modeling under changing climate conditions

Climate and agricultural modeling tools can provide pertinent information for evaluating the implications of climate change, assisting stakeholders in making decisions to mitigate its negative effects in the short and long-term period (Vanli et al., 2019). This highlights the value of crop models for impact research, enhancing crop forecasting, and creating an index of climate variability for examining climate variability and change (Capa-Morocho et al., 2014) which can be helpful for agricultural insurance programs. It successfully illustrates the importance of taking into account various crop management factors in the simulation of climate models, examination of observed climate trends, and development of resilient policies by highlighting the effects of extreme scenarios at local scales (Lobell et al., 2006). These projections could be added to crop simulation models to aid in the adaptation to climate change by adjusting agricultural techniques, crop patterns, and application of smart technology (Mahdi, 2019). Then, it is necessary to take into account crop modeling methodologies since, in studies that analyze and assess the impacts of climate change, it is crucial to take into account the interactions between crop management and climate as well as the differences between crops (Rezaei et al., 2017). When properly calibrated for the given crops, modeling tools provide an accurate simulation of actual crop yields across a range of soil types and seasons (Cooper et al., 2008). Given that they are driven by daily weather data, they can also be satisfactorily used to evaluate the impacts of temperature and rainfall change scenarios. For instance, crop models are more accurate in simulating how crops would react to the current weather variability, which aims to identify crop management strategies for climate parameter variability (Corbeels et al., 2018) which is relevant in the Sahel zone where we have erratic rainfall patterns. Therefore, the most crucial requirement for climate change effect and risk assessments as well as agricultural adaptation strategies is enhancement in understanding crop responses to environmental conditions and climate factors.

2.9. Farmers' Perceptions and Determinants of climate-smart management strategies adoption

Farmers' perceptions of climate change and variability play a significant role in their decision-making process regarding the adoption of CSA practices (Zagre et al., 2024). Studies have shown that farmers in different regions have varying levels of awareness and understanding of climate change, often influenced by their experiences and exposure to climatic events. Muita et al. (2021) and Abdurehman, (2021) found that farmers in Ethiopia, and Kenya recognize the changes in climate patterns and their adverse effects on agricultural productivity, prompting them. Several factors influence farmers' decisions to adopt CSA practices. These determinants include socioeconomic status, access to resources, education level, and institutional support (Diallo et al., 2020; Ouédraogo et al., 2023; Sanfo et al., 2022; Zagre et al., 2024). Research by Diouf et al. (2019) highlights the importance of these factors in facilitating or hindering the adoption of climate-smart technologies. Farmers with better access to financial resources, extension services, and educational opportunities are more likely to implement CSA practices. Tschakert, (2007) and Zagre et al. (2024) suggest that targeted interventions, such as improving access to credit, enhancing extension services, and developing supportive policies can be crucial for the widespread adoption and success of climate-smart agriculture. Ragasa et al. (2016) and Galiwango et al. (2022) emphasize that enabling environments created by institutional support and favorable socioeconomic conditions significantly enhance the likelihood of farmers adopting climate-smart practices. Besides, Gender dynamics significantly affect the adoption of CSA practices. Women often face more significant barriers than men due to limited access to resources, information, and decision-making power (Perez et al., 2015). Meinzen-Dick et al. (2012), Diouf et al. (2019), and Antwi-Agyei et al. (2021) argue that addressing these gender disparities is essential for equitable and effective CSA adoption. In that case, understanding and incorporating gender-specific needs and challenges can lead to more inclusive and successful implementation of climate-smart strategies.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1. Description of the study areas

The study was conducted at five locations in Senegal located in four agroecological zones: Meouane (15°3′59.76"N, 16°45′26.28" W) in the Thies region, the Bambey research station of ISRA/CNRA (14°42′31.32"N, 16°28′47.28"W) in the Diourbel region are located in the old peanut basin while Daga Birame (13°56′39.84" N, 15°30′47.88" W) in the Kaffrine region is located in the new peanut basin. Thiel (14°52′12.00" N, 15°5′0.24" W) in the Louga region is located in the sylvopastoralism zone while Koumpetum (14°0′6.48"N, 14°34′21" W) in the Tambacounda region is located in the Eastern and Upper Casamance agroecological zone (Figure 2).

Meouane, Bambey and Thiel are located within the Sudano-Sahelian climatic zone, with annual rainfall ranging from 350 to 500 mm (Joseph et al., 2023). Daga Birame and Bambey fall within the Sudano-Sahelian climatic zone, receiving between 500 and 700 mm of rainfall annually. Koumpentoum belongs to the Sudanian climatic zone, with rainfall amounts reaching up to 700 mm. These areas exhibit high variability in annual rainfall (Araya et al., 2022; Joseph et al., 2023). The soils in these zones are predominantly sandy with low fertility and seasonally waterlogged or flooded clays, commonly referred to as *Dior soils* (FAO, 1993; Faye et al., 2023). The community is made up mainly of farmers who practice a small-scale mixed farming system, raising livestock and growing food and cash crops on small plots of land (McClintock and Diop, 2005). The major crops grown in the area include pearl millet, groundnuts, and cowpeas. Monoculture is the dominant farming system (Adiku et al., 2015). Also, the agroforestry system grows crops and preserves several acacia trees (bushes) such as *Faidherbia albida*, *Guiera senegalensis*, *Piliostigma reticulatum*, and *Anacardium occidentale* (Caju nut), especially in the old peanut basin, one of the study areas, is located (Badiane et al., 2001).

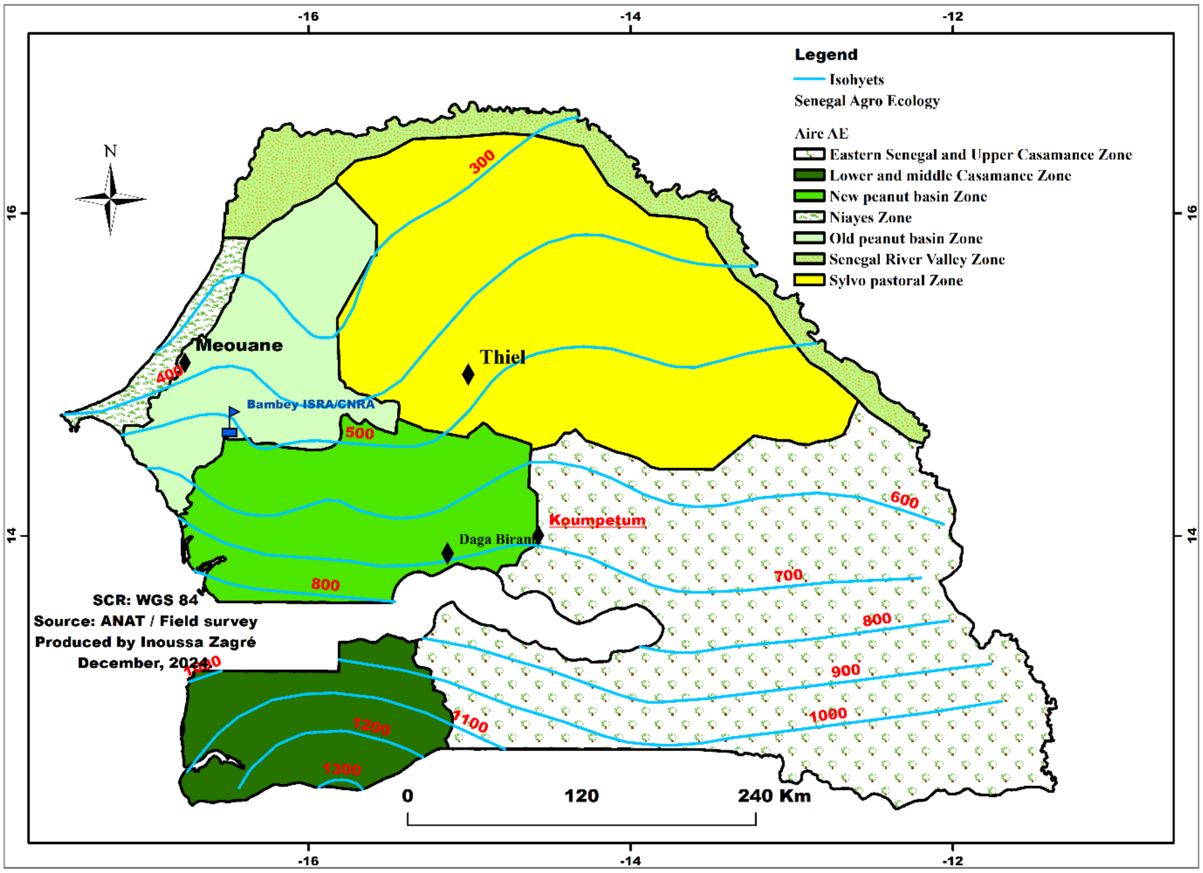


Figure 2: Map illustrating the study areas

3.2. Data requirement

To assess the impact of climate change on pearl millet production in Senegal, the study required the integration of various datasets, including survey, crop, soil, and climate data. Survey data were collected from household farmers across three rainfall gradients that fall within three agroecological zones (Old Peanut Basin, New Peanut Basin, and Sylvopastoralism zone), capturing essential information on agricultural practices, land use systems, and input management, which influence millet yields.

Crop data, including detailed phenology, biomass, and grain yield were gathered from field experiments during the growing seasons of 2022 and 2023 across the rainfall gradients assessing three factors such as variety (SL 28, SL 423, Souna 3, and Thialack 2), plant population (12,500hills/ha and 25,000hills/ha) and micro-dosing fertilizer strategies. These informations were crucial for calibrating the DSSAT CERES-Millet model to local conditions. Soil data on physical and chemical properties, such as bulk density, organic carbon, pH, and nutrient content (nitrogen, phosphorus, potassium), were obtained through field sampling and laboratory analysis, ensuring accurate simulation of soil fertility effects on millet growth.

Finally, rainfall data were collected for the trial years using automatic and manual rain gauges at the community scale across the study areas. Furthermore, climate data for the baseline period (1985-2014) and future climate projections (2040-2069) under SSP2-4.5 and SSP5-8.5 were derived from six GCM models of the CMIP6 framework. This comprehensive dataset allowed for a robust simulation of pearl millet production dynamics under varying climate conditions, providing insights into the potential impacts of climate change on food security in Senegal.

3.3. Equipment

The successful execution of field experiments and data collection for this study relied on a combination of advanced tools and equipment. Vegetal material consisted of four pearl millet varieties (SL 28, SL 423, Souna 3, and Thialack 2), chosen for their adaptability to the local agroecological conditions and relevance to the study area (Table 1). To monitor crop growth and development, a Leaf Area Index (LAI) sensor was employed to capture real-time measurements of canopy coverage, providing critical data for model calibration. Additionally, Internet of Things (IoT) devices were deployed in the field to collect continuous environmental data, such as rainfall providing the precision of monitoring. Manual rain gauges were also installed across the study area at the community scale to validate rainfall data from other sources, ensuring accuracy in precipitation measurements. This combination of cutting-edge technology and manual instrumentation enabled comprehensive monitoring of both crop growth and environmental conditions, essential for the robust simulation of millet production under climate change scenarios.

Table 1: Pearl millet cultivars characteristics used in this study

Pearl millet variety	Souna 3	Thialack 2	SL-423	SL-28
Target Use	Local	Dual-Purpose	Dual-Purpose	Dual-Purpose
Cycle	Short	Medium	Short	Short
Potential yield (t/ha)	2.4-3.5	2-3	2.5-3.5	2.5-3.5
Photoperiod Sensitivity	High	Moderate	Moderate	Moderate

Source: CILSS, (2017) and ISRA, (2014)

3.4. Methods

3.4.1. Assessment of Climate Change Adaptation Strategies among Smallholder Farmers

3.4.1.1 Sampling Procedure and Sample Size

Data from a cross-sectional household survey were collected from farmers who raised crops and livestock in the three rainfall gradient areas during the post-harvest season (November and December 2022) to assess their agricultural practices and adaptation strategies. The study considered the definition of a household as “a group of people living in the same dwelling space who have at least one common plot together or one income-generating activity together and who acknowledge the authority of a man or woman who is the head of household” given by Beaman and Dillon (2012). These locations were defined based on the different rainfall patterns and land use systems (three agroecological zones). These three locations are therefore located in a transition zone between the sylvo-pastoral zone (Thiel) and the peanut basin-new zone of intensive peanut farming (Daga birame) with the old peanut basin (Meouane) migrants in a pastoralist context taking into account both concerns, namely the difference in rainfall pattern and land use system (Figure 3). Furthermore, the choice of these locations was motivated by the implementation of a technologies package by the national research institute, national extension office, and AICCRA project (Accelerating Impacts of CGIAR Climate Research for Africa) to showcase the performance of climate-smart management practices such as of improved varieties, efficient use of fertilizer such as integrated soil fertility management (micro-dose) and climate service information (CSI). The communities were randomly selected from a list of communities located within the target locations. In that case, two-stage stratified sampling techniques were used to select sample households. First, purposive sampling was applied to select at least six (6) villages in each rainfall gradient considered as a cluster. Daga Birame cluster, the concerned villages were Nandjigui, Darou Nandjigui, Keur Sawely, Simbara, Mbeuleup, Diatta Fakha, and Daga Birame (Ndjognik district). In Meouane cluster, it was Meouane Meghor, Ndiane, Mborine, Ainomane, Ndombil, and Ndiouffene (Meouane district). In the last cluster Thiel, Thiel Serere, Darou Nahim Danedji, Touba Danedji, Mola, Touba Ndiagne, and Hodiolde-3 (Thiel district) were concerned. Yet again, from among each cluster, the selection of households was based on the main crop values chain grown across the study areas namely peanut, millet, cowpea, and livestock. This information was carried out based on the workshops with the various stakeholders (two lead farmers per village, extension agents, and researchers) which were prior held in each cluster before the beginning of the rainy season 2022. These workshops raise the main crop grown in these locations. The sample size for each cluster was purposely selected based on the approach given by Waha et al. (2016), where they raised that to minimize the sampling errors, the number of sampling units per district should be between 30 and 60. Following the sampling approach for the assessment of climate adaptation strategies and climate information service at the community scale by the previous study mentioned above, the sample size was first set to 90 households for the three clusters considered in this study. Oversampling was done to increase the sample to 145 households over the three clusters. Approximately forty-eight (48), forty-nine (49), and forty-eight (48) households were selected from the Daga Birame, Meouane, and Thiel clusters, respectively, based on our logistical capacity.

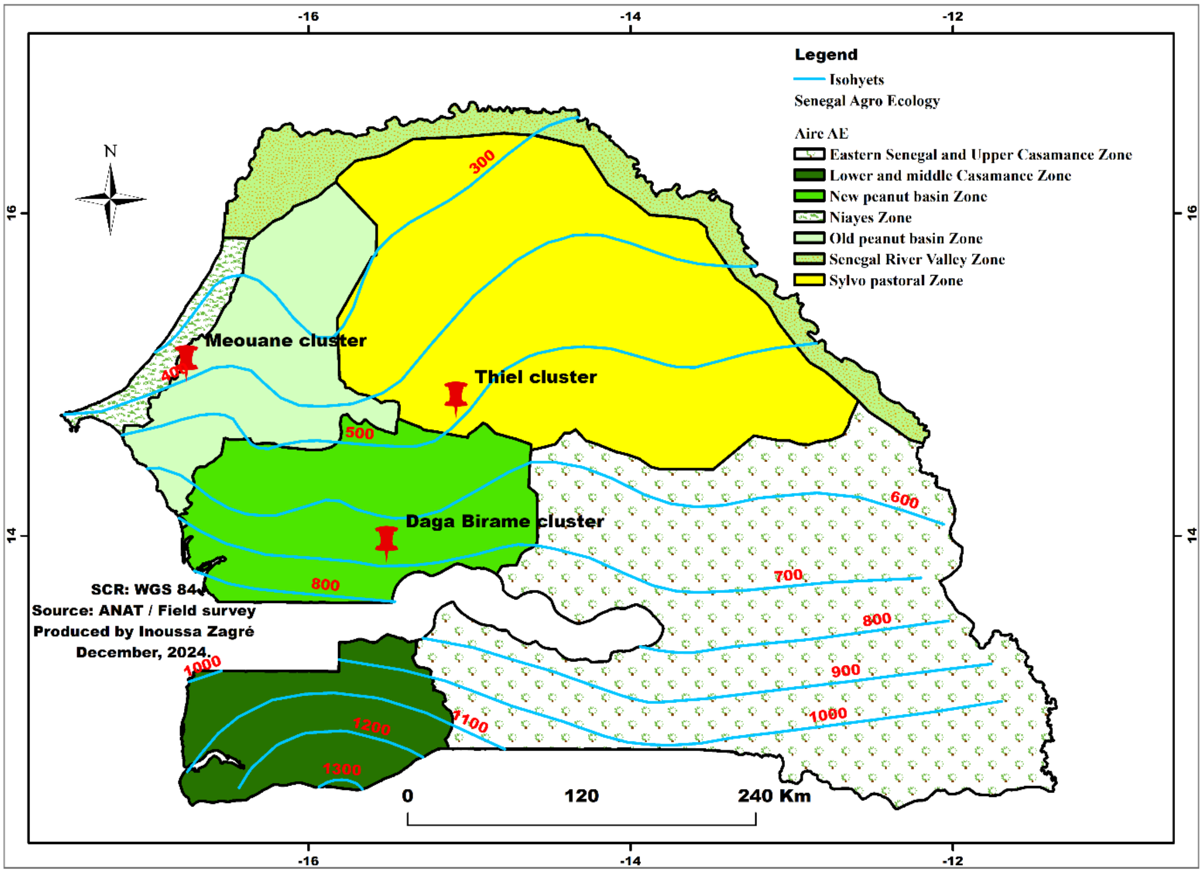


Figure 3: Map illustrating the targeted three clusters for survey data collection

3.4.1.2. Survey data collection

The sample data was gathered based on several socioeconomic and environmental characteristics, and it contained important details on farmers' perceptions of climatic variability and change as well as their coping strategies. Climate variability is one of the factors influencing the variation in crop growth, development, and yields from year to year (Akinseye, et al., 2023; Soler et al., 2008). To capture the perception of this variability by farmers, questions about their observations of climatic indicators over the previous thirty (30) years, including annual rainfall, temperature, the onset and cessation of the growing season, and its length were asked. A good understanding of climate change and its impacts could be key to leading the adaptation of the majority of farming methods. To address that, questions about climate-smart management practices' adaption were adequately asked. As a definition, climate smart-smart management involves a range of practices aimed at enhancing agricultural productivity, improving resilience to climate change, and reducing greenhouse gas emissions (Partey et al., 2018). These practices help farmers cope with changing climate conditions and improve their resilience to climate change. The practices recorded in SSA are various and vary from one area to another based-on farmers' knowledge and environmental conditions (Moutouama et al., 2022). The common set addressed in this study is related to crop operation, improved crop varieties, improved soil management, and water-harvesting techniques. Therefore, to test the quality and farmers' understanding of the questions, one village was previously selected with 10 heads of households in each location to ascertain and validate the questionnaire's effectiveness.

3.4.1.3. Conceptual framework of socio-economic data

To appreciate the influence of the factors (Table 2) on farmers' decisions, the different types of models namely linear probability, Logit, and Probit models, were used by early studies (Diallo et al., 2020; Gadédjisso-Tossou, 2015; Gebru et al., 2020; Ibitoye, 2011; Kassa, 2013; Sanfo et al., 2022). Therefore, according to Greene, (2012), the Logit model is more robust and more explanatory since it does not follow the normal distribution, which is suitable for adoption studies in our case. In that, by using the Binomial Logit model, we focused on social, economic, and institutional factors at the household and community level (Patnaik, 2021) to understand their impact on farmers' perceptions of climate change, adoption of improved variety as a climate-smart practice, and ability to adjust crop operation during the growing season. Thereby, the questions were asked to get the binary responses. Related to climate-smart management practices, we targeted the adoption of improved varieties. In that, the question was addressed to know 1=if farmers use improved varieties in their farming system to cope with climate variability or 0= if otherwise. Furthermore, crop operation adjustment during the growing season by farmers was defined 1=if the farmers agree that they adjusted the crop operation according to any information or support compared to their first plan at the beginning of the growing season and 0=if they do not. On the other hand, the climate change perception of farmers was also categorized as 1= if farmers agree based on their experience that there is a change in climate conditions and 0= if they don't agree (Ntim-Amo et al., 2022).

Table 2: The factors determined as likely to have an impact on the decision to adopt climate-smart management practices and understand climate change

Variables	Type	Description
Age	Quantitative	Respondent's age (years)
Gender	Qualitative	Gender of the respondent-male or female
Education level	Qualitative	Respondent's years of formal education (years)
Credit access	Qualitative	The farmer benefits from credit for investment
Access to extension service	Qualitative	Respondent has access to the extension agent's advice
Farmland erosion	Qualitative	Respondent perceives the state of erosion of a farm
Soil fertility	Qualitative	Respondent perceives the state of the fertility of a farm
Farmer association membership	Qualitative	The farmer belongs to a local association.
Experience in farming	Quantitative	Years that the respondent has worked in agriculture
Number of contacts with an extension agent	Quantitative	Number of farm visits of extension agent
Distance to extension office (km)	Quantitative	The distance from the farmer to the extension agent's office
Rainfall gradient	Quantitative	The three locations with their average rainfall amount
Access to Government subsidies	Qualitative	Respondent has access to Government subsidies such as improved seeds
Access to climate information	Qualitative	Respondent has access to climate information from the meteorological agency during the growing season

3.4.1.4. Data analysis

The analyses conducted using StataCorp. (2021) were descriptive statistics such as percentages and modeling analysis. The household was seen as a random variable. The Logit model was used to examine farmers' perceptions of climate change and their adoption of smart management practices. It examined whether farmers perceived change or not, adopted improved varieties as a climate-smart strategy or not, and adjusted their crop operation over the growing season or not. The farmers' perception and adoption of adaptation practices will likely be influenced by household, farm, and institutional variables. The Logit model takes into account the link between a set of binary or continuous independent variables and a binary dependent variable. The statistical significance of the Logit model's coefficients is necessary for their interpretation. The corresponding explanatory (independent) variables in Table 1 and the dependent variables were (i) improved variety adoption as a climate-smart practice, (ii) adjustment of crop operation during the growing season as a climate-smart practice, and (iii) Farmers' perception of climate change. For these dependent variables, the questions were set to get the closed response (1=yes or 0=no) which implies the use of the binary logit model. The direction and severity of the influence are reflected in the coefficient's magnitude. A positive correlation with the likelihood of adoption is indicated by positive coefficients, whereas a negative correlation is indicated by negative coefficients. The formula is given by (Greene, 2003):

$$log\left(\frac{1}{1-P}\right) = \beta_0 + \beta_1 x \qquad (Eq1)$$

Where log represents the natural logarithm.

p is the probability of the event (with 1= yes, 0=no) and x is an independent variable listed in Table 1. β_0 is the intercept (constant). β_1 is the coefficient associated with the predictor variable x. log (1/1-p), is the log-odds or logit of the probability p.

3.4.2. Improving Pearl Millet Production Through Participatory Research for Farm-level Intervention across Rainfall Gradients

3.4.2.1. Demonstration trials

The interventions in this study follow the participatory research and extension approach (PREA) which is expected to accelerate the adoption of CSA packages dissemination toward climate risk management (Ajeigbe and Dashiell, 2010). Three agricultural innovation technologies were deployed through multi-location demonstration plots during the rainy seasons of 2022 and 2023. This was to evaluate pearl millet varieties' response to variable climate risks and farm management practices and promote best-bet climate-smart management practices for adoption and seasonal yield forecasting using DSTs- decision-support tools. Therefore, based on the low level of soil fertility at the farm level, integrated soil fertility management (ISFM) such as micro-dosing fertilization approach and improved varieties were demonstrated. Two levels of trials were implemented in this study, including plant density assessment at the agroecological zone scale with four pearl millet varieties under the recommended fertilizer rate of Senegal (150kg of NPK (15:15:15) + 100kg of Urea (46%N)) using micro-dosing strategy in four locations (Meouane, Research station of ISRA/CNRA at Bambey, Daga Birame, and Koumpetum). The improved density comprised 25,000 hills ha^{-1} compared to farmers' practice (12,500 hills ha^{-1}), while the improved variety was dual-purpose (SL 28, SL 423, and Thialack 2) compared to farmers' improved local (Souna 3). This trial was designed in a complete randomized Block (RCBD) to assess the adaptability of dual-purpose millet varieties along the rainfall gradient to improve resilience to climate variability and promote sustainable farming practices. The plots contained 5 rows, sown within a row at 0.9m for low density and 0.45m for high density. The plot size was 5 rows, 5m long and 4.5m wide. The space between the rows was 0.9m and the block size was $22.5m^2$ (5 m × 4.5 m). The space between the sub-plot was 1m, the block was 1.5m, and the plot size was 792 m^2 (Figure 4).

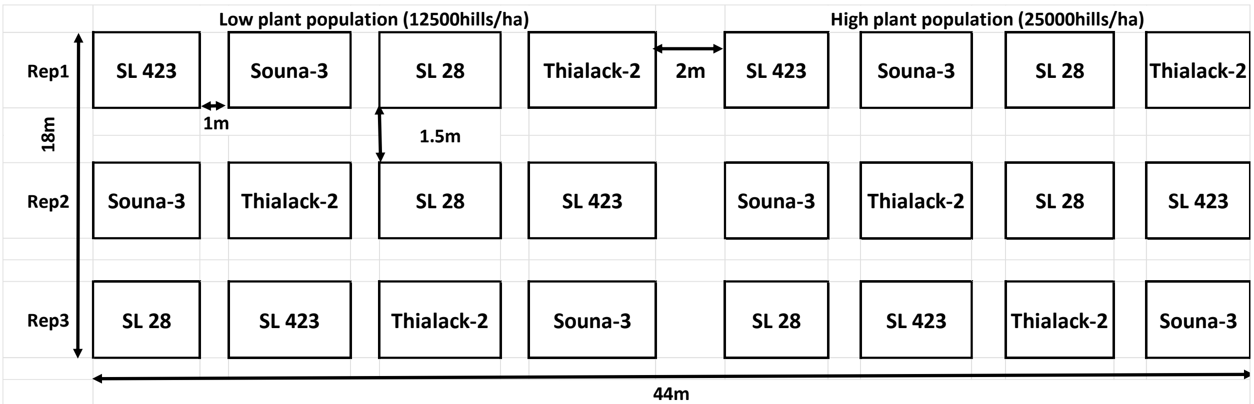


Figure 4: Experimental designs across three agroecological zones in Senegal

The second demonstration trial plots were focused on a farm scale and assessed the organo-mineral micro-dosing fertilizer with farmers' local variety compared to dual-purpose varieties and carried out across three clusters (Daga Birame, Meouane, and Thiel). The demonstration plots were carried out in three clusters across 18 villages during the growing seasons of 2022 and 2023. In each cluster, six villages were associated, and, in each village, four farmers were selected and given a total of 72 demonstration plots per year. The ISFM technology comprised four levels of organo-mineral fertilizer strategy using micro-dosing techniques. Based on these treatments, the quantity of fertilizer per hill was derived. Previous studies by Tabo et al. (2007) and Akinseye et al. (2023)adopted micro-dosing techniques for sorghum and pearl millet in a similar environment. This implies that F1- 6g/hill of NPK + 4g/hill of Urea, F2- 6g/hill of NPK+ 4g/hill of Urea+100g/hill of Cow manure, F3-3g/hill of NPK + 2g/hill of Urea + 50g/hill of Cow manure, and F4-3g/hill of NPK + 100g/hill of Cow manure. The demonstration plots had four fertilizer treatments and two millet varieties; farmers within the same village were used as replications, and each sub-plot size was 63m^2 (10 m × 6.3 m) with 7 rows, sown at 0.45m within a row, given a total 620.4m^2 (Figure 5).

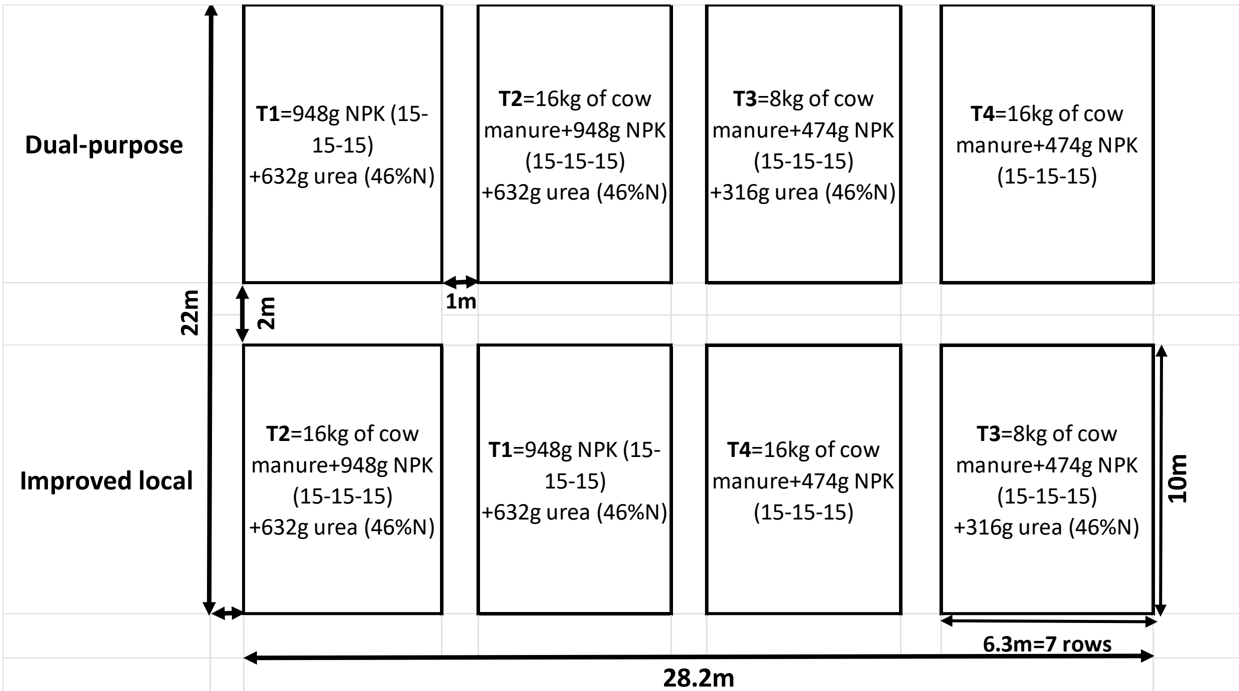


Figure 5: Experimental designs at an on-farm scale in 18 villages across three clusters

3.4.2.2. Crop data collection and measurements

For the experimental trial, different data were collected including crop phenology (date to anthesis, and physiological maturity), leaf number, leaf area index (LAI), biomass time series, grain, and aboveground biomass yield at harvest. Anthesis and physiological maturity dates were determined using plants in the three middle rows of each plot. Regarding the morphology parameters such as leaf number and LAI, they were measured from three weeks after planting to 9 weeks with intervals of two weeks between each measurement. Leaf area index (LAI) was measured using the DELTA PAR/LAI Sensor. Concerning farmers' demonstration plots, grain and aboveground biomass at harvest were measured. Millet panicles and fodder were harvested at physiological maturity from the three central lines of each plot (7.29 m^2) to avoid border effects. Stover weight was taken after sun drying for 14 days when almost no change in weight was observed between consecutive measurements (Reddy et al., 2010). The yield was extrapolated and then reported on a hectare basis. The panicles were threshed and weighed to determine grain yield. The grain and stover yields from each plot were estimated in kg ha^{-1}. Furthermore, the Harvest Index (HI) was computed to appreciate the efficiency of a crop in converting resources into harvested yield based on each variety and fertilization level. The formula is given:

$$Harvest\ Index\ (HI) = \frac{Grain\ yield\ (kg.ha^{-1})}{Above\ dry\ matter\ (kg.ha^{-1})} \qquad (Eq\ 2)$$

Only the data from the trial were considered for agronomic analysis regarding the climate-smart technologies' performance assessment, namely micro-dosing fertilizer strategies, plant population, and variety. These include Meoaune, Daga Birame, and Thiel locations, where we have at least two years of trial carried out (2022 and 2023). For the CNRA research station and Koumpentoum locations, data from the 2023 trials were used for CERES-Millet model parameterization.

Moreover, Crop water use efficiency (WUE) was computed using FAO ETo Calculator software (version 3.2) to extract the daily reference evapotranspiration (ETo [mm day^{-1}]) based on the FAO-56 Penman-Monteith method (Allen et al., 1998). The model was provided with two years (2022 and 2023) of climatic data (solar radiation, minimum, and maximum temperatures) at each site. Thereafter, the model was run to get the daily ETo values for the whole two years. From there, the cumulative reference evapotranspiration Eto values for the growing season (sowing date to harvest date) were further calculated for each variety type (Dual-purpose and Improved local) and plant population (farmer practice and improved density). Thereby, the cumulative reference Eto was used in equation 3 below described by Allen et al. (1998) to determine crop evapotranspiration or crop water use, while equation 4 was used to calculate water use efficiency (WUE).

$$ET_c = Et_0 \times K_c \qquad (Eq\ 3)$$

$$WUE = \frac{Crop\ grain\ yield}{ET_c} \qquad (Eq\ 4)$$

where: ETc = crop evapotranspiration or crop water use in (mm), ETo = reference evapotranspiration in (mm), and Kc = crop coefficient for pearl millet in this study was 0.71 as stated in FAO-56 manual (Allen et al., 1998).

3.4.3. Application of the DSSAT-CERES-Millet Model to Simulate Growth and Yield of Pearl Millet Varieties

3.4.3.1. Weather input data during trial years

Weather files for 2022 and 2023 were created using daily minimum and maximum air temperatures, rainfall, and solar radiation and plotted using the WeatherMan utility program in DSSAT (Pickering et al., 1994). In each community, manual and automatic rain gauges were established for rainfall data collection during the growing seasons of 2022 and 2023. In Meouane, Daga Birame, and Thiel locations, the trials were conducted during the growing seasons of 2022 and 2023, while in CNRA Bambey research station and Koumpetum, it was only during the growing seasons of 2023. Furthermore, unlike the rainfall data, which were recorded directly at the experimental site, daily minimum and maximum temperatures and solar radiation were obtained from the NASA Climatology Resource for Agroclimatology database, using the corresponding location reference coordinates (http://power.larc.nasa.gov).

3.4.3.2. Soil input data

Each year, before sowing, soil samples were collected at various depths (0-15cm, 15-30cm, and 30-60cm) for experimental trials and in each village for on-farm demonstration plots. Soil samples were analyzed at the ICRISAT soil analysis laboratory at Sadore, Niger for physical-chemical properties namely Bulk Density (g/cm^3), sand (%), silt (%), clay (%), Soil pH measured in water using a 1:2.5 soil-to-water ratio, Organic Carbon (%), Total Nitrogen (%), Phosphorus (mg/kg), Potassium (%), and Cation Exchange Capacity ($cmol^+/kg$) (Table 1). The soil profile information is key in the cropping modeling system for running the simulation (Tsuji et al., 1994), additional data of two layers (60-100 and 100-200cm) were downscaled with the corresponding farm's reference coordinates of each location from SoilGrids1km at 10-km resolution using the approach given by (Han et al., 2019). The analysis emphasized that the soil across the locations was mainly sandy loam in texture with a low percentage of organic carbon and nitrogen. The sand content ranges from 65 to 87.2% across all the sites surveyed in this study (Table 3). The bulk density, silt content, and clay content range respectively from 1.42 to 1.58 g/cm^3, 5.2 to 23.8%, and 8.2 to 13.3%. The soil was moderately acidic to slightly acidic to neutral pH across the locations (Table 3). Furthermore, the fertility determinant (SLPF) factor was manually adjusted for each location based on the initial set of cultivar coefficients. As input, measured soil physical-chemical properties mentioned above were used. Soil hydrological properties such as soil water content at field capacity (drained upper limit = DUL), at permanent wilting point (lower limit = LL), and saturation (SAT) were parameterized from SoilBuild following the approach given by Ritchie, (1981) and Gijsman et al. (2002).

