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Systemic Vulnerability and Adaptation Traps in The Gambia's Agricultural Sector under Climate Change

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Abstract

The Gambia's agricultural sector, which is predominantly rain-fed and employs 70% of the labor force, is exceptionally vulnerable to climate change. This study assesses the impacts of projected climate change on crop water requirements and the broader agro-ecological system to inform national adaptation planning. A hybrid modeling framework is employed that integrates a biophysical crop water model (CROPWAT 8.0) with a system dynamics (SD) model. The CROPWAT analysis uses CMIP6 climate projections for two Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5) for the mid-century period (2040-2059) to quantify changes in reference evapotranspiration (ETo) and crop water requirements (CWR) for five major crops. The SD model simulates the long-term (2020-2060) behavior of the interconnected agricultural, water, and socioeconomic subsystems under three policy scenarios. These are the Business-as-Usual (BAU), Infrastructure Investment, and Crop Diversification scenarios. Results from the CROPWAT model indicate a significant increase in atmospheric water demand, with ETo rising by 6.3% - 7.4% and CWR for all crops increasing by 3.3% - 4.3%. The net irrigation requirement for rice, an important staple, is projected to increase by a substantial 14.9% - 21.9%. The SD model reveals a concerning long-term decline in the food security index and average farmer income across all scenarios, even with policy interventions. These interventions provide only marginal improvements over BAU, highlighting a systemic "adaptation trap" where climate-induced poverty suppresses the capacity to invest in resilience. The findings demonstrate that incremental, field-level adaptation strategies are insufficient to counter the systemic pressures of climate change and population growth. This study concludes that a shift towards impactful, national-level policies focused on structural economic change and large-scale water management is imperative for building long-term resilience in The Gambia.

Keywords

Climate Change, System Dynamics, CROPWAT, Food Security, The Gambia, Adaptation Policy

1. Introduction

Sub-Saharan Africa, and West Africa in particular, confronts a profound challenge at the intersection of climate change, food security, and economic development. The region's agricultural systems, predominantly rain-fed and operated by smallholder farmers, exhibit a pronounced sensitivity to climatic shifts (Sultan & Gaetani, 2016). This inherent vulnerability is amplified by limited economic and institutional capacities to buffer against climate variability and extremes. The Gambia, a nation where agriculture constitutes a significant portion of the gross domestic product (GDP) and employs a large part of the workforce, epitomizes this regional predicament. The country's reliance on a short, often erratic, rainy season to sustain its primary crops renders its food production systems and the livelihoods dependent on them exposed to the consequences of a changing climate (Ceesay & Ndiaye, 2022). With over 90% of its agriculture being rain-fed and only a marginal fraction of cultivated land under irrigation, any alteration in temperature and precipitation patterns directly translates into risks for crop productivity and, by extension, national food security (FAO, 2024).

The scientific consensus, articulated in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), confirms that West Africa is experiencing a rapid and unequivocal warming trend, accompanied by an increase in the frequency and intensity of extreme weather events, including heatwaves and intense rainfall episodes (IPCC, 2022). While historical trends since the mid-1990s have shown a partial recovery of monsoonal precipitation after the severe droughts of the 1970s and 1980s, future projections remain uncertain, particularly concerning the volume and distribution of summer rainfall, which is the lifeblood of the region's agriculture. Despite this uncertainty in rainfall, a robust body of evidence points towards a consistent projection of yield losses for major staple crops across West Africa, a trend driven primarily by rising temperatures (Sultan et al., 2023). This situation presents a formidable obstacle to achieving food security in a region where the population and food demand are projected to grow in the coming decades (Carr et al., 2024).

For The Gambia, these regional trends have specific and acute implications. The nation's agricultural landscape is dominated by a few key crops, including groundnut, its primary cash crop, and staple cereals like rice, maize, and millet. The country already imports a substantial portion of its staple foods, particularly rice, and any decline in domestic production will further strain its economy and exacerbate food insecurity (Hadida et al., 2022). Understanding the precise nature of future climate impacts on the water requirements of these specific crops is therefore not merely an academic exercise; it is a fundamental prerequisite for designing effective, evidence-based adaptation strategies. Without a quantitative assessment of how crop water needs will change, policymakers and farmers alike will be ill-equipped to make the necessary adjustments to cultivation practices, irrigation infrastructure, and crop choices.

This study addresses a critical gap in the existing literature by providing a detailed, crop-specific analysis of the impacts of climate change on agricultural water requirements in The Gambia. While previous studies have examined climate impacts in the region, many have relied on older climate model ensembles (e.g., CMIP5), which project different climate futures for West Africa than the more recent CMIP6 models (Sultan et al., 2023). This research leverages the latest high-resolution climate projections from the CMIP6 ensemble to assess future changes in crop water requirements (CWR) and net irrigation requirements (NIR) for five key Gambian crops: groundnut, rice, maize, millet, and sorghum. By employing the widely used FAO CROPWAT 8.0 model, this paper aims to deliver precise, actionable insights into the future of agricultural water demand in The Gambia, thereby providing a scientific foundation for building a more resilient agricultural sector.

Study Objectives:

The primary goal of this study is to assess the impact of projected climate change on the water requirements of key agricultural crops in The Gambia. The specific objectives are:

1. To quantify the changes in crop water requirements (CWR) for groundnut, rice, maize, millet, and sorghum based on high-resolution CMIP6 climate projections for the mid-21st century (2041-2060) under intermediate (SSP2-4.5) and high (SSP5-8.5) emission scenarios.
2. To estimate the corresponding changes in net irrigation requirements (NIR) for each crop, thereby identifying the potential future gap between water demand for agriculture and water availability from rainfall.
3. To identify the most vulnerable crops and periods within their growth cycles that are likely to experience the most significant changes in water demand.
4. To provide a quantitative basis to inform the development of targeted adaptation strategies aimed at enhancing the resilience of The Gambia's agricultural sector to the impacts of climate change.

2. Literature Review

To address these objectives, the following section reviews the existing literature on climate change impacts on agriculture, vulnerability frameworks, and adaptation traps, establishing the theoretical foundation for the conceptual model developed in this study.