Table 3: Physical and chemical properties used for model parameterization in each cluster

Site	Profile Depth (cm)	BD (g/cm3)	OC (%)	Sand (%)	Silt (%)	Clay (%)	pH/H2O	N (%)	Phosphore (mg/kg)	Potassium (%)	CEC-AgTu ($cmol^+/kg$)
Experimental trials											
Daga Birame	0-200	1.52	0.18	71.7	17.3	11.1	5.6	0.015	44.3	0.05	4.57
Meouane	0-200	1.43	0.30	84.2	6.2	9.7	6.3	0.025	88.4	0.05	3.41
Bousra	0-200	1.42	0.15	82.3	10.3	10.4	6.0	0.013	92.3	0.10	5.23
Bambey	0-200	1.51	0.05	81.3	9.3	9.2	6.2	0.005	90.4	0.05	3.73
Daga Birame cluster											
Diatta Fakha	0-200	1.52	0.12	77.6	14.3	8.2	5.8	0.012	78.3	0.08	3.91
Keur Sawely	0-200	1.52	0.19	70.9	16.5	12.7	5.7	0.020	111.6	0.14	5.33
Mbeuleup	0-200	1.50	0.19	65.7	23.5	10.8	5.9	0.016	82.4	0.11	3.84
Nandjigui	0-200	1.50	0.15	76.5	10.3	13.3	5.9	0.017	89.3	0.10	3.64
Ngouye	0-200	1.51	0.15	65.0	23.8	11.3	5.9	0.016	33.9	0.12	4.95
Meouane cluster											
Ainomane	0-200	1.51	0.06	85.4	6.5	8.2	6.1	0.007	46.1	0.05	4.59
Ndombil	0-200	1.46	0.08	87.2	5.2	7.7	6.2	0.011	90.6	0.06	3.60
Ndiane	0-200	1.58	0.12	78.1	9.7	12.3	5.8	0.014	154.6	0.04	3.92
Ndiouffene	0-200	1.43	0.07	78.5	14.0	7.6	6.2	0.008	89.7	0.05	3.41

Site	Profile Depth (cm)	BD (g/cm3)	OC (%)	Sand (%)	Silt (%)	Clay (%)	pH/H2O	N (%)	Phosphore (mg/kg)	Potassium (%)	CEC-AgTu ($cmol^{+}/kg$)
Mborine	0-200	1.58	0.09	77.0	10.1	13.0	5.9	0.009	91.8	0.06	4.47
Thiel cluster											
Touba Ndiagne	0-200	1.42	0.15	80.8	9.5	10.0	6.9	0.015	75.3	0.07	7.04
Mola	0-200	1.42	0.10	78.8	11.0	10.5	6.6	0.012	77.5	0.10	3.53
Touba Danedji	0-200	1.42	0.11	82.3	9.1	9.0	6.6	0.012	70.8	0.06	4.23
Darou Naim	0-200	1.42	0.13	82.1	9.0	9.2	6.7	0.012	65.7	0.07	4.57
Thiel Serere	0-200	1.42	0.10	81.1	9.8	9.4	6.8	0.012	79.6	0.10	5.39
Hondiolde 3	0-200	1.42	0.09	72.7	18.8	8.7	6.6	0.011	82.4	0.11	5.06
Cow manure											

BD=bulkdensity,OC=organiccarboncontent,N=percentNitrogen,and CEC= Cation exchange capacity

3.4.3.3. CERES-Millet model description and calibration procedure

The CERES Millet model of the DSSAT Version 4.8 (Hoogenboom et al., 2019) was selected for a system analysis approach. The model simulates crop growth, development, and yield by capturing both vegetative and reproductive processes, as well as the dynamics of water, nitrogen, and carbon in the soil, and weather and cultivar traits. Ritchie et al. (1998) and Jones et al. (2003) provide detailed explanations of these processes. To accurately simulate the growth and yield of a pearl millet cultivar, the model requires specific crop and cultivar parameters, also known as genetic coefficients (GCs). Additionally, it incorporates a thermal time calculation similar to growing degree days, which considers the optimal temperature range where plant development rates increase linearly with rising temperatures. Thereby, the Priestley and Taylor method for evapotranspiration was applied in this study. Furthermore, radiation efficiency for millet photosynthesis was considered as described by Jones et al. (2003), and the CENTURY method was used to simulate soil carbon and nitrogen dynamics (Gijsman et al., 2002). To ensure the model's accuracy and reliability for the specific conditions of this study, a thorough calibration process was undertaken. The model was calibrated using the optimum treatment (recommended rate of mineral fertilization, including a micro-dosing strategy) under two plant population densities (12,500 and 25,000 hills/ha) for pearl millet. This was applied to three dual-purpose varieties (Thialack 2, SL 28, and SL 423) and one farmer-improved local variety (Souna 3), across four contrasting environments (Meouane, ISRA/CNRA Bambey research station, Daga Birame, and Koumpentoum) during the 2022 and 2023 growing seasons. The genetic coefficient was estimated during model calibration using field data on phenology, growth, grain, and aboveground biomass yields. The best value for each phenological and development coefficient was chosen using an iterative process (Garba et al., 2024; Kamara et al., 2023; Nissanka et al., 2015). The model's performance was assessed using anthesis, maturity dates, growth, and yield. This approach was done following a sequential order, starting with the phenological development coefficients and progressing to the crop growth and yield coefficients (Bowen et al., 1998). Since the millet cultivars used in the experiment had not been previously modeled with DSSAT, the genetic coefficients were calibrated by choosing an early-maturing cultivar from Niger (Zatib) calibrated by Akponipke (2008) as a reference. The combination of coefficients that resulted in the smallest root mean square error (RMSE) and the highest coefficient agreement (d-stat) between observed and simulated values were selected as the final cultivar coefficients. Table 2 displays the adjusted genetic coefficient for each variety. Initially, the phenology-controlling coefficients (P1, P20, P2R, P5, and PHINT) were adjusted to correspond with the dates of anthesis and maturity as well as the number of leaves. Afterward, to reduce the RMSE between the simulated and measured LAI, biomass, and yield, the G1, G4, G5, and GT parameters were changed (Jones et al., 2003). After modifying the species-specific parameters, the soil fertility factor (SLPF) was modified. After manual modification, the error between the simulated and observed total biomass was minimized, and the value was set at 0.75.

3.4.3.4. Description of cultivars

The four cultivars have been described by ISRA, (2014) and CILSS, (2017). Souna 3, an improved local variety, is early-maturing (85–95 days), generally photoperiod insensitive, and has a yield potential of 2.4 to 3.5 t/ha. Thialack 2, a dual-purpose variety, has moderate photoperiod sensitivity, a medium maturity cycle (90–95 days), and a yield potential of 2 to 3 t/ha. SL-423 and SL-28, also dual-purpose varieties, are photoperiod-insensitive, early-maturing (85–95 days), and have a yield potential of 2.5 to 3.5 t/ha. Table 4 shows the generated values for the cultivar coefficients for each variety. The genotypic coefficient P1 was 310 ◦C day for Souna 3. SL 28 and SL 423, while it was 240 ◦C day for Thialack 2. The P20 was 12.8 hours for Souna 3. SL 28 and SL 423, while it was 11.6 hours for Thialack 2. There was low variation between the varieties in P2R, P5 G1, and GT, while no variation was observed in G4 and G5. Therefore, the thermal time between successive leaf tip appearances (PHINT) was slightly different between the four varieties.

Table 4: Genetic coefficients for model calibration

Variables	Description	Default	Souna 3	SL 28	SL 423	Thialack 2
P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 10°C) during which the plant is not responsive to changes in photoperiod	340.0	310.0	310.0	310.0	240.0
P20	Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. At values greater than P2O, the rate of development is reduced	12.0	12.8	12.8	12.8	11.6
P2R	Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P2O	260.0	310.0	340.0	340.0	130.0
P5	Thermal time (degree days above a base temperature of 10°C) from beginning of grain filling (3-4 days after flowering) to physiological maturity	285.0	240.0	210.0	230.0	260.0
G1	Scaler for relative leaf size	0.5	1.4	1.2	1.0	0.7
G4	Scaler for partitioning of assimilates to the panicle (head)	0.9	1.9	1.9	1.9	1.9
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances	43.0	68.0	70.0	68.0	65.0
GT	Tillering coefficient, equivalent to G1, but on tillers	1.0	1.3	1.3	1.5	1.5
G5	Potential grain size, mg	11.0	11.0	11.0	11.0	11.0

3.4.3.5. CERES-Millet Model Evaluation

To appreciate the accuracy of the model, the calibrated model was evaluated using final grain and aboveground biomass yield of independent data from on-farm demonstration plots in each rainfall gradient of the 2022 and 2023 growing seasons. The accuracy of model simulations was assessed based on the Mean Bias Error (MBE), Root Mean Square Error (RMSE), normalized Root Mean Square Error (nRMSE), and coefficient of agreement (d-index) (Bélanger, 2000; Willmot, 1982) .

The simulations in each cluster were performed across 24 selected farmers for each year (2022 and 2023) for both Daga Birame and Meouane clusters, while in Thiel it was for only the 2023 growing season. Daga Birame cluster was concerned by Souna 3 and SL 28, Meaoune, Souna 3 and SL 423, while Thiel was Souna 3 and Thialack 2. The soil survey across the community indicated a very low fertility class, which implies the adjustment of SLPF to minimize the error between the observed and simulated total biomass, ranked between 0.45 to 0.75 in Daga Birame, 0.41 to 0.65 in Thiel, and 0.53 to 0.6 in Meouane cluster. The accuracy and reliability of the model were assessed by calculating the statistical indices between observed and simulated values. Statistical indices are shown in Eqs. (5)–(8):

$$MBE = \frac{1}{N}\sum_{i=1}^{n}(O_i - S_i) \qquad (Eq\ 5)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{N}} \qquad (Eq\ 6)$$

$$nRMSE = \left[\frac{RMSE}{\bar{o}}\right] \times 100 \qquad (Eq\ 7)$$

$$d - index = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(|S_i - \bar{O}| + |O_i - \bar{O}|)^2} \qquad (Eq\ 8)$$

S_i is the simulated values; O_i is the observed values and n is the number of observations. The simulation is considered excellent with a normalized RMSE less than 10 %, good if the nRMSE is greater than 10 and less than 20%, fair if the normalized RMSE is greater than 20% and less than 30%, and poor if the normalized RMSE is greater than 30%(Loague and Green, 1991).

3.4.4. Simulation of future climate conditions impact across agroecological zones of Senegal

3.4.4.1. Selection of Coupled Model Intercomparison Project Phase 6 for Future Climate Impact Prediction

This study used six Global circulation models (GCMs) from datasets from NEX-GDDP-CMIP6 to project future changes. Several studies have used the NEX-GDDP-CMIP6 dataset for climate impact studies (Sawadogo et al., 2024; Waongo et al., 2024, Sultan et al., 2023). These datasets are statistically downscaled climate scenarios derived from CMIP6 models to a horizontal resolution of 0.25◦ with a bias correction and spatial disaggregation (BCSD) method (Thrasher et al., 2022). The selected models are ACCESS-CM2, CanESM5, CNRM-CM6-1, HadGEM3-GC31-LL, MPI-ESM1-2-HR, and UKESM1-0-LL (Table 5). These models provide climate simulations for both historical (1950-2014) and future (2015-2100) periods, offering projections under various Shared Socioeconomic Pathways (SSPs), specifically SSP2-4.5 and SSP5-8.5 (O'Neill et al., 2017). The models were chosen based on their (i) use in recent IPCC Assessment Reports, (ii) Availability of high-resolution, bias-corrected data for the study region, making them suitable for localized climate impact studies (Almazroui et al., 2020; Kouman et al., 2024; Shiogama et al., 2021), and (iii) Performance in representing key climate variables (precipitation, temperature) in West Africa, as identified by Eyring et al. (2016) and O'Neill et al. (2016). Daily data such as precipitation, maximum, and minimum temperature, and solar radiation were derived from the dataset using R scripts. These variables were selected based on their critical role in influencing agricultural productivity and water availability in the study region (Lobell and Burke, 2010; Roudier et al., 2011) and their relevance as crop model inputs. The selection of the six GCMs was also based on their proven performance in simulating contrasting climate patterns in West Africa (Ajibola et al., 2020; Almazroui et al., 2020; Bobde et al., 2024; Kouman et al., 2024; Shiru and Chung, 2021; Tebaldi et al., 2021; Wada et al., 2022). The selected SSP2-4.5 and SSP5-8.5 scenarios represent different pathways of socio-economic development and associated greenhouse gas emissions. SSP2-4.5 is a moderate scenario where climate policies gradually shift toward mitigation, resulting in a radiative forcing of 4.5 W/m² by 2100 while SSP5-8.5 is a high-emission scenario that assumes rapid economic growth with limited mitigation, leading to a radiative forcing of 8.5 W/m² by 2100 (O'Neill et al., 2017). For the mid-century period (2040–2069), the projected

CO_2 concentration levels for the SSP2-4.5 and SSP5-8.5 scenarios are around 540 ppm and 680 ppm respectively (Meinshausen et al., 2020; O'Neill et al., 2017)**.** The choice of these pathways provides a contrast between moderate and extreme future climate conditions, offering a broader range of potential outcomes for adaptation strategies. The historical period from 1985 to 2014 was used in this study as a baseline to assess climate change impacts on millet production. Future climate conditions were obtained for the period 2040-2069, a timeframe considered relevant for mid-century adaptation planning (Akinseye et al., 2024). To address uncertainties inherent in climate modeling, the ensemble approach was further assessed. This involved averaging the output of the projection from the six selected GCMs, as recommended by (Shelia et al., 2019; Tebaldi and Knutti, 2007). The ensemble approach reduces the impact of biases from any single model and increases the robustness of the projections.

Additionally, for the six specified GCM models, the length of the growing season and the onset and cessation of the rainy season were determined using Instat+ software, version 3.36. Following the Sahelian zone, the onset was identified by Sivakumar, (1988) as the day after May 1st, when there was no dry spell for more than seven days in the next 30 days, and 20 mm of rain fell over three consecutive days (Akinseye et al., 2016). According to earlier research that has been widely applied across Sahelian zones, the cessation was defined as the first day after September 1st when the climatic water balance is less than or equal to 0.5 mm, or when the soil is completely dry down to a depth of 100 cm with daily potential evapotranspiration of 5 mm (Akinseye et al., 2016; Lodoun et al., 2013). The duration of a specific region's rainy season (Sivakumar, 1992) states that a threshold rainfall of 0.85 mm was utilized in these computations to identify a rainy day.

Table 5: Details on CMIP6 GCMs used for crop simulation

CMIP6 model name	Institution	Spatial Resolution	References
ACCESS-CM2	Australian Community Climate and Earth System Simulator	1.88° x 1.25°	(Bi et al., 2020)
CanESM5	Canadian Center for Climate Modeling and Analysis	2.8° x 2.8°	(Swart et al., 2019)
CNRM-CM6-1	National Centre for Meteorological Research, France	1.4° x 1.4°	(Voldoire et al., 2019)
HadGEM3-GC31-LL	Hadley Centre Global Environment Model version 3, U.K.	1.9° x 1.3°	(Williams et al., 2018)
MPI-ESM1-2-HR	Max-Planck-Institut für Meteorologie, Germany	0.9° x 0.9°	Gutjahr et al. (2019)
UKESM1-0-LL	Met Office and Natural Environment Research Council of U. K.	1.9° x 1.3°	(Sellar et al., 2019)

3.4.4.2. Selection of Agroecological Zones and Climate Models Data Extraction

For climate impact assessment under current and future scenarios of Senegal, four agroecological zones (AEZs) were selected based on their representativeness of the country's major AEZs for pearl millet production and based on the availability of the data (soil and climate) required to parameterize the crop simulation models. This includes the Old Peanut Basin (OPB), New Peanut Basin (NPB), Sylvopastorislm Zone (SVPZ), and Eastern and Upper Casamance Zone (EUC). Though millet is a common crop in all four AEZs and each agroecological zone is characterized by distinct climate and environmental conditions that influence agricultural productivity. Four representative sites were selected based on rainfall isohyets in each agroecological zone to ensure that the aggregated simulation output accurately reflects the rainfall distribution and its influence on agricultural outcomes within each agroecological zone (Van Wart et al., 2013). Indeed, in the Old Peanut Basin, Meouane, Louga, Bambey, and Touba were chosen, New Peanut Basin (Daga Birame, Nioro du Rip, Babane Oualof, Karang), Eastern and Upper Casamance (Koumpetum, Kedougou, Vellingara, Kolda and Goudiri Foulbe), and Sylvopastoralism Zone (Thiel, Poua Diamo, Gueye Kadar,and Mboune) (Figure 6). The approach of aggregating simulation output at the agroecological scale is to capture the overall impact of climate change on crop yields across a larger zone rather than focusing on local-scale variations (Falconnier et al., 2020). This approach ensures that the climate data used for simulations represent the overall conditions of the agroecological zone, leading to more consistent and comparable results across different zones (Rosenzweig et al., 2013). This methodology ensures a robust assessment of climate impacts on crop yields, accounting for both the spatial variability within agroecological zones and the broader regional trends (Challinor et al., 2014; Wang et al., 2018).

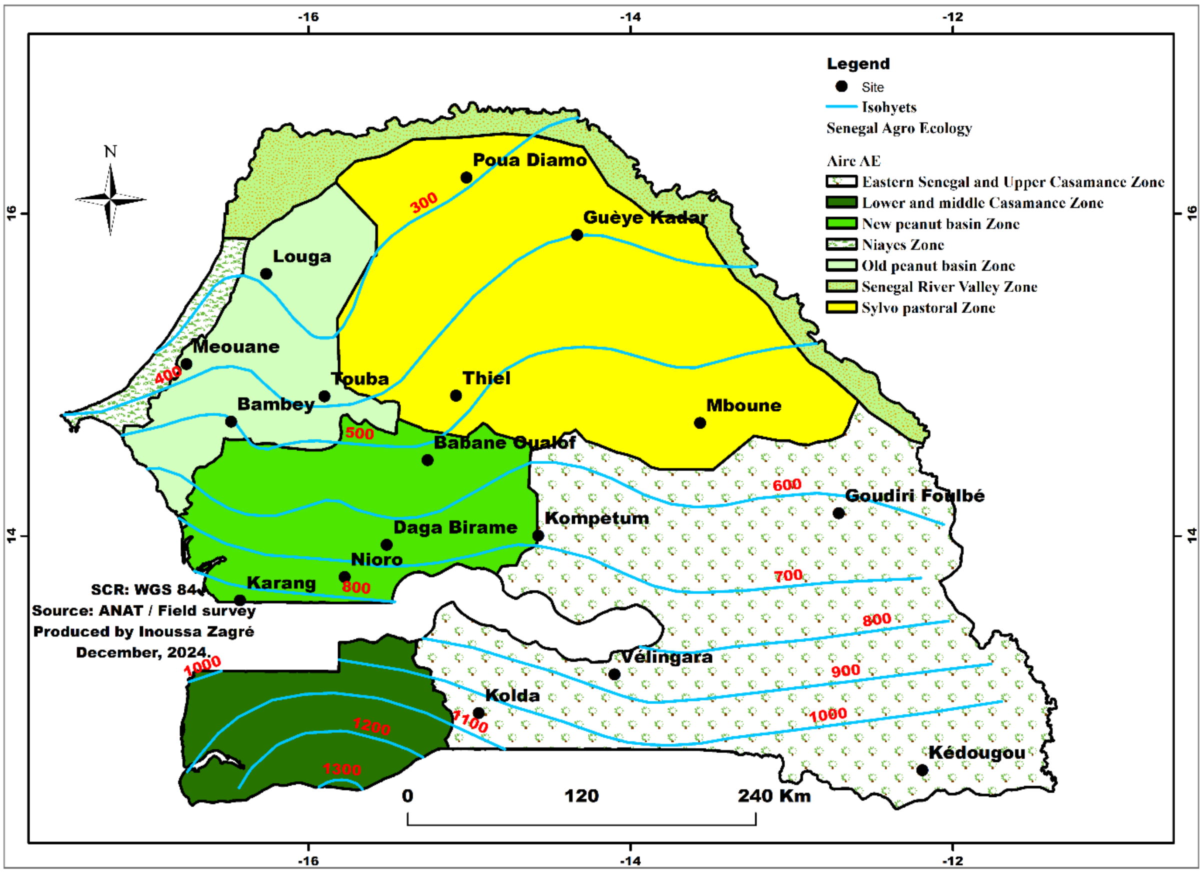


Figure 6: Different sites used for agroecological scale simulation of current and future climate conditions

3.4.4.3. Seasonal Analysis for Climate Impact Assessment

Global circulation models (GCMs) are increasingly capable of making relevant predictions of seasonal and long-term climate variability, thus improving prospects of predicting impact on crop yields. The climate projections derived from these six models and the ensemble model were used as inputs for the DSSAT crop model (CERES-Millet) to simulate the impacts of future climate change on pearl millet yield. This was to assess the impact of climate change on grain yield and biomass to identify the optimum micro-dosing fertilizer strategy across the agroecological zones of Senegal. Based on the definition of rainy season onset in the Sahel given by (Sivakumar, 1988) and confirmed to be suitable for this zone (Akinseye et al., 2016; Joseph et al., 2023; Zagre et al., 2024). The model's initial water, nitrogen, and organic matter contents were set at the beginning of each simulation (1 May). This allows the elimination of the residual effect of these parameters in the soil profile on crop growth and development for the current season (Beah et al., 2021). Analysis of the onset and the cessation of the rainy season across the clusters (Zagre et al., 2024) allows for setting the optimum planting window from June 26 to July 25, covering the targeted AEZs. In the simulations for the current climate, a CO_2 concentration was set at 360 ppm, while in the future climate simulations, a CO_2 concentration was 540 ppm under SSP2-4.5 and 680 ppm under SSP5-8.5 for mid-century (Meinshausen et al., 2020). Four organo-mineral micro-dosing strategies were used to determine the optimum combination of N application rate in each AEZ. The simulation was set at two planting densities (12,500 hills/ha and 25,000 hills/ha). In each AEZ, the simulation was done for the four varieties (SL28, SL423, Thialack 2, and Souna3) used above for model calibration and evaluation. The application procedure was applied in the long-term seasonal simulation. The cow manure rates were applied at the sowing. NPK rates were applied two weeks after planting, while urea rates were applied three weeks after NPK application.

3.4.4.4. Data analysis

Statistical analyses were conducted using R software version 4.3.3. A two-way ANOVA was performed to evaluate the effects of variety type, plant population, and micro-dosing fertilizer on grain yield, stalk yield, and harvest index. Before conducting ANOVA, the normality of the data was assessed using the Kolmogorov-Smirnov (KS) test. Mean comparisons were conducted using the Tukey test at $p < 0.05$ for each location. Additionally, the accuracy of the CERES-Millet model in simulating the phenological stages, growth, and yield of pearl millet cultivars across contrasting environments was assessed using statistical indices such as Mean Bias Error (MBE), Root Mean Square Error (RMSE), normalized RMSE (nRMSE), and the d-statistic. For the climate impact assessment to determine the underlying anomalies, relative change (%) (Eq. 9) and absolute change (Eq. 10) were calculated using GCM climate data and long-term yield simulations. Positive and negative anomalies indicate, respectively the increase and decrease of the variables in the future period.

$$\Delta Future\ (\%) = \left[\frac{Future\ scenario - Baseline}{Baseline}\right] \times 100 \qquad (Eq\ 9)$$

$$\Delta Future\ = Future\ scenario - Baseline \qquad (Eq\ 10)$$

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4-1. RESULTS

4.1.1. The perception of farmers toward changes in temperature, wind speed, and rainfall patterns

Table 6 displays farmers' perceptions of climate change across the three zones. The findings revealed that 62% of respondents across all AEZ observed an increase in annual rainfall. About 68% of farmers' respondents agreed that the rainy season starts late and 67% agreed that the rainy season stops early. Only 37% of farmers who responded to the survey confirmed a rising tendency, whereas 60% confirmed the rainy season's shortening over time. Temperature changes were widely acknowledged, with 84% of farmers confirming a rise in temperature in recent years. Furthermore, 72% of farmers' respondents reported increased wind intensity. The investigation within each rainfall gradient revealed that in Daga Birame location, farmers perceived an increased trend of annual rainfall amount (84%), rainy season length (77%), temperature (92%), and wind intensity (50%). Most of these farmers (90%) concurred that the rainy season started early and ended late (96%). In Thiel, all farmers (100%) reported an increase in annual rainfall, while 98% observed rising temperatures and 75% noted stronger winds. However, 68% believed the rainy season has shortened, and all respondents (100%) stated that the rainy season now starts later and ends earlier. The farmers in Meouane noticed that yearly rainfall (96%) and the length of the rainy season (94%) were trending downward. Related to temperature and wind intensity, they claimed an increasing trend respectively 67% and 96%. Most of them (96%) also concluded that the rainy season started later than usual and ended earlier than expected (96%).

Table 6: Perceptions of farmers in Meouane, Thiel, and Daga Birame (%) regarding changes to several climate indices

Climate indicators		Daga Birame	Thiel	Meouane	Overall
Annual precipitation	Increase	84	100	4	62
	No change	6	0	0	1
	Decrease	10	0	96	37
	No opinion	0	0	0	0
Length of cropping season	Increase	77	30	6	37
	No change	6	2	0	3
	Decrease	17	68	94	60
	No opinion	0	0	0	0
Temperature	Increase	92	98	67	84
	No change	6	2	2	4
	Decrease	2	0	31	12
	No opinion	0	0	0	0
Variation in wind speed	Increase	50	75	96	72
	No change	15	15	0	10
	Decrease	33	10	4	17
	No opinion	2	0	0	1
Onset of the rainy season	Late	8	100	96	68
	No change	2	0	0	0
	Early	90	0	4	32
	No opinion	0	0	0	0
Cessation of the rainy season	Late	96	0	4	33
	No change	2	0	0	0
	Early	2	100	96	67
	No opinion	0	0	0	0

4.1.2. Farmers' Perspectives on the Weather Variabilities on Livestock and Crop Systems

Weather anomalies, which include delayed or early onset of the rainy season, low seasonal rainfall, dry spells during critical crop growth stages, strong winds, and high temperatures, were closely linked to seasonal patterns (Table 7). The findings demonstrated that farmers understood how various weather-related scenarios might affect their crops and livestock systems. Table 7 below lists the common impacts emphasized by farmers. The main effects of weather anomaly scenarios on crop and livestock systems are what farmers along the three rainfall gradients observe.

Table 7: Farmers in the Meouane, Thiel, and Daga Birame zones' assessments of how weather anomalies affect crop and livestock systems

Weather indicators	Scenario	Impact	Frequency
Amount of seasonal precipitation	Deficit	Crop water shortage leading to decreased yield	72%
Onset	Delayed	Loss of yield due to late sowing	88%
		Lack of grain maturation and filling	90%
Dry spells near the end of the season or an early cessation of the season	Frequent	Loss of productivity due to crop drying out and insufficient grain filling and maturation	68%
		fodder shortage	36%
Extended dry spells in the early stages of the rainy season	Prolonged	Loss of seedlings due to a lack of water	39%
		Crop growth delay leading to decreased yield	76%
Strong wind	Strong	Causes soil erosion, which reduces soil fertility	44%
		Crop fall resulting in yield loss	49%
High temperature	High	Crop drying out, which reduces yield	30%
		More crop water is required, and pastoral boreholes are drying up earlier	39%
		Lead of animal disease	32%

4.1.3. Adoption Measures in Response to Change

Table 8 shows that the farmers in the three locations used different adaptation measures to deal with climate unpredictability. This includes the use of improved varieties, rotation with leguminous, shifting the date of sowing, crop diversification, use of organic manure, improved animal race, efficient use of inorganic fertilizer, Farmer Managed Natural Regeneration (FMNR), mulching, and irrigation. Farmers in the Daga Birame primarily use improved varieties (65%), rotate with leguminous (55%), and alter planting dates (55%). In the Thiel, farmers primarily used rotation with leguminous (98%) and crop diversification (76%) as well as shifting the date of sowing (46%). In Meouane, the findings revealed that farmers use more Farmer Managed Natural

Regeneration (FMNR) (96%) than any other strategy, along with shifting the date of planting (71%), to deal with weather fluctuation during the cropping season. Otherwise, more analysis was conducted to quickly record farmers' responses when they learn about a climatic occurrence, such as an increasing dry spell. According to the findings, 60% of farmers in all three areas reported adjusting their crop operations due to the climatic information they received during the rainy season. However, apart from a few farmers (5%) who mentioned utilizing irrigation with solar energy systems, none have claimed to practice rainwater harvesting practices such as half-moon, *zaï*, and runoff water collection basins.

Table 8: Farmer's adoption measures in Daga Birame, Thiel, and Meouane locations in percentage (%)

Smart management practices	**Daga Birame (%)**	**Thiel (%)**	**Meouane (%)**
Improved varieties	65	17	63
Rotation with leguminous	55	98	43
Change of planting date	55	46	71
Crop diversification	15	76	41
Use of organic manure	25	24	10
Improved animal breed	25	12	14
Efficiency use of inorganic fertilizer	30	27	11
Farmer Managed Natural Regeneration (FMNR)	45	2	96
Mulching	5	29	0
Irrigation	0	5	6
Rainwater harvesting (Runoff water collection basin, Half-moon, Zaï)	0	0	0

4.1.4. Small-scale farmers' expectations and the variables influencing their demand for climate-smart management techniques

The Logit model described in Eq (1) was used to analyze how socioeconomic and institutional factors affected farmers' perceptions of the need for smart management practices as described in Table 9. The dependent variables in this model were the household's adoption of improved varieties as a climate-smart management method, adjustment of crop operation during the growing season, and perception of climate change, in that order. The probability estimates of the logit model results demonstrate that adopting improved varieties as a climate-smart management technique has been strongly influenced by six factors at 1%, 5%, and 10%. The likelihood is influenced by access to credit, extension service, the frequency of extension agent visits, and access to government subsidies. Farmers' perceptions of soil erosion and the distance to the extension office have an unlikely negative impact at a 5% significance level. The model showed that a farmer's perception of soil erosion level and farming experience positively affect the change of crop operation at a 5% significance level concerning a farmer's ability to adjust crop operation during the growing season. Farmers' knowledge was positively correlated with access to government subsidies to farmers' impression of the changing climate at a 1% significance level.

Table 9: Adoption of climate-smart practices and farmer perception using Binomial logit model

Variables	Improved variety adoption as a climate-smart practice	Adjustment of crop operation during the growing season as a climate-smart practice	Perception of climate change
Age	-0.08 (0.06)	-0.07 (0.05)	0.04 (0.16)
Gender	2.61 (1.63)	0.91 (0.96)	20.77 (2.47)
Education level	-0.21 (0.22)	-0.01 (0.22)	-17.28 (2.14)
Credit access	**3.05* (1.76)**	-0.26 (0.8)	-0.07 (1.77)
Access to extension service	**1.84* (1.07)**	0.37 (0.95)	0.46 (2.46)
Farmland erosion	**-1.59** (0.69)**	**2.27** (0.97)**	0.58 (1.46)
Soil fertility	0.99 (1.06)	-0.46 (0.42)	0.66 (0.93)
Farmers' group membership	0.67 (0.55)	-0.41 (0.4)	-1.4 (1.25)
Farming experience	0.02 (0.05)	**0.10** (0.04)**	-0.06 (0.14)
Number of contacts with an extension agent	**0.41*** (0.14)**	-0.01 (0.13)	0.45 (0.58)
Distance to extension office (km)	**-0.26** (0.1)**	0.06 (0.05)	0.03 (0.13)
Access to Government subsidies	**2.03* (1.06)**	1.39 (0.93)	**2.98* (1.77)**
Rainfall gradient	-0.52 (0.70)	**1.53** (0.60)**	0.77 (0.41)
Access to climate information	-2.29 (1.62)	1.11 (0.88)	1.26 (0.34)
Constant	**9.93* (5.19)**	**-5.20* (3.11)**	57.55 (8.589)
Observations	136	136	136

Survey data collected in post-harvest 2022, Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1, the values in bold are statically significant

4.1.5. Weather information of the trial year

The results revealed notable variability in rainfall patterns across the study locations. In Meouane, total rainfall during the 2022 growing season was 463 mm, decreasing to 358 mm in 2023 (Figure 7A). In Daga Birame, higher rainfall was recorded, with 783 mm in 2022 and 697 mm in 2023 (Figure 7B). In Thiel, the recorded rainfall was 560 mm in 2022 and 523 mm in 2023 (Figure 7C). For the remaining two sites, Bambey and Koumpentoum, data were only collected for the 2023 season, with total rainfall of 480 mm and 592 mm, respectively (Figure 7D).

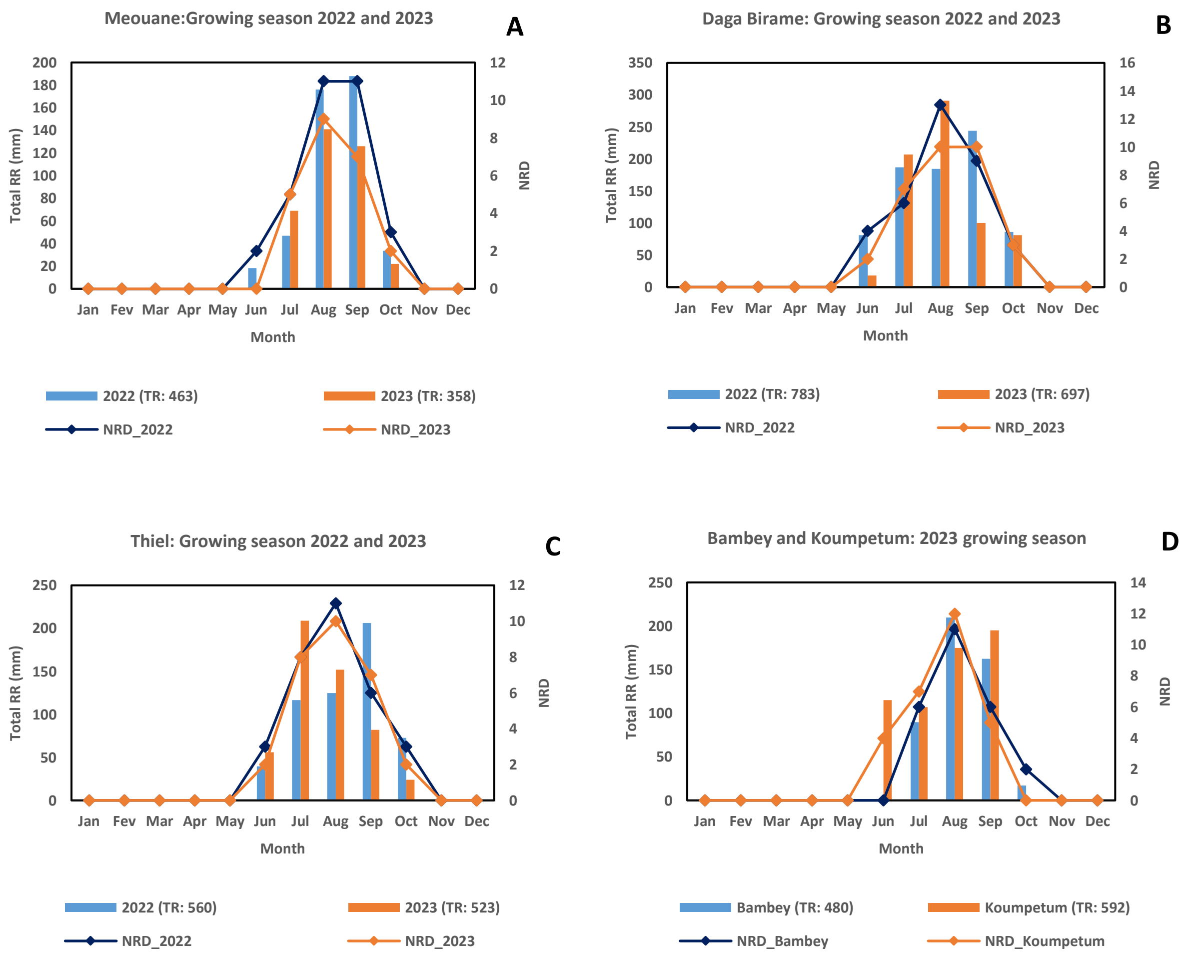


Figure 7: Rainfall pattern during the trial years (TR=Total rainfall; NRD=Number of Rainy Days)

4.1.6. Effects of Variety Type and Micro-dosing Fertilization Strategies on Millet Grain Yield, Stover Yield, and Harvest Index at farm scale

The evaluation of ISFM and dual-purpose millet varieties as climate-smart technologies, combined with improved plant population density at the farm scale, showed a significant ($p < 0.05$) effect on grain yield compared to the farmer-improved local variety in the Meouane and Thiel clusters, except in Daga Birame (Table 10). Grain yield increased by 37% in Thiel, 15% in Meouane, and 8% in Daga Birame with the dual-purpose variety compared to the improved local variety. For stover yield, a significant increase was observed only in Meouane. The application of micro-dosing fertilizer strategies had a significant positive effect on grain yield across all three clusters. However, stover yield and the harvest index, significant effects were observed in Daga Birame and Meouane. The interaction between the micro-dosing fertilizer strategies and variety type did not significant effect on grain yield, stover yields, and harvest index.

Table 10: p-value of ANOVA test of varieties and fertilization on millet grain and stover yields and Harvest index at farm scale in three clusters in Senegal

	Gain yield			**Stover yield**			**Harvest Index (HI)**		
Factor	**Daga Birame**	**Meouane**	**Thiel**	**Daga Birame**	**Meouane**	**Thiel**	**Daga Birame**	**Meouane**	**Thiel**
Variety type (VT)									
Improved local	1800	1450	1265	5538	4882	4759	0.32	0.29	0.34
Dual-purpose	1941	1646	1501	5654	5206	4850	0.35	0.31	0.38
LSD (P-value)	282.3^{ns}	195.6^{*}	224.4^{*}	235.1^{ns}	210.2^{***}	552.5^{ns}	0.04^{ns}	0.04^{ns}	0.05^{ns}
CV (%)	37.7	41.8	28.5	12.5	13.6	33.5	25.1	27.7	31
Fertilizer (F)									
F1	1951	1690	1532	5704	5176	4912	0.33	0.32	0.36
F2	2254	2041	1600	5984	5591	5318	0.37	0.36	0.37
F3	1653	1314	1340	5438	4838	4582	0.3	0.27	0.37
F4	1424	1158	1148	5263	4579	4417	0.27	0.25	0.36
LSD (P-value)	326.9^{***}	240.1^{***}	305.5^{*}	307.2^{***}	258.2^{***}	767.2^{ns}	0.05^{**}	0.05^{***}	0.06^{ns}
CV (%)	35.2	38	31.1	11.3	11.8	33.9	23.1	26.9	32.4

Ns, *, **, and *** indicate that the source of variation was significant at $p < 0.05$, 0.01, and 0.001, respectively.

4.1.7. Effects of Variety Type and Plant Population Density on Millet Grain Yield, Stover Yield, and Harvest Index

The evaluation of an improved plant population as a climate-smart technology, compared to the farmers' practice of using a low plant population, revealed a significant ($p < 0.05$) effect on both grain and stover yields across the three locations (Table 11). Additionally, dual-purpose varieties outperformed the farmer-improved local variety, showing significant effects across all three sites. Grain yield increased by 53% in Daga Birame, 51% in Meouane, and 56% in Thiel with the improved plant population compared to the low plant population practice. Similarly, stover yield increased by 55%, 62%, and 64% at these locations, respectively. Although the harvest index (HI) was slightly higher under the improved plant population, no statistically significant effect was observed. However, dual-purpose varieties exhibited a higher HI compared to the farmer-improved local variety, with a significant effect observed only in the wettest location, Daga Birame. The interaction effect of plant population and variety was shown only in Meouane for stover yield.

Table 11: p-value of ANOVA test of density and variety on millet grain and stover yields and Harvest index in three agroecological zones in Senegal

	Grain yield (kg ha^{-1})			Stover (kg ha^{-1})			Harvest Index (HI)		
Treatments	**Daga Birame**	**Meoaune**	**Thiel**	**Daga Birame**	**Meoaune**	**Thiel**	**Daga Birame**	**Meoaune**	**Thiel**
Density (D)									
HD (25,000 hills ha^{-1})	3424	3294	2855	6541	5297	5346	0.35	0.35	0.37
LD (12,500 hills ha^{-1})	2242	2187	1831	3995	3260	3446	0.33	0.34	0.36
LSD (P-value)	287.4***	509.3***	575.9**	578.9***	872.8***	749***	0.03^{ns}	0.04^{ns}	0.07^{ns}
Increase (%)	53	51	56	64	62	55	6	3	3
Variety type (VT)									
Dual-purpose	2916	2875	2633	5306	4313	5055	0.35	0.36	0.37
Improved local	2586	2338	2246	5154	4174	4176	0.31	0.31	0.36
LSD (P-value)	387.8*	474.9*	428.5*	1460^{ns}	1447^{ns}	1240*	0.03*	0.04^{ns}	0.09^{ns}

Ns, *, **, and *** indicate that the source of variation was significant at $p < 0.05$, 0.01, and 0.001, respectively.
HD=high density, LD=low density

4.1.8. Effects of Variety and Plant Density on Water Use Efficiency

The results demonstrated that dual-purpose millet varieties exhibited more efficient water use than the farmer-improved local variety in Meouane and Daga Birame, except in Thiel (Figure 8). However, no significant difference was observed across all study areas. On the other hand, plant population had a highly significant impact on water use efficiency (WUE) across all three locations over the two-year trials. Increasing the plant population to 25,000 hills per hectare significantly enhanced water use efficiency compared to farmers' traditional low-density planting practices.

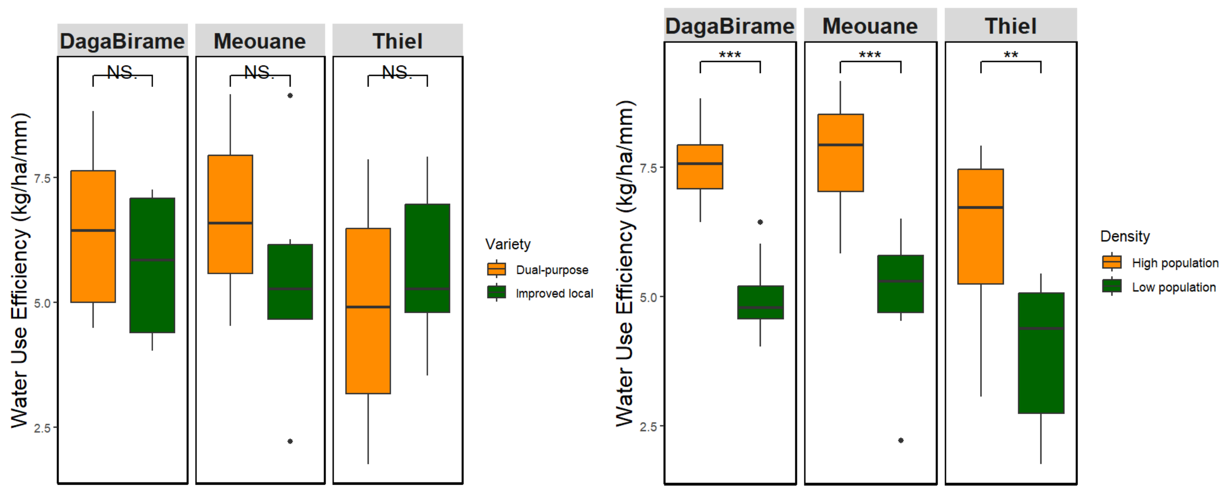


Figure 8: Variety and plant population effect on water use efficiency across the three locations Daga Birame, Meouane, and Thiel for both years of experimental trial (2022 and 2023)

4.1.9. Model performance

The CERES Millet model under the shell of Decision Support System for Agro-Technology Transfer (DSSAT) V4.8 was used for this study. The model was calibrated with optimum conditions and two density levels for the pearl millet cultivars (Souna 3, SL 28, SL 423, and Thialack 2) in four contrasting environments (Meouane, Bambey ISRA/CNRA, Daga birame, and Koumpetum) during the growing season of 2023. The iterative process of genetic coefficient adjustment was used to fit the simulated values close to the observed. The model globally predicted well the anthesis and physiological maturity dates across the contrasting environments for all the cultivars (Table 12). The coefficient of agreement (d-index) for anthesis ranged between 0.52 to 0.91, while it was from 0.8 to 0.86 for physiological maturity for the four cultivars across the contrasting environments. The model overestimated the anthesis date for Souna 3, SL 28, and SL

423 ranked from 2 to 3 days, while it underestimated for Thialack 2 by one day. The maturity date was overestimated for all the cultivars by 1 to 2 days. Regarding the morphological parameters, the performance of the model was appreciable. The d-index was ranked between 0.62 to 0.85 and 0.75 to 0.8 for LAI and leaf number respectively. These results indicate a satisfactory level of agreement between simulated and observed data for these key growth indicators. The yield components (aboveground biomass and Grain yield) were globally well simulated for all the cultivars. The model underestimated AGB for three dual-purpose cultivars (SL 28, SL 423, and Thialack 2) while it overestimated for Souna 3. Similarly, for grain yield, the model overestimated for Souna 3 and Thialach 2 while it underestimated for SL 28 and SL 423 (Table 12). The RMSE (nRMSE) was low for the four cultivars and ranged from 208 to 747 kg ha^{-1} (3.4 to 12%) for AGB and from 257 to 698 kg ha^{-1} (9.8 to 25.5%) for grain yield.

Table 12: Results of model calibration of phenological and growth parameters for the four selected varieties under contrasting environments in 2022 and 2023

Parameters/ Cultivars	Unit	Mean observed	Mean predicted	MBE	RMSE	d-index
			Souna 3			
Anthesis	DAP	60	62	2	3	0.91
Physiological maturity	DAP	85	87	2	3	0.86
LAI-Max	m2/m2	3.5	3.43	-0.1	0.3	0.62
Leaf Number		13	13	0.3	1	0.79
AGB	Kg/ha	6206	6627	421	747	0.89
Grain yield	Kg/ha	2537	2541	4	443	0.69
			SL 28			
Anthesis	DAP	61	64	3	4	0.60
Physiological maturity	DAP	85	87	2	4	0.80
LAI-Max	m2/m2	3.49	3.72	0.2	0.4	0.83
Leaf Number		13	13	1	1	0.80
AGB	Kg/ha	6602	6506	-96	560	0.91
Grain yield	Kg/ha	2627	2464	-163	257	0.97
			SL 423			
Anthesis	DAP	60	63	3	5	0.52
Physiological maturity	DAP	86	87	1	2	80
LAI-Max	m2/m2	3.2	3.4	0.2	0.3	0.85
Leaf Number		12	13	0.5	1	0.75
AGB	Kg/ha	6226	6590	-35.8	640	0.83
Grain yield	Kg/ha	2736	2432	-305	698	0.64

Parameters/ Cultivars	Unit	Mean observed	Mean predicted	MBE	RMSE	d-index
			Thialack 2			
Anthesis	DAP	61	60	-1	3	0.73
Physiological maturity	DAP	85	87	2	4	0.86
LAI-Max	m2/m2	3.15	3.27	0.1	0.3	0.82
Leaf Number		13	14	1	1	0.79
AGB	Kg/ha	6096	6062	-34	208	0.98
Grain yield	Kg/ha	2666	2706	40	389	0.78

AGB: Aboveground biomass

4.1.10. Model Validation: Performance with participatory farm-level Yields

After calibration, the model performance was checked with on-farm data for each cluster (Meoauen, Daga Birame, and Thiel) under high density and four levels of organo-mineral fertilizer using a micro-dosing approach during the years 2022 and 2023. The accuracy and reliability of the model were assessed by calculating the statistical indices between observed and simulated values as described by Loague and Green (1991) and (White et al. (2015). Statistical indices are shown in Eq. (1)–(4). The model demonstrated satisfactory AGB and grain yield agreement between the simulated and observed data across the three clusters. The coefficient of agreement (d-index) ranges between 0.74 to 0.83 for AGB and from 0.64 to 0.98 for grain yield (Figure 9). Deeply, in Daga Birame, the nRMSE of Souna 3 was 9.5% and 14.1% for AGB and grain yield, respectively, while it was 10.8% and 17.4% for SL 28 (Figure 9 A, B). In Meouane, nRMSE of Souna 3 was 11.8% and 15.3% for AGB and grain yield, respectively, while SL423 exhibited nRMSE equal to 14.8% for AGB and 16.7% for grain (Figure 9 C, D). In the last cluster, Thiel, nRMSE of Souna 3 was 18.1% for AGB and 12.5% for grain yield, while it was 18.2% and 14.1% for Thialack 2 (Figure 9 E, F).

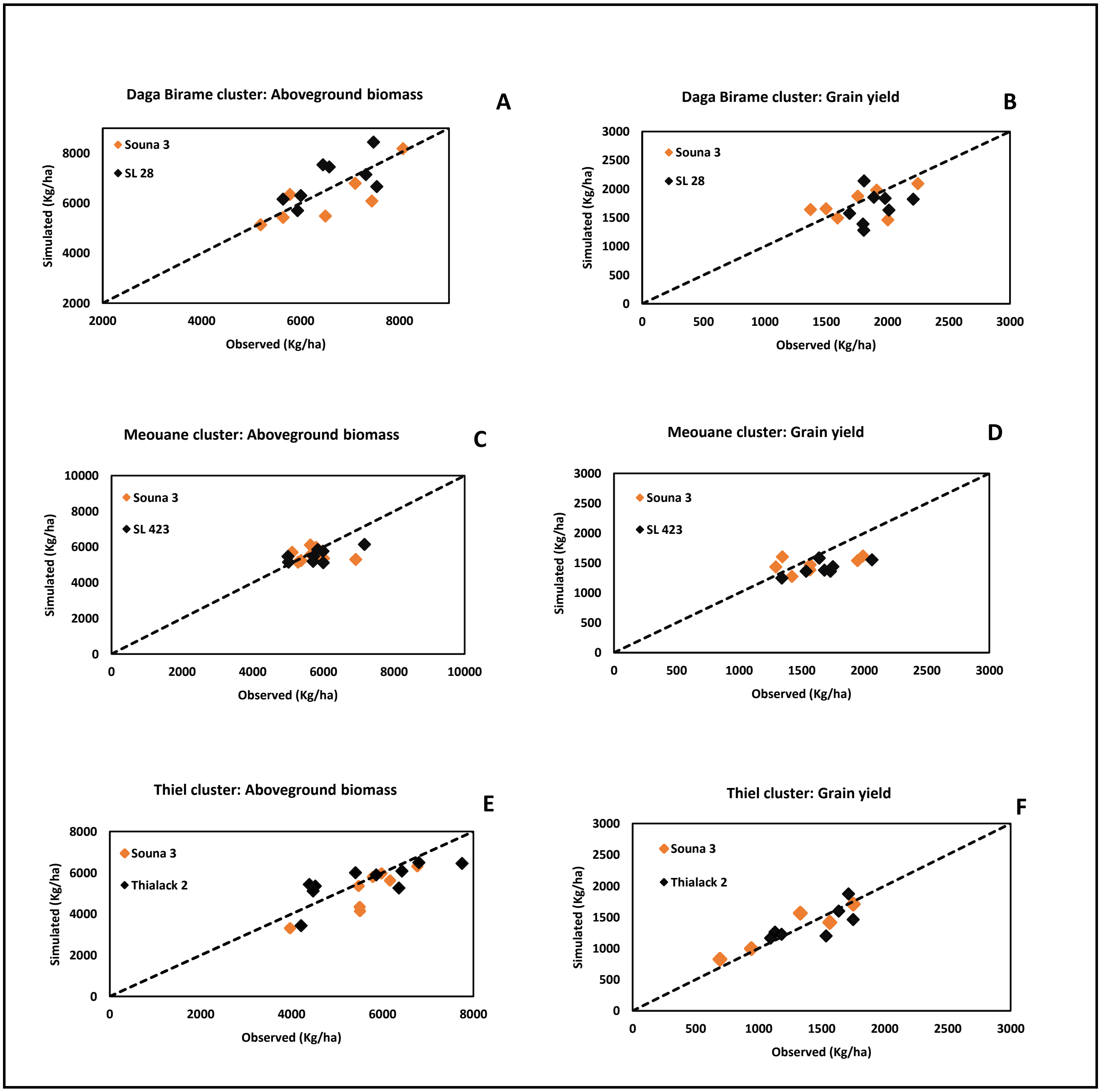


Figure 9: Simulated vs observed for aboveground biomass (AGB), and grain yield for model evaluation across three clusters.

Daga Birame cluster: **(A) AGB** Statistics: [***Souna 3**:* MBE: -332, RMSE: 619, nRMSE: 9.5%, d-Stat: 0.87; ***SL 28**:* MBE: 312, RMSE: 717, nRMSE: 10.8%, d-Stat: 0.76]. **(B) Grain yield** Statistics: [***Souna 3**:* MBE: -25, RMSE: 251, nRMSE: 14.1%, d-Stat: 0.83; ***SL 28**:* MBE: -207, RMSE: 332, nRMSE: 17.4%, d-Stat: 0.78]. **Meouane cluster**: **(C) AGB** Statistics: [***Souna 3**:* MBE: -158, RMSE: 677, nRMSE: 11.8%, d-Stat: 0.80; ***SL 423**:* MBE: -273, RMSE: 546, nRMSE: 14.8%, d-Stat: 0.74]. **(D) Grain yield** Statistics: [***Souna 3**:* MBE: -119, RMSE: 244, nRMSE: 15.3%, d-Stat: 0.68; ***SL 423**:* MBE: -233, RMSE: 280, nRMSE: 16.7%, d-Stat: 0.64]. **Thiel cluster**: **(E) AGB** Statistics: [***Souna 3**:* MBE: -1086, RMSE: 1024, nRMSE: 18.1%, d-Stat: 0.83; ***Thialack 2**:* MBE: -125, RMSE: 1023, nRMSE: 18.2%, d-Stat: 0.83]. **(F) Grain yield** Statistics: [***Souna 3**:* MBE: 57, RMSE: 158, nRMSE: 12.5%, d-Stat: 0.98; ***Thialack 2**:* MBE: -45, RMSE: 202, nRMSE: 14.1%, d-Stat: 0.98].

3.4.11. Climate model trends across the agroecological zones

3.4.11.1. Projected Precipitation Anomalies Across Agroecological Zones of Senegal Using Six GCMs for Mid-Century

Relative differences in precipitation were calculated using Eq. 9 to assess projected anomalies across the four agroecological zones compared to the baseline (Figure 10). The analysis revealed divergent trends among the six selected GCMs (Global Climate Models) under both SSP2-4.5 and SSP5-8.5 scenarios. In the Eastern and Upper Casamance (EUC), New Peanut Basin (NPB), and Sylvopastoralism Zone (SVPZ), four models ACCESS-CM2, CNRM-CM6-1, HadGEM3-GC-LL, and UKESM1-LL, projected a decline in rainfall. Under SSP2-4.5, the projected decrease ranged from 5% to 16%, and under SSP5-8.5, the decline was more pronounced, ranging from 14% to 25%. In contrast, MPI-ESM1-2-HR showed mixed results. For EUC and NPB, it projected a moderate increase in rainfall of 2% to 5% under SSP2-4.5 but a decrease of 4% to 6% under SSP5-8.5. However, in SVPZ, this model projected significant increases, with 17% under SSP2-4.5 and 9% under SSP5-8.5. CanESM5 also projected increased rainfall in EUC and NPB, ranging from 2% to 4% under SSP2-4.5 and 5% to 15% under SSP5-8.5. For SVPZ, it projected a slight decline (2%) under SSP2-4.5, followed by a notable increase (15%) under SSP5-8.5. In the Old Peanut Basin (OPB), model projections were more varied. ACCESS-CM2 and CNRM-CM6-1 forecasted increases in rainfall, with 15% and 11% to 17%, respectively, under both scenarios. In contrast, HadGEM3-GC-LL and MPI-ESM1-2-HR predicted declines ranging from 1% to 2% under SSP2-4.5 and 2% to 10% under SSP5-8.5. CanESM5 showed a notable decrease (8%) under SSP2-4.5 but a strong increase (29%) under SSP5-8.5. Finally, UKESM1-LL projected no change under SSP2-4.5 and a slight decline (2%) under SSP5-8.5.

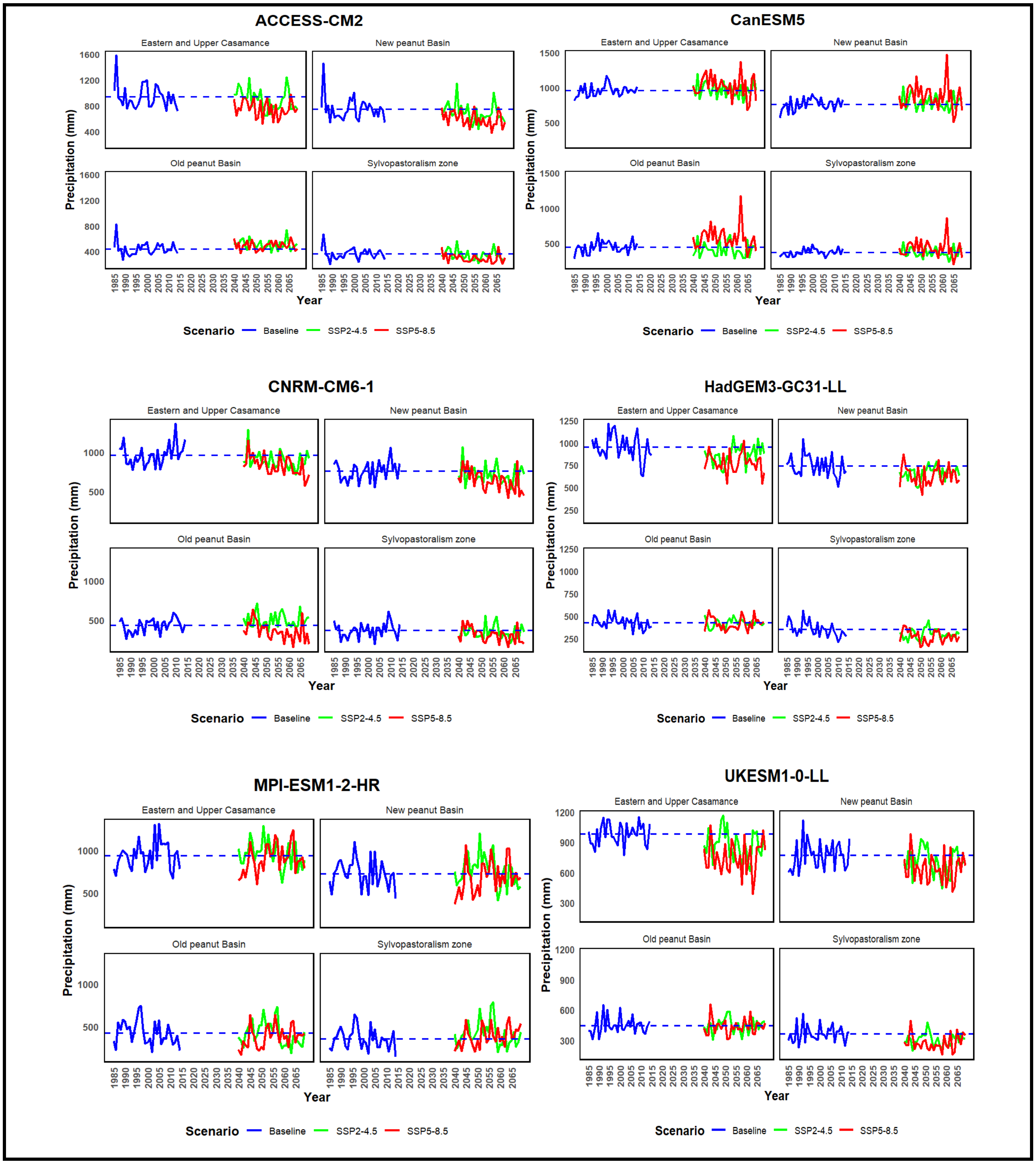


Figure 10: Temporal variability in annual precipitation between the baseline (1985-2014) and mid-century (2040-2069) of six GCM models for the SSP2-4.5 and SSP5-8.5 scenarios across four agroecological zones of Senegal. The dashed blue line represents the average rainfall for the baseline period

3.4.11.2. Projected Temperature Anomalies Across Agroecological Zones of Senegal Using Six GCMs for Mid-Century

Absolute differences in maximum and minimum temperatures were estimated relative to the 1985–2014 baseline using Eq. 10. All six GCMs consistently projected mid-century (2040–2069) warming across Senegal's four agroecological zones, with variations depending on the model and emission scenario (SSP2-4.5 and SSP5-8.5). For maximum temperatures, projected increases ranged from 0.39°C to 3.42°C. Models such as ACCESS-CM2, CanESM5, and UKESM1-LL projected the highest warming (up to 3.42°C), particularly under SSP5-8.5, while MPI-ESM1-2-HR consistently showed the lowest increases (Figure 11). Minimum temperatures followed a similar trend, with projected increases ranging from 0.40°C to 3.33°C. Again, higher warming was associated with SSP5-8.5, and the same models (ACCESS-CM2, CanESM5, and UKESM1-LL) showed the most pronounced changes (Figure 12). These projections indicate a clear warming signal for both daily temperature extremes, with implications for crop growth planning at agroecological scale.

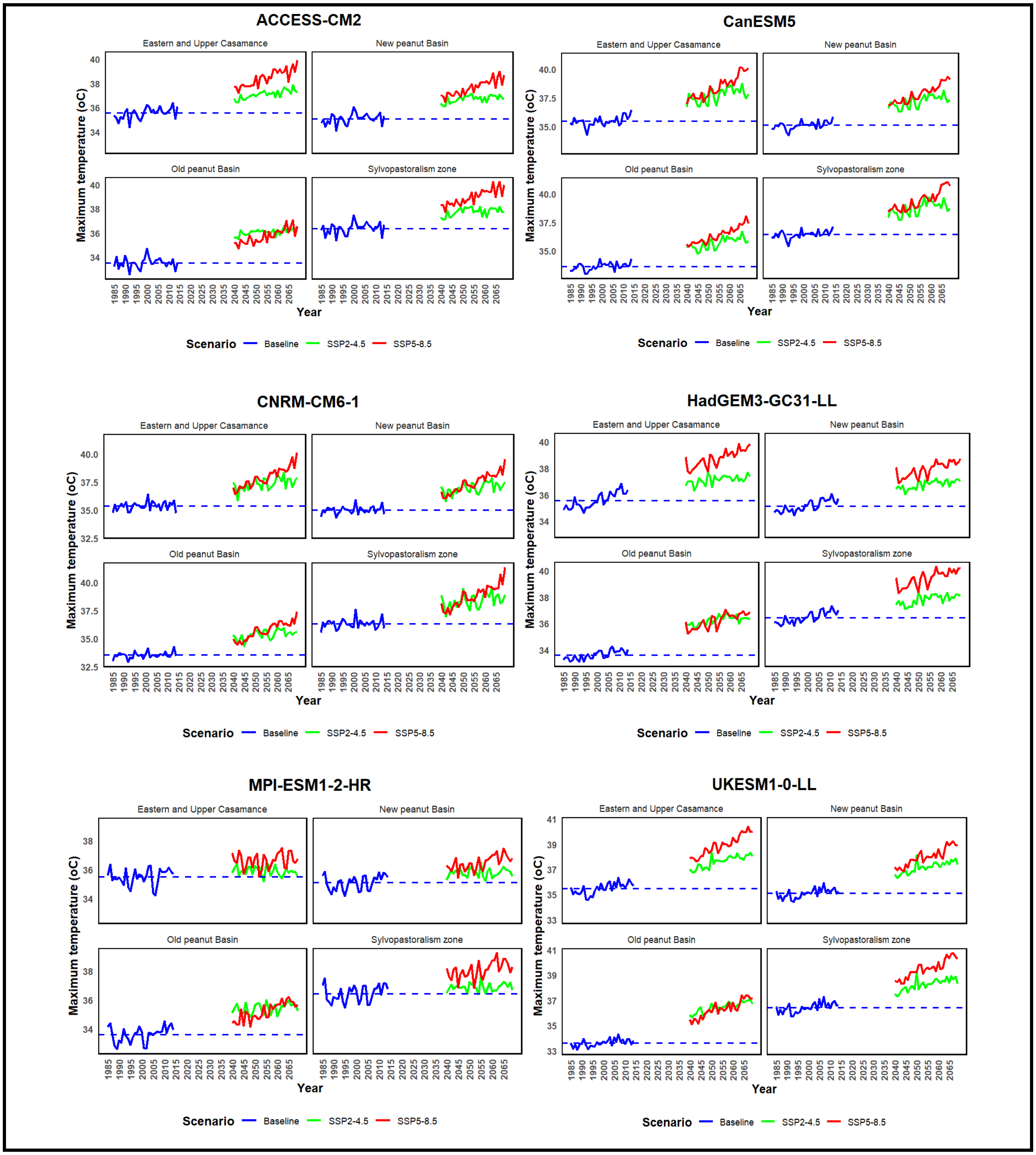


Figure 11: Temporal variability in annual maximum temperature between the baseline (1985-2014) and mid-century (2040-2069) of six GCM models for the SSP2-4.5 and SSP5-8.5 scenarios across four agroecological zones of Senegal. The dashed blue line represents the average maximum temperature for the baseline period

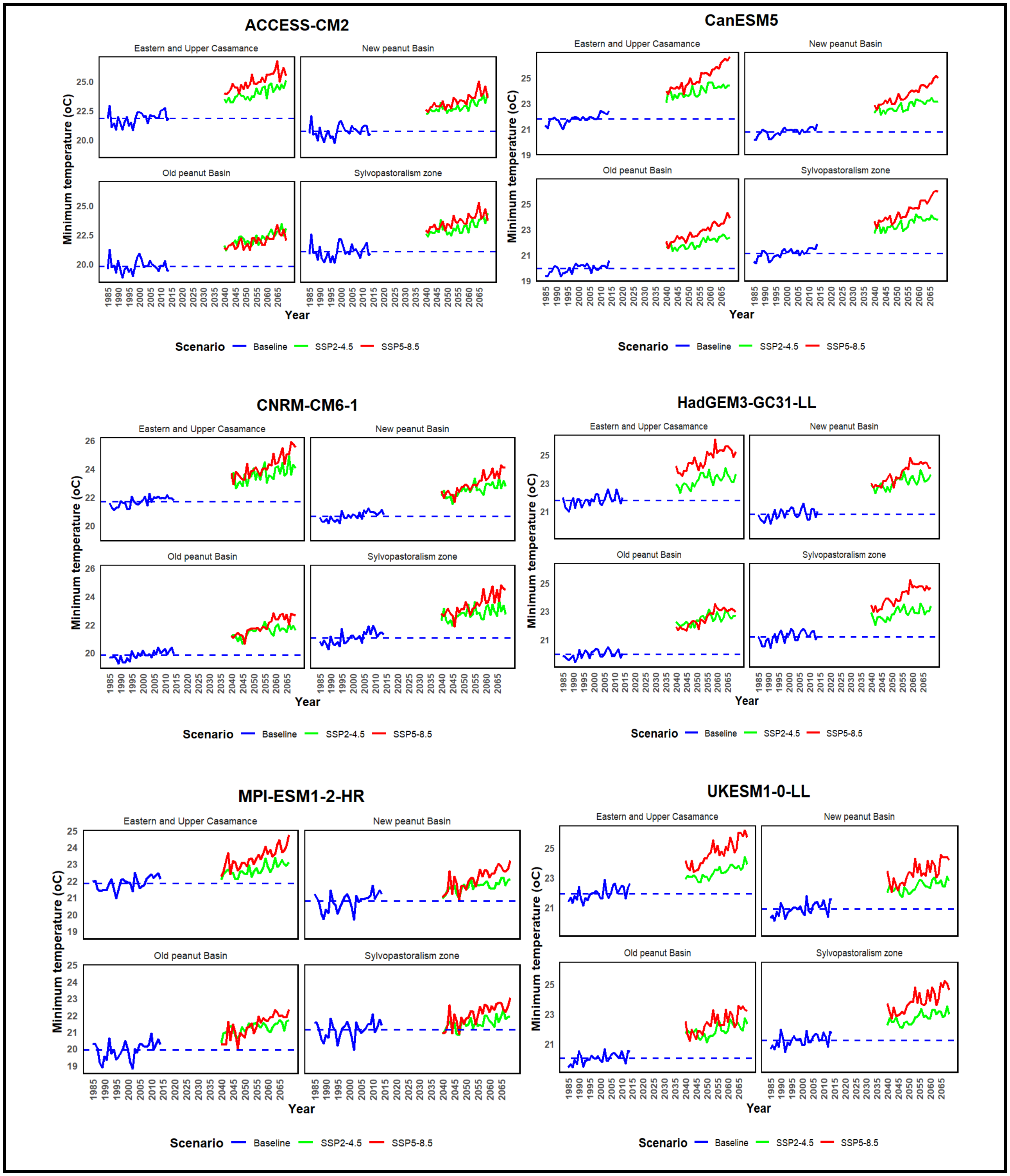


Figure 12: Temporal variability in annual minimum temperature between the baseline (1985-2014) and mid-century (2040-2069) of six GCM models for the SSP2-4.5 and SSP5-8.5 scenarios across four agroecological zones of Senegal. The dashed blue line represents the average minimum temperature for the baseline period

3.4.11.3. Projected Changes in Onset and Length of the Rainy Season Across Agroecological Zones

An ensemble of six climate models was used to assess the climate variability and change on the onset and length of the rainy season (Figure 13). In the Eastern and Upper Casamance (EUC), the rainy season is projected to be delayed by 6 days under SSP2-4.5 and by 8 days under SSP5-8.5 compared to the baseline, including the decreased length of the rainy season by 6 and 8 days. In the New Peanut Basin (NPB), the rainy season will shorten by 3 days under SSP2-4.5 and by 4 days under SSP5-8.5. However, in the Old Peanut Basin (OPB), the rainy season is projected to lengthen by 4 days under SSP2-4.5 and by 1 day under SSP5-8.5. In the Sylvopastoralism (SVPZ), the rainy season will shorten significantly, with declines of 7 days under SSP2-4.5 and 19 days under SSP5-8.5.

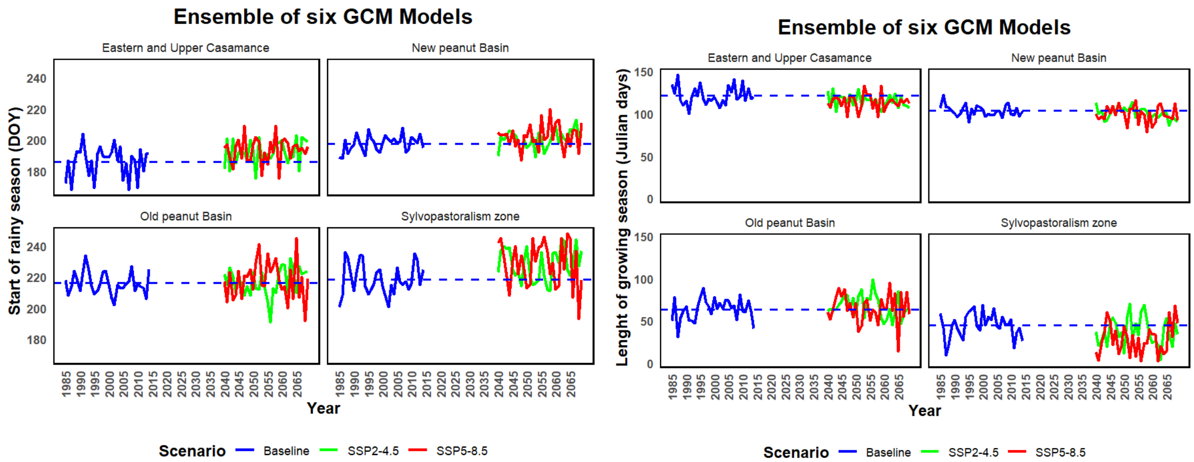


Figure 13: Temporal variability in annual onset and length of growing season between the baseline (1985-2014) and mid-century (2040-2069) of the ensemble of six GCM models for the SSP2-4.5 and SSP5-8.5 scenarios across four agroecological of Senegal. The dashed blue line represents the average rainfall onset (left) and length of rainy season (right) for the baseline period.

3.4.11.4. Projected Millet Yield Responses of Four Varieties to Climate Change Across Agroecological Zones Based on Six GCM Models

The six GCMs exhibited varying trends across agroecological zones under both SSP2 and SSP5 scenarios (Figure 14). In the Old Peanut Basin, four models predicted yield declines for all four varieties, while CanESM5 and CNRM-CM6-1 projected increases under SSP2. Under SSP5, CNRM-CM6-1 and UKESM1-LL indicated yield increases for SL 28, Souna 3, and Thialack 2. In the New Peanut Basin, most GCMs projected yield decreases, except for MPI-ESM1-2-HR, which showed increases for all four varieties under SSP2 and for SL 28, Thialack 2, and Souna 3 under SSP5. In Eastern and Upper Casamance, ACCESS-CM2, HadGEM3-GC-LL, and UKESM1-LL predicted slight increases for Souna 3 and Thialack 2 under SSP2, while CanESM5 forecasted only a marginal increase for Souna 3. In the Sylvopastoralism Zone, MPI-ESM1-2-HR was the sole model to predict yield increases for all varieties under SSP2, and under SSP5, it projected an increase only for Thialack 2.