2.1. Climate Change Scenarios and Projections for West Africa

The climate of West Africa is characterized by a strong north-south rainfall gradient and a unimodal monsoon season that provides the vast majority of the region's annual precipitation. This system is inherently variable, with a history of profound multi-decadal fluctuations, most notably the severe Sahelian droughts of the 1970s and 1980s (Sultan & Gaetani, 2016). Since the mid-20th century, however, a clear and consistent warming trend has been superimposed upon this natural variability. The IPCC's Sixth Assessment Report (AR6) states with high confidence that surface temperatures across Africa have increased at a faster rate than the global average (IPCC, 2022). For West Africa specifically, observations show an average temperature increase of 1˚C - 3˚C since the mid-1970s, with the most pronounced warming occurring in the interior Sahelian zones. This warming has been accompanied by a marked increase in the frequency and intensity of heatwaves and a rise in the number of tropical nights (IPCC, 2022).

While temperatures have risen, rainfall patterns have exhibited a more complex evolution. Following the extended drought period, there has been a partial and spatially heterogeneous recovery of rainfall since the mid-1990s, a phenomenon sometimes referred to as the "Sahel greening" (Mechiche-Alami & Abdi, 2020). This recovery has not been a simple return to previous conditions. The character of the rainfall has changed, with evidence suggesting a trend towards fewer, but more intense, rainfall events and a higher frequency of extreme rainfall leading to flooding (IPCC, 2022). This shift towards more intense, erratic rainfall, coupled with rising temperatures that increase evaporative demand, creates a complex and challenging environment for agriculture.

Future climate projections for the region, while consistent in forecasting continued and significant warming, exhibit considerable uncertainty regarding precipitation. This uncertainty is a major challenge for impact modeling and adaptation planning. The projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6), which represent the latest generation of global climate models, suggest a different potential future for West Africa compared to the previous CMIP5 ensemble. A key study by Sultan et al. (2023) found that CMIP6 models, on average, project a wetter and slightly cooler future for the Sahel by mid-century compared to the hotter and drier scenarios common in CMIP5. This divergence is substantial, as it significantly alters the potential impacts on crop yields and water resources. Nonetheless, under all emission scenarios, temperatures are projected to continue to rise, with West Africa warming at a rate higher than the global average. Under an intermediate emissions scenario (SSP2-4.5), West Africa is projected to experience warming of approximately 2˚C by mid-century (2041-2060), while under a high emissions scenario (SSP5-8.5), this could reach 2.4˚C in the same period, and as high as 4.4˚C by the end of the century (IPCC, 2022). Such temperature increases, irrespective of rainfall changes, will inevitably intensify evapotranspiration and place additional stress on crops.

2.2. Agricultural Vulnerability and Food Security in the Gambia

The Gambian economy and the livelihoods of a majority of its population are intrinsically linked to the performance of its agricultural sector. The sector is dominated by smallholder farmers practicing subsistence and semi-commercial farming, with a heavy reliance on direct rainfall. This dependence on a brief and variable monsoon season is the central element of the country's vulnerability to climate change (Ceesay & Ndiaye, 2022). The agricultural system is characterized by low levels of mechanization, limited use of modern inputs such as improved seeds and fertilizers, and most importantly (within the context of this study), a near-total absence of irrigation infrastructure. According to FAO (2024), only about 1.12% of the total cultivated area in The Gambia is equipped for irrigation, leaving the remaining 99% entirely exposed to the vagaries of the rainy season. This situation is precarious. Any delay in the onset of the rains, a mid-season dry spell, or a premature end to the monsoon can have devastating consequences for crop yields and rural incomes. Antwi-Agyei et al. (2013) demonstrated that household vulnerability to climate variability in Ghana is shaped by multiple interacting factors, including livelihood strategies, access to resources, and institutional support, findings that are applicable to similar contexts across West Africa, including The Gambia.

The country's crop production is concentrated on a few key commodities. Groundnut is the traditional cash crop and a major source of export earnings, occupying a substantial portion of the arable land. The main food crops are coarse grains such as millet, maize, and sorghum, which form the bedrock of household food consumption, particularly in rural areas (Yengoh, 2026). Rice is also a major staple, but domestic production falls far short of national demand, leading to a heavy reliance on imports. It is estimated that The Gambia imports between 80% and 90% of its rice, making the national food supply highly susceptible to fluctuations in international market prices and supply chain disruptions (Hadida et al., 2022). This structural food deficit highlights the importance of strengthening domestic production, a goal that is directly threatened by the impacts of climate change. The socioeconomic context further compounds this vulnerability. High rates of poverty, particularly in rural areas, limit the capacity of farmers to invest in adaptive measures. Access to credit, extension services, and markets remains a challenge for many smallholders. Furthermore, land degradation, driven by a combination of factors including population pressure and unsustainable farming practices, has reduced the productive capacity of the soil in many parts of the country. These baseline stressors mean that even minor climatic shocks can push vulnerable households into food insecurity. As noted by Carr et al. (2024), under current trends of population growth and agricultural productivity, The Gambia will not be able to meet its domestic food demand by 2050, a gap that climate change is expected to widen.

2.3. Climate Change Impacts on Crop Water Requirements and Yields

The physiological processes of crops are intricately linked to climatic conditions, primarily temperature and water availability. Climate change impacts agricultural productivity by altering these fundamental drivers. The most direct impact of rising temperatures is an increase in atmospheric evaporative demand, a phenomenon described by the Penman-Monteith equation, which forms the basis for estimating reference evapotranspiration (ETo). As temperatures rise, the rate at which water evaporates from the soil surface and transpires from plants increases, meaning that crops require more water to maintain optimal growth and produce a given yield (Gabr, 2023). Therefore, even if rainfall were to remain constant or increase slightly, the higher evaporative demand caused by warming could lead to increased water stress for crops.