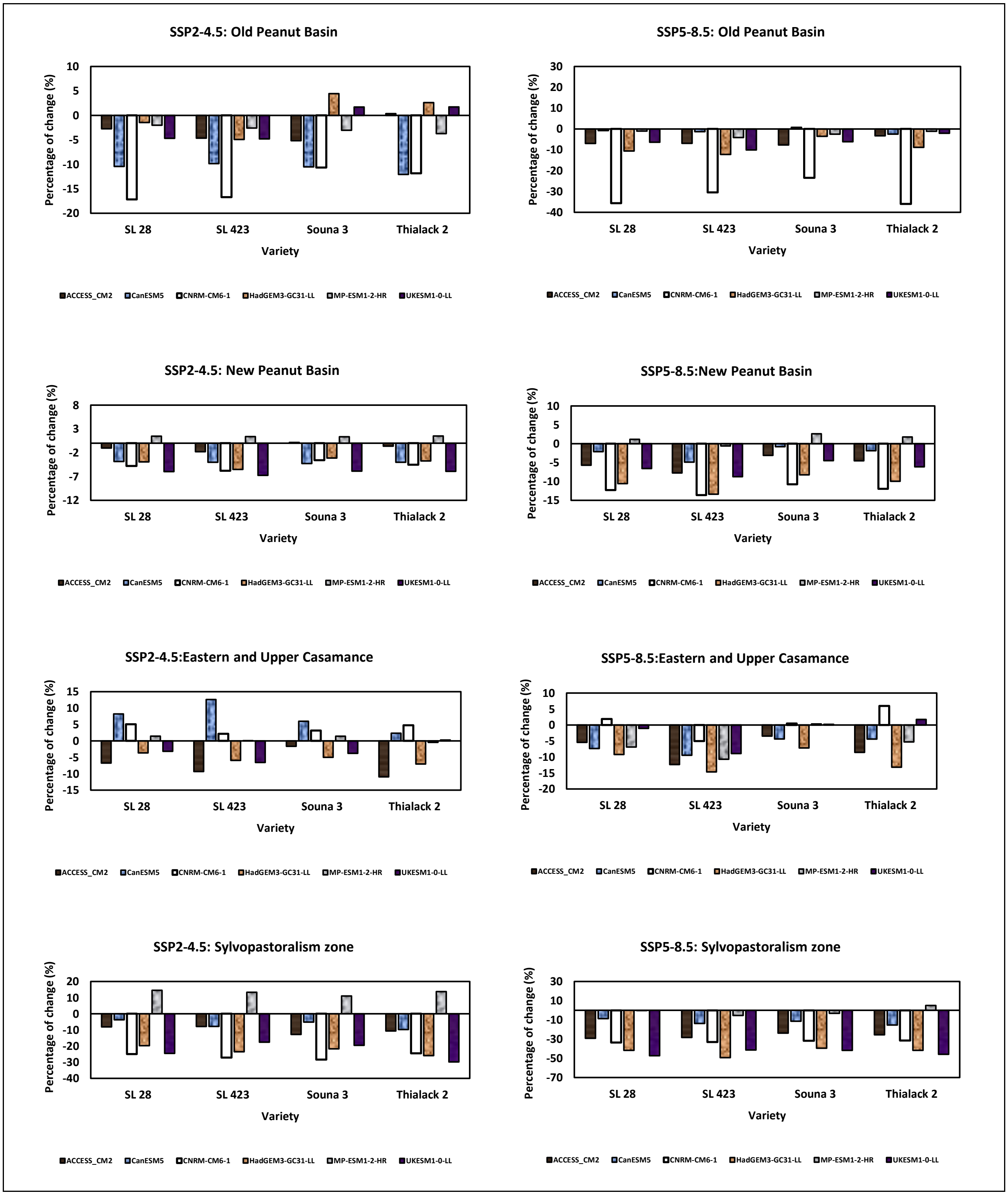


Figure 14: Change on grain yield of the four varieties across four agroecological zones in Senegal for the six GCMs

3.4.11.5. Sensitivity of Micro-Dosing Fertilizer Levels to Climate Change Across Agroecological Zones Based on Six GCM Models

The output of the six GCM models revealed that among the four micro-dosing fertilizer strategies used in this climate impact simulation, fertilizer levels 1 and 2 were more sensitive than levels 3 and 4 across the four agroecological zones (Figure 15). This was particularly evident in the Old Peanut Basin, where all six GCMs projected increases for F3 and F4 under SSP2 and SSP5. However, aside from CanESM5, which predicted increases for F1 and F2 under SSP2, the other models forecasted decreases for these fertilizer levels under SSP2 and SSP5. In the New Peanut Basin, ACCESS-CM2, CanESM5, CNRM-CM6-1, HadGEM3-GC-LL, and UKESM1-LL projected declines for F1 and F2 under SSP2, while all six GCMs indicated decreases under SSP5. Conversely, five of the six GCMs predicted increases for F3 and F4 under SSP2 and four of the six models projected increases under SSP5 for these same fertilizer strategies. In Eastern and Upper Casamance, all six GCMs projected declines for F1 and F2 under SSP2 and SSP5, while the projections for F3 and F4 varied among the models. In the Sylvopastoralism Zone, except for MPI-ESM1-2-HR, which predicted increases across all fertilizer strategies under SSP2, other GCMs forecasted declines under both SSP2 and SSP5, although some models showed slight increases for F3 and F4 under SSP5.

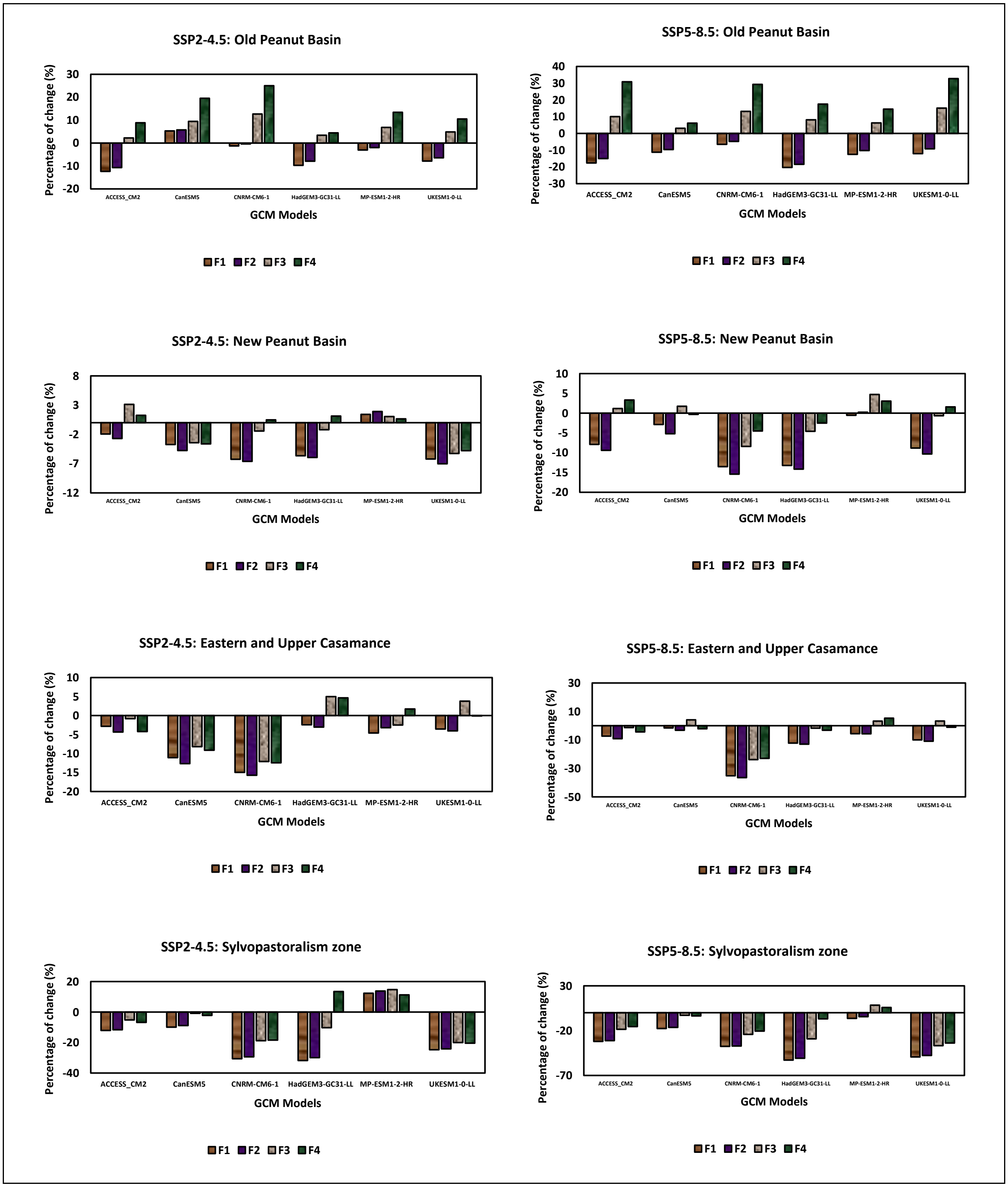


Figure 15: Change on grain yield of the four micro-dosing fertilizer strategies across four agroecological zones in Senegal for the six GCMs

3.4.11.6. Sensitivity of Millet Grain Yield to Climate Change under Low and High Plant Populations Across Agroecological Zones Based on Six GCM Models

The results showed that farmers' practice, which includes low plant population, are more sensitive to future climate change than high plant populations across the four agroecological zones (Figure 16). In the Old Peanut Basin, all six GCMs projected a yield decrease for low plant populations under both SSP2 and SSP5, with a higher magnitude than for high plant populations. However, the high plant population increased for CanESM5 and CNRM-CM6-1 under SSP2 and CNRM-CM6-1 under SSP5. In the New Peanut Basin, five of the six GCMs predicted yield declines for low plant populations under SSP2, and all six GCMs projected a decrease under SSP5. For a high plant population, only MPI-ESM1-2-HR showed slight increases under both SSP2 and SSP5, while the other five GCMs indicated declines. All six GCMs predicted yield declines for low plant populations under both SSP2 and SSP5, with varying magnitudes in Eastern and Upper Casamance. For a high plant population, HadGEM3-GC-LL projected slight increases under SSP2, while CanESM5 showed a marginal increase under SSP5. In the Sylvopastoralism Zone, except for MPI-ESM1-2-HR, which predicted a slight increase, the other five GCMs projected declines for both low and high plant populations under SSP2. Under SSP5, all six GCMs predicted a decrease for low plant population, while five of the six projected decreases for high plant population.

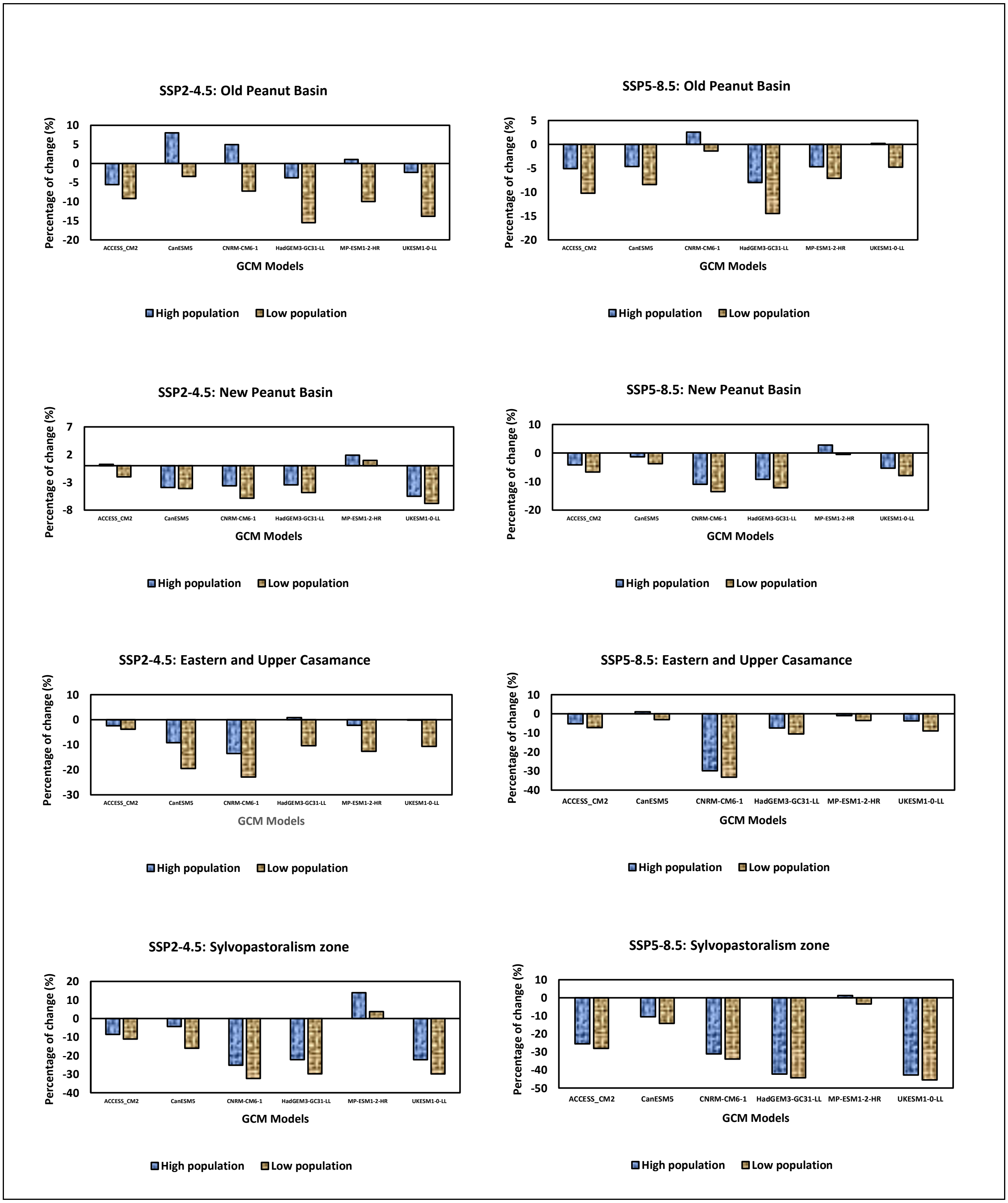


Figure 16: Change on grain yield of the two plant population densities across four agroecological zones in Senegal for the six GCMs

3.4.11.7. Projected Impacts of Climate Change on Millet Yields Across Agroecological Zones Based on Six GCM Models

Crop simulation models (CSMs) of millet yields suggest that the impacts of climate change will be predominantly negative across agroecological zones (Figure 17). In the Sylvopastoralism Zone, yield reductions are expected to be the most severe, while the impacts are moderate to slightly negative in the New Peanut Basin, Old Peanut Basin, and Eastern and Upper Casamance. These trends are consistent across all six GCMs under both SSP2 and SSP5, with varying degrees of severity.

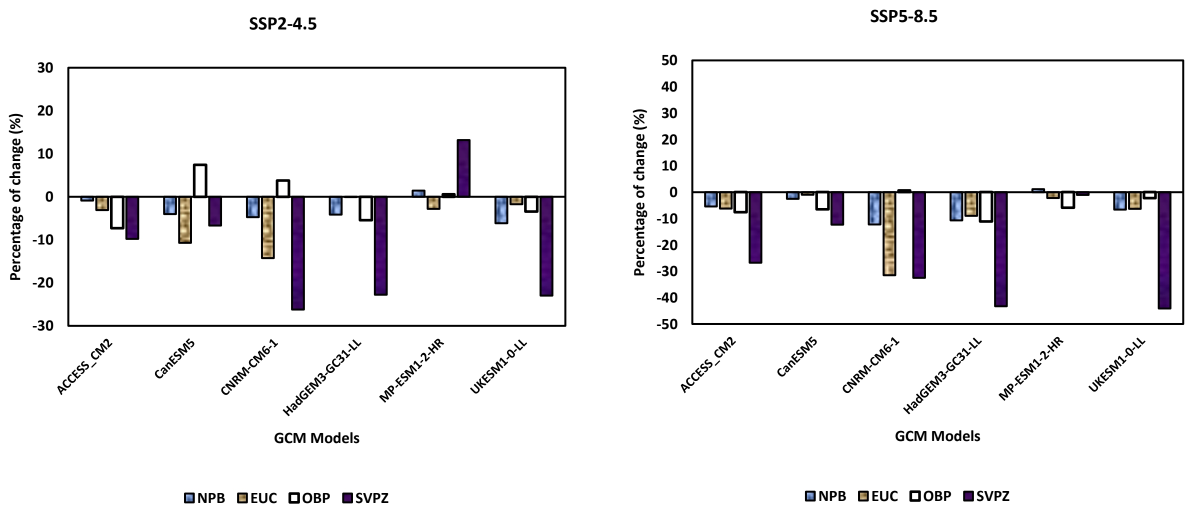


Figure 17: Change on grain yield across the four agroecological zones of Senegal for the six GCMs

3.4.11.8. Effect of Agroecological Zone, Climate Scenario, Variety, Variety type, Planting Density, and Fertilizer on Millet Grain Yield Based on ANOVA

The analysis of variance (ANOVA) revealed that factors such as Agroecological Zone (AEZ), Climate Scenario (Baseline, SSP2-4.5, SSP5-8.5), Variety, Variety Type, Planting Density, and Fertilizer had statistically significant effects on millet grain yield ($p < 0.05$) (Table 13).

Table 13: Effects of AEZ, Climate Scenario, Variety, Variety Type, Density, and Fertilizer on Millet Grain Yield

		Yield	F-value	Pr (>F)
AEZ	NPB	1604	357.09	0.001
	OPB	1278		
	EUC	1512		
	SVPZ	1200		
Variety	SL 28	1423	77.04	0.001
	SL 423	1506		
	Souna 3	1295		
	Thialack 2	1370		
Variety Type	Dual-purpose	1433	7.64	0.005
	Improved local	1295		
Density	High population	1471	196.59	0.001
	Low population	1329		
Fertilizer	F1	1798	778.31	0.001
	F2	1843		
	F3	1140		
	F4	739		
Climate	Baseline	1483	98.02	0.001
	SSP2-4.5	1403		
	SSP5-8.5	1310		

Signif. codes: ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05, ns; NPW: New Peanut Basin, OPB: Old Peanut Basin, EUC: Eastern and Upper Casamance, SVPZ: Sylvopastoralism Zone

Table 14 further analyzes the interaction of factors such as AEZ, Variety, Variety type, plant density, and micro-dosing fertilizer strategies with climate scenarios. The results reveal a significant interaction effect between AEZ and climate scenarios. It also demonstrates a notable impact of micro-dosing fertilizer strategies and climate scenarios ($P < 0.05$).

Table 14: Effects of AEZ, Variety, Variety Type, Density, and Fertilizer on Millet Grain Yield under Different Climate Scenarios

	Baseline	SSP2-4.5	SSP5-8.5
AEZ			
NPB	1654	1603	1554
OPB	1305	1295	1234
EUC	1590	1505	1441
SVPZ	1382	1207	1012
P-value		***	
Variety			
SL 28	1508	1430	1331
SL 423	1613	1517	1387
Souna 3	1360	1296	1231
Thialack 2	1451	1368	1292
P-value		ns	
Variety Type			
Dual-purpose	1508	1430	1331
Improved local	1475	1393	1303
P-value		ns	
Density			
High population	1546	1477	1391
Low population	1423	1332	1233
P-value		ns	
Fertilizer			
F1	1948	1804	1642
F2	2001	1848	1681
F3	1158	1143	1120
F4	742	740	733
P-value		***	

Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05, ns; NPW: New Peanut Basin, OPB: Old Peanut Basin, EUC: Eastern and Upper Casamance, SVPZ: Sylvopastoralism Zone

3.4.11.9. Long-Term Trends and Variability in Millet Yield Projections Across Agroecological Zones Under Climate Change Scenarios

To capture long-term trends and account for variability, a 5-year moving average was applied to the millet yield data for each scenario (Baseline, SSP2-4.5, and SSP5-8.5) and compared to the baseline average for each variety across the agroecological zones (Figure 18). In the New Peanut Basin (NPB), yields are projected to decline by 3-4% under SSP2-4.5 and 4-8% under SSP5-8.5. In the Old Peanut Basin (OPB), Souna 3 remained stable compared to the baseline, while the three dual-purpose varieties are expected to decrease slightly by up to 1% under SSP2-4.5. Under SSP5-8.5, all four varieties show declines between 2% and 10%. In Eastern and Upper Casamance (EUC), Souna 3 is projected to increase slightly by 2% under SSP2-4.5, while the dual-purpose varieties are expected to decline by 4-7%. Under SSP5-8.5, all varieties are expected to decline further, with reductions ranging from 7-11%. In the Sylvopastoralism Zone (SVPZ), the impact of future climate is projected to be negative, with yield reductions of 8-15% for all varieties under SSP2-4.5. Under SSP5-8.5, the results are more variable, with Souna 3 showing a projected increase of 21%, while the dual-purpose varieties are expected to decline by 27-30%. The results also highlighted that the SVPZ is more sensitive to future climate changes for all varieties with different magnitudes. Additionally, the shading representing the 10th and 90th interquartile ranges was used to illustrate the uncertainty and spread of GCM model outputs. The ensemble median consistently indicated decreasing yields under both SSP2-4.5 and SSP5-8.5 scenarios. The extent of the interquartile shading varied across zones, reflecting differences in model variability. In the Sylvopastoralism Zone (SVPZ), the shading was the widest, indicating the greatest uncertainty in future yield projections. This zone also experienced the steepest declines in yields, particularly under SSP5-8.5, where most models projected yields well below the baseline by mid-century. The Eastern and Upper Casamance (EUC) showed similar trends, with broad shading that highlighted considerable variability in the projections, though the declines in yield were less severe compared to the SVPZ. In contrast, the New Peanut Basin (NPB) exhibited the narrowest shading, indicating lower variability among the models. While the projected declines in millet yield were less severe in the NPB compared to the SVPZ and EUC, the interquartile range still underscored notable variability in future projections. Similarly, the Old Peanut Basin (OPB) showed less dramatic declines in yields compared to the SVPZ, but the wide shading indicated significant model variability in this zone as well. These results underscore the spatial variability in millet yield responses across the different zones, with the SVPZ and EUC showing higher uncertainty and more severe declines, while the NPB and OPB displayed more moderate declines with narrower interquartile ranges.

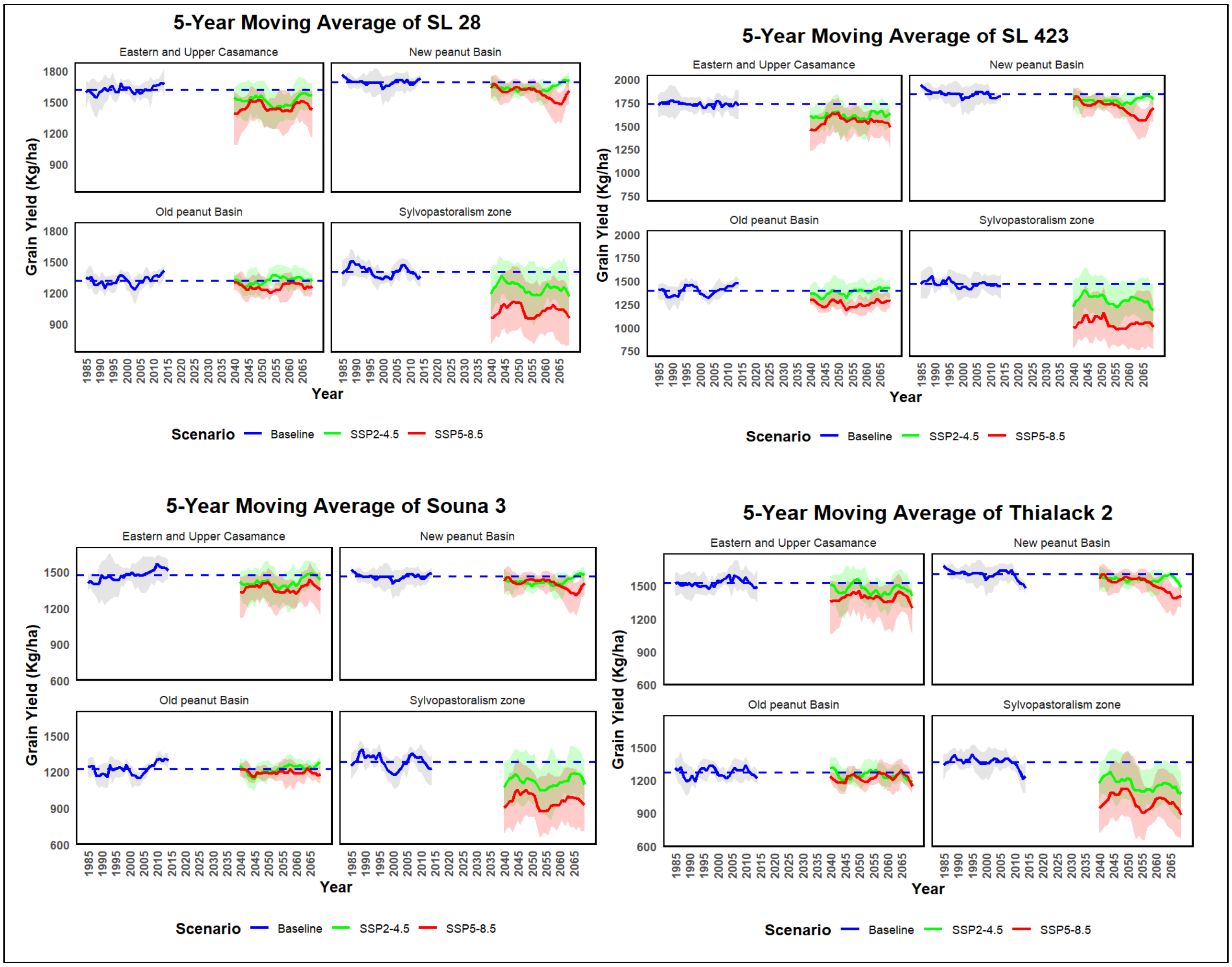


Figure 18: Evolution of the 5-year moving average of four varieties of millet yields in the four AEZs. The blue curve represents the baseline yield; the green and red curves are the yields under the SSP2-4.5 and SSP5-8.5 scenarios, respectively, and the dotted blue horizontal lines represent the average yield for the reference period 1985–2014. The shading indicates the interquartile ensemble spread of the six GCMs (range between the 10th and 90th percentiles) for baseline, SSP2-4.5, and SSP5-8.5.

3.4.11.10. Analysis of Grain Yield Performance Under Climate Scenarios and Fertilizer Strategies

The analysis of mean performance presented in Table 13 indicates that F2 achieved the highest grain yield, followed by F1, F3, and F4, across both current and future climate scenarios. Additionally, Table 14 highlights the significant interaction effect of climate scenario with Agroecological Zone (AEZ) and micro-dosing fertilizer strategies. Based on these findings, the relative change in average yield was computed and illustrated across AEZ (Figure 19). The results reveal that F1 is particularly sensitive to future climate change across AEZ, with yield declines ranging from 4% to 16% under SSP2 and from 8% to 33% under SSP5 compared to a baseline yield of 1,948 kg/ha. F2 is projected to decline by 4% to 15% under SSP2 and 9% to 32% under SSP5 relative to a baseline yield of 2,001 kg/ha. F3 shows a decrease in yields across the New Peanut Basin (NPB), Eastern and Upper Casamance (EUC), and Sylvopastoral Zone (SVPZ), with declines ranging from 1% to 8% under SSP2 and from 1% to 17% under SSP5 compared to baseline yield of 1219 kg/ha. In contrast, F3 is expected to see yield increases of up to 7% and 9% in the Old Peanut Basin (OPB) under SSP2 and SSP5, respectively, against a baseline yield of 973 kg/ha. F4 demonstrates yield declines of 1% to 5% under SSP2 in NPB, EUC, and SVPZ compared to a baseline yield of 837kg/ha, while it predicts a significant increase of 13% in OPB for the same scenario. Under SSP5, the impact is negative only in EUC and SVPZ, with declines ranging from 5% to 13%, while yields remain stable in NPB and are projected to increase by 22% in OPB.

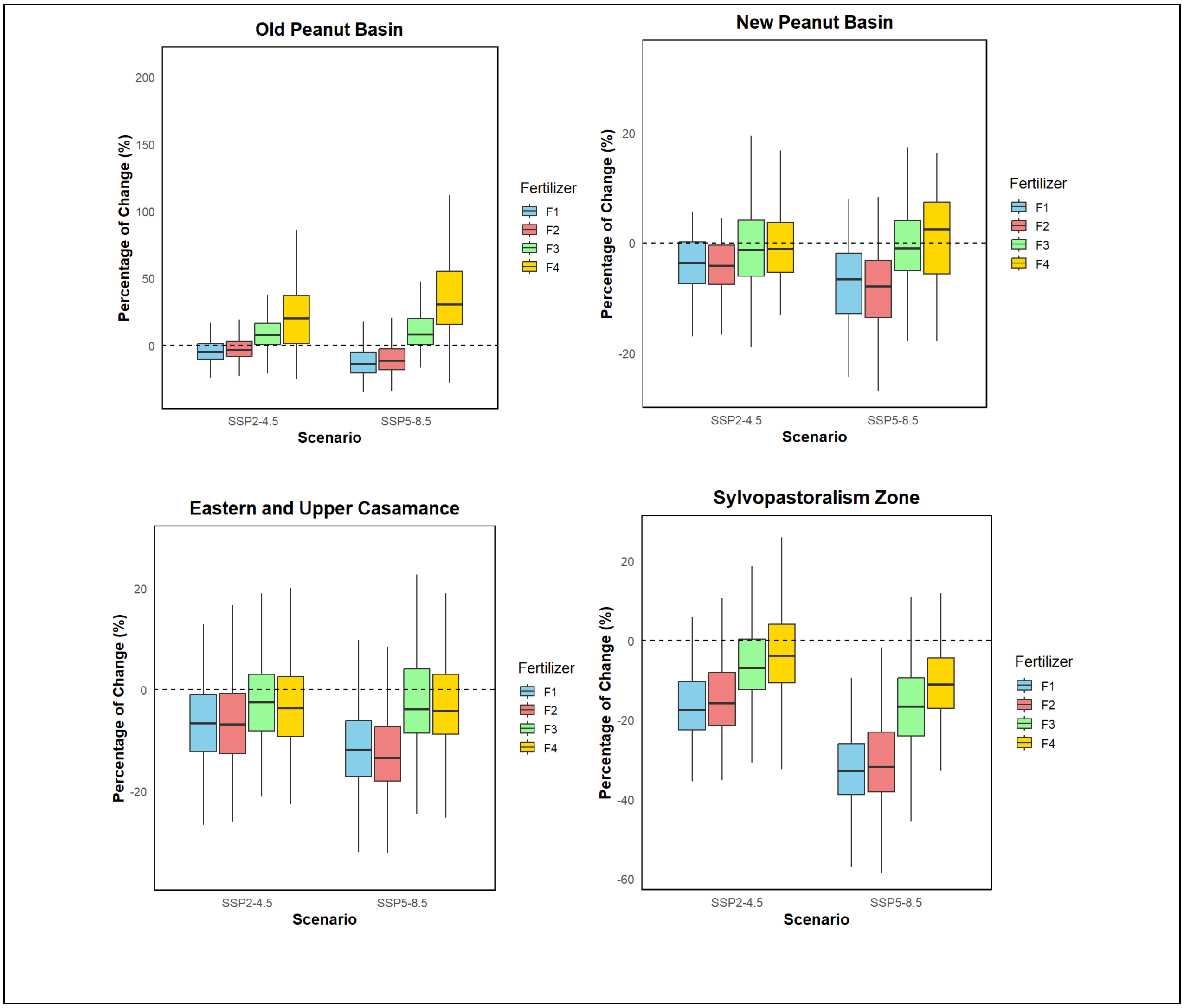


Figure 19: Yield change of micro-dosing fertilizer strategies across agroecological zones

3.4.11.11. Analysis of Grain Yield Performance Under Climate Scenarios and Plant Population

The variance analysis presented in Table 13 indicates that a high plant population significantly outperforms a low plant population in terms of grain yield ($P < 0.05$). To evaluate the impact of future climate change on these management practices, the relative changes in yields were computed and plotted. The results highlight that farmers' current planting density is more sensitive to future climate conditions than the high plant population (Figure 20). Across all agroecological zones (AEZ), the low plant population is projected to decline by 2% to 14% under SSP2, relative to a baseline yield of 1,424 kg/ha. In comparison, the high plant population is expected to decrease by 2% to 11% in the New Peanut Basin (NPB), Eastern and Upper Casamance (EUC), and

Sylvopastoral Zone (SVPZ), based on a baseline yield of 1,603 kg/ha, while remaining stable in the Old Peanut Basin (OPB) under the same scenario. Under SSP5, the low plant population is projected to decline by 7% to 28%, compared to the baseline yield of 1,424 kg/ha, while the high planting density is expected to decrease by 3% to 25% across all AEZ.

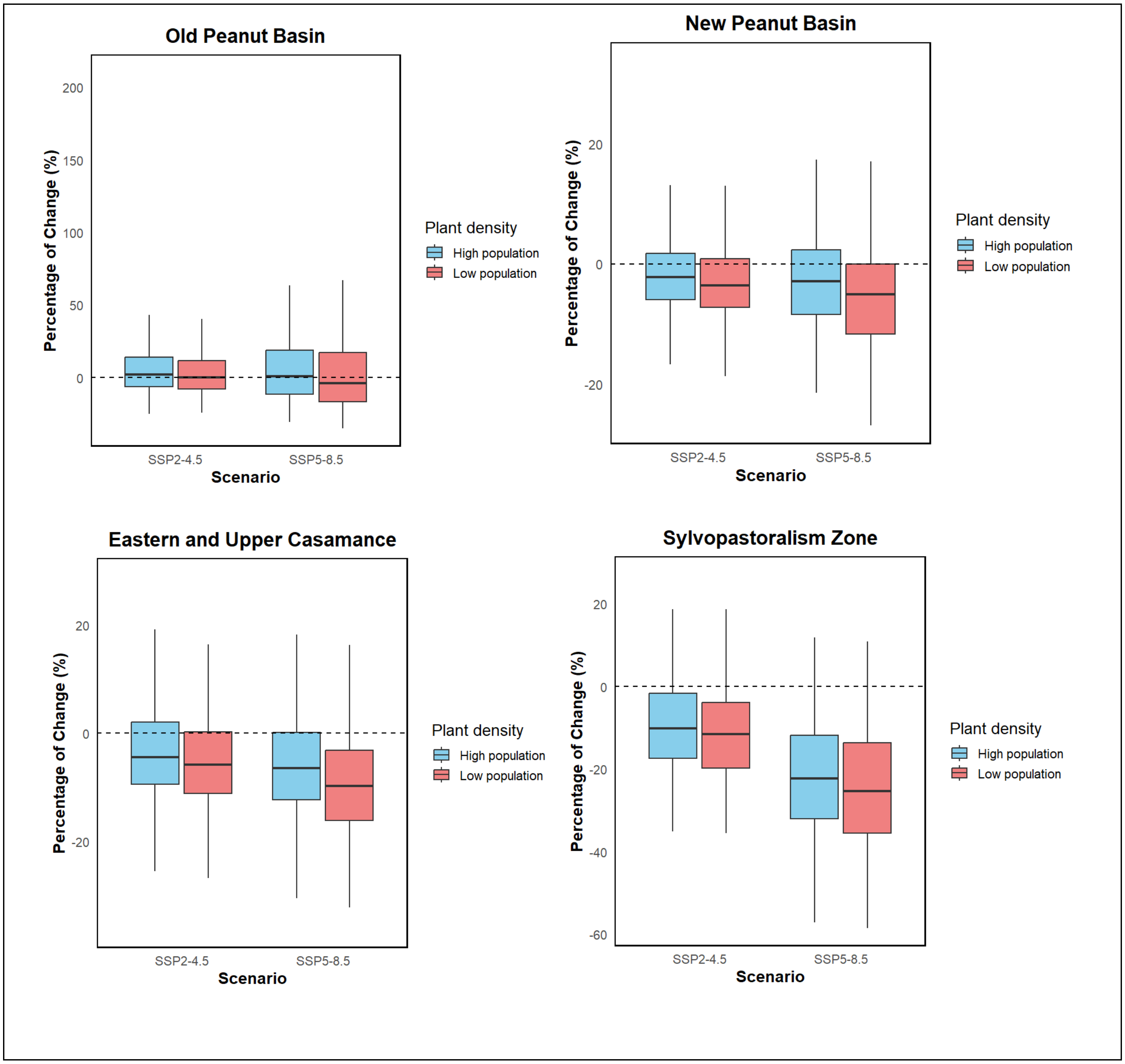


Figure 20: Yield change of plant population density across agroecological zones

3.4.11.12. Analysis of Grain Yield Performance Under Climate Scenarios and Variety Type

The results indicate that dual-purpose millet varieties significantly outperformed the local variety across all agroecological zones (AEZs) (Table 13), with a notable effect ($P<0.05$). However, these dual-purpose varieties will experience more pronounced negative impacts under future climate conditions. Figure 21 illustrates the yield decline for both variety types across AEZs, with dual-purpose varieties showing a steeper reduction. Specifically, dual-purpose varieties are expected to decline by 1 to 13% under SSP2-4.5 and by 6 to 27% under SSP5-8.5, relative to a baseline average yield of 1524 kg/ha across AEZs. In contrast, the local variety exhibits varied responses and remains stable in the Old Peanut Basin (OPB) and increases by 2% in the Eastern and Upper Casamance (EUC), but decreases by 3% in the New Peanut Basin (NPB) and by 13% in the Sylvopastoralism Zone (SVPZ) under SSP2-4.5. Under SSP5-8.5, the local variety declines across AEZs, ranging from 2 to 25%, compared to a baseline average yield of 1361 kg/ha.