Numerous studies have projected the consequences of this for crop water requirements (CWR) and irrigation water requirements (IWR) across Africa. Sylla et al. (2018), using high-resolution regional climate models, projected that under a 2˚C global warming scenario, crop water demand and irrigation needs would increase across West Africa. Gabr (2023), in a study on the Nile Delta, predicted that agricultural water requirements could increase by as much as 9.7% to 18.2% under a high emissions scenario (RCP 8.5) by the end of the century. These findings are consistent with the general understanding that a warmer world will be a thirstier world, particularly for agriculture. This increased water demand, when set against a backdrop of potentially more erratic rainfall, translates directly into negative impacts on crop yields, especially in rain-fed systems. A meta-analysis by Roudier et al. (2011) found that projected impacts on crop yields in several African countries were predominantly negative, with average losses ranging from −10% to −6%.

The IPCC AR6 reinforces this conclusion, stating with high confidence that climate change has already reduced agricultural productivity across Africa. The report highlights that for West Africa, maize and wheat yields have already seen average reductions of 5.8% and 2.3%, respectively, due to historical climate change. Looking forward, the IPCC projects further declines; for instance, at 1.5˚C of global warming, sorghum yields are expected to decline, and maize yields could fall by 9% if adaptation measures are limited (IPCC, 2022). Rippke et al. (2016) identified three overlapping adaptation phases: incremental, preparatory, and transformational, and demonstrated that many regions in sub-Saharan Africa will require transformational adaptation within the next few decades as current cropping systems become unviable. Akinnagbe and Irohibe (2014), on the other hand, reviewed common agricultural adaptation strategies across Africa, including drought-resistant crop varieties, crop diversification, changes in cropping patterns and planting calendars, and improved irrigation efficiency, noting that strengthening human capital through education and extension services is fundamental to enhancing adaptive capacity.

The impact of climate change on crop yields and production in Africa has been keenly examined. A meta-analysis by Knox et al. (2012) projected mean yield changes of −17% for wheat, −5% for maize, −15% for sorghum, and −10% for millet across Africa by the 2050s, underscoring the severity of climate threats to food production in the region. The work of Sultan et al. (2023) provides a more nuanced perspective by comparing CMIP5 and CMIP6 projections. While their findings suggest that the CMIP6 ensemble projects less severe negative impacts for sorghum and millet in the Sahel compared to CMIP5, largely due to the wetter projections in CMIP6, the impact on maize yields remains negative. This indicates that the impact is crop-specific and that temperature-induced stress remains a dominant factor. The study also highlights the potential mitigating effect of elevated atmospheric CO_2 concentrations, which can improve water use efficiency in some crops (C3 plants like rice and groundnut). The magnitude of this CO_2 fertilization effect in real-world field conditions remains a subject of scientific debate and is often insufficient to offset the negative impacts of heat and water stress.

For The Gambia, these regional findings imply a significant future challenge. The projected increases in temperature will drive up the CWR for all major crops. For rain-fed crops like groundnut, millet, and sorghum, this will increase the risk of yield failure during dry spells. For rice, which is often grown in lowland areas that retain water, changes in the timing and intensity of rainfall could disrupt the growing cycle, while increased temperatures will still elevate water demand. Quantifying these changes in CWR is the first and most important step in assessing climate risk to Gambian agriculture and in formulating viable adaptation pathways.

3. Methods

This study employs a hybrid analytical framework that integrates a biophysical crop water requirement model with a socio-ecological system dynamics model. This dual approach allows for a quantitative assessment of direct climate impacts on crop water needs and a wider exploration of the systemic feedback mechanisms, adaptation pathways, and policy implications. The methodology is structured in two main parts: 1) the calculation of crop water and irrigation requirements using the FAO CROPWAT 8.0 model, and 2) the development of a system dynamics model to simulate the long-term behavior of The Gambia's agricultural system under various climate and policy scenarios.

3.1. Study Area

The Gambia is physically defined by the River Gambia (**Figure 1**), which bisects the country and creates distinct agro-ecological zones that shape national farming systems. The river's floodplain supports extensive rice cultivation, the country's staple crop, particularly in the freshwater zones of the Central River Region, while the upland plateaus are dominated by rain-fed groundnut and coarse-grain production. This riverine geography dictates a gradient of agricultural practices, where tidal irrigation potential along the river banks contrasts with the drought-prone sandy soils of the uplands, making the entire agricultural sector highly sensitive to hydrological variability.

The agroclimatology of The Gambia is defined by a pronounced dry season and a concentrated wet season that creates a narrow window for crop production. It is characterized by a short, unimodal rainy season from June to October, which governs its predominantly rain-fed agricultural system (Figure 3). The country's economy is heavily reliant on agriculture, which employs approximately 70% of the labor force and is dominated by smallholder farming. The primary crops include groundnut (the main cash crop) and staple cereals such as rice, maize, sorghum, and millet. With very limited irrigation infrastructure, the agricultural sector is especially vulnerable to variations in rainfall and temperature, making it a valid case for studying climate change impacts and adaptation.

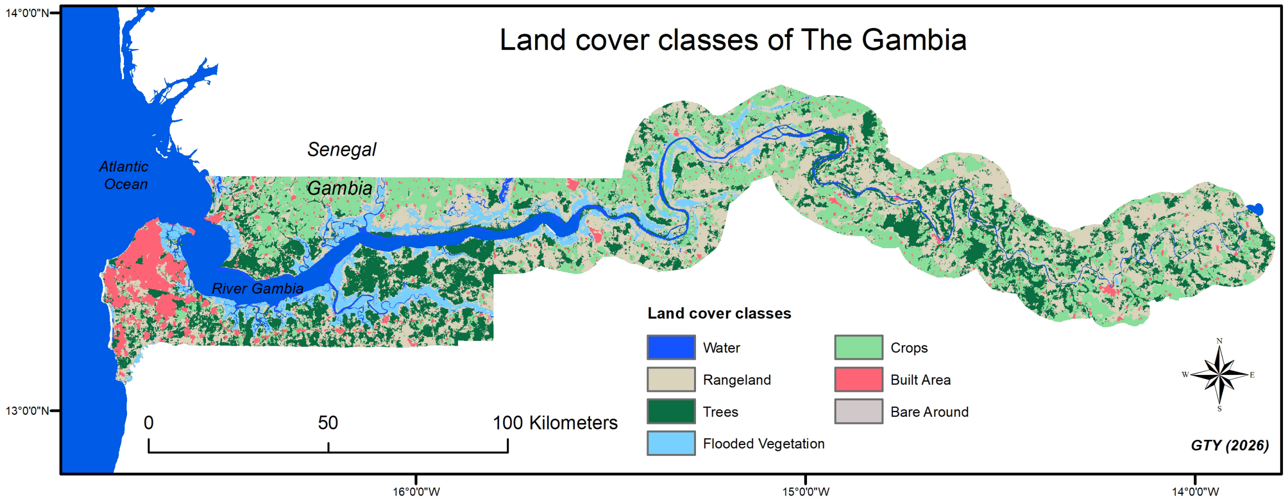

Figure 1. Land cover distribution of The Gambia derived from the Environmental Systems Research Institute's annual 10-meter global land use/land cover maps. These maps are based on the ESA Sentinel-2 imagery at 10 m resolution. It illustrates the dominance of agricultural land use along the River Gambia corridor (flooded vegetation) and the distinct transition between riverine rice cultivation zones and upland cropping systems.

3.2. Analysis of Crop Water Requirements

The first stage of the analysis focuses on quantifying the direct impact of climate change on the water needs of key crops. This is achieved using the CROPWAT 8.0 software, a decision-support tool developed by the Land and Water Division of the Food and Agriculture Organization (FAO) of the United Nations (FAO, 2021).

3.2.1. Reference Evapotranspiration (ETo)

The foundation of the crop water requirement calculation is the reference evapotranspiration (ETo), which represents the evaporative demand of the atmosphere. ETo was calculated using the FAO Penman-Monteith equation (Equation 1), which is recommended as the standard method for its accuracy and ability to account for all major climatic parameters (Allen et al., 1998). The equation is given as:

$$ETo = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T+273} u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \tag{1}$$

where: ETo is the reference evapotranspiration [mm day^{-1}], R_n is the net radiation at the crop surface [MJ m^{-2} day^{-1}], G is the soil heat flux density [MJ m^{-2} day^{-1}], T is the mean daily air temperature at 2 m height [˚C], u_2 is the wind speed at 2 m height [m s^{-1}], e_s is the saturation vapor pressure [kPa], e_a is the actual vapor pressure [kPa], $e_s - e_a$ is the saturation vapor pressure deficit [kPa], Δ is the slope of the vapor pressure curve [kPa °C^{-1}], γ is the psychrometric constant [kPa °C^{-1}].

The parameter values used and the assumptions made are described in **Appendix**.

3.2.2. Climate Data and Scenarios

Climate data required for the Penman-Monteith equation (minimum and maximum temperature, humidity, wind speed, and sunshine hours) were sourced for two distinct periods. A historical baseline period (1995-2014) was established using data from the FAO CLIMWAT 2.0 database, which provides long-term monthly averages for over 5000 stations worldwide (FAO, 2021). For future projections, downscaled climate data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) were obtained from the World Bank's Climate Change Knowledge Portal. The ensemble mean of available models is selected for a mid-century period (2041-2060) under two Shared Socioeconomic Pathways (SSPs): SSP2-4.5, an intermediate emissions scenario, and SSP5-8.5, a high-emissions, fossil-fuel-intensive development scenario. These scenarios were chosen to bound a range of plausible future climate conditions.

3.2.3. Crop Parameters and Crop Water Requirement (CWR)

Five crops of central importance to The Gambia's food security and economy were selected for analysis (groundnut, rice, maize, millet, and sorghum). The crop-specific water requirement (ETc), also known as crop water requirement (CWR), was calculated by adjusting the reference evapotranspiration (ETo) based on the specific characteristics of each crop, using the crop coefficient (Kc) approach (Equation (2)):

$$ET_c = K_c \times ET_o \tag{2}$$

Table 1. Crop parameters used in CROPWAT analysis.

Crop	Kc ini	Kc mid	Kc end	Total Growing Period (days)
Groundnut	0.40	1.15	0.60	135
Rice (paddy)	1.05	1.20	0.90	135
Maize	0.30	1.20	0.40	125
Millet	0.30	1.00	0.30	120
Sorghum	0.30	1.05	0.55	125

Source: Adapted from Allen et al. (1998) and Abdulmumin & Misari (1990).

The crop coefficient (Kc) varies over the growing season, reflecting changes in crop canopy and physiological development (Table 1). Stage-specific Kc values (initial, mid-season, and late-season) and the length of each growth stage were derived from FAO-56 guidelines and supplemented with data from regional studies in West Africa to ensure local relevance (Allen et al., 1998; Abdulmumin & Misari , 1990). The parameters used are detailed in **Table 1**.

3.2.4. Net Irrigation Requirement (NIR)

The net irrigation requirement (NIR) was calculated as the difference between the crop water requirement (ETc) and the effective rainfall (Peff), which is the portion of total rainfall that is available for crop use. Effective rainfall is calculated using the USDA Soil Conservation Service method (USDA Soil Conservation Service, 1970):

If $P \leq 250$ mm/month:

$$\text{Peff} = P \times (125 - 0.2 \times P)/125$$

If $P > 250$ mm/month:

$$\text{Peff} = 125 + 0.1 \times P \tag{3}$$

where: Peff = Effective rainfall [mm/month]; P = Total monthly rainfall [mm/month].

This calculation identifies the water deficit that needs to be supplied by irrigation to avoid crop water stress (see **Appendix** for how the irrigation water supply and the water stress factor are implemented in the model).

3.3. System Dynamics Modeling

System dynamics (SD) is used to analyze the systemic implications of the changes in water requirements calculated in Part 1. This approach allows for the exploration of feedback mechanisms, long-term trends, and the potential impacts of policy interventions (Forrester, 2012; Sterman, 2000). The model was implemented in Python 3.11, utilizing the NumPy library for numerical calculations and Matplotlib for generating visualizations. This approach was chosen to allow for direct integration with the CROPWAT data processing scripts and to ensure full programmatic control over the simulation experiments and scenario analysis. The complete model specification, including equations and parameters, is provided in **Appendix**.