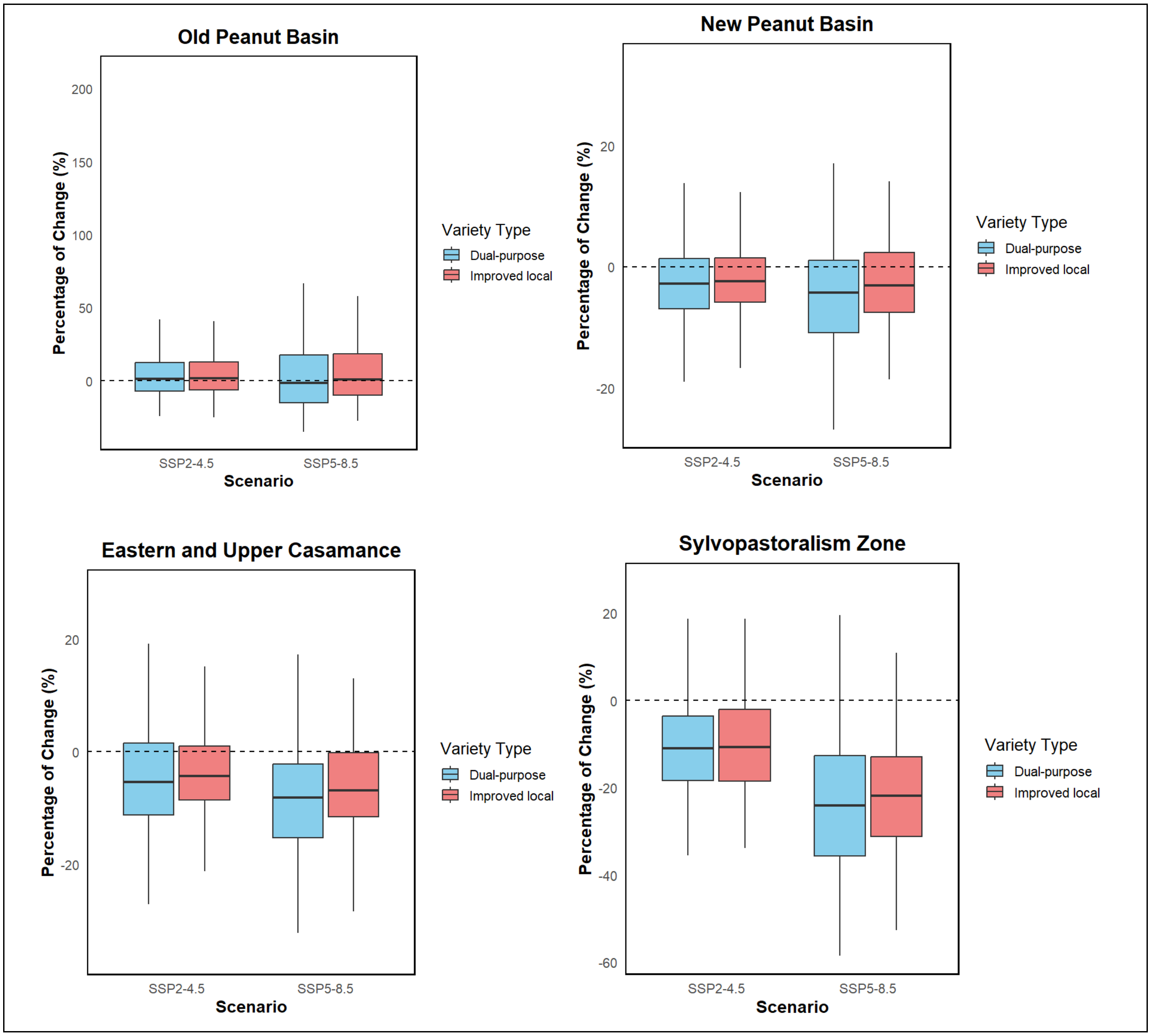


Figure 21: Yield change of variety type across agroecological zones

3.4.11.13. Response of climate-smart technology to future climate conditions

The overall assessment of climate-smart technologies, including variety selection, planting density, and fertilizer strategies used in this study, indicates a lower magnitude of change in millet population density under climate change across all agroecological zones (AEZs) (Figure 22).

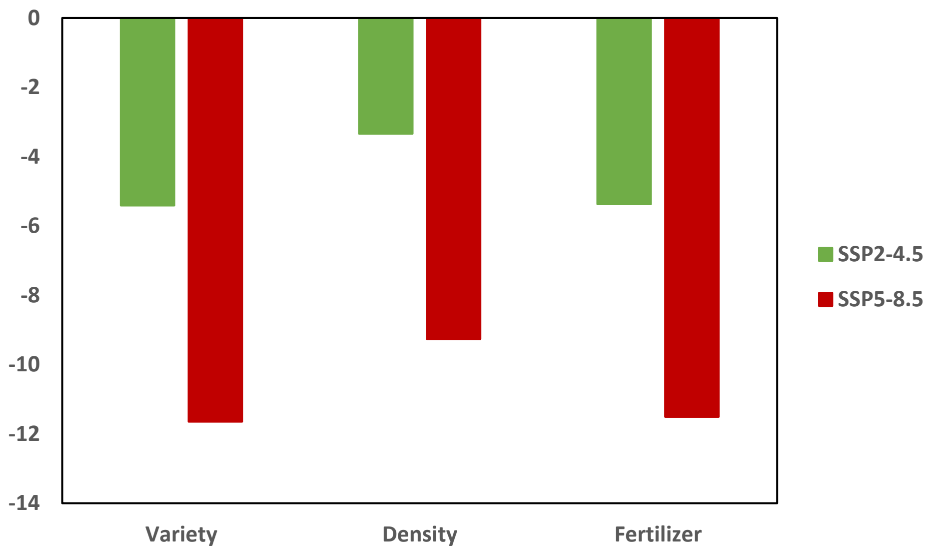


Figure 22: Change on Climate-Smart Technologies under Pearl Millet Production

4.2. DISCUSSIONS

4.2.1. Analysis of climate change perception and determinants of climate-smart technologies adoption

4.2.1.1. Farmers' perception of changes in temperature and rainfall patterns

Climate observations are reflected in survey results on how certain farmers perceive historical climatic changes. A majority (62%) of farmers in the three locations reported an increase in rainfall. This increase has been attributed to a higher frequency of heavy rain days (HRD) across the study areas. Similarly, Ibrahim et al. (2012) projected a 15% increase in intense rainfall events, while Toukal Assoumana et al. (2016) and Traore et al. (2013) observed slight rainfall increases in Niger and Mali, respectively. This finding highlighted that in Sahel zones, the key constraint of farmers is not usually the amount of rainfall declining over time, but rather the great year-to-year unpredictability of rainfall in this area (Traore et al., 2013; Akinseye et al., 2016). Earlier research has demonstrated that the Sahelian zone recorded a high degree of rainfall variability (Akinseye et al., 2013, 2016). This indicates that one of the major challenges that is becoming increasingly evident in the Sahelian zone and harms agriculture, and livestock systems is rainfall variability. Additionally, the findings indicated that farmers have a proper awareness of when the cropping season begins and ends. In the study areas, 68% of farmers felt that the rainy season had been delayed. This result was supported by the finding of Zagre et al. (2024) confirmed a shortage of growing seasons over the past 41 years. Toukal Assoumana et al. (2016), and Traore et al. (2014) also supported that farmer in Niger and Mali acknowledged a delayed start and an early cessation of the rainy season. Farmers agreed with an increase in temperature in the areas of Daga Birame, Thiel, and Meouane by 92%, 98%, and 67%, respectively. Sub-Saharan Africa, which already has a severely damaged ecosystem, is predicted to see a temperature increase that is 1.5 times greater than the global average, according to Debonne and Hillerbrand (2019). The analyses of six GCM models from the study areas confirm that statement. All six GCMs exhibited an increase in minimum and maximum temperature under SSP2-4.5 and SSP5-8.5 by mid-century compared to the baseline. Almazroui et al. (2020) confirmed projected warming values for the near and long-term periods in mean annual temperature over West Africa under SSP1-2.6, SSP2-4.5, and SSP5-

8.5. In that line, Gadédjisso-Tossou (2015) and Traore et al. (2014) also show the accurate perception of temperature trends in Togo and Mali, respectively.

4.2.1.2. Farmer’s perception of weather anomalies' impact on crop and livestock production and coping measures

In the mid-21st century, climate change is expected to reduce average crop yields by 22% across Sub-Saharan Africa, which could threaten food security in low-income and agriculture-based economies (IPCC, 2014). To assess farmers’ awareness of climate impacts on agricultural systems, this study incorporated primary meteorological anomalies previously identified in the Sahelian region (Traore et al., 2014). The survey has further highlighted those farmers perceive most of the impact of weather anomalies on crop and livestock systems. This is consistent with (Traore et al., 2014), who discovered that farmers in southern Mali believe weather anomalies have an impact on crop productivity. The farmers in this survey agreed that there is a connection between weather anomalies and crop and livestock productivity. Farmers across the three locations claimed clearly that the late start and early end of the rainy season led to late sowing, which reduced yields and prevented the grain from filling up and maturing demonstrated by previous research (Bedeke et al., 2019). This can be explained, probably by the lack of moisture during the grain filling and maturation phases (Sultan et al., 2005). The regional monsoon tends to strengthen the link between water supply and plant water use, possibly leading to increased crop water demand (Sultan et al., 2005). Several studies on the effects of climate variability on crop production have shown that irregular rainfall distributions may subject the crop to a variety of mild to severe intra-seasonal water stresses, which could then affect the yield, especially during the crucial stages of flowering and grain-filling (Akinseye et al., 2012, 2016, 2023; Traore et al., 2014). The best sowing window is one of the key aspects of avoiding yield loss. They also raised that different weather anomalies mentioned in Table 7 led either to crop or livestock loss which is in line with the IPCC (2014) forecast that by 2050, crop and fodder growing seasons in Western Africa may be shortened by an average of 20%, leading to a 40% reduction in grain yields and biomass for livestock. Moreover, Mohamed et al. (2023) predicted that the impacts of sowing dates on production could lead to millet yield reductions of up to 50% in the Sahel zone. In addition to animal illnesses and water scarcity, warming trends are one of the factors contributing to increased damage to livestock farms in the Sahelian region (Sylla et al., 2018; Traore and Owiyo, 2013). Furthermore, Rhodes et al.

(2014) emphasized that the intensity and distribution of animal diseases, changes in pasture yield, changes in plant species composition, and changes in water availability are all likely to have a significant influence on livestock. Smallholder farmers should be motivated to adopt climate-smart management strategies to deal with the effects by having a proper understanding of rainfall unpredictability and temperature increase, which are the key constraints in the Sahelian zone (Akinseye et al., 2012).

4.2.1.3. Adaptation measures across smallholder farmers

Our study revealed the potential of several adaptive strategies to deal with the weather's unpredictability across three rainfall gradients, farmers agreed that rotation with leguminous crops is a frequent practice. This is consistent with previous studies (Araya et al., 2022; Vieira Junior et al., 2023) which highlighted that the Senegal cropping system is dominated by monocropping with rotation from one year to another. Their rotation cropping system is dominated by the groundnut-millet and millet-cowpea cycle with groundnuts often occupying a larger area (Adiku et al., 2015; Faye et al., 2018; Housseini Malam Laminou et al., 2020; Salack et al., 2011). They also mentioned that crop diversification, using an improved variety, shifting the planting date, and Farmer Management Natural Regeneration (FMNR) are their main coping strategies. Previous research has demonstrated that these practices were mostly employed in the Sahelian region to mitigate the consequences of climate variability and change (Akponikpè et al., 2010; Danso et al., 2018; Rhodes et al., 2014). The Farmer Management Natural Regeneration (FMNR) which refers to the agroforestry system to restore the land degraded was mainly used in Meaoune located in the old peanut basin. The land is more degraded in this part than in the new peanut basin, Daga Birame, and the agro-pastoralism zone (Thiel). Also, the Meouane location recorded less average amount of rainfall compared two others. In fact, by doing FMNR, contributes more to restoring degraded land and establishing a favorable micro-climate which can reduce the effects of climate change such as temperature increase. The result showed that across the rainfall, there is still more effort to do since the uptake of smart fertility management practices such as the use of organic manure. This might be due to a lack of input for composting since crop residues are mostly used in those areas to feed animals. Therefore, using more rotation with leguminous across the three rainfall gradients demonstrates that this practice is mainly used by farmers in those areas to cope with soil fertility depletion. On the other hand, the high percentage of farmers who use improved varieties and change the planting date depending on the rainy season pattern emphasizes their understanding and capacity across the rainfall gradient to cope with climate variability and change. However, regarding the rainwater harvesting practices such as runoff collect basin, half-moon, and *zai*, which are common in the Sahel zone, the results revealed that those practices are underscored across the three locations where the study was carried out. Indeed, (Faye et al., 2022) have mentioned that the rainwater harvest practices that are common in Sahel countries are not observable everywhere in Senegal. This deficiency may stem from the prevalent soil's sandy texture, which is not favorable to those practices (Zougmoré et al., 2014) due to the low capacity of water holding (Fatondji et al., 2012). According to that, Yameogo et al. (2011) emphasized that the soil type is a required condition for the success of rainwater harvest practices. They added that practices such as half-moon and *zai* practices are suitable in crusted soil which can explain why the farmers have not claimed these practices. Hence, it can also be due to a lack of knowledge related to rainwater harvesting techniques. Hence, the overall results revealed that smallholder farmers have real knowledge about the state of their environment, which could be an opportunity to strengthen their resilience to climate effects through participatory actions.

4.2.1.4. Socio-economic and Institutional Influence on Smallholder Farmers' Perception and Smart Management Practices Adoption

Interventions for accelerating adaptation on a community scale are primarily influenced by socio-economic and institutional factors (Tesfaye et al., 2019). On the other hand, the findings indicate that some of the socioeconomic and institutional variables mentioned in this study had an impact on farmers' perceptions of climate change, their ability to implement improved varieties as a climate-smart management strategy, and their capacity to modify crop operations during the growing season. As expected, having access to credit considerably increases the possibility of improved variety adoption as a climate-smart management practice across the three locations. These results support the findings of Bedeke et al. (2019), Fonta et al. (2018), and Diallo et al. (2020), who discovered that having access to finance increases the likelihood of coping with climate change. Access to financing should be the best option to assist the poorest farmers in making investments in their fields to combat climate variability, increase crop yield, and guarantee food security. By 2030, developing countries' adaptation costs are predicted to reach up to US$ 340 billion annually, according to IFAD (2021). In this report, the annual cost of mitigation might reach US$ 850 billion. This IFAD study highlights the value of funding at the national, regional, and local levels for least-developed countries to deal with the effects of climate change effectively. This explains that access to credit as an expectation might increase farmers’ capacity to adopt improved varieties as a smart technology in this study. Therefore, sustainable financial resources and investments are required to increase farmers' adaptability to climate change. According to Rhodes et al. (2014), the impact of climate change is lessened by factors including access to land, resources, financing, and markets, which emphasizes the importance of learning more about socioeconomic and institutional aspects in coping with climate change. They were statistically more likely to adopt improved variety as a climate-smart management strategy if they had access to extension services. This result adds to the evidence that getting assistance from extension agents promotes the adoption of adaptation strategies to increase crop production in response to the effects of climate change (Theriault et al., 2017). This is consistent with earlier research (Bedeke et al., 2019; Gebru et al., 2020; Ngigi et al., 2017) that found farmers' access to extension services significantly increases their awareness of cropping technology packages. According to our expectations, farmers' perceptions of the severity of their farmland erosion reduce the likelihood of using improved varieties as climate-smart management practices. Indeed, several studies (Harr et al., 2014; Jamala et al., 2021; Mwase et al., 2015) have shown that in the Sahel region, farmers typically prefer to keep their land in a fallow system for a while when they notice how severely their land is eroding. Then, until soil fertility is restored, they make fewer investments in this degraded property. When farmers perceive advanced erosion of farms, this should be the main factor explaining the negative impact of climate-smart management practice uptake in this study. Therefore, the model showed that farmers' ability to change crop operations during the growing season, when they have a good knowledge of farmland erosion, can still be a smart practice. Crop operation adjustments during the growing season are more likely when a farmer has more experience**.** Experienced farmers are more likely to adjust crop operations during the growing season to deal with climate effects like dry spells in the study location. These findings support those of Ibitoye (2011), Yegbemey et al. (2014), Gadédjisso-Tossou (2015), and Fonta et al. (2018), who have underlined the importance of farming experience in coping with climate unpredictability. This demonstrates that a farmer's ability to adapt to climate unpredictability and change is greatly influenced by their level of agricultural experience. Many contacts with extension agents raise the likelihood of adopting improved variety as a climate-smart management practice.

Farmers' awareness and the frequency of extension agent visits increase their ability to use the innovation packages and success (Yegbemey et al., 2014). One of the key elements that can increase farmers' knowledge and capacity to use smart management technology is frequent contact with extension agents. According to Partey et al. (2020), crop management would benefit from extension partnerships in the creation and national service of early warning systems and the continued refinement of the current climate projections, resulting in information that is useful for nearby farmers. Ngigi et al. (2017) have found that the adoption of innovation packages is improved in Kenya by the number of farm visits by extension agents. The findings indicate that the improved variety's adoption as a climate-smart management strategy was adversely impacted by the farmer's distance to the extension office. Kassa (2013) discovered that distance is a factor that negatively affects how innovation packages are adopted, which is consistent with our findings. Farmers are expected to make the adoption of the measures easier since they trust extension agents to promote climate change adaptation (Bedeke et al., 2019). As a result, farmers' capacity for adaptability may be lowered by the distance, preventing extension agents from visiting them as frequently during the growing season. Toukal Assoumana et al. (2016) indicated in the prior study that farmers had a poor ability to adjust to climate variability due to a lack of help from extension services, which corroborates that distance has a negative effect in this study. Additionally, access to government subsidies raises the likelihood that farmers will adopt improved varieties as a climate-smart management practice and have a more positive attitude toward climate change. Crop inputs like improved varieties, fertilizer, climate service information, etc., are the major factors that allow farmers to realize the accuracy of innovation packages, which are the main targets of government subsidies. In such instances, government subsidies are a factor that boosts farmers' confidence in innovation packages and their uptake. By supplying enough information and relevant experience regarding the negative effects of climate change, this confidence increases farmers' and extension workers' capacity to employ adaptation measures (Bedeke et al., 2019). The rainfall gradient (study location) positively influenced farmers' decisions to adjust their crop operations. This can be explained by the different magnitudes between the three locations in terms of onset, cessation, and length of the rainy season emphasized by Zagre et al. (2024). This implies that the variability of the rainy season across the three locations led farmers to adjust crop operations, which emphasizes their good perception of climate indicators shown in Table 3. Therefore, for smallholder farming systems, climate information services (CIS) are still very useful (Ramaraj et al., 2023; Zougmoré et al., 2014) to enhance their resilience vis-à-vis climate effects. Gadédjisso-Tossou (2015) discovered that the usage of short-duration varieties and changes in planting dates were both influenced by climate information for farmers in Togo. In Senegal, the national meteorological agency and many projects have worked great to release CIS close to the community. The results show that climate-based agro advisory was implemented within many communities in Senegal through the platform via Short Message Service (SMS) and voice messages in different local languages. So, this could be the main reason that the climate information service did not influence farmers' decisions in this study, since they are already well-informed about climate information which might reduce the variability of decisions taken from one farmer to another within the community.

4.3. Analysis of climate-smart management practices performance on Pearl millet stover and grain yields

The evaluation types of variety such as dual-purpose and farmers-improved local show that dual-purpose outperformed grain and stover yields across experimental trials at farmer and cluster scales (Tables 10 and 11). This justifies that dual-purpose millet varieties have been chosen to generate high-quality fodder without compromising grain production (Faye et al., 2023; Tounkara et al., 2020). The grain yield increased by 37% in Thiel, 15 % in Meouane, and 8% in Daga Birame for dual-purpose than the improved local variety. These results are in line with Faye et al. (2023) who found the improved local variety to be lower yielding compared to dual-purpose millet varieties in several environments of Senegal. Furthermore, the WUE and HI of dual-purpose variety recorded slightly greater values compared to improved local.

Micro-dosing fertilizer strategies, as climate-smart management practices, significantly impacted grain yield across all three sites and also influenced stover yield and HI in Daga Birame and Meouane. Tounkara et al. (2023) also highlighted how the use of micro-dosing technology increased grain yield in Senegal by 62% when compared to farmers' practices and by 148% when compared to the control group. Badiane et al. (2001) underlined that in Senegal's semi-arid agroecological zone, millet output significantly increased when farmers applied both mineral and organic fertilizers. They further highlighted that the efficiency of the fertilizer applied was better with the micro-dosing technology than with the recommended rate. Indeed, Hayashi et al. (2008) noted that the application of micro-dosing alone increases millet yield by 56% above the control.

But combining with crop residue or manure increased millet grain yield to 140% over the control. These results can explain the importance of combining organic and inorganic fertilizers in micro-dosing technology. Smallholder farmers often cannot afford the recommended rates of mineral fertilizers (150 kg/ha of NPK and 100 kg/ha of urea) and organic manure (5 tons/ha). Consequently, adopting micro-dosing practices using the targeted rates implemented in this study presents a viable alternative that can help reduce yield gaps and increase the availability of fodder for livestock.

Besides, improving the plant population to 25,000 hills/ha outperformed the farmers' planting density with a significant effect on grain and stover yields. The improved plant population further significantly affects the WUE compared to farmers' practices (Figure 8). The grain yield was increased by 53% in Daga Birame, 51% in Meouane, and 56% in Thiel for improved density compared to farmers' practices (low density). Also, the stover was increased by 55%, 62%, and 64% across the locations. The great performance associated with improved plant density illustrates the importance of optimizing planting density as a smart agricultural practice to enhance yields. This is in line with Faye et al. (2023) and Pilloni et al. (2022) who found that increasing the plant density to 25,000 hills ha^{-1} significantly enhances millet fodder and grain yield in India and Senegal. The performance of high density can likely be attributed to the good vegetation cover associated with higher plant populations, which could reduce evapotranspiration and keep more soil moisture. This finding also aligns with research by Lecina et al., (2003) who emphasized the role of canopy architecture in influencing WUE by moderating soil evaporation. Additionally, Pilloni et al. (2022) found that higher plant densities in semi-arid regions of Senegal and India enhanced WUE due to reduced soil evaporation and increased transpiration efficiency among crops.

4.4. DSSAT's CERES-Millet Model performance for Millet cultivars prediction

The strong agreement between simulated and observed phenological data for anthesis and maturity across four contrasting environments and cultivars highlights the robustness of the CERES-Millet model within the Decision Support System for Agrotechnology Transfer (DSSAT) framework. The application of the CERES-Millet model of DSSAT for simulating millet varieties under varying conditions underscores the value of modeling approaches in understanding and predicting crop performance (Mohamed et al., 2023). Statistical indices, including lower Root Mean Square Error (RMSE) and a good coefficient of agreement (d-index), ranging from 0.52 to 0.91 for anthesis and from 0.80 to 0.86 for maturity date, highlight the model's capability to accurately predict phenological stages under varying environmental conditions which is in line with Garba et al. (2024) who also found a good agreement for phenological parameters of millet across two agroecological zones in Niger. This further aligns with findings from previous studies such as those by Soler et al. (2008) and Ullah et al. (2019), emphasizing the model's adaptability across arid and semi-arid climates for crops such as millet. Furthermore, Akinseye et al. (2017), Tovihoudji et al. (2019), and Ullah et al. (2019) have proven that DSSAT has the potential to simulate phenology reasonably well under semi-arid climatic conditions respectively under sorghum, maize, and millet production.

Moreover, the CERES-Millet model demonstrates its proficiency in simulating crop growth parameters, notably the Leaf Area Index (LAI) and leaf number, with statistical indices indicating a good agreement coefficient ranging from 0.62 to 0.85 and 0.75 to 0.8 respectively. Jones et al. (2003) extended these findings by demonstrating the model's applicability in simulating crop growth and development in semi-arid zones, applicable to both monoculture and intercrop systems. Therefore, the model overestimated LAI for the three dual-purpose varieties (SL 28, SL 423, and Thialack 2) except for the farmer common local variety (Souna 3). This is in line with Fechter et al. (1991) who found that CERES-Millet model overestimated leaf area index LAI by 46%. Additionally, the model exhibited good agreement for Above Ground Biomass (AGB) and grain yield predictions, with d-index values ranging from 0.83 to 0.98 for AGB and 0.64 to 0.97 for grain yield, alongside lower RMSE values (Table 12). This suggests the model's effectiveness across different planting densities and environmental contrasts as also mentioned by Garba et al. (2024). Ullah et al. (2019) highlighted the model's success in simulating plant density and nitrogen application effects in arid and semi-arid conditions in Pakistan, while Soler et al. (2008) noted the CSM–CERES-Millet model's accuracy in simulating growth, development, and yield for millet in two contrasting environments. White et al. (2015) also reported favorable outcomes for maximum LAI, AGB, and grain yield simulations under the CERES–Sorghum model. Furthermore, the model effectively evaluated AGB and grain yield across different micro-dosing organo-mineral fertilizer levels at the farm scale, with lower RMSE values ranging from 281 to 789 kg ha^{-1} and 144 to 332 kg ha^{-1} (Figure 9). These findings underscore the model's utility in accurately simulating crop growth dynamics across various agronomic conditions. Specifically, the DSSAT's ability to accurately simulate AGB and grain yield at the farm scale, particularly with micro-dosing strategies, presents a valuable tool for decision-making of the four varieties in semi-arid regions of Senegal, and potentially beyond. The analysis of long-term weather information highlights significant year-to-year variability in rainfall across the clusters, which can have implications for agricultural productivity. The observed trends in increased rainfall and the negative correlation between the onset and length of the growing season offer valuable insights into the most important factors that control a longer growing season (Akinseye et al., 2017).

4.5. Future climate trend across agroecological zones of Senegal

The results reveal significant variability in projected precipitation across agroecological zones (Figure 10), which will directly affect agricultural productivity, particularly in rain-fed systems. The average output of six GCM models projected a decline in all four AEZs with different magnitudes in precipitation, particularly under SSP5-8.5, with reductions reaching up to 25%. This decrease could exacerbate water scarcity, increase the need for drought-tolerant crops, and initiate timely adjustments in planting seasons to align with rainfall patterns. These findings align with projections indicating increased drought risks across the Sub-Saharan Africa (SSA) region under high-emission scenarios (Adiku et al., 2015; Almazroui et al., 2020; Kouman et al., 2024; Shiru and Chung, 2021). Such variability will likely have wide-ranging impacts on agricultural systems, emphasizing the need for adaptive strategies tailored to specific zones. Furthermore, the results indicate notable variability, with some agroecological zones experiencing delayed onsets and shorter rainy seasons ranging from 3 to 19 days, especially in NPB, EUC, and SVPZ, while OPB may see marginally longer seasons ranging from 1 to 4 days under both scenarios by the mid-century (Figure 13). The decrease in the length of the rainy season poses challenges for crop maturity, potentially leading to lower yields. This trend aligns with early studies (Akinseye et al., 2016, 2023; Gbode et al., 2022; Sylla et al., 2018; Traore et al., 2014) in the West African region, where delayed rains have been linked to lower productivity and increased food insecurity under future climate scenarios. The differences in projected rainy season changes between agroecological zones also emphasize the importance of localized climate adaptation policies that reflect the distinct vulnerabilities of each region.

Regarding the projected temperature anomalies across Senegal's targeted agroecological zones, the results revealed an increase of both maximum and minimum temperatures by mid-century under both SSP2-4.5 and SSP5-8.5 scenarios (Figures 11 and 12). These substantial temperature rises will likely exacerbate heat stress since agricultural and livestock systems are heavily dependent on climate-sensitive processes. This agrees with the study of Adiku et al. (2015) and Kouman et al. (2024) mentioned the warm trend for maximum and minimum temperature in West Africa using respectively CMIP5 and CMIP6 GCM models. Almazroui et al. (2020) also highlighted that employing 27 GCM models of CMIP6, the projected warming temperature value over West Africa would be 1.4 and 1.7 degrees Celsius for the near term, 2.4 degrees Celsius for the long term, and 4.2 degrees Celsius for the long term. These warming projections underscore the importance of developing climate adaptation strategies, such as heat-tolerant crop varieties and water harvest techniques, to mitigate the anticipated negative impacts on agriculture and food security. Moreover, the range of projected temperature increases across different models highlights the uncertainty in climate outcomes and the need for flexible, region-specific adaptation measures (Wada et al., 2022).

4.6. Climate-smart management practices Adaptation options

Pearl Millet has been recognized as one of the smart crops that thrive in challenging environmental conditions in arid and semi-arid zones across the world (Ullah et al., 2017; Uppal et al., 2015). However, climate variability and change impact productivity in Sub-Saharan Africa (SSA) and smallholder farmers' livelihoods and incomes (Faye, et al., 2022; Sultan et al., 2023). To address these challenges, our study focused on evaluating the effectiveness of climate-smart management practices for pearl millet production. Analysis of the model's simulation output emphasized the good performance of these practices for current and future climate conditions. Our results indicate that micro-dosing fertilizer strategies, particularly Senegal's recommended mineral rates combined with 2.5 tons of organic manure (F2) and recommended mineral rates sole (F1), exhibited the best yield performance across agroecological zones (AEZs) under both current and future climates (Table 13). Notably, the impact of fertilizer application was statistically significant across all AEZs studied. These findings align with research conducted by Tabo et al. (2007), Vanlauwe et al. (2015), and Akinseye et al. (2023) who found that micro-dosing fertilizer significantly improved crop yields in West Africa. Additionally, we observed that increasing plant population density to

25,000 hills per hectare outperformed the traditional farmer practice of lower-density planting (12,500 hills/ha). This improvement was consistent across all AEZs under both current and projected future climates, with the difference being statistically significant. Our results support the findings of a study by Pilloni et al. (2022), which demonstrated that optimized plant spacing can lead to increased millet yields in various environments, including Senegal. Furthermore, dual-purpose varieties showed consistently good performance across AEZs compared to local farmers' varieties under both current and future climatic conditions. This observation is consistent with research by Sanou et al. (2016), which highlighted the potential benefits of dual-purpose crops in improving food security and livestock productivity in sub-Saharan Africa. Importantly, our long-term seasonal simulation outputs corroborated the results obtained from two-year experimental trials published by Zagre et al. (2025), reinforcing the effectiveness of micro-dosing fertilizer strategies, improved plant population densities, and dual-purpose varieties across the study areas. These findings are also supported by a comprehensive climate risk assessment study conducted by Zagre et al. (2025), which emphasized the sustained performance of these agricultural practices under current climate conditions.

4.7. Future climate impacts vis-à-vis climate-smart management strategies

The projected millet yield responses across Senegal's agroecological zones highlight the variability of climate change impacts on crop production. This climate impact variability across the agroecological zones corroborates with studies (Ibrahim et al., 2014; Müller et al., 2011; Schlenker and Lobell, 2010; van Oort and Zwart, 2018) that emphasized the high variability effect of climate change on temporal and spatial scales in Sub-Sahara Africa (SSA). Indeed, the six GCM models project divergent trends, particularly between the SSP2-4.5 and SSP5-8.5 scenarios across different agroecological zones, underscoring the localized nature of climate change impacts on agricultural systems. The average output of GCM models indicates expected moderate to slightly negative yield impacts on pearl millet varieties' grain yield in the Old Peanut Basin (OPB), potentially linked to earlier rainfall onset and increased rainfall predicted in this AEZ. In dryland agricultural systems, the onset and the length of the growing season are a key parameter that impacts crop productivity (Akinseye et al., 2016, 2023; Kamara et al., 2023; Soler et al., 2008). Sylla et al. (2018) also mentioned that delayed rains have been linked to lower productivity and increased food insecurity under future climate scenarios in the West African region. At the same time, the other AEZs such as New Peanut Basin (NPB), Eastern and Upper Casamance (EUC), and Sylvopastoralism Zone (SVPZ) exhibited a notable decline in grain yield. The SVPZ presents a more challenging scenario, with most models projecting yield declines for all varieties (Figure 14). The significant reduction in yield for most varieties under the high-emission scenario highlights the vulnerability of this AEZ to the combined effects of increased CO_2 and heat stress, reduced rainfall up to 25%, and a shorter growing season (up to 19 days) highlighted by climate parameters analysis by the mid-century mentioned above. This AEZ, heavily dependent on millet and livestock, may require more transformative adaptation strategies, such as integrating sustainable water management practices to ensure long-term food security. In the NPB, the impacts of climate change are projected to be moderate but still negative. While the yield declines are not as drastic as in the SVPZ, they remain a concern, particularly under SSP5-8.5, where increased temperatures and more pronounced rainfall variability could further reduce millet productivity. This aligns with the projected climate trends for this AEZ, which indicate a shorter rainy season and a reduced growing period for millet by mid-century. These changes can delay the planting window and subsequently affect yield (Akinseye et al., 2016; Joseph et al., 2023). For EUC, while the AEZ is projected to maintain relatively favorable growing conditions compared to other zones, climate change will still exert negative pressure on millet yields. The GCM models indicated slight declines under both SSP scenarios, though the impact is less pronounced here due to the region's relatively higher rainfall and better soil fertility. Nevertheless, the projected temperature increases and rainfall variability still pose challenges for sustaining millet yields in the long-term period. Furthermore, the application of a 5-year moving average to millet yield (Figure 18) across climate scenarios (Baseline, SSP2-4.5, and SSP5-8.5) highlights long-term negative trends and the variability in yield projections across the four AEZs. These trends illustrate a generally negative outlook under future climate scenarios, with yield declines more pronounced under the more extreme SSP5-8.5 scenario. Moreover, using interquartile shading (representing the 10th to 90th percentile range) helps illustrate the variability and uncertainty in the six model outputs. The wide interquartile ranges in SVPZ and EUC indicate significant variability between GCM model projections, underscoring the challenges in accurately predicting future yield outcomes. The ensemble median consistently showed declining trends across all AEZs, with the most dramatic decreases in the SVPZ, where the 5-year moving average indicated significant declines in yield under SSP5-8.5. In contrast, the OPB and NPB exhibited less severe declines but still showed substantial variability, as reflected in the wide interquartile range.

The results indicate that while the recommended mineral fertilizer rate (F1) and the combination of mineral fertilizer recommended rate with 2.5 tons/ha of cow manure (F2) perform well compared to the other doses (F3 and F4), they are more sensitive to future climate conditions across all AEZs (Figure 19). Notably, F4, which combines a lower mineral fertilizer (75kg/ha of NPK) rate with 2.5 tons/ha of cow manure, demonstrated greater resilience to future climate conditions, followed by F3 (75kg/ha of NPK and 50kg/ha of Urea with 1.25 tons/ha of manure). The sole micro-dosing mineral fertilizer application (F1) is the most sensitive to future climate impacts compared to the three other organo-mineral fertilizers. This finding supports the idea that the sole application of mineral fertilizer cannot be a sustainable approach in the dryland agriculture system under changing climatic conditions. This is in line with Zagre et al. (2025) who already emphasized that the sole mineral fertilizer strategy exhibited high year-to-year yield variability compared to the organo-mineral fertilizer strategy. This suggests that organo-mineral fertilizer strategies may help mitigate the adverse effects of climate stressors such as increased temperatures or shifting rainfall patterns. The enhanced nutrient availability and soil health maintenance provided by organic amendments can enable crops to better endure water stress and other environmental challenges (Ochieng' et al., 2023; Ranjan et al., 2023). Indeed, regular application of organic manure has been shown to build soil organic carbon stocks, which enhances the soil's fertility over time (Adekiya et al., 2020; Bationo and Buerkert, 2001). The incorporation of organic manure into soil is crucial for enhancing soil health and improving crop performance to cope with climate effects. Organic amendments improve the soil's ability to buffer against climate variability by stimulating microbial activity, which supports the breakdown of organic matter and nutrient cycling (Bekunda et al., 1997; Hayashi et al., 2008). Active soil microbial communities contribute to the development of beneficial soil properties, such as increased cation exchange capacity (CEC), that improve nutrient availability to crops like millet (Dunjana et al., 2012; Fairhurst et al., 2012). For example, organic matter can modulate soil temperature and help retain soil moisture during dry spells, which is critical for crops such as millet which are often cultivated in regions with challenging rainfall patterns (Glatzle et al., 2021; Saidia et al., 2019). These findings highlight the importance of adapting fertilizer strategies to specific agroecological conditions for improved resilience.