3.3.1. Conceptual Model Development

Key relationships in the climate and food production dynamics in The Gambia are characterized as a coupled socio-hydrological and land-use system where climatic forcing shapes crop water stress and yields, and where yield shocks propagate into food production, livelihoods, and demographic change (**Figure 2**). Temperature-driven increases in atmospheric demand and rainfall-mediated effective rainfall alter water stress, which controls realized crop yield and, through potential yield and irrigation coverage, the scope for buffering drought impacts. Within a system dynamics framing, these linkages are naturally interpreted through reinforcing and balancing feedback structures that help explain non-linear responses and threshold behaviour in food systems (Sterman, 2000; Stave & Kopainsky, 2015). Walters et al. (2016) demonstrated how system dynamics modelling can integrate qualitative and quantitative data to explore the systemic interaction of drivers affecting economic, environmental, and social sustainability in agricultural production, providing a methodological foundation for the approach adopted in this study.

The first balancing mechanism (B1) operates as a distress-driven regulator. As the food security gap widens, rural livelihoods deteriorate, raising out-migration and/or mortality and thereby reducing population and food demand, which can narrow the gap (**Figure 2**). This loop stabilizes the accounting of food security at the expense of welfare and human capital, consistent with work highlighting the importance and potential erosion of stabilizing feedbacks in social-ecological systems (Mastrangelo & Cumming, 2024).

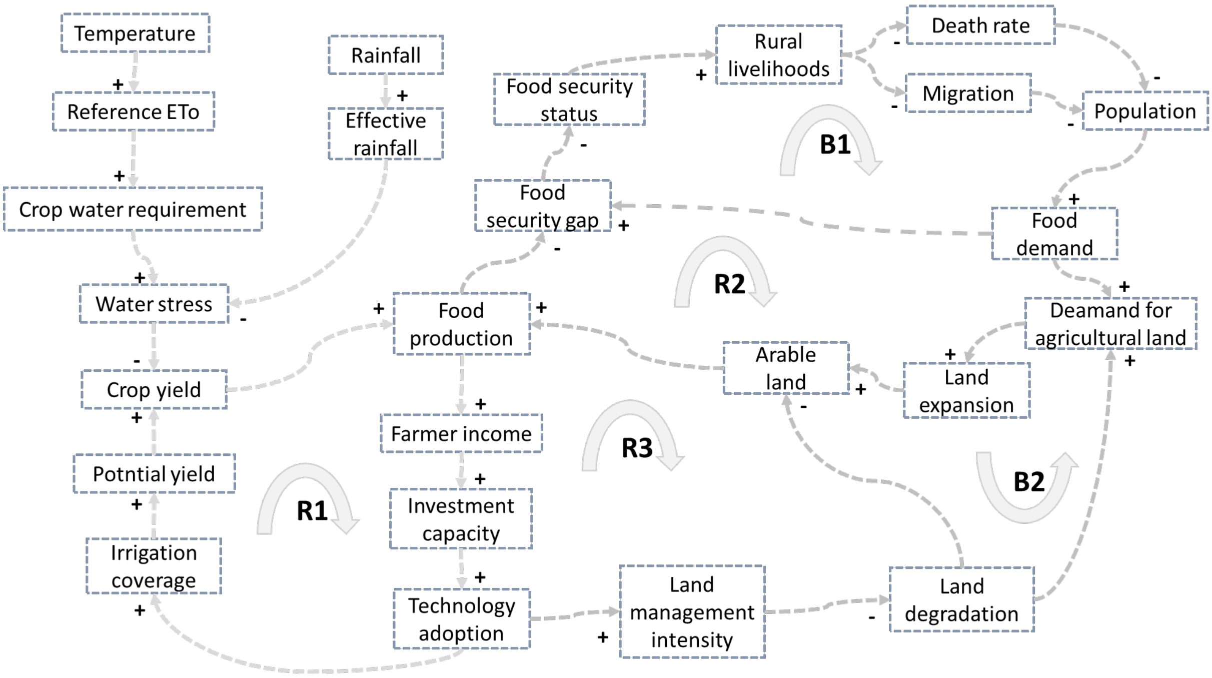

Figure 2. Conceptual presentation of the relationship between climate, food production, and land in the systems analysis modeling.

The various loops in the system are described as follows:

B1. *Food insecurity-demographic buffering*. A widening food security gap undermines rural livelihoods, increasing mortality and/or out-migration, which reduces population and food demand and partially dampens the original gap (a stabilizing mechanism with high welfare costs).

B2. *Degradation-expansion land compensation*. Loss of arable land and rising demand trigger land expansion to compensate for degradation-driven constraints, partially restoring arable land while shifting pressure across the land system.

R1. *Investment-irrigation yield intensification*. Higher yields raise production and income, strengthening investment capacity and technology adoption that expand irrigation coverage and potential yield, reinforcing crop yield gains.

R2. *Production-population-land expansion*. Higher production improves food security and livelihoods, supporting population growth and food demand, which raise land demand and expansion, increasing arable land and reinforcing production.

R3. *Investment-land stewardship* (*sustainable intensification*). Production-driven income supports investment and adoption of improved practices; better land management can reduce degradation and stabilize arable land, reinforcing production through a maintained land base.

The land subsystem mediates longer-run trajectories through a tension between intensification and degradation. Reinforcing loop R1 describes a productivity-led pathway: higher crop yields increase food production and farmer income, which strengthen investment capacity and technology adoption, expand irrigation coverage, and raise potential yield, pushing yields upward. R2 adds a demand-mediated growth channel, where improved food security supports livelihoods and population growth, increasing food demand, driving demand for agricultural land and land expansion, and increasing arable land to sustain production. R3 represents a second investment pathway in which capital and improved practices raise land management intensity; when management quality is high, this can reduce land degradation and maintain arable land, aligning with sustainable intensification principles that seek higher output from existing land while conserving the resource base (FAO, 2011). The countervailing balancing loop B2 reflects land constraints. Here, degradation reduces arable land and can depress production, but the resulting pressure induces expansion to compensate, risking a trap in which short-term gains are offset by further degradation. Tittonell and Giller (2013) demonstrated that continued cropping without sufficient inputs of nutrients and organic matter leads to soil degradation and renders many soils in a non-responsive state, creating a chronic poverty trap where smallholder farmers cannot benefit from increased inputs of fertiliser and labour. These dynamics echo broader assessments that land degradation and climate pressures interact with food security and livelihoods, and that managing cross-sectoral linkages is necessary for robust policy design (IPCC, 2019; Giordano et al., 2024).

3.3.2. Model Simulation and Policy Analysis

Once calibrated using historical data on crop production and population, as well as recent studies on farmer incomes in Gambia's rural agricultural landscapes, such as Yengoh (2026), the model is used to simulate the system's behavior from the baseline period through 2060 under the SSP2-4.5 and SSP5-8.5 climate scenarios. The primary outputs for analysis will be national food security (measured as the self-sufficiency ratio), average farmer income, and groundwater sustainability.

Three policy scenarios will be simulated to assess their effectiveness as adaptation strategies:

1. *Business-as-Usual* (*BAU*). No significant new investment in agricultural wa-

ter management.

2. *Infrastructure investment*. A phased investment in expanding the area equipped for irrigation by 10% over two decades.
3. *Crop diversification*. A program that incentivizes a gradual shift of 15% of land from water-intensive crops to more drought-tolerant traditional grains (millet and sorghum).

The results of these simulations will be compared to identify high-leverage interventions and potential trade-offs, providing a dynamic and policy-relevant extension to the static CROPWAT analysis.

The system dynamics model was validated against historical data from 2010 to 2020 to ensure its structural and behavioral realism, using data from the World Bank and FAOSTAT (see **Appendix**). The results showed a structural bias of −5.5% for population and 66.7% for total crop production. The normalized root mean square error (NRMSE) was 5.5% for population and 68.0% for total production, indicating the model's simulated population figures were closely aligned with historical data, while simulated crop production showed a significant overestimation compared to observed figures.

4. Results

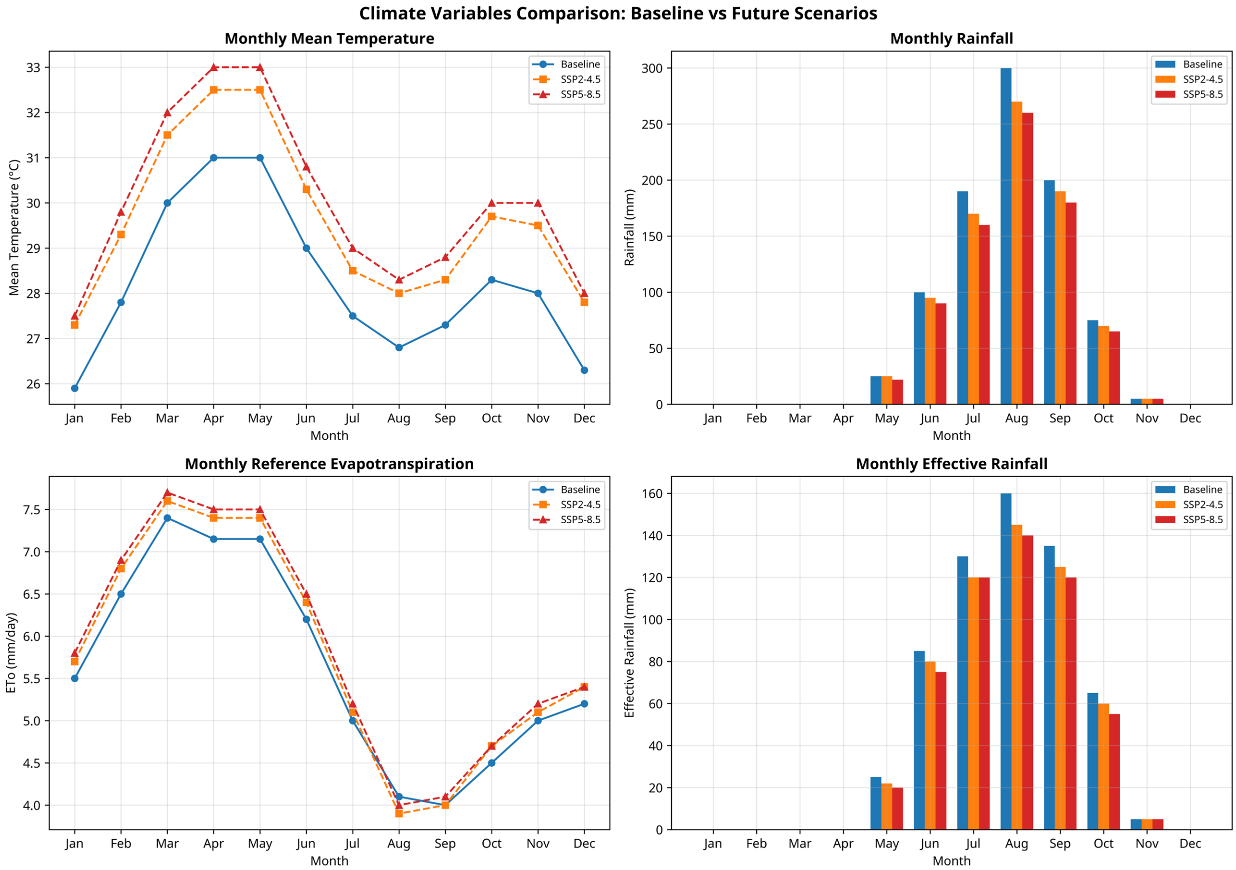

Figure 3. Monthly climate variables under baseline (1995-2014) and projected future conditions (2040-2059) for SSP2-4.5 and SSP5-8.5 scenarios.

Under baseline conditions (1995-2014), mean monthly temperatures range from approximately 26˚C in December-January to a peak of 31˚C during the hot, dry months of April and May, before moderating slightly with the onset of the rains (**Figure 3**). Annual rainfall totals approximately 880 mm, but this precipitation is highly concentrated, with August alone receiving nearly 300 mm, while the seven months from November to May are virtually rainless.