The analysis of millet grain yield under two plant population densities reveals a significant trend that traditional low plant populations are more vulnerable to future climate scenarios compared to higher plant populations (Figure 20). This trend is consistent across all four AEZs and is particularly pronounced under the high-emission SSP5-8.5 scenario. These findings suggest low plant density practices used currently by farmers across Senegal are especially susceptible to climate change stresses, such as increased temperatures and altered rainfall patterns. The greater yield losses observed for low plant densities likely result from limited crop coverage, which can exacerbate moisture loss and reduce the crop's ability to withstand climate variability. The consistent yield declines projected for low plant densities across most models and scenarios emphasize the need to move away from traditional practices and adopt more climate-resilient strategies such as corresponding to optimum planting density. Conversely, higher plant populations show more optimistic projections, indicating that increased planting density may mitigate certain adverse climate impacts by improving soil moisture retention and optimizing resource use. An early study by Pilloni et al. (2022) mentioned that higher planting population density at 25,000 hills/ha of pearl millet increases productivity and water use efficiency in high evaporative demand seasons in India and Senegal. This explains why high plant density is less sensitive to future climate conditions for our projection across the AEZs. This indicates that high optimum plant population densities may offer a buffer against climate stress and provide resilience (Gbode et al., 2022), particularly in specific regions and under lower-emission scenarios. The findings imply that transitioning to higher optimum planting densities could be a beneficial adaptation strategy for mitigating the impacts of climate change. These findings support the assertions of several authors (Ahmad et al., 2004; Faye et al., 2023; Mahmood et al., 2012; Pilloni et al., 2022) that sowing density is one of the critical factors for mitigating the effects of climate change in semi-arid conditions. Adjusting planting density can help crops better withstand drought stress and improve resource use in areas with limited water availability, common challenges in SSA's drylands supported by the finding which highlighted the resilience of optimum plant population compared to farmers' practices. This corroborates with IPCC, (2021) which underscores the critical role of sustainable land management practices, such as optimizing planting densities, in mitigating climate vulnerability across SSA. Similarly, Oppong-Sekyere et al. (2023) advocate for adjustments to sowing density as part of integrated soil and water conservation strategies to enhance climate resilience. Building on this, our study emphasizes farmers' adoption of optimal high plant populations as a practical approach for mitigating climate impacts. This strategy, supported by our projections, demonstrates the potential for achieving more stable yields and improved food security under changing climatic conditions.

The results also underscore the performance of dual-purpose millet varieties over farmer local variety across all agroecological zones (Table 13), as indicated by a statistically significant effect ($P<0.05$). This demonstrates the potential of dual-purpose varieties to enhance productivity due to their improved traits (Faye et al., 2023; Tounkara et al., 2020). However, projections reveal that these varieties are more vulnerable to the negative impacts of future climate conditions by mid-century. Figure 9 shows the yield decline for both variety types across AEZs, with dual-purpose varieties showing a more pronounced reduction. This suggests that, despite their potential yield advantage, dual-purpose varieties may face significant challenges as climate conditions worsen, potentially due to their higher resource requirements or sensitivity to stress factors (Foulkes et al., 2011; Hammer et al., 2010; Sadras and Lawson, 2013). This suggests that while local varieties are less productive than dual-purpose types under current conditions, they may exhibit greater resilience to climate stressors. This could be due to lower water and nutrient requirements capacity or better adaptation to environmental variability compared to dual-purpose varieties (Cossani and Reynolds, 2012). These findings align with studies that highlight the trade-offs between high-yielding crop varieties and climate resilience. Varieties bred for higher productivity often have greater water and nutrient demands, which can make them more susceptible to yield reductions under climate stress (Boote et al., 2017). Traore et al. (2014) also emphasized that early maturity will exhibit more yield decline in Mali by mid-century. This aligns with findings from previous research (Jarvis et al., 2008; Mercer and Perales, 2010; Vigouroux et al., 2011), which highlights that although landrace varieties typically have lower yield potential compared to improved high-yielding crops, they exhibit greater resilience to climate variability. In that case, a need for breeding programs to consider both productivity and resilience traits to support sustainable agriculture in the face of climate change. Adapting planting strategies and selecting varieties that balance yield potential with climate adaptability is crucial for mitigating future risks.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1. CONCLUSIONS

This study underscores the significance of innovative agricultural practices in enhancing the resilience and productivity of smallholder farmers in dryland farming systems. It examined the perception of climate variability and change among farmers in semi-arid regions of Senegal, as well as the factors influencing their adoption of climate-smart management practices. Specifically, the research focused on improved millet varieties, optimum plant population density, and micro-dosing fertilizer strategies. These strategies demonstrated the potential to improve crop yields through a participatory research and extension approach (PREA), which is expected to accelerate the adoption and dissemination of climate-smart agricultural (CSA) packages for managing climate risks in challenging environments. A decision-support tool, the DSSAT CERES-Millet model, was employed to accurately simulate phenology, morphology, grain yield, and aboveground biomass for various millet cultivars across diverse environments. High-resolution climate projections using six GCM models from CMIP6 were also conducted to assess the impacts of climate change under SSP2-4.5 and SSP5-8.5 scenarios for the mid-century period (2040-2069) across Senegal's agroecological zones.

The findings revealed that 2. Farmers were acutely aware of the detrimental effects of insufficient seasonal rainfall (72%), delayed onset of the growing season (88%), frequent dry spells (68%), and prolonged dry spells (76%), all of which led to decreased grain and fodder yields. Using the Logit model, the study identified significant ($p<0.05$) socioeconomic and institutional factors influencing farmers' decisions to adopt Climate-Smart Technology (CST). These factors include access to credit, extension services, farming experience, frequency of interaction with extension agents, and access to government subsidies. Conversely, the study highlighted the negative impact of distance from extension offices, underscoring the urgent need to improve the accessibility of extension services, particularly in rural areas.

The crop modeling approach used in this study demonstrated that the model satisfactorily simulated phenology and morphology, grain yield, and aboveground biomass (AGB) for all cultivars across contrasting environments, within acceptable statistical indices. The research offers valuable insights for smallholder farmers, suggesting that adopting dual-purpose cultivars and optimized fertilizer strategies can significantly enhance millet productivity and sustainability in dryland environments facing multiple challenges. This serves as a foundation for promoting Integrated Soil Fertility Management (ISFM) in millet production, particularly in regions experiencing challenging and changing climatic conditions. By integrating high-resolution climate projections with the DSSAT CERES-Millet model, the study emphasizes the importance of adopting climate-resilient millet varieties, optimizing planting densities, and implementing site-specific micro-dosing fertilizer strategies. Integrated soil fertility management practices, such as the combined use of organic and mineral fertilizers and higher planting densities, were shown to enhance yield performance and resource efficiency under both current and future climates. The findings suggest that organo-mineral microdosing fertilizer provides greater resilience to future climate change by reducing reliance on mineral fertilizers while enhancing organic inputs. To mitigate the impacts of future climate conditions, farmers should adopt ISFM practices, which promote increased organic fertilizer use and improve soil health. However, the vulnerability of high-yield dual-purpose varieties (SL 28, SL 423, and Thialack 2) under future climates, despite their initial performance advantages, highlights a trade-off that must be balanced with resilience traits found in landrace varieties. The resilience of traditional varieties suggests their potential role in sustainable agricultural systems under changing climates.

The projected reduction in precipitation by up to 25% and the shortening of rainy seasons in most agroecological zones (AEZs), particularly under SSP5-8.5, pose significant challenges for rain-fed agriculture, especially in the New Peanut Basin (NPB), Eastern and Upper Casamance (EUC), and Sylvopastoralism Zone (SVPZ). Rising temperatures, with increases of up to 3.42°C under SSP5-8.5 by mid-century, are expected to exacerbate heat stress on crops and livestock, further threatening food security. Conversely, more optimistic projections for the Old Peanut Basin (OPB), where rainfall may increase and the growing season may lengthen marginally, provide a foundation for localized adaptation strategies. The study highlights the importance of tailoring climate-smart practices to local contexts and emphasizes the need for long-term, coordinated efforts to facilitate seed exchange and variety migration across regions to address future climate challenges. These findings offer actionable insights for policymakers, researchers, and stakeholders, providing a roadmap to enhance the resilience of smallholder farming systems and ensure sustainable agricultural productivity in the face of climate variability and change.

5.2. RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed to enhance future research, policy development, and practical implementation.

1. Strengthen the adoption of Integrated Soil Fertility Management (ISFM) practices: Promote the use of organo-mineral micro-dosing fertilizer strategies combined with optimized plant population densities (25,000 hills/ha) and dual-purpose millet varieties (SL 28, SL 423 and Thialack 2) to enhance productivity and resource efficiency under both current and future climate conditions, while reducing dependency on mineral fertilizers.

2. Improve the accessibility and effectiveness of agricultural extension services: Expand and decentralize extension infrastructure to rural areas and increase the frequency of farmer-extension interactions. This will support knowledge transfer, facilitate the adoption of climate-smart technologies (CSTs), and address barriers such as distance to extension offices and limited access to credit and inputs.

3. Develop and scale localized, climate-informed adaptation strategies: Utilize high-resolution climate projections and crop modeling tools (e.g., DSSAT CERES-Millet) to tailor CSA packages to agroecological zones.

Future perspectives

Crop modeling tools are essential for developing climate-resilient insurance schemes in Sub-Saharan Africa, where weather variability challenges traditional risk assessments. Models like DSSAT enhance accuracy by simulating crop responses to diverse climatic and agronomic conditions, supporting early warning systems and enabling better index-based insurance. These tools help reduce uncertainty in yield forecasts, aiding policymakers and insurers in designing responsive and sustainable insurance mechanisms. To strengthen the effectiveness and applicability of crop modeling, further efforts should focus on:

1. Expanding Crop Coverage: Include a broader range of pearl millet cultivars and staple crops to tailor climate-smart practices to various agroecological zones.

2. Simulating Long-Term Soil Health: Model soil organic carbon and nitrogen dynamics to assess the sustainability of farming practices and support carbon sequestration aligned with global climate goals.

3. Using Multiple Crop Models: Combine models such as DSSAT, APSIM, SIMPLACE, and STICS to enhance accuracy and robustness across diverse farming systems.

4. Diversifying Climate Scenarios: Broaden the range of Global Circulation Models (GCMs) used to better capture climate uncertainties.

5. Assessing Economic Viability: Evaluate the profitability of climate-smart practices like micro-dosing and plant density variation to ensure practical, cost-effective adoption.

REFERENCES

Abdurehman, M., & Abdi, M. (2021). Determinants of farmers adoption decision of improved crop varieties in Ethiopia: Systematic review. *African Journal of Agricultural Research*, *17*(7), 953–960. https://doi.org/10.5897/ajar2020.15197

Adam, M., MacCarthy, D. S., Traoré, P. C. S., Nenkam, A., Freduah, B. S., Ly, M., & Adiku, S. G. K. (2020). Which is more important to sorghum production systems in the Sudano-Sahelian zone of West Africa: Climate change or improved management practices? *Agricultural Systems*, *185*. https://doi.org/10.1016/j.agsy.2020.102920

Adekiya, A. O., Ejue, W. S., Olayanju, A., Dunsin, O., Aboyeji, C. M., Aremu, C., Adegbite, K., & Akinpelu, O. (2020). Different organic manure sources and NPK fertilizer on soil chemical properties, growth, yield and quality of okra. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-73291-x

Adiku, S. G. K., Maccarthy, D. S., Hathie, I., Diancoumba, M., Freduah, B. S., Amikuzuno, J., Sibiry Traore, P. C., Traore, S., Koomson, E., Agali, A., Lizaso, J. I., Fatondji, D., Adams, M., Tigana, L., Diarra, D. Z., N'diaye 10, O., & Valdivia, R. O. (2015). Climate change impacts on West African agriculture: an integrated regional assessment (CIWARA). *Handbook of Climate Change and Agroecosystems, 25–73.*

Ahmad, A., Rafiq, M., Ibrahim, M., Wajid, A., Hussain, A., & Goheer, A. R. (2004). Effect of Sowing Date and Plant Density on Growth, Light Interception and Yield of Wheat under Semi Arid Conditions. *International Journal of Agriculture & Biology*,Volume 6, Issue 6, 1119-1123

Ajeigbe, H. A., & Dashiell, K. (2010). *Participatory research extension approach: N 2 Africa extension method Putting nitrogen fixation to work for smallholder farmers in Africa (N 2 Africa)*. www.iita.org

Ajibola, F. O., Zhou, B., Gnitou, G. T., & Onyejuruwa, A. (2020). Evaluation of the performance of cmip6 highresmip on west african precipitation. *Atmosphere*, *11*(10). https://doi.org/10.3390/atmos11101053

(Akanksha) Patnaik, H. (2021). Gender and participation in community based adaptation: Evidence from the decentralized climate funds project in Senegal. *World Development*, *142*. https://doi.org/10.1016/j.worlddev.2021.105448

Akinseye, F. M., Adam, M., Agele, S. O., Hoffmann, M. P., Traore, P. C. S., & Whitbread, A. M. (2017). Assessing crop model improvements through comparison of sorghum (sorghum bicolor L. moench) simulation models: A case study of West African varieties. *Field Crops Research*, *201*, 19–31. https://doi.org/10.1016/j.fcr.2016.10.015

Akinseye, F. M., Agele, S. O., Traore, P. C. S., Adam, M., & Whitbread, A. M. (2016). Evaluation of the onset and length of growing season to define planting date ‘a case study for Mali (West Africa).’ *Theoretical and Applied Climatology*, *124*(3–4), 973–983. https://doi.org/10.1007/s00704-015-1460-8

Akinseye, F. M., Ajegbe, H. A., Kamara, A. Y., Adefisan, E. A., & Whitbread, A. M. (2020). Understanding the response of sorghum cultivars to nitrogen applications in the semi-arid Nigeria using the agricultural production systems simulator. *Journal of Plant Nutrition*, *43*(6), 834–850. https://doi.org/10.1080/01904167.2020.1711943

Akinseye, F. M., Ajeigbe, H. A., Kamara, A. Y., Omotayo, A. O., Tofa, A. I., & Whitbread, A. M. (2023). Establishing Optimal Planting Windows for Contrasting Sorghum Cultivars across Diverse Agro-Ecologies of North-Eastern Nigeria: A Modelling Approach. *Agronomy*, *13*(3), 727. https://doi.org/10.3390/agronomy13030727

Akinseye, F. M., Birhanu, B. Z., Ajeigbe, H. A., Diancoumba, M., Sanogo, K., & Tabo, R. (2023). Impacts of fertilization management strategies on improved sorghums varieties in smallholder farming systems in Mali: Productivity and profitability differences. *Heliyon*, *9*(3). https://doi.org/10.1016/j.heliyon.2023.e14497

Akinseye, F. M., Ogunjobi, K. O., & Okogbue, E. C. (2012). Climate variability and food crop production in Nigeria. *International Journal of Academic Research*, *4*(5), 107–111. https://doi.org/10.7813/2075-4124.2012/4-5/a.13

Akinseye, F. M., Vincent, A., & Oladitan, T. O. (2013). *Assessing the impacts of climate variability on crop yield over Sudano-Sahelian zone in Nigeria Change Detection and Trend Analysis of Future Temperature and Rainfall over West Africa View project WASCAL View project*. https://www.researchgate.net/publication/264582019

Akinseye, F. M., Zagre, I., Faye, A., Joseph, J. E., Worou, O. N., & Whitbread, A. M. (2024). Exploring adaptation strategies for smallholder farmers in dryland farming systems and impact on pearl millet production under climate change in West Africa. *Frontiers in Agronomy*, *6*. https://doi.org/10.3389/fagro.2024.1428630

Akponikp, P. B. I., Grard, B., & Bielders, C. L. (2014). Soil water crop modeling for decision support in millet-based systems in the Sahel: a challenge. *African Journal of Agricultural Research*, *9*(22), 1700–1713. https://doi.org/10.5897/ajar10.263

Akponikpè, P. B. I., Gérard, B., Michels, K., & Bielders, C. (2010). Use of the APSIM model in long term simulation to support decision making regarding nitrogen management for pearl millet in the Sahel. *European Journal of Agronomy*, *32*(2), 144–154. https://doi.org/10.1016/j.eja.2009.09.005

Akponipke. (2008). *Millet Response to Water and Soil Fertility Management in the Sahelian Niger: Experiments and Modeling. Doctorat thesis, Université catholique de Louvain, 200 p.*

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56*.

Almazroui, M., Saeed, F., Saeed, S., Nazrul Islam, M., Ismail, M., Klutse, N. A. B., & Siddiqui, M. H. (2020). Projected Change in Temperature and Precipitation Over Africa from CMIP6. *Earth Systems and Environment*, *4*(3), 455–475. https://doi.org/10.1007/s41748-020-00161-x

Amouzou, K. A., Lamers, J. P. A., Naab, J. B., Borgemeister, C., Vlek, P. L. G., & Becker, M. (2019). Climate change impact on water- and nitrogen-use efficiencies and yields of maize and sorghum in the northern Benin dry savanna, West Africa. *Field Crops Research*, *235*, 104–117. https://doi.org/10.1016/j.fcr.2019.02.021

Antwi-Agyei, P., Amanor, K., Hogarh, J. N., & Dougill, A. J. (2021). Predictors of access to and willingness to pay for climate information services in north-eastern Ghana: A gendered perspective. *Environmental Development*, *37*. https://doi.org/10.1016/j.envdev.2020.100580

Anuradha, N., Satyavathi, T., Sankar, M., Bharadwaj, C., & Pathy, T. L. (2018). Association of agronomic traits and micronutrients in pearl millet. *181 ~ International Journal of Chemical Studies*, *6*(1), 181–184.

Araya, A., Hoogenboom, G., Luedeling, E., Hadgu, K. M., Kisekka, I., & Martorano, L. G. (2015). Assessment of maize growth and yield using crop models under present and future climate in southwestern Ethiopia. *Agricultural and Forest Meteorology*, *214–215*, 252–265. https://doi.org/10.1016/j.agrformet.2015.08.259

Araya, A., Jha, P. K., Zambreski, Z., Faye, A., Ciampitti, I. A., Min, D., Gowda, P. H., Singh, U., & Prasad, P. V. V. (2022). Evaluating crop management options for sorghum, pearl millet and peanut to minimize risk under the projected midcentury climate scenario for different locations in Senegal. *Climate Risk Management*, *36*. https://doi.org/10.1016/j.crm.2022.100436

Badiane, A., Faye, A., Yamoah, C. F., & Dick, R. P. (2001). Use of compost and mineral fertilizers for millet production by farmers in the semiarid region of Senegal. *Biological Agriculture and Horticulture*, *19*(3), 219–230. https://doi.org/10.1080/01448765.2001.9754926

Bagayoko, M., Maman, N., Palé, S., Sirifi, S., Taonda, S. J. B., Traore, S., & Mason, S. C. (2011). Microdose and N and P fertilizer application rates for pearl millet in West Africa CRSP-Legume Lab Innovation View project Optimizing fertilizer Use in Africa (OFRA) View project Microdose and N and P fertilizer application rates for pearl millet in West Africa. In

Article in African Journal of Agricultural Research (Vol. 6, Issue 5). http://www.academicjournals.org/AJAR

Bağçaci, S. Ç., Yucel, I., Duzenli, E., & Yilmaz, M. T. (2021). Intercomparison of the expected change in the temperature and the precipitation retrieved from CMIP6 and CMIP5 climate projections: A Mediterranean hot spot case, Turkey. *Atmospheric Research*, *256*. https://doi.org/10.1016/j.atmosres.2021.105576

Bationo A., A. Hartemink, O. Lungu, M. Naimi, P. Okoth, E. Smaling, and, & L. Thiombiano. (2006). *African Soils: Their Productivity and Profitability of Fertilizer Use. Background paper for the African Fertilizer Summit, June 9–13, 2006, Abuja, Nigeria. 29p.*

Bationo, A., & Buerkert, A. (2001). Soil Organic Carbon Management for Sustainable Land Use in Sudano-Sahelian West Africa. Nutrient Cycling in Agroecosystems, 61(1–2), 131–142. https://doi.org/10.1023/A:1013355822946

Bationo, A., Ngaradoum, D., Youl, S., Lompo, F., & Fening, J. O. (2018). Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems. In *Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems* (Vol. 1). Springer International Publishing. https://doi.org/10.1007/978-3-319-58789-9

Bationo, A., & Waswa, B. S. (2011). New Challenges and Opportunities for Integrated Soil Fertility Management in Africa. In *Innovations as Key to the Green Revolution in Africa* (pp. 3–17). Springer Netherlands. https://doi.org/10.1007/978-90-481-2543-2_1

Beah, A., Kamara, A. Y., Jibrin, J. M., Akinseye, F. M., Tofa, A. I., & Adam, A. M. (2021). Simulating the response of drought-tolerant maize varieties to nitrogen application in contrasting environments in the nigeria savannas using the APSIM model. *Agronomy*, *11*(1). https://doi.org/10.3390/agronomy11010076

Beaman, L., & Dillon, A. (2012). Do household definitions matter in survey design? Results from a randomized survey experiment in Mali. *Journal of Development Economics*, *98*(1), 124–135. https://doi.org/10.1016/j.jdeveco.2011.06.005

Bedeke, S., Vanhove, W., Gezahegn, M., Natarajan, K., & Van Damme, P. (2019). Adoption of climate change adaptation strategies by maize-dependent smallholders in Ethiopia. *NJAS - Wageningen Journal of Life Sciences*, *88*, 96–104. https://doi.org/10.1016/j.njas.2018.09.001

Bekunda, M. A., Bationo, A., & Ssali, H. (1997). Soil Fertility Management in Africa: A Review of Selected Research Trials. In R. J. Buresh, P. A. Sanchez, & F. Calhoun (Eds.), *Replenishing Soil Fertility in Africa* (SSSA Special Publication No. 51, pp. 63–79). Madison, WI: Soil Science Society of America.

Bélanger, G. (2000). *Impacts des changements climatiques sur l'agriculture au Québec*. 65e Congrès de l'Ordre des agronomes du Québec, juin 2002, 13p.

Berg, A., De Noblet-Ducoudré, N., Sultan, B., Lengaigne, M., & Guimberteau, M. (2013). Projections of climate change impacts on potential C4 crop productivity over tropical regions. *Agricultural and Forest Meteorology*, *170*, 89–102. https://doi.org/10.1016/j.agrformet.2011.12.003

Berhanu, D., Alamirew, T., Taye, M. T., Tibebe, D., Gebrehiwot, S., & Zeleke, G. (2023). Evaluation of CMIP6 models in reproducing observed rainfall over Ethiopia. *Journal of Water and Climate Change*, *14*(8), 2583–2605. https://doi.org/10.2166/wcc.2023.502

Bi, D., Dix, M., Marsland, S., O'farrell, S., Sullivan, A., Bodman, R., Law, R., Harman, I., Srbinovsky, J., Rashid, H. A., Dobrohotoff, P., Mackallah, C., Yan, H., Hirst, A., Savita, A., Dias, F. B., Woodhouse, M., Fiedler, R., & Heerdegen, A. (2020). Configuration and spin-up of ACCESS-CM2, the new generation Australian Community Climate and Earth System Simulator Coupled Model. *Journal of Southern Hemisphere Earth Systems Science*, *70*(1), 225–251. https://doi.org/10.1071/ES19040

Blessing, O. C., Ibrahim, A., Safo, E. Y., Yeboah, E., Abaidoo, R. C., Logah, V., & Ifeyinwa Monica, U. (2017). *African Journal of Agricultural Research Fertilizer micro-dosing in West African low-input cereals cropping: Benefits, challenges and improvement strategies*. *12*(14), 1169–1176. https://doi.org/10.5897/AJAR2016.11559

Bobde, V., Akinsanola, A. A., Folorunsho, A. H., Adebiyi, A. A., & Adeyeri, O. E. (2024). Projected regional changes in mean and extreme precipitation over Africa in CMIP6 models. *Environmental Research Letters*, *19*(7). https://doi.org/10.1088/1748-9326/ad545c

Boote, K. J., Prasad, V., Allen, L. H., Singh, P., & Jones, J. W. (2017). *Modeling Sensitivity of Grain Yield to Elevated Temperature in the DSSAT Crop Models for Peanut, Soybean, Dry Bean, Chickpea, Sorghum, and Millet*.

Bossa, A. Y., & Diekkrüger, B. (2014). Scenario-based simulations of the impacts of rainfall variability and management options on maize production in Benin Runoff Prediction and Comparison in West Africa using IHACRES and GR4J Lumped Models over Mono River Basin (Togo, West Africa View project WASCAL (West African Service Science Center on Climate Change and Adapted Land Used) View project. *Article in African Journal of Agricultural Research*. https://doi.org/10.5897/AJAR2014.8757

Bowen, W. T., Thornton, P. K., & Hoogenboom, G. (1998). The simulation of cropping sequences using DSSAT. In G. Y. Tsuji, G. Hoogenboom, & P. K. Thornton (Eds.), *Understanding Options for Agricultural Production* (pp. 313–327). Dordrecht: Kluwer Academic Publishers. https://doi.org/10.1007/978-94-017-3624-4_15

Capa-Morocho, M., Rodríguez-Fonseca, B., & Ruiz-Ramos, M. (2014). Crop yield as a bioclimatic index of El Niño impact in Europe: Crop forecast implications. *Agricultural and Forest Meteorology*, 198–199, 42–52. https://doi.org/10.1016/j.agrformet.2014.07.012

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., & Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, *4*(4), 287–291. https://doi.org/10.1038/nclimate2153

Chen, C., Wang, E., & Yu, Q. (2010). Modeling wheat and maize productivity as affected by climate variation and irrigation supply in North China plain. *Agronomy Journal*, *102*(3), 1037–1049. https://doi.org/10.2134/agronj2009.0505

Chiputwa, B., Wainaina, P., Nakelse, T., Makui, P., Zougmoré, R. B., Ndiaye, O., & Minang, P. A. (2020). Transforming climate science into usable services: The effectiveness of co-production in promoting uptake of climate information by smallholder farmers in Senegal. *Climate Services*, *20*. https://doi.org/10.1016/j.cliser.2020.100203

Choudhary, B. K., Majumdar, K., & Datta, B. K. (2016). Effects of land use on the Soil Organic Carbon storage potentiality and soil edaphic factors in Tripura, Northeast India. *American Journal of Climate Change*, *05*(03), 417–429. https://doi.org/10.4236/ajcc.2016.53031

CILSS. (2017). *Catalogue Régional des Espèces et Variétés Végétales CEDEAO-UEMOA-CILSS*. Ouagadougou, Burkina Faso: Institut du Sahel (INSAH)/CILSS,109 p.

Cooper, P. J. M., Dimes, J., Rao, K. P. C., Shapiro, B., Shiferaw, B., & Twomlow, S. (2008). Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agriculture, Ecosystems and Environment*, *126*(1–2), 24–35. https://doi.org/10.1016/j.agee.2008.01.007

Corbeels, M., Berre, D., Rusinamhodzi, L., & Lopez-Ridaura, S. (2018). Can we use crop modelling for identifying climate change adaptation options? *Agricultural and Forest Meteorology*, *256–257*, 46–52. https://doi.org/10.1016/j.agrformet.2018.02.026

Cossani, C. M., & Reynolds, M. P. (2012). Physiological traits for improving heat tolerance in wheat. *Plant Physiology*, *160*(4), 1710–1718. https://doi.org/10.1104/pp.112.207753

Couturon, E., Mariac, C., Bezançon, G., Lauga, J., & Renno, J. F. (2003). Impact of natural and human selection on the frequency of the F1 hybrid between cultivated and wild pearl millet (*Pennisetum glaucum* (L.) R. Br.). *Euphytica*, *133*(3), 329–337. https://doi.org/10.1023/A:1025773313096

Danso, I., Webber, H., Bourgault, M., Ewert, F., Naab, J. B., & Gaiser, T. (2018). Crop management adaptations to improve and stabilize crop yields under low-yielding conditions in the Sudan Savanna of West Africa. *European Journal of Agronomy*, *101*, 1–9. https://doi.org/10.1016/j.eja.2018.08.001

De Longueville, F., Hountondji, Y. C., Kindo, I., Gemenne, F., & Ozer, P. (2016). Long-term analysis of rainfall and temperature data in Burkina Faso (1950–2013). *International Journal of Climatology*, *36*(13), 4393–4405. https://doi.org/10.1002/joc.4640

Debonne, N., & Hillerbrand, R. (2019). *Farming and Context* in *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* (pp. 1–99).

Diallo, A., Donkor, E., & Owusu, V. (2020). Climate change adaptation strategies, productivity and sustainable food security in southern Mali. *Climatic Change*, *159*(3), 309–327. https://doi.org/10.1007/s10584-020-02684-8

Diangar S., Fofana A., Diagne M., Yamoah C. F., & Dick R. P. (2004). Pearl millet based intercropping system in the semi-arid areas of Senegal. *African Crop Science Journal*, *12*, 133–130.

Diatta, S., & Thomason, W. E. (2016). *Improving Pearl Millet (Pennisetum glaucum (L.) R.Br.) Productivity in Salt-affected soils in Senegal: A Greenhouse and Field investigation*.

Diouf, N. S., Ouedraogo, I., Zougmoré, R. B., Ouedraogo, M., Partey, S. T., & Gumucio, T. (2019). Factors influencing gendered access to climate information services for farming in Senegal. *Gender, Technology and Development*, *23*(2), 93–110. https://doi.org/10.1080/09718524.2019.1649790

Diouf, N. S., Ouedraogo, M., Ouedraogo, I., Ablouka, G., & Zougmoré, R. (2020). Using seasonal forecast as an adaptation strategy: Gender differential impact on yield and income in senegal. *Atmosphere*, *11*(10). https://doi.org/10.3390/atmos11101127

Dodds, P. E. (2010). Development of a Crop Model to Examine Crop Management and Climate Change in Senegal. Ph.D thesis, University of Leeds, 276 p. DOI: 10.2134/agronj2016.03.0162.

Dunjana, N., Nyamugafata, P., Shumba, A., Nyamangara, J., & Zingore, S. (2012). Effects of cattle manure on selected soil physical properties of smallholder farms on two soils of Murewa, Zimbabwe. *Soil Use and Management*, *28*(2), 221–228. https://doi.org/10.1111/j.1475-2743.2012.00394.x

Egbebiyi, T. S., Crespo, O., Lennard, C., Zaroug, M., Nikulin, G., Harris, I., Price, J., Forstenhäusler, N., & Warren, R. (2020). Investigating the potential impact of 1.5, 2 and 3 ◦C global warming levels on crop suitability and planting season over West Africa. *PeerJ*, *2020*(3). https://doi.org/10.7717/peerj.8851

Ekwangu, J., Anguria, P., Andiku, C., Tenywa, J. S., Bisikwa, J., Wanyera, N., & Ugen, M. A. (2020). Fertilizer Micro-dosing and Timing of Weeding for Enhancing Finger-Millet Production in Eastern Uganda. *Journal of Agricultural Science*, *12*(11), 290. https://doi.org/10.5539/jas.v12n11p290

El Bilali, H., Bassole, I. H. N., Dambo, L., & Berjan, S. (2020). Climate change and food security. *Agriculture and Forestry*, *66*(3), 197–210. https://doi.org/10.17707/AgricultForest.66.3.16

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Eyshi Rezaei, E., Gaiser, T., Siebert, S., Sultan, B., & Ewert, F. (2014). Combined impacts of climate and nutrient fertilization on yields of pearl millet in Niger. *European Journal of Agronomy*, *55*, 77–88. https://doi.org/10.1016/j.eja.2014.02.001

Eyshi Rezaei, E., Siebert, S., & Ewert, F. (2017). Climate and management interaction cause diverse crop phenology trends. *Agricultural and Forest Meteorology*, *233*, 55–70. https://doi.org/10.1016/j.agrformet.2016.11.003

Fairhurst, T., Africa Soil Health Consortium, & C.A.B. International. (2012). *Handbook for Integrated Soil Fertility Management*. Africa Soil Health Consortium, Nairobi. ISBN (e-book): 978 1 78064 285 7; ISBN (paperback): 978 1 78064 291 8.

Falconnier, G. N., Corbeels, M., Boote, K. J., Affholder, F., Adam, M., MacCarthy, D. S., Ruane, A. C., Nendel, C., Whitbread, A. M., Justes, É., Ahuja, L. R., Akinseye, F. M., Alou, I. N., Amouzou, K. A., Anapalli, S. S., Baron, C., Basso, B., Baudron, F., Bertuzzi, P., … Webber, H. (2020). Modelling climate change impacts on maize yields under low nitrogen input conditions in sub-Saharan Africa. *Global Change Biology*, *26*(10), 5942–5964. https://doi.org/10.1111/gcb.15261

FAO. (1993). *FESLM: An international framework for evaluating sustainable land management*. World Soil Resources Report 73. Food and Agriculture Organization of the United Nations.

FAO. (2016). *The State of Food and Agriculture 2016: Climate change, agriculture and food security*. Food and Agriculture Organization of the United Nations. ISBN 978-92-5-109374-0.

FAOSTAT. (2021). World Food and Agriculture – Statistical Yearbook 2021. In *World Food and Agriculture – Statistical Yearbook 2021*. FAO. https://doi.org/10.4060/cb4477en

Fatondji, D., Bationo, A., Tabo, R., Jones, J. W., Adamou, A., & Hassane, O. (2012). Water Use and Yield of Millet Under the Zai System: Understanding the Processes Using Simulation. In *Improving Soil Fertility Recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT)* (pp. 77–100). Springer Netherlands. https://doi.org/10.1007/978-94-007-2960-5_6

Faye, A., Akplo, T. M., Stewart, Z. P., Min, D., Obour, A. K., Assefa, Y., & Prasad, P. V. V. (2023). Increasing Millet Planting Density with Appropriate Fertilizer to Enhance Productivity and System Resilience in Senegal. *Sustainability (Switzerland)*, *15*(5). https://doi.org/10.3390/su15054093

Faye, A., Camara, I., Diop, M., OuryDiallo, A., Sine, B., Noblet, M., Faye, B., Defrance, D., Sultan, B., & Ndour, N. Y. B. (2022). Millet and sorghum yield simulations under climate change scenarios in Senegal. *Regional Environmental Change*, *22*(3). https://doi.org/10.1007/s10113-022-01940-0

Faye, A., Faye, A., Sagna, N., Nourou-Dine Yessoufou, A., Zagre, I., Ewulo, R., Nadine Worou, O., & Whitbread, A. (2022). *Inventaire des technologies et pratiques de l'Agriculture Intelligente face au climat (AIC) au Sénégal Document de travail*. AICCRA Report. Accelerating Impacts of CGIAR Climate Research for Africa (AICCRA), 22p.

Faye, B., Webber, H., Diop, M., Mbaye, M. L., Owusu-Sekyere, J. D., Naab, J. B., & Gaiser, T. (2018). Potential impact of climate change on peanut yield in Senegal, West Africa. *Field Crops Research*, *219*, 148–159. https://doi.org/10.1016/j.fcr.2018.01.034

Faye, N. F., Diagne, A., Sawadogo, K., & Dia, D. (2018). Impact of Adoption of Improved Pearl Millet Varieties on Productivity in Central Senegal. *JOURNAL OF AGRICULTURE AND ENVIRONMENTAL SCIENCES*, *7*(2). https://doi.org/10.15640/jaes.v7n2a10

Fechter, J., Allison, B. E., Sivakumar, M. V. K., Van Der Ploeg, R. R., & Bley, J. (1991). An evaluation of the SWATRER and CERES-Millet models for southwest Niger. In *Soil Water Balance in the Sudano-Sahelian Zone: Proceedings of the Niamey Workshop, February 1991* (Issue 199, pp. 505–513). IAHS Press.