This extreme seasonality means that effective rainfall, the portion actually available to crops, peaks at around 155 mm in August and drops to near zero for more than half the year. Reference evapotranspiration (ETo) follows an inverse pattern to rainfall, reaching its maximum of approximately 7.4 mm/day during the hot, dry months of March-April when atmospheric demand for water is highest, and declining to around 3.8 mm/day in August when cloud cover and humidity increase. This mismatch between peak evaporative demand in the dry season and water availability during the wet season creates a fundamental constraint on agricultural productivity, one that climate change is projected to intensify as temperatures rise and rainfall becomes more erratic.

4.1. Climate Change Impacts on Evapotranspiration and Crop Water Requirements

The analysis began by quantifying the projected changes in key climate variables that directly influence crop water needs. Using downscaled CMIP6 data for The Gambia, the reference evapotranspiration (ETo) for the mid-century period (2040-2059) is calculated under two shared socioeconomic pathways, SSP2-4.5 (medium emissions) and SSP5-8.5 (high emissions), and compared to the historical baseline (1995-2014).

4.1.1. Projected Changes in Reference Evapotranspiration (ETo)

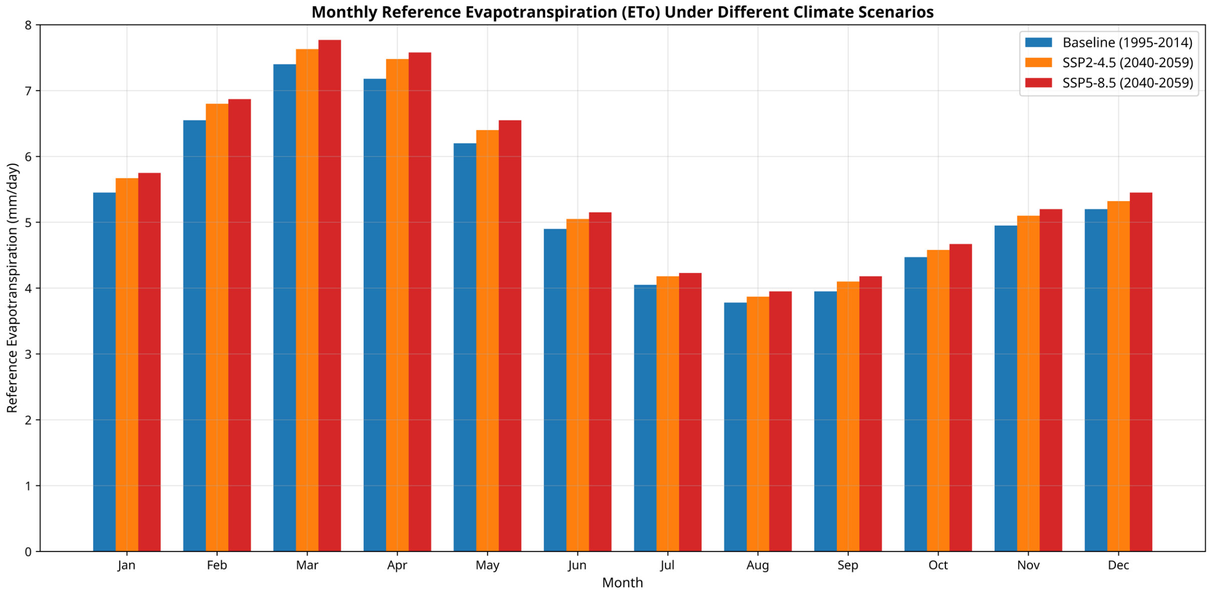

Figure 4. Monthly Reference Evapotranspiration (ETo) under different climate scenarios.

The analysis shows a consistent and significant increase in ETo across all months under both future scenarios, driven primarily by rising temperatures (**Figure 4**). For the baseline period, the total annual ETo was approximately 1870 mm. Under the SSP2-4.5 scenario, this is projected to increase by 6.3% to 1988 mm annually. The high-emissions SSP5-8.5 scenario results in a more pronounced increase of 7.4%, bringing the total annual ETo to 2009 mm. **Figure 4** illustrates the monthly ETo values for the baseline and the two future scenarios, highlighting that the largest absolute increases are projected to occur during the dry season (January to April), when temperatures are highest.

4.1.2. Crop-Specific Water Requirements (CWR)

The increased atmospheric water demand, reflected in higher ETo, translates directly to higher crop water requirements (CWR) for all five major crops analyzed. As shown in **Figure 5** and detailed in **Table 2**, rice consistently has the highest water requirement, while millet has the lowest. Under the SSP5-8.5 scenario, the seasonal CWR for rice is projected to increase by 4.3%, from 714 mm to 745 mm. Similar increases are projected for the other crops, with groundnut, maize, millet, and sorghum showing CWR increases of 4.3% under the same high-emissions scenario.