Feleke, H. G., Savage, M. J., & Tesfaye, K. (2021). Calibration and validation of APSIM–Maize, DSSAT CERES–Maize and AquaCrop models for Ethiopian tropical environments. *South African Journal of Plant and Soil*, *38*(1), 36–51. https://doi.org/10.1080/02571862.2020.1837271

Fernandez-Granja, J. A., Casanueva, A., Bedia, J., & Fernandez, J. (2021). Improved atmospheric circulation over Europe by the new generation of CMIP6 earth system models. *Climate Dynamics*, *56*(11–12), 3527–3540. https://doi.org/10.1007/s00382-021-05652-9

Fisher, M., Abate, T., Lunduka, R. W., Asnake, W., Alemayehu, Y., & Madulu, R. B. (2015). Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: Determinants of adoption in eastern and southern Africa. *Climatic Change*, *133*(2), 283–299. https://doi.org/10.1007/s10584-015-1459-2

Fonta, W. M., Sanfo, S., Kedir, A. M., & Thiam, D. R. (2018). Estimating farmers' willingness to pay for weather index-based crop insurance uptake in West Africa: Insight from a pilot initiative in Southwestern Burkina Faso. *Agricultural and Food Economics*, *6*(1). https://doi.org/10.1186/s40100-018-0104-6

Fotso-Nguemo, T. C., Chamani, R., Yepdo, Z. D., Sonkoué, D., Matsaguim, C. N., Vondou, D. A., & Tanessong, R. S. (2018). Projected trends of extreme rainfall events from CMIP5 models over Central Africa. *Atmospheric Science Letters*, *19*(2). https://doi.org/10.1002/asl.803

Foulkes, M. J., Slafer, G. A., Davies, W. J., Berry, P. M., Sylvester-Bradley, R., Martre, P., Calderini, D. F., Griffiths, S., & Reynolds, M. P. (2011). Raising yield potential of wheat. III. Optimizing partitioning to grain while maintaining lodging resistance. In *Journal of Experimental Botany* (Vol. 62, Issue 2, pp. 469–486). https://doi.org/10.1093/jxb/erq300

Freduah, B. S., MacCarthy, D. S., Adam, M., Ly, M., Ruane, A. C., Timpong-Jones, E. C., Traore, P. S., Boote, K. J., Porter, C., & Adiku, S. G. K. (2019). Sensitivity of maize yield in smallholder systems to climate scenarios in semi-arid regions of West Africa: Accounting for variability in farm management practices. *Agronomy*, *9*(10). https://doi.org/10.3390/agronomy9100639

Gadédjisso-Tossou, A. (2015). Understanding Farmers' Perceptions of and Adaptations to Climate Change and Variability: The Case of the Maritime, Plateau and Savannah Regions of Togo. *Agricultural Sciences*, *06*(12), 1441–1454. https://doi.org/10.4236/as.2015.612140

Gaetani, M., & Mohino, E. (2013). Decadal prediction of the sahelian precipitation in CMIP5 simulations. *Journal of Climate*, *26*(19), 7708–7719. https://doi.org/10.1175/JCLI-D-12-00635.1

Galiwango, H., Miiro, R. F., Turyahabwe, N., & Egeru, A. (2022). Does the climate-smart village extension model enhance farmer empowerment? In *Outlook on Agriculture* (Vol. 51, Issue 3, pp. 281–292). SAGE Publications Inc. https://doi.org/10.1177/00307270221113600

Garba, M., Kamara, A. Y., Mohamed, A. M. L., Tofa, A. I., Mahamane, S. A., Salissou, H., Kapran, B. I., Abdoulaye, T., & Garba, I. I. (2024a). Assessing the effects of plant density and nitrogen on millet yield in Southern Niger using the CERES-millet model. *CABI Agriculture and Bioscience*, *5*(1). https://doi.org/10.1186/s43170-024-00254-x

Gbode, I. E., Diro, G. T., Intsiful, J. D., & Dudhia, J. (2022). Current Conditions and Projected Changes in Crop Water Demand, Irrigation Requirement, and Water Availability over West Africa. *Atmosphere*, *13*(7). https://doi.org/10.3390/atmos13071155

Gebru, G. W., Ichoku, H. E., & Phil-Eze, P. O. (2020). Determinants of smallholder farmers' adoption of adaptation strategies to climate change in Eastern Tigray National Regional State of Ethiopia. *Heliyon*, *6*(7). https://doi.org/10.1016/j.heliyon.2020.e04356

Gijsman, A. J., Jagtap, S. S., & Jones, J. W. (2002). Wading through a swamp of complete confusion: how to choose a method for estimating soil water retention parameters for crop models. *European Journal of Agronomy*, *18*(1–2), 77–106. https://doi.org/10.1016/s1161-0301(02)00098-9

Glatzle, S., Stuerz, S., Giese, M., Pereira, M., de Almeida, R. G., Bungenstab, D. J., Macedo, M. C. M., & Asch, F. (2021). Seasonal dynamics of soil moisture in an integrated-crop-livestock-forestry system in Central-west Brazil. *Agriculture (Switzerland)*, *11*(3). https://doi.org/10.3390/agriculture11030245

Graef, F., & Haigis, J. (2001). Spatial and temporal rainfall variability in the Sahel and its effects on farmers' management strategies. *Journal of Arid Environments*, *48*(2), 221–231. https://doi.org/10.1006/jare.2000.0747

Greene H W. (2003). *Econometric Analysis*. (5th ed.). New Jersey, USA: New York University. 1058p.

Greene, W. H. (2012). *Econometric analysis* (7th ed.). Prentice Hall. New Jersey, USA: Pearson Education, 1241p.

Habte Werede, M., Smith, J. U., & Boke Ambaye, S. (2018). Integrated soil fertility management for sustainable teff (Eragrostistef) production in Halaba, Southern Ethiopia. *Cogent Food and Agriculture*, *4*(1). https://doi.org/10.1080/23311932.2018.1519008

Haile, M. (2005). Weather patterns, food security and humanitarian response in sub-Saharan Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1463), 2169–2182. https://doi.org/10.1098/rstb.2005.1746

Hammer, G. L., Van Oosterom, E., McLean, G., Chapman, S. C., Broad, I., Harland, P., & Muchow, R. C. (2010). Adapting APSIM to model the physiology and genetics of complex adaptive traits in field crops. In *Journal of Experimental Botany* (Vol. 61, Issue 8, pp. 2185–2202). https://doi.org/10.1093/jxb/erq095

Han, E., Ines, A. V. M., & Koo, J. (2019). Development of a 10-km resolution global soil profile dataset for crop modeling applications. *Environmental Modelling and Software*, *119*, 70–83. https://doi.org/10.1016/j.envsoft.2019.05.012

Hansen, J., Hellin, J., Rosenstock, T., Fisher, E., Cairns, J., Stirling, C., Lamanna, C., van Etten, J., Rose, A., & Campbell, B. (2019). Climate risk management and rural poverty reduction. *Agricultural Systems*, *172*, 28–46. https://doi.org/10.1016/j.agsy.2018.01.019

Hansen, J. W., Vaughan, C., Kagabo, D. M., Dinku, T., Carr, E. R., Körner, J., & Zougmoré, R. B. (2019). Climate Services Can Support African Farmers' Context-Specific Adaptation Needs at Scale. In *Frontiers in Sustainable Food Systems* (Vol. 3). Frontiers Media S.A. https://doi.org/10.3389/fsufs.2019.00021

Harr, R. N., Wright Morton, L., Rusk, S. R., Engle, D. M., Miller, J. R., & Debinski, D. (2014). Landowners' perceptions of risk in grassland management: Woody plant encroachment and prescribed fire. *Ecology and Society*, *19*(2). https://doi.org/10.5751/ES-06404-190241

Hayashi, K., Abdoulaye, T., Gerard, B., & Bationo, A. (2008). Evaluation of application timing in fertilizer micro-dosing technology on millet production in Niger, West Africa. *Nutrient Cycling in Agroecosystems*, *80*(3), 257–265. https://doi.org/10.1007/s10705-007-9141-3

Hempel, S., Frieler, K., Warszawski, L., Schewe, J., & Piontek, F. (2013). A trend-preserving bias correction – The ISI-MIP approach. *Earth System Dynamics*, *4*(2), 219–236. https://doi.org/10.5194/esd-4-219-2013

Hess A', T. M., Stephens, W., & Maryah, U. M. (1995). Rainfall trends in the North East Arid Zone of Nigeria 1961–1990. *Agricultural and Forest Meteorology*, *74*(1–2), 87–97. https://doi.org/10.1016/0168-1923(94)02179-NSCIRP

Hoogenboom, G., Porter, C. H., Boote, K. J., Shelia, V., Wilkens, P. W., Singh, U., White, J. W., Asseng, S., Lizaso, J. I., Moreno, L. P., Pavan, W., Ogoshi, R., Hunt, L. A., Tsuji, G. Y., & Jones, J. W. (2019). *The DSSAT crop modeling ecosystem* (pp. 173–216). https://doi.org/10.19103/as.2019.0061.10

Housseini Malam Laminou, R., Ndiaye, S., Diallo, D., Badara Dieye, A., Dalanda Diallo, M., & Guisse, A. (2020). Mineral Fertilizer Microdosing Alone or Combined with Urea on Maize and According to the Soil Chemical Elements Variation (Thies, Senegal). *American Journal of Agriculture and Forestry*, *8*(3), 69. https://doi.org/10.11648/j.ajaf.20200803.13

Ibitoye, S. J. (2011a). The influence of socio-economic variables of farmers on their choice of cassava varieties in Kogi state, Nigeria. Int. J. Agric. Sci. Res. Technol. 1, 185–193.

Ibrahim, A., Abaidoo, R. C., Fatondji, D., & Opoku, A. (2016). Determinants of fertilizer microdosing-induced yield increment of pearl millet on an acid sandy soil. *Experimental Agriculture*, *52*(4), 562–578. https://doi.org/10.1017/S0014479715000241

Ibrahim, A., Pasternak, D., & Fatondji, D. (2015). Impact of depth of placement of mineral fertilizer micro-dosing on growth, yield and partial nutrient balance in pearl millet cropping system in the Sahel. *Journal of Agricultural Science*, *153*(8), 1412–1421. https://doi.org/10.1017/S0021859614001075

Ibrahim, B., Karambiri, H., Polcher, J., Yacouba, H., & Ribstein, P. (2014). Changes in rainfall regime over Burkina Faso under the climate change conditions simulated by 5 regional climate models. *Climate Dynamics*, *42*(5–6), 1363–1381. https://doi.org/10.1007/s00382-013-1837-2

Ibrahim, B., Polcher, J., Karambiri, H., & Rockel, B. (2012). Characterization of the rainy season in Burkina Faso and it's representation by regional climate models. *Climate Dynamics*, *39*(6), 1287–1302. https://doi.org/10.1007/s00382-011-1276-x

IFAD. (2021). *IFAD Annual Report 2021*. Rome, Italy: International Fund for Agricultural Development. 150 p.

IFDC. (2016). *Final Report: External Strategic Review of the International Fertilizer Development Center (IFDC)*. USAID, Washington, DC, 115 p.

IFDC. (2022). *IFDC Annual Report 2022.Alabama, USA*, 48p.

IPCC. (2013). *Summary for Policymakers*. In: *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

IPCC. (2014a). *Climate Change 2014: Synthesis Report – Longer Report*. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. Cambridge University Press.

IPCC. (2021). *Climate Change 2021: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35–115. https://doi.org/10.59327/IPCC/AR6-9789291691647

ISRA. (2014). *Variétés de mil*. Institut Sénégalais de Recherche Agricole.22p.

Jägermeyr, J., Müller, C., Ruane, A. C., Elliott, J., Balkovic, J., Castillo, O., Faye, B., Foster, I., Folberth, C., Franke, J. A., Fuchs, K., Guarin, J. R., Heinke, J., Hoogenboom, G., Iizumi, T., Jain, A. K., Kelly, D., Khabarov, N., Lange, S., … Rosenzweig, C. (2021). Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nature Food*, *2*(11), 873–885. https://doi.org/10.1038/s43016-021-00400-y

Jamala, G., Shehu, H., Yidau, J., Jamala, G. Y., Shehu, H. E., Yidau, J. J., & Joel, L. (2021). Assessment of agrochemicals utilization by small-scale farmers in Guyuk, Adamawa State, Nigeria. *IOSR Journal of Environmental Science, Toxicology and Food Technology*, *6*(6), www.iosrjournals.org.

Jamil, M., Charnikhova, T., Jamil, T., Ali, Z., Eldin, N., Mohamed, M. A., Mourik, T. Van, & Bouwmeester, H. J. (2014). Influence of fertilizer microdosing on strigolactone production and Striga hermonthica parasitism in pearl millet. *INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGYJ. Bouwmeester*, *16*, 935940. http://www.fspublishers.org

Jarvis, D. I., D Brown, A. H., Hung Cuong, P., Collado-Panduro, L., Latournerie-Moreno, L., Gyawali, S., Tanto, T., Sawadogo, M., Mar, I., Sadiki, M., Thi-Ngoc Hue, N., Arias-Reyes, L., Balma, D., Bajracharya, J., Castillo, F., Rijal, D., Belqadi, L., Rana, R., Saidi, S., … Hodgkin, T. (2008). *A global perspective of the richness and evenness of traditional crop-variety diversity maintained by farming communities*. www.pnas.org/cgi/content/full/

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J., & Ritchie, J. T. (2003). The DSSAT cropping system model. *European Journal of Agronomy*, *18*(3–4), 235–265. https://doi.org/10.1016/S1161-0301(02)00107-7

Jones, J. W., Naab, J., Fatondji, D., Dzotsi, K., Adiku, S., & He, J. (2012). Uncertainties in Simulating Crop Performance in Degraded Soils and Low Input Production Systems. In *Improving Soil Fertility Recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT)* (pp. 43–59). Springer Netherlands. https://doi.org/10.1007/978-94-007-2960-5_4

Jones, P. G., & Thornton, P. K. (2003). The potential impacts of climate change on maize production in Africa and Latin America in 2055. In *Global Environmental Change* (Vol. 13, Issue 1, pp. 51–59). Elsevier Ltd. https://doi.org/10.1016/S0959-3780(02)00090-0

Joseph, J. E., Akinseye, F. M., Worou, O. N., Faye, A., Konte, O., Whitbread, A. M., & Rötter, R. P. (2023). Assessment of the relations between crop yield variability and the onset and intensity of the West African Monsoon. *Agricultural and Forest Meteorology*, *333*, 109431. https://doi.org/10.1016/j.agrformet.2023.109431

Kamara, A. Y., Garba, M., Tofa, A. I., Mohamed, A. M. L., Souley, A. M., Abdoulaye, T., & Kapran, B. I. (2023). Assessment of the impact of crop management strategies on the yield of early-maturing maize varieties in the drylands of Niger Republic: Application of the DSSAT-CERES-Maize model. *Heliyon*, *9*(7). https://doi.org/10.1016/j.heliyon.2023.e17829

Kassa, Y. (2013). Impact of Integrated Soil and Water Conservation Program on Crop Production and Income in West Harerghe Zone, Ethiopia. *International Journal of Environmental Monitoring and Analysis*, *1*(4), 111. https://doi.org/10.11648/j.ijema.20130104.11

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N. I., Hargreaves, J. N. G., Meinke, H., Hochman, Z., Mclean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., … Smith, C. J. (2003). *An overview of APSIM, a model designed for farming systems simulation*. www.apsim-help.tag.csiro.au

Kim, M. K., Yu, D. G., Oh, J. S., Byun, Y. H., Boo, K. O., Chung, I. U., Park, J. S., Park, D. S. R., Min, S. K., & Sung, H. M. (2020). Performance Evaluation of CMIP5 and CMIP6 Models on Heatwaves in Korea and Associated Teleconnection Patterns. *Journal of Geophysical Research: Atmospheres*, *125*(23). https://doi.org/10.1029/2020JD032583

Knox, J., Hess, T., Daccache, A., & Wheeler, T. (2012). Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*, *7*(3). https://doi.org/10.1088/1748-9326/7/3/034032

Koo, J., Cox, C. M., Bacou, M., Azzarri, C., Guo, Z., Wood-Sichra, U., Gong, Q., & You, L. (2016). CELL5M: A geospatial database of agricultural indicators for Africa South of the Sahara. *F1000Research*, *5*. https://doi.org/10.12688/f1000research.9682.1

Kouman, K. D., Akpoti, K., Kouadio, B. H., Kabo-bah, A. T., Dembélé, M., Siabi, E. K., & Mensah, J. K. (2024). Assessment of climate change in the North-East region of Côte d‘Ivoire: Future precipitation, temperature, and meteorological drought using CMIP6 models. *Cogent Engineering*, *11*(1). https://doi.org/10.1080/23311916.2024.2345506

Kretzschmar, R. M., Hafner, H., Bationo, A., & Marschner, H. (1991). Long-and short-term effects of crop residues on aluminum toxicity, phosphorus availability and growth of pearl millet in an acid sandy soil*. In *Plant and Soil* (Vol. 136). Kluwer Academic Publishers.

Laux, P., Kunstmann, H., & Bárdossy, A. (2008). Predicting the regional onset of the rainy season in West Africa. *International Journal of Climatology*, *28*(3), 329–342. https://doi.org/10.1002/joc.1542

Lecina, S., Martínez-Cob, A., Pérez, P. J., Villalobos, F. J., & Baselga, J. J. (2003). Fixed versus variable bulk canopy resistance for reference evapotranspiration estimation using the Penman-Monteith equation under semiarid conditions. *Agricultural Water Management*, *60*(3), 181–198. https://doi.org/10.1016/S0378-3774(02)00174-9

Liang, S., Zhang, X., Sun, N., Li, Y., Xu, M., & Wu, L. (2019). Modeling crop yield and nitrogen use efficiency in wheat and maize production systems under future climate change. *Nutrient Cycling in Agroecosystems*, *115*(1), 117–136. https://doi.org/10.1007/s10705-019-10013-4

Loague, K., & Green, R. E. (1991). Statistical and graphical methods for evaluating solute transport models: Overview and application. In *Journal of Contaminant Hydrology* (Vol. 7).

Lobell, D. B., Bala, G., & Duffy, P. B. (2006). Biogeophysical impacts of cropland management changes on climate. *Geophysical Research Letters*, *33*(6). https://doi.org/10.1029/2005GL025492

Lobell, D. B., & Burke, M. B. (2010). On the use of statistical models to predict crop yield responses to climate change. *Agricultural and Forest Meteorology*, *150*(11), 1443–1452. https://doi.org/10.1016/j.agrformet.2010.07.008

Lodoun, T., Giannini, A., Traoré, P. S., Somé, L., Sanon, M., Vaksmann, M., & Rasolodimby, J. M. (2013). Changes in seasonal descriptors of precipitation in Burkina Faso associated with late 20th century drought and recovery in West Africa. *Environmental Development*, *5*(1), 96–108. https://doi.org/10.1016/j.envdev.2012.11.010

MacCarthy, D. S., Vlek, P. L. G., Bationo, A., Tabo, R., & Fosu, M. (2010). Modeling nutrient and water productivity of sorghum in smallholder farming systems in a semi-arid region of Ghana. *Field Crops Research*, *118*(3), 251–258. https://doi.org/10.1016/j.fcr.2010.06.005

Mahmood, A., Javaid, M. M., Shahzad, A. N., Aziz, M., Shahzad, A. N., Rehman, A., & Honermeier, B. (2012). YIELD AND QUALITY RESPONSE OF SORGHUM HYBRIDS TO DIFFERENT PLANTING DENSITIES AND SOWING TIMES. In *Int. J. Agric. Appl. Sci* (Vol. 4, Issue 1). https://www.researchgate.net/publication/340535577

Mamane Bello, G. H., & Malam Maman, M. N. (2015). A Ricardian Analysis of the Impact of Temperature and Rainfall Variability on Ag-riculture in Dosso and Maradi Regions of Niger Republic. *Agricultural Sciences*, *06*(07), 724–733. https://doi.org/10.4236/as.2015.67070

Mason, S. C., Maman, N., & Palé, S. (2015). PEARL MILLET PRODUCTION PRACTICES in SEMI-ARID WEST Africa: A REVIEW. *Experimental Agriculture*, *51*(4), 501–521. https://doi.org/10.1017/S0014479714000441

McClintock, N. C., & Diop, A. M. (2005). Soil fertility management and compost use in senegal's peanut basin. *International Journal of Agricultural Sustainability*, *3*(2), 79–91. https://doi.org/10.1080/14735903.2005.9684746

Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J. G., Daniel, J. S., John, A., Krummel, P. B., Luderer, G., Meinshausen, N., Montzka, S. A., Rayner, P. J., Reimann, S., … Wang, R. H. J. (2020). The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, *13*(8), 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020

Meinzen-Dick, R., Van Koppen, B., Behrman, J., Karelina, Z., Akamandisa, V., Hope, L., & Wielgosz, B. (2012). *Putting Gender on the Map Methods for Mapping Gendered Farm Management Systems in Sub-Saharan Africa Barbara van Koppen, International Water Management Institute*. 11p.

Mercer, K. L., & Perales, H. R. (2010). Evolutionary response of landraces to climate change in centers of crop diversity. *Evolutionary Applications*, *3*(5–6), 480–493. https://doi.org/10.1111/j.1752-4571.2010.00137.x

Michels, K., & Bielders, C. L. (2006). Pearl millet growth on an erosion-affected soil in the Sahel. *Experimental Agriculture*, *42*(1), 1–17. https://doi.org/10.1017/S0014479705002899

Mohamed, A. M. L., Jibrin, J. M., Auwalu, B. M., Garba, M., & Lawan, B. A. (2023a). Application of Ceres-Millet model of DSSAT for simulating millet varieties under different sowing windows in Niger. *Journal of Crop Improvement*, *37*(1), 41–59. https://doi.org/10.1080/15427528.2022.2048764

Moutouama, F. T., Tepa-Yotto, G. T., Agboton, C., Gbaguidi, B., Sekabira, H., & Tamò, M. (2022). Farmers' Perception of Climate Change and Climate-Smart Agriculture in Northern Benin, West Africa. *Agronomy*, *12*(6). https://doi.org/10.3390/agronomy12061348

Msongaleli, B., Rwehumbiza, F., Tumbo, S. D., & Kihupi, N. (2014). Sorghum Yield Response to Changing Climatic Conditions in Semi-Arid Central Tanzania: Evaluating Crop Simulation Model Applicability. *Agricultural Sciences*, *05*(10), 822–833. https://doi.org/10.4236/as.2014.510087

Muita, R., Dougill, A., Mutemi, J., Aura, S., Graham, R., Awolala, D., Nkiaka, E., Hirons, L., & Opijah, F. (2021). Understanding the Role of User Needs and Perceptions Related to Sub-Seasonal and Seasonal Forecasts on Farmers' Decisions in Kenya: A Systematic Review. In *Frontiers in Climate* (Vol. 3). Frontiers Media S.A. https://doi.org/10.3389/fclim.2021.580556

Müller, C., Cramer, W., Hare, W. L., & Lotze-Campen, H. (2011). Climate change risks for African agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(11), 4313–4315. https://doi.org/10.1073/pnas.1015078108

Murendo, C., & Wollni, M. (2015). Ex-post impact assessment of fertilizer microdosing as a climate-smart technology in Sub-Saharan Africa. *Agricultural Systems*, *134*, 77-85. https://doi.org/10.1016/j.agsy.2014.11.002.

Muzari, W., Gatsi, W., & Muvhunzi, S. (2012). The Impacts of Technology Adoption on Smallholder Agricultural Productivity in Sub-Saharan Africa: A Review. *Journal of Sustainable Development*, *5*(8). https://doi.org/10.5539/jsd.v5n8p69

Mwase, W., Sefasi, A., Njoloma, J., Nyoka, B. I., Manduwa, D., & Nyaika, J. (2015). Factors Affecting Adoption of Agroforestry and Evergreen Agriculture in Southern Africa. *Environment and Natural Resources Research*, *5*(2). https://doi.org/10.5539/enrr.v5n2p148

Namatsheve, T., Cardinael, R., Corbeels, M., & Chikowo, R. (2020). Productivity and biological N2-fixation in cereal-cowpea intercropping systems in sub-Saharan Africa. A review. In *Agronomy for Sustainable Development* (Vol. 40, Issue 4). Springer. https://doi.org/10.1007/s13593-020-00629-0

Ngigi, M. W., Mueller, U., & Birner, R. (2017). Gender Differences in Climate Change Adaptation Strategies and Participation in Group-based Approaches: An Intra-household Analysis From Rural Kenya. *Ecological Economics*, *138*, 99–108. https://doi.org/10.1016/j.ecolecon.2017.03.019

Nissanka, S. P., Karunaratne, A. S., Perera, R., Weerakoon, W. M. W., Thorburn, P. J., & Wallach, D. (2015). Calibration of the phenology sub-model of APSIM-Oryza: Going beyond goodness of fit. *Environmental Modelling and Software*, *70*, 128–137. https://doi.org/10.1016/j.envsoft.2015.04.007

Ntim-Amo, G., Yin, Q., Ankrah, E. K., Liu, Y., Ankrah Twumasi, M., Agbenyo, W., Xu, D., Ansah, S., Mazhar, R., & Gamboc, V. K. (2022). Farm households' flood risk perception and adoption of flood disaster adaptation strategies in northern Ghana. *International Journal of Disaster Risk Reduction*, *80*, 103223. https://doi.org/10.1016/J.IJDRR.2022.103223

Nyadzi, E., Nyamekye, A. B., Werners, S. E., Biesbroek, R. G., Dewulf, A., Slobbe, E. Van, Long, H. P., Termeer, C. J. A. M., & Ludwig, F. (2018). Diagnosing the potential of hydro-climatic information services to support rice farming in northern Ghana. *NJAS - Wageningen Journal of Life Sciences*, *86–87*, 51–63. https://doi.org/10.1016/j.njas.2018.07.002

Nyamekye, C., Thiel, M., Schönbrodt-Stitt, S., Zoungrana, B. J. B., & Amekudzi, L. K. (2018). Soil and water conservation in Burkina Faso, West Africa. In *Sustainability (Switzerland)* (Vol. 10, Issue 9). MDPI. https://doi.org/10.3390/su10093182

Ochieng', I. O., Ranjan, S., Seleiman, M. F., Padhan, S. R., Psiwa, R., Sow, S., Wasonga, D. O., & Gitari, H. I. (2023). Increasing rainwater use efficiency, gross return, and grain protein of rain-fed maize under nitrate and urea nitrogen forms. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, *51*(3). https://doi.org/10.15835/nbha51313293

Olson, K., Ebelhar, S. A., & Lang, J. M. (2014). Long-Term Effects of Cover Crops on Crop Yields, Soil Organic Carbon Stocks and Sequestration. *Open Journal of Soil Science*, *04*(08), 284–292. https://doi.org/10.4236/ojss.2014.48030

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., & Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, *42*, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J. F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, *9*(9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Oppong-Sekyere, D., Ben-Laouane, R., Radovanovi´c, V. R., Badu, M., & Org, B. M. (2023). *Soil and water conservation measures to adapt cropping systems to climate change facilitated water stresses in Africa*. http://kenvironews.wordpress.com

Ouédraogo, H., Diallo, Y., Hien, E., Yaméogo, L. P., & Udo, N. (2023). Socio-economic indigenous drivers of soils and water conservation practices use to cope with climate change in the region of Plateau Central in Burkina Faso. *International Journal of Biological and Chemical Sciences*, *16*(6), 2841–2856. https://doi.org/10.4314/ijbcs.v16i6.29

Ouedraogo, I., Diouf, N. S., Ouédraogo, M., Ndiaye, O., & Zougmoré, R. B. (2018). Closing the gap between climate information producers and users: Assessment of needs and uptake in Senegal. *Climate*, *6*(1). https://doi.org/10.3390/cli6010013

Parkes, B., Defrance, D., Sultan, B., Ciais, P., & Wang, X. (2018). Projected changes in crop yield mean and variability over West Africa in a world 1.5K warmer than the pre-industrial era. *Earth System Dynamics*, *9*(1), 119–134. https://doi.org/10.5194/esd-9-119-2018

Partey, S. T., Dakorah, A. D., Zougmoré, R. B., Ouédraogo, M., Nyasimi, M., Nikoi, G. K., & Huyer, S. (2020). Gender and climate risk management: evidence of climate information use in Ghana. *Climatic Change*, *158*(1), 61–75. https://doi.org/10.1007/s10584-018-2239-6

Partey, S. T., Zougmoré, R. B., Ouédraogo, M., & Campbell, B. M. (2018). Developing climate-smart agriculture to face climate variability in West Africa: Challenges and lessons learnt. In *Journal of Cleaner Production* (Vol. 187, pp. 285–295). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2018.03.199

Pasternak Dov, Ali Ibrahim and, & Ayantunde Augustine. (2012). Evaluation of five pearl millet varieties for yield and forage quality under two planting densities in the Sahel. *AFRICAN JOURNAL OF AGRICULTURAL RESEEARCH*, *7*(32), 4526–4535. https://doi.org/10.5897/ajar11.1569

Perez, C., Jones, E. M., Kristjanson, P., Cramer, L., Thornton, P. K., Förch, W., & Barahona, C. (2015). How resilient are farming households and communities to a changing climate in

Africa? A gender-based perspective. *Global Environmental Change*, *34*, 95–107. https://doi.org/10.1016/j.gloenvcha.2015.06.003

Pickering, N. B., Hansen, J. W., Jones, J. W., Wells, C. M., Chan, V. K., Godwin, D. C., Picketing, N., Hansen, J., Jones, J., & Eng Dep, A. (1994). *WeatherMan: A Utility for Managing and Generating Daily Weather Data (AJ)*.

Pilloni, R., Faye, A., Kakkera, A., Kholova, J., Badji, R., Faye, C., & Vadez, V. (2022). Higher sowing density of pearl millet increases productivity and water use efficiency in high evaporative demand seasons. *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/fpls.2022.1035181

Raes, D., Waongo, M., Vanuytrecht, E., & Mejias Moreno, P. (2021). Improved management may alleviate some but not all of the adverse effects of climate change on crop yields in smallholder farms in West Africa. *Agricultural and Forest Meteorology*, *308–309*. https://doi.org/10.1016/j.agrformet.2021.108563

Ragasa, C., Mazunda, J., & Kadzamira, M. (2016). The impact of agricultural extension services in the context of a heavily subsidized input system: The case of Malawi. *Food Policy, 59*, 1-11. https://doi.org/10.1016/j.foodpol.2015.11.004.

Ramaraj, A. P., Rao, K. P. C., Kumar, G. K., Ugalechumi, K., Sujatha, P., Rao, S. A., Dhulipala, R. K., & Whitbread, A. M. (2023). Delivering context specific, climate informed agro-advisories at scale: A case study of iSAT, an ICT linked platform piloted with rainfed groundnut farmers in a semi-arid environment. *Climate Services*, *31*. https://doi.org/10.1016/j.cliser.2023.100403

Ranjan, S., Kumar, S., Dutta, S. K., Padhan, S. R., Dayal, P., Sow, S., Roy, D. K., Nath, D., Baral, K., & Bharati, V. (2023). Influence of 36 years of integrated nutrient management on soil carbon sequestration, environmental footprint and agronomic productivity of wheat under rice-wheat cropping system. *Frontiers in Environmental Science*, *11*. https://doi.org/10.3389/fenvs.2023.1222909

Reddy, C. R., Khan, A. A., Prasad, K. V. S. V, Ravi, D., Reddy, B. S. V, Rego, T., Blümmel, M., Reddy, C. R., Prasad, A. A., Ravi, K. V. S. V, Rego, D. V, & Blümmel, T. (2010). *Stover Quality Traits for Improvement of Dual-Purpose Sorghum*.

Rhodes, E. R., Jalloh, A., & Diouf, A. (2014). *Review of research and policies for climate change adaptation in the agriculture sector in West Africa*. www.future-agricultures.org

Ritchie, J. T. (1981). Soil water availability. *Plant and Soil*, *58*(1–3), 327–338. https://doi.org/10.1007/BF02180061

Ritchie, J. T., Singh, U., Godwin, D. C., Bowen, W. T., & Peru, L. (1998). Cereal growth, development, and yield. *In Cereal Science and Technology* (pp. 57-76). Springer. https://doi.org/10.1007/978-1-4615-2323-2_6.

Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., Boote, K. J., Thorburn, P., Antle, J. M., Nelson, G. C., Porter, C., Janssen, S., Asseng, S., Basso, B., Ewert, F., Wallach, D., Baigorria, G., & Winter, J. M. (2013). The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agricultural and Forest Meteorology*, *170*, 166–182. https://doi.org/10.1016/j.agrformet.2012.09.011

Roudier, P., Sultan, B., Quirion, P., & Berg, A. (2011). The impact of future climate change on West African crop yields: What does the recent literature say? *Global Environmental Change*, *21*(3), 1073–1083. https://doi.org/10.1016/j.gloenvcha.2011.04.007

Ruane, A. C., & McDermid, S. P. (2017). Selection of a representative subset of global climate models that captures the profile of regional changes for integrated climate impacts assessment. *Earth Perspectives*, *4*(1). https://doi.org/10.1186/s40322-017-0036-4

Rusinamhodzi, L., Corbeels, M., Zingore, S., Nyamangara, J., & Giller, K. E. (2013). Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe. *Field Crops Research*, *147,* 40–53. https://doi.org/10.1016/j.fcr.2013.03.014

Sabaï, K., Sossa, E. L., Anago, N. F., Tovihoudji, P. G., Chabi, T. O. Y., Kiki, F. G. H., De-Souza, J. F., Agbangba, C. E., & Sinsin, B. A. (2020). Influence of Microdose of Mineral Fertilizer and Organic Manure on the Production of Groundnuts in Southern Benin. *International Journal of Plant & Soil Science*, 21–28. https://doi.org/10.9734/ijpss/2020/v32i130232

Sadras, V. O., & Lawson, C. (2013). Nitrogen and water-use efficiency of Australian wheat varieties released between 1958 and 2007. *European Journal of Agronomy*, *46*, 34–41. https://doi.org/10.1016/j.eja.2012.11.008

Saidia, P., & Kahimba, F. (2019). Effect of fertilizer micro-dose and moisture management practices on agronomic and economic performances of groundnut in semi-arid areas. *Agriculture, Ecosystems & Environment, 275,* 1-9. https://doi.org/10.1016/j.agee.2019.02.022.

Saidia, P. S., Asch, F., Kimaro, A. A., Germer, J., Kahimba, F. C., Graef, F., Semoka, J. M. R., & Rweyemamu, C. L. (2019). Soil moisture management and fertilizer micro-dosing on yield and land utilization efficiency of inter-cropping maize-pigeon-pea in sub humid Tanzania. *Agricultural Water Management*, *223*. https://doi.org/10.1016/j.agwat.2019.105712

Salack, S., Muller, B., & Gaye, A. T. (2011). Rain-based factors of high agricultural impacts over Senegal. Part I: Integration of local to sub-regional trends and variability. *Theoretical and Applied Climatology*, *106*(1–2), 1–22. https://doi.org/10.1007/s00704-011-0414-z

Sanfo, S., Salack, S., Saley, I. A., Daku, E. K., Worou, N. O., Savadogo, A., Barro, H., Guug, S., Koné, H., Ibrahim, B., Rojas, A., Raymond, C., & Ogunjobi, K. O. (2022). Effects of customized climate services on land and labor productivity in Burkina Faso and Ghana. *Climate Services*, *25*. https://doi.org/10.1016/j.cliser.2021.100280

Sang, Y., Ren, H. L., Shi, X., Xu, X., & Chen, H. (2021). Improvement of Soil Moisture Simulation in Eurasia by the Beijing Climate Center Climate System Model from CMIP5 to CMIP6. *Advances in Atmospheric Sciences*, *38*(2), 237–252. https://doi.org/10.1007/s00376-020-0167-7

Sanou, J., Bationo, B. A., Barry, S., Nabie, L. D., Bayala, J., & Zougmore, R. (2016). Combining soil fertilization, cropping systems and improved varieties to minimize climate risks on farming productivity in northern region of Burkina faso. *Agriculture and Food Security*, *5*(1). https://doi.org/10.1186/s40066-016-0067-3

Sanoussi, S. I. M., Dougbedji, F., Matthew, E., Okhimamhe, A. A., Ibrahim, A., & Sule, I. (2020). Assessing soil nutrient change under long-term application of mineral fertilizer micro-dosing to pearl millet [pennisetum glaucum (L.) R. Br.] on a sahelian sandy soil. *Eurasian Journal of Soil Science*, *9*(1), 34–42. https://doi.org/10.18393/ejss.642212

Schlenker, W., & Lobell, D. B. (2010). Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, *5*(1). https://doi.org/10.1088/1748-9326/5/1/014010

Sellar, A. A., Jones, C. G., Mulcahy, J. P., Tang, Y., Yool, A., Wiltshire, A., O'Connor, F. M., Stringer, M., Hill, R., Palmieri, J., Woodward, S., de Mora, L., Kuhlbrodt, T., Rumbold, S. T., Kelley, D. I., Ellis, R., Johnson, C. E., Walton, J., Abraham, N. L., … Zerroukat, M. (2019). UKESM1: Description and Evaluation of the U.K. Earth System Model. *Journal of Advances in Modeling Earth Systems*, *11*(12), 4513–4558. https://doi.org/10.1029/2019MS001739

Shelia, V., Hansen, J., Sharda, V., Porter, C., Aggarwal, P., Wilkerson, C. J., & Hoogenboom, G. (2019). A multi-scale and multi-model gridded framework for forecasting crop production, risk analysis, and climate change impact studies. *Environmental Modelling and Software*, *115*, 144–154. https://doi.org/10.1016/j.envsoft.2019.02.006

Sheraz Mahdi, S. (Ed.). (2019). Climate change and agriculture in India: Impact and adaptation. *Springer*. https://doi.org/10.1007/978-3-030-15639-7.

Shiogama, H., Ishizaki, N. N., Hanasaki, N., Takahashi, K., Emori, S., Ito, R., Nakaegawa, T., Takayabu, I., Hijioka, Y., Takayabu, Y. N., & Shibuya, R. (2021). Selecting CMIP6-Based Future Climate Scenarios for Impact and Adaptation Studies. *SOLA*, *17*(0), 57–62. https://doi.org/10.2151/sola.2021-009

Shiru, M. S., & Chung, E. S. (2021). Performance evaluation of CMIP6 global climate models for selecting models for climate projection over Nigeria. *Theoretical and Applied Climatology*, *146*(1–2), 599–615. https://doi.org/10.1007/s00704-021-03746-2

Silungwe, F. R., Graef, F., Bellingrath-Kimura, S. D., Chilagane, E. A., Tumbo, S. D., Kahimba, F. C., & Lana, M. A. (2019). Modelling rainfed pearl millet yield sensitivity to abiotic stresses in semi-arid central Tanzania, Eastern Africa. *Sustainability (Switzerland)*, *11*(16). https://doi.org/10.3390/su11164330

Singh, P., Boote, K. J., Kadiyala, M. D. M., Nedumaran, S., Gupta, S. K., Srinivas, K., & Bantilan, M. C. S. (2017). An assessment of yield gains under climate change due to genetic modification of pearl millet. *Science of the Total Environment*, *601–602*, 1226–1237. https://doi.org/10.1016/j.scitotenv.2017.06.002

Singh, R., Singh, D. P., & Tyagi, P. K. (2003). Effect of azotobacter, farmyard manure and nitrogen fertilization on productivity of pearl millet hybrids (Pennisetum Glaucum (L) r. br) in semi-arid tropical environment. *International Journal of Phytoremediation*, *21*(1), 21–24. https://doi.org/10.1080/03650340301498

Singh, S. L., Sahoo, U. K., Gogoi, A., & Kenye, A. (2018). Effect of Land Use Changes on Carbon Stock Dynamics in Major Land Use Sectors of Mizoram, Northeast India. *Journal of Environmental Protection*, *09*(12), 1262–1285. https://doi.org/10.4236/jep.2018.912079

Sivakumar. (1988). Predicting rainy season potential form the onset of the rins in southern sahelian and sudanian climatic zones of West Africa. *Agricultural and Forest Meteology*, *42*, 295–305.