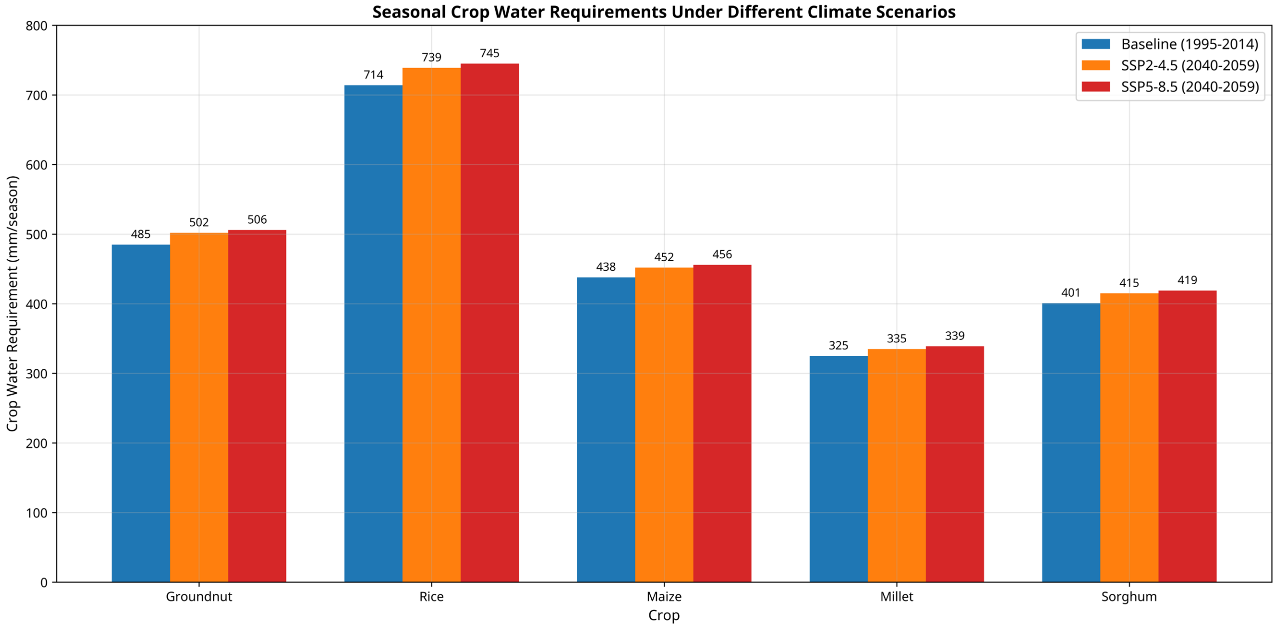

Figure 5. Seasonal crop water requirements under different climate scenarios.

The direct biophysical consequence of rising temperatures and changing climatic conditions is a consistent increase in the seasonal Crop Water Requirement (CWR) for all major crops in The Gambia. As illustrated in **Figure 6**, by the mid-century period (2040-2059), all five crops studied—groundnut, rice, maize, millet, and sorghum—are projected to experience a uniform increase in water demand. Under the moderate emissions scenario (SSP2-4.5), CWR increases by approximately 3.3% - 3.4% relative to the 1995-2014 baseline. Under the high emissions scenario (SSP5-8.5), this increase is more pronounced, with all crops requiring approximately 4.3% more water over their growing season. This uniform rise in CWR across different crop types highlights the systemic nature of the impact, driven primarily by the higher evaporative demand (ETo) resulting from increased temperatures.

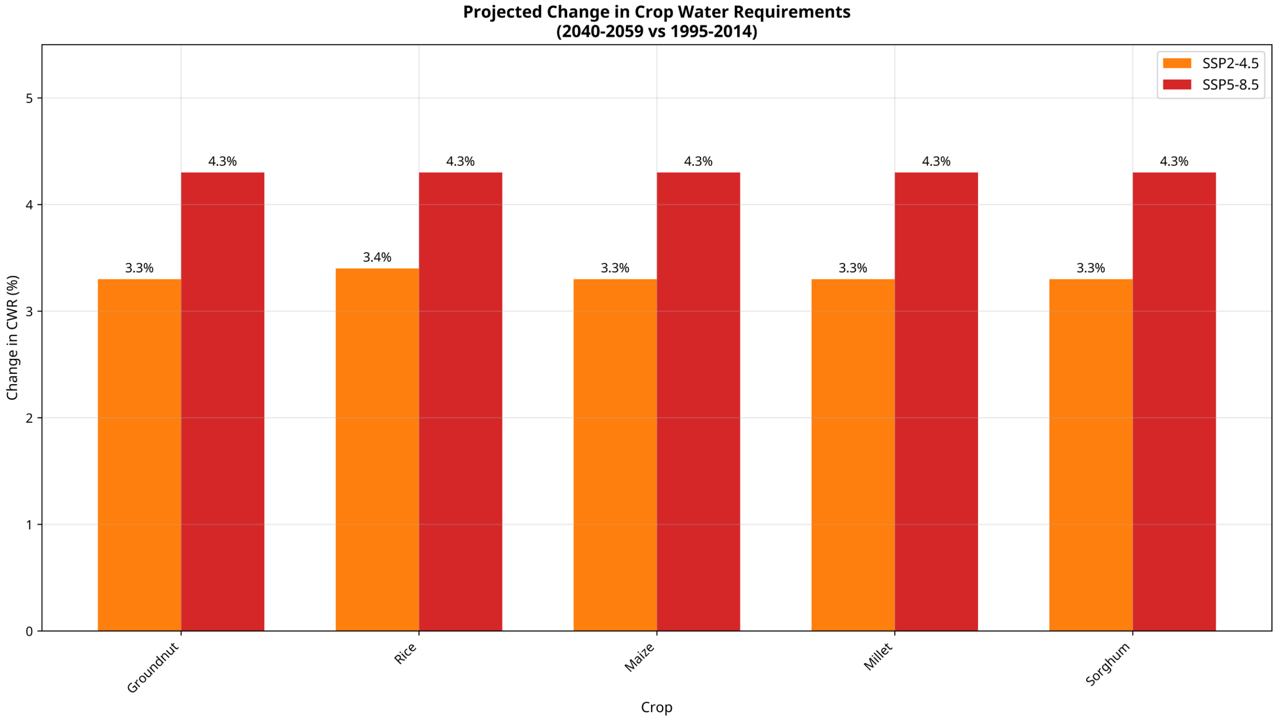

Figure 6. Projected change in water requirements for all crops in 2040-2059, relative to the baseline period of 1995-2014.

4.1.3. Net Irrigation Requirements

The combination of higher CWR and a slight projected decrease in effective rainfall during the growing season results in a substantial increase in the NIR, which represents the water deficit that must be supplied by irrigation to avoid crop water stress. For the baseline period, only rice, with its high water needs, showed a significant irrigation requirement of 227 mm per season (Figure 7). For all other crops, the effective rainfall was sufficient to meet the CWR. While the other rain-fed crops still do not show a seasonal water deficit in this aggregated model, the shrinking gap between water supply and demand indicates a rising vulnerability to mid-season droughts, a factor explored in the system dynamics model.

Table 2 presents a comparative summary of the seasonal Crop Water Requirement (CWR), effective rainfall (Peff), and Net Irrigation Requirement (NIR) for the five major crops under baseline and projected climate scenarios. The results reveal a consistent pattern across all crops. CWR increases while Peff decreases under both future scenarios. For the rain-fed crops groundnut, maize, millet, and sorghum, the effective rainfall during the growing season exceeds the CWR under all scenarios, resulting in a NIR of zero. This indicates that, on a seasonal aggregate basis, these crops can theoretically