Sivakumar, M. V. K. (1992). Climate change and implications for agriculture in Niger. *International Journal of Climatology*, *12*(2), 151-160. https://doi.org/10.1002/joc.3370120206.

Sivakumar, M. V. K., Das, H. P., & Brunini, O. (2005). Impacts of present and future climate variability and change on agriculture and forestry in the arid and semi-arid tropics. *Climate Change*, *70*(1-2), 31-72. https://doi.org/10.1007/s10584-005-5935-9.

Soler, C. M. T., Maman, N., Zhang, X., Mason, S. C., & Hoogenboom, G. (2008). Determining optimum planting dates for pearl millet for two contrasting environments using a modelling approach. *Journal of Agricultural Science*, *146*(4), 445–459. https://doi.org/10.1017/S0021859607007617

Soler, C. M. T., Sentelhas, P. C., & Hoogenboom, G. (2007). Application of the CSM-CERES-Maize model for planting date evaluation and yield forecasting for maize grown off-season in a subtropical environment. *European Journal of Agronomy*, *27*(2–4), 165–177. https://doi.org/10.1016/j.eja.2007.03.002

Stewart, Z. P., Pierzynski, G. M., Middendorf, B. J., & Vara Prasad, P. V. (2020). Approaches to improve soil fertility in sub-Saharan Africa. *Journal of Experimental Botany*, *71*(2), 632–641. https://doi.org/10.1093/jxb/erz446

Sultan, B., Ahmed, A. I., Faye, B., & Tramblay, Y. (2023). Less negative impacts of climate change on crop yields in West Africa in the new CMIP6 climate simulations ensemble. *PLOS Climate*, *2*(12), e0000263. https://doi.org/10.1371/journal.pclm.0000263

Sultan, B., Baron, C., Dingkuhn, M., Sarr, B., & Janicot, S. (2005). Agricultural impacts of large-scale variability of the West African monsoon. *Agricultural and Forest Meteorology*, *128*(1–2), 93–110. https://doi.org/10.1016/j.agrformet.2004.08.005

Sultan, B., Defrance, D., & Iizumi, T. (2019). Evidence of crop production losses in West Africa due to historical global warming in two crop models. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-49167-0

Sultan, B., & Gaetani, M. (2016). Agriculture in West Africa in the twenty-first century: Climate change and impacts scenarios, and potential for adaptation. In *Frontiers in Plant Science* (Vol. 7, Issue AUG2016). Frontiers Media S.A. https://doi.org/10.3389/fpls.2016.01262

Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., Ciais, P., Guimberteau, M., Traore, S., & Baron, C. (2013). Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. *Environmental Research Letters*, *8*(1). https://doi.org/10.1088/1748-9326/8/1/014040

Swart, N. C., Cole, J. N. S., Kharin, V. V., Lazare, M., Scinocca, J. F., Gillett, N. P., Anstey, J., Arora, V., Christian, J. R., Hanna, S., Jiao, Y., Lee, W. G., Majaess, F., Saenko, O. A., Seiler, C., Seinen, C., Shao, A., Sigmond, M., Solheim, L., … Winter, B. (2019). The Canadian Earth System Model version 5 (CanESM5.0.3). *Geoscientific Model Development*, *12*(11), 4823–4873. https://doi.org/10.5194/gmd-12-4823-2019

Sylla, M. B., Pal, J. S., Faye, A., Dimobe, K., & Kunstmann, H. (2018). Climate change to severely impact West African basin scale irrigation in 2 °C and 1.5 °C global warming scenarios. *Scientific Reports*, *8*(1). https://doi.org/10.1038/s41598-018-32736-0

Tabo, R., Bationo, A., Gerard, B., Ndjeunga, J., Marchal, D., Amadou, B., Annou, M. G., Sogodogo, D., Sibiry Taonda, J.-B., Hassane, O., Diallo, M. K., & Koala, S. (2007). Improving cereal productivity and farmers' income using a strategic application of fertilizers in West Africa. *Field Crops Research, 100*(1), 34-40. https://doi.org/10.1016/j.fcr.2006.06.007.

Tebaldi, C., Debeire, K., Eyring, V., Fischer, E., Fyfe, J., Friedlingstein, P., Knutti, R., Lowe, J., O'Neill, B., Sanderson, B., Van Vuuren, D., Riahi, K., Meinshausen, M., Nicholls, Z., Tokarska, K., Hurtt, G., Kriegler, E., Meehl, G., Moss, R., … Ziehn, T. (2021). Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. *Earth System Dynamics*, *12*(1), 253–293. https://doi.org/10.5194/esd-12-253-2021

Tebaldi, C., & Knutti, R. (2007). The use of the multi-model ensemble in probabilistic climate projections. In *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* (Vol. 365, Issue 1857, pp. 2053–2075). Royal Society. https://doi.org/10.1098/rsta.2007.2076

Tesfaye, A., Hansen, J., Kassie, G. T., Radeny, M., & Solomon, D. (2019). Estimating the economic value of climate services for strengthening resilience of smallholder farmers to climate risks in Ethiopia: A choice experiment approach. *Ecological Economics*, *162*, 157–168. https://doi.org/10.1016/j.ecolecon.2019.04.019

Theriault, V., Smale, M., & Haider, H. (2017). How Does Gender Affect Sustainable Intensification of Cereal Production in the West African Sahel? Evidence from Burkina Faso. *World Development*, *92*, 177–191. https://doi.org/10.1016/j.worlddev.2016.12.003

Thornton, P., & Cramer, L. (2012). *Impacts of climate change on the agricultural and aquatic systems and natural resources within the CGIAR's mandate*. www.ccafs.cgiar.org

Thrasher, B., Wang, W., Michaelis, A., Melton, F., Lee, T., & Nemani, R. (2022). NASA Global Daily Downscaled Projections, CMIP6. *Scientific Data*, *9*(1). https://doi.org/10.1038/s41597-022-01393-4

Tian, B., & Dong, X. (2020). The Double-ITCZ Bias in CMIP3, CMIP5, and CMIP6 Models Based on Annual Mean Precipitation. *Geophysical Research Letters*, *47*(8). https://doi.org/10.1029/2020GL087232

Totin, E., Segnon, A. C., Schut, M., Affognon, H., Zougmoré, R. B., Rosenstock, T., & Thornton, P. K. (2018). Institutional perspectives of climate-smart agriculture: A systematic literature review. In *Sustainability (Switzerland)* (Vol. 10, Issue 6). MDPI. https://doi.org/10.3390/su10061990

Toukal Assoumana, B., Ndiaye, M., Der Puije, G. Van, Diourte, M., & Gaiser, T. (2016). Comparative Assessment of Local Farmers' Perceptions of Meteorological Events and Adaptations Strategies: Two Case Studies in Niger Republic. *Journal of Sustainable Development*, *9*(3), 118. https://doi.org/10.5539/jsd.v9n3p118

Tounkara, A., Camara, B., Ndiaye, A., Gomis, E., Faye, M., Fall, T., & Ngom, D. (2023). Effects of microdose fertilization on Sanio millet (Pennisetum glaucum (L.) R. Br.) in Low Casamance (Southern Senegal). *International Journal of Agriculture, Environment and Bioresearch*, *8*(2), 139–149. https://doi.org/10.35410/IJAEB.2023.5823.

Tounkara, A., Clermont-Dauphin, C., Affholder, F., Ndiaye, S., Masse, D., & Cournac, L. (2020). Inorganic fertilizer use efficiency of millet crop increased with organic fertilizer application in rainfed agriculture on smallholdings in central Senegal. *Field Crops Research*, *251*, 107804. https://doi.org/10.1016/j.fcr.2020.107804.

Toure, H. A., Serme, I., Traore, K., & Kyei-Baffour, N. (2018). Assessment of the changes in the yields of millet crop under different scenarios of climate change using DSSAT model. *International Journal of Biological and Chemical Sciences*, *12*(1), 363. https://doi.org/10.4314/ijbcs.v12i1.29

Tovihoudji, P. G., Akponikpè, P. B. I., Agbossou, E. K., & Bielders, C. L. (2019). Using the DSSAT model to support decision making regarding fertilizer microdosing for maize production in the sub-humid region of Benin. *Frontiers in Environmental Science*, *7*(FEB). https://doi.org/10.3389/fenvs.2019.00013

Traore, B., Corbeels, M., van Wijk, M. T., Rufino, M. C., & Giller, K. E. (2013). Effects of climate variability and climate change on crop production in southern Mali. *European Journal of Agronomy*, *49*, 115–125. https://doi.org/10.1016/j.eja.2013.04.004

Traore, B., Van Wijk, M. T., Descheemaeker, K., Corbeels, M., Rufino, M. C., & Giller, K. E. (2014). Evaluation of climate adaptation options for Sudano-Sahelian cropping systems. *Field Crops Research*, *156*, 63–75. https://doi.org/10.1016/j.fcr.2013.10.014

Traore, S., & Owiyo, T. (2013). Dirty droughts causing loss and damage in Northern Burkina Faso. *International Journal of Global Warming*, *5*(4), 498–513. https://doi.org/10.1504/IJGW.2013.057288

Tschakert, P. (2007). Views from the vulnerable: Understanding climatic and other stressors in the Sahel. *Global Environmental Change*, *17*(3–4), 381–396. https://doi.org/10.1016/j.gloenvcha.2006.11.008

Tsuji, G. Y., Uehara, Goro., Balas, S., International Benchmark Sites Network for Agrotechnology Transfer., International Consortium for Agricultural Systems Application., & University of Hawaii (Honolulu). (1994). *DSSAT : version 3*. International Benchmark Sites Network for Agrotechnology Transfer.

Ullah, A., Ahmad, A., Khaliq, T., & Akhtar, J. (2017). Recognizing production options for pearl millet in Pakistan under changing climate scenarios. In *Journal of Integrative Agriculture*

(Vol. 16, Issue 4, pp. 762–773). Chinese Academy of Agricultural Sciences. https://doi.org/10.1016/S2095-3119(16)61450-8

Ullah, A., Ahmad, I., Ahmad, A., Khaliq, T., Saeed, U., M. Habib-ur-Rahman, Hussain, J., Ullah, S., & Hoogenboom, G. (2019). Assessing climate change impacts on pearl millet under arid and semi-arid environments using CSM-CERES-Millet model. *Environmental Science and Pollution Research*, *26*(7), 6745–6757. https://doi.org/10.1007/s11356-018-3925-7

Upadhyaya, H. D., Reddy, K. N., Gowda, E., Ahmed, I., & Singh, S. (2007). Agroecological Patterns of Diversity in Pearl Millet [Pennisetum glaucum (L.) R. Br.] Germplasm from India. In *Journal ofPlant Genetic Resources* (Vol. 20, Issue 3). www.IndianJournals.com

Uppal, R. K., Wani, S. P., Garg, K. K., & Alagarswamy, G. (2015). Balanced nutrition increases yield of pearl millet under drought. *Field Crops Research*, *177*, 86–97. https://doi.org/10.1016/j.fcr.2015.03.006

Van Ittersum, M. K., Van Bussel, L. G. J., Wolf, J., Grassini, P., Van Wart, J., Guilpart, N., Claessens, L., De Groot, H., Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., Van Oort, P. A. J., Van Loon, M. P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., … Cassman, K. G. (2016). Can sub-Saharan Africa feed itself? *Proceedings of the National Academy of Sciences of the United States of America*, *113*(52), 14964–14969. https://doi.org/10.1073/pnas.1610359113

van Oort, P. A. J., & Zwart, S. J. (2018). Impacts of climate change on rice production in Africa and causes of simulated yield changes. *Global Change Biology*, *24*(3), 1029–1045. https://doi.org/10.1111/gcb.13967

Van Oosterom, E. J., O'leary, G. J., Carberry, P. S., Craufurd, P. Q., Au, E. J., & Van, O.). (2002). Simulating growth, development, and yield of tillering pearl millet. III. Biomass accumulation and partitioning. *Field Crops Research, 77*(3), 171–186. https://doi.org/10.1016/S0378-4290(02)00010-4.

Van Wart, J., van Bussel, L. G. J., Wolf, J., Licker, R., Grassini, P., Nelson, A., Boogaard, H., Gerber, J., Mueller, N. D., Claessens, L., van Ittersum, M. K., & Cassman, K. G. (2013). Use of agro-climatic zones to upscale simulated crop yield potential. *Field Crops Research*, *143*, 44–55. https://doi.org/10.1016/j.fcr.2012.11.023

Vanlauwe, B., Amede, T., Bationo, A., Bindraban, P., Breman, H., Cardinael, R., Couedel, A., Chivenge, P., Corbeels, M., Dobermann, A., Falconnier, G., Fatunbi, W., Giller, K., Harawa, R., Kamau, M., Merckx, R., Palm, C., Powlson, D., Rusinamhodzi, L., … Groot, R. (2023). Fertilizer and Soil Health in Africa: The Role of Fertilizer in Building Soil Health to Sustain Farming and Address Climate Change. *Agriculture, Ecosystems & Environment, 318,* 107–126. https://doi.org/10.1016/j.agee.2021.107607.

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., & Zingore, S. (2015). Integrated soil fertility management in sub-Saharan Africa: Unravelling local adaptation. *SOIL*, *1*(1), 491–508. https://doi.org/10.5194/soil-1-491-2015

Vanli, Ö., Ustundag, B. B., Ahmad, I., Hernandez-Ochoa, I. M., & Hoogenboom, G. (2019). Using crop modeling to evaluate the impacts of climate change on wheat in southeastern turkey. *Environmental Science and Pollution Research*, *26*(28), 29397–29408. https://doi.org/10.1007/s11356-019-06061-6

Vieira Junior, N., Carcedo, A. J. P., Min, D., Diatta, A. A., Araya, A., Prasad, P. V. V., Diallo, A., & Ciampitti, I. (2023). Management adaptations for water-limited pearl millet systems in Senegal. *Agricultural Water Management*, *278*. https://doi.org/10.1016/j.agwat.2023.108173

Vigouroux, Y., Mariac, C., de Mita, S., Pham, J. L., Gérard, B., Kapran, I., Sagnard, F., Deu, M., Chantereau, J., Ali, A., Ndjeunga, J., Luong, V., Thuillet, A. C., Saïdou, A. A., & Bezançon, G. (2011). Selection for earlier flowering crop associated with climatic variations in the Sahel. *PLoS ONE*, *6*(5). https://doi.org/10.1371/journal.pone.0019563

Voldoire, A., Saint-Martin, D., Sénési, S., Decharme, B., Alias, A., Chevallier, M., Colin, J., Guérémy, J. F., Michou, M., Moine, M. P., Nabat, P., Roehrig, R., Salas y Mélia, D., Séférian, R., Valcke, S., Beau, I., Belamari, S., Berthet, S., Cassou, C., … Waldman, R. (2019). Evaluation of CMIP6 DECK Experiments With CNRM-CM6-1. *Journal of Advances in Modeling Earth Systems*, *11*(7), 2177–2213. https://doi.org/10.1029/2019MS001683

Wada, I. M., Usman, H. S., Amechi, S. N., Makhai, N. U., & Selamawit, H. G. (2022). Selection of CMIP6 representative climate models and downscaling in Northern Nigeria. *Scientific Reports*, *12*(1), Article 3670. https://doi.org/10.21203/rs.3.rs-2002273/v1.

Wada, M. I., Shehu Usman, H., Nwankwegu Amechi, S., & Usman Makhai, N. (2023). Selection of CMIP6 representative climate models and downscaling in Northern Nigeria. *Theoretical and Applied Climatology*, 22. https://doi.org/10.21203/rs.3.rs-2002273/v1

Waha, K., Zipf, B., Kurukulasuriya, P., & Hassan, R. M. (2016). An agricultural survey for more than 9,500 African households. In *Scientific Data* (Vol. 3). Nature Publishing Groups. https://doi.org/10.1038/sdata.2016.20

Wang, Z., Shi, P., Zhang, Z., Meng, Y., Luan, Y., & Wang, J. (2018). Separating out the influence of climatic trend, fluctuations, and extreme events on crop yield: a case study in Hunan Province, China. *Climate Dynamics*, *51*(11–12), 4469–4487. https://doi.org/10.1007/s00382-017-3831-6

Waongo, M., Laux, P., & Kunstmann, H. (2015). Adaptation to climate change: The impacts of optimized planting dates on attainable maize yields under rainfed conditions in Burkina Faso.

Agricultural and Forest Meteorology, *205*, 23–39. https://doi.org/10.1016/j.agrformet.2015.02.006

Waswa, B. S., Vlek, P. L. G., Tamene, L. D., Okoth, P., Mbakaya, D., & Zingore, S. (2013). Evaluating indicators of land degradation in smallholder farming systems of western Kenya. *Geoderma*, *195–196*, 192–200. https://doi.org/10.1016/j.geoderma.2012.11.007

Wehner, M. F. (2020). Characterization of long period return values of extreme daily temperature and precipitation in the CMIP6 models: Part 2, projections of future change. *Weather and Climate Extremes*, *30*. https://doi.org/10.1016/j.wace.2020.100284

White, J. W., Alagarswamy, G., Ottman, M. J., Porter, C. H., Singh, U., & Hoogenboom, G. (2015). An overview of CERES–sorghum as implemented in the cropping system model version 4.5. *Agronomy Journal*, *107*(6), 1987–2002. https://doi.org/10.2134/agronj15.0102

White, J. W., Hoogenboom, G., Kimball, B. A., & Wall, G. W. (2011). Methodologies for simulating impacts of climate change on crop production. *Field Crops Research*, *124*(3), 357–368. https://doi.org/10.1016/j.fcr.2011.07.001

Williams, P. A., Crespo, O., Abu, M., & Simpson, N. P. (2018). A systematic review of how vulnerability of smallholder agricultural systems to changing climate is assessed in Africa. In *Environmental Research Letters* (Vol. 13, Issue 10). Institute of Physics Publishing. https://doi.org/10.1088/1748-9326/aae026

Willmot Cort J. (1982). Some comments on the Evaluation of Model Performance. *American Meteorological Society*, *63*(12), 1309–1317.

Wimalasiri, E. M., Ashfold, M. J., Jahanshiri, E., Walker, S., Azam-Ali, S. N., & Karunaratne, A. S. (2023). Agro-climatic sensitivity analysis for sustainable crop diversification: The case of proso millet (Panicum miliaceum L.). *PLoS ONE, 18*(3), e0283298. https://doi.org/10.1371/journal.pone.0283298.

Wood, S. A., Bradford, M. A., Gilbert, J. A., Mcguire, K. L., Palm, C. A., Tully, K. L., Zhou, J., & Naeem, S. (2015). Agricultural intensification and the functional capacity of soil microbes on smallholder African farms. *Journal of Applied Ecology*, *52*(3), 744–752. https://doi.org/10.1111/1365-2664.12416

Xin, X., Wu, T., Zhang, J., Yao, J., & Fang, Y. (2020). Comparison of CMIP6 and CMIP5 simulations of precipitation in China and the East Asian summer monsoon. *International Journal of Climatology*, *40*(15), 6423–6440. https://doi.org/10.1002/joc.6590

Yadav, O. P., Singh, D. V., Vadez, V., Gupta, S. K., Rajpurohit, B. S., & Shekhawat, P. S. (2017). Improving pearl millet for drought tolerance- Retrospect and prospects. In *Indian Journal of*

Genetics and Plant Breeding (Vol. 77, Issue 4, pp. 464–474). Indian Society of Genetics and Plant Breeding. https://doi.org/10.5958/0975-6906.2017.00062.1

Yameogo, J. T., Hien, M., Lykke, A. M., Some, A. N., & Thiombiano, A. (2011). Effet des techniques de conservation des eaux et des sols, zaï forestier et cordons pierreux, sur la réhabilitation de la végétation herbacée à l'Ouest du Burkina Faso. *Int. J. Biol. Chem. Sci*, *5*(1), 56–71. http://indexmedicus.afro.who.int

Yegbemey, R. N., Yabi, J. A., Aïhounton, G. B., & Paraïso, A. (2014). Modélisation simultanée de la perception et de l'adaptation au changement climatique: Cas des producteurs de maïs du Nord Bénin (Afrique de l'Ouest). *Cahiers Agricultures*, *23*(3), 177–187. https://doi.org/10.1684/agr.2014.0697

Zagre, I., Akinseye, F. M., Worou, O. N., Kone, M., & Faye, A. (2024). Climate change adaptation strategies among smallholder farmers in Senegal's semi-arid zone: role of socio-economic factors and institutional supports. *Frontiers in Climate, 6*. 17p. https://doi.org/10.3389/fclim.2024.1332196

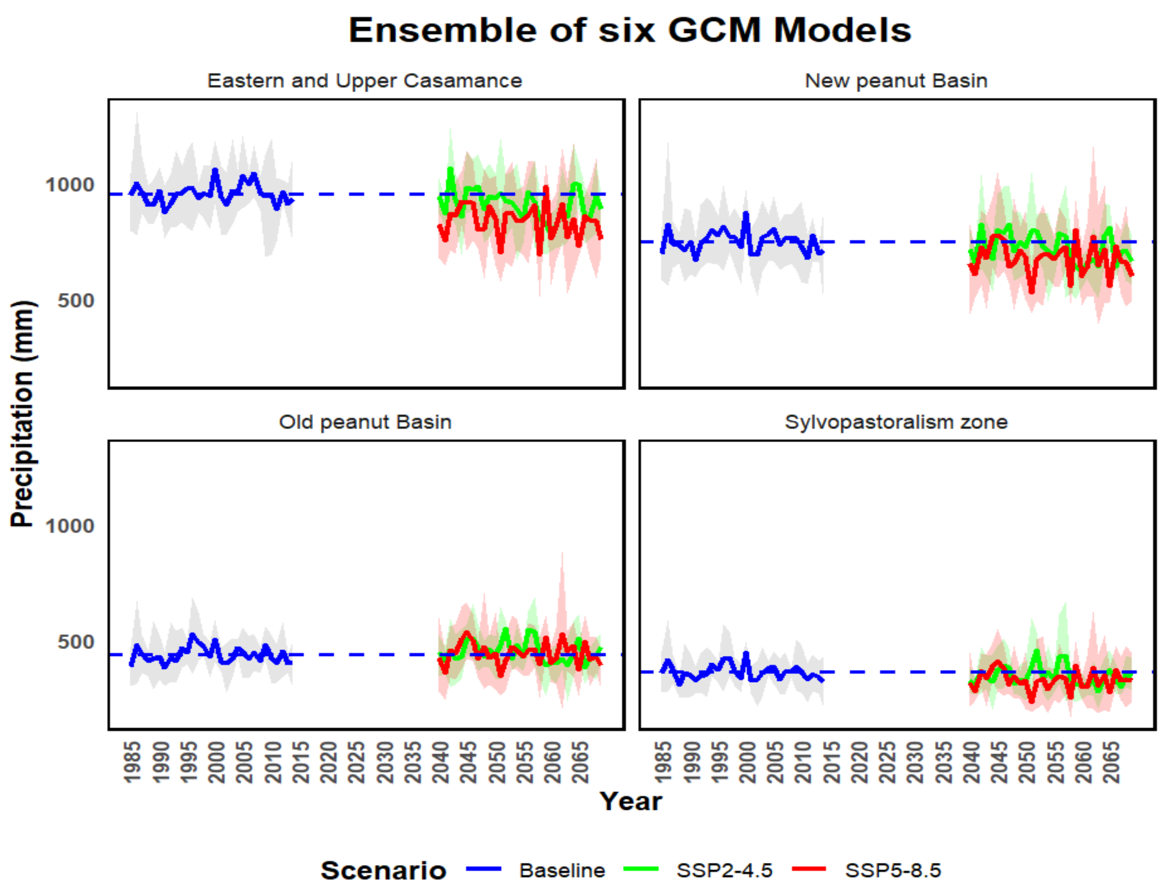
Zagre, I., Worou, O. N., Akinseye, F. M., Joseph, J. E., Faye, A., Kone, M., & Whitbread, A. M. (2025). Simulating pearl millet growth and yield with DSSAT-CERES-millet model: Evaluating climate-smart practices for uptake across diverse environments in Senegal. *CABI Agriculture and Bioscience*. 17p.https://doi.org/10.1079/ab.2025.0011

Zamani, Y., Hashemi Monfared, S. A., Azhdari moghaddam, M., & Hamidianpour, M. (2020). A comparison of CMIP6 and CMIP5 projections for precipitation to observational data: the case of Northeastern Iran. *Theoretical and Applied Climatology*, *142*(3–4), 1613–1623. https://doi.org/10.1007/s00704-020-03406-x

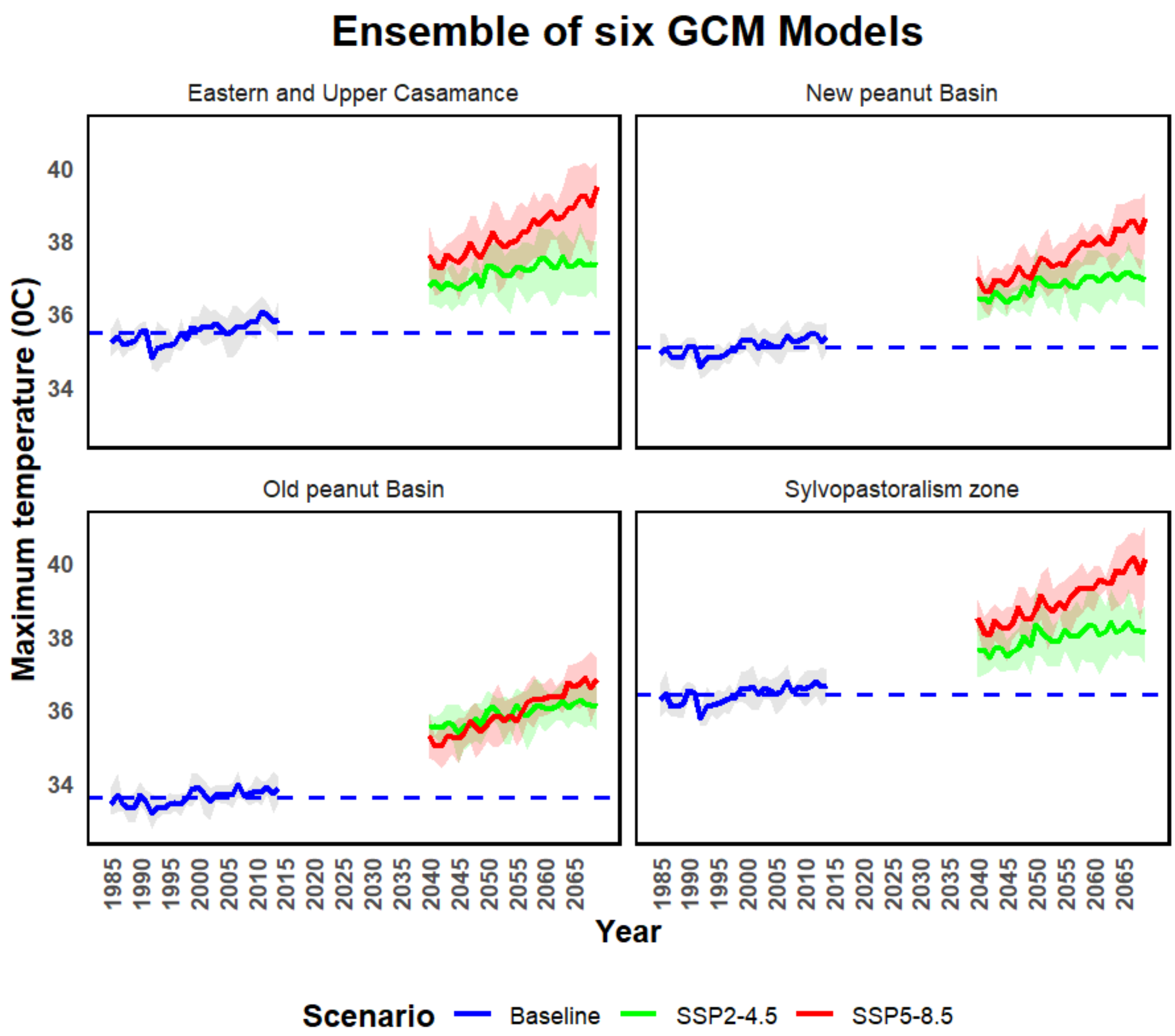
Zougmoré, R., Jalloh, A., & Tioro, A. (2014). Climate-smart soil water and nutrient management options in semiarid West Africa: A review of evidence and analysis of stone bunds and zaï techniques. *Agriculture & Food Security, 3*(1), 16. http://www.agricultureandfoodsecurity.com/content/3/1/16.

ANNEX

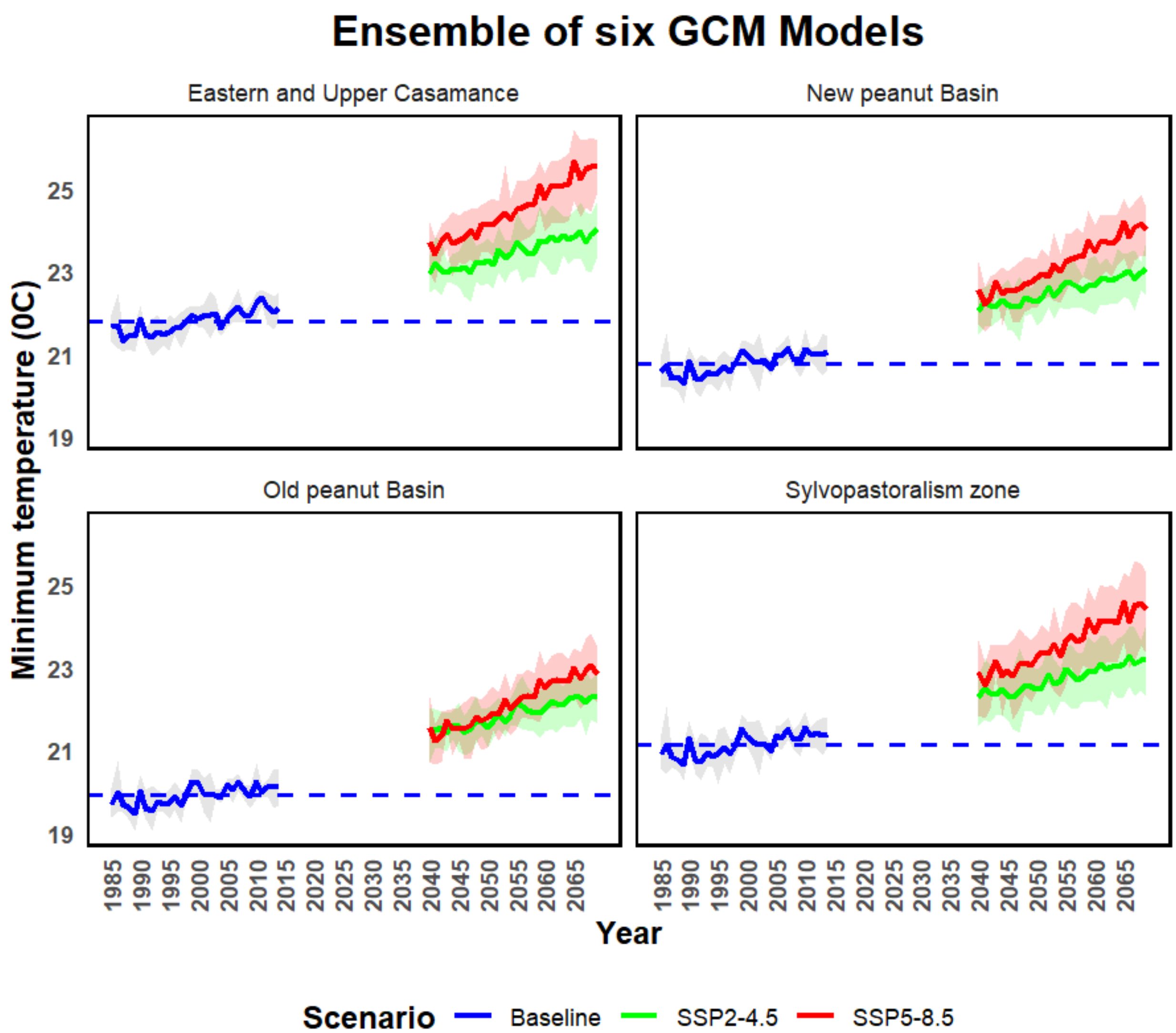
Annex I: Rainfall trend for the six GCM models across AEZs



Annex II: Maximum temperature trend for the six GCM models across AEZs



Annex III: Maximum temperature trend for the six GCM models across AEZs



Annex IV: Rainfall data collection instruments used in this study

A manual rain gauge (left) and IoT (right)

Annex V: Leaf Area Index Sensor and Photoperiod Active Radiation tool used for data collection

Annex VI: GCMs data depository link for downscaling

The NEX-GDDP-CMIP6 can be downloaded via the NASA Center for Climate Simulation platform using R scripts https://nex-gddp-cmip6.s3.us-west-2.amazonaws.com/index.html#NEX-GDDP-CMIP6/

Annex VII: Illustration of farm participatory demonstration plots

Annex VIII: Scientific Publications and Communications

Articles

- **Zagre I**, Akinseye FM, Worou ON, Kone M and Faye A (2024). Climate change adaptation strategies among smallholder farmers in Senegal's semi-arid zone: role of socio-economic factors and institutional supports. 17p, *Front. Clim*. 6:1332196. **doi: 10.3389/fclim.2024.1332196.**

- **Zagre I ,** Worou ON, Akinseye FM, Joseph JE, Faye A, Kone M, and Whitbread AM (2025). Application of the DSSAT-CERES-Millet Model to Simulate Growth and Yield of Pearl Millet Varieties: An Approach to Uptake climate-smart Management Practices in a Contrasting Environment in Senegal, CABI Agriculture and Bioscience, 6:1, 17p.**https://doi.org/10.1079/ab.2025.0011**
- **Inoussa ZAGRE**, Folorunso M. AKINSEYE, Nadine O. WOROU, Jacob E. Joseph, Aliou FAYE, Mama KONE, and Anthony M. WHITBREAD (*in review*). Assessing the Impact of Future Climate Scenarios on Pearl Millet Yield under Climate-Smart Management Practices Across Senegal's Agroecological Zones.

Contribution

- Akinseye FM, **Zagre I**, Faye A, Joseph JE, Worou ON and Whitbread AM (2024). Exploring adaptation strategies for smallholder farmers in dryland farming systems and impact on pearl millet production under climate change in West Africa.12p, *Front. Agron*. 6:1428630. **doi: 10.3389/fagro.2024.1428630.**
- Helene Melnick Sephora Nzapa Nzeouango, **Inoussa ZAGRE**, Taiwo EWULO, Aboubacry KANE, Sékouna DIATTA and Akinseye Mathew Folorunso (*in review*). Assessment of Yield Potential of Peanut Varieties Along the Rainfall Gradient in the Semi-Arid Zone of Senegal.

Scientific communications

- **Inoussa ZAGRE**, Folorunso Mathew AKINSEYE, Nadine Omonlola WOROU, Mama KONE, Aliou FAYE, (2023). Socio-economic and Institutional Supports for Influencing Farmers' Understanding of Climate Change and their Adaptation Strategies in Senegal, West Africa. Conference of Sciences for Sustainable Livelihoods Interdisciplinary Forum on Research-Based Approaches for Climate Resilience, from June 12th to 16th, Mittweida, Germany.

- **Inoussa ZAGRE**, Folorunso Mathew AKINSEYE, Nadine Omonlola WOROU, Mama KONE, Aliou FAYE, (2023). Socio-economic and Institutional Supports for Influencing Farmers' Understanding of Climate Change and their Adaptation Strategies in Senegal, West Africa. World Climate Research Programme Open Science Conference, from October 23rd to 27th, Kigali, Rwanda.

- **Inoussa ZAGRE**, Omonlola Nadine Worou, Folorunso Mathew Akinseye, Aliou Faye, Doudou Diouf, and Mama Kone (2024). Improving Pearl Millet Production in Senegal's Semi-arid Zone Through Participatory Research for Farm-level Intervention across Rainfall Gradients**.** 3rd Biennial Africa Climate Smart Agriculture Stakeholders Conference, from 29th to 31st July, Kigali, Rwanda.
- Folorunso M. AKINSEYE, **Inoussa ZAGRE**, Jacob E. Joseph, Nadine O. WOROU, Shalander KUMAR, and Anthony M. WHITBREAD, (2025). Do climate-smart management practices minimize the risk for millet productivity under climate change? Modeling approach.10th AgMIP Global Workshop: March 31-April 4, Mexico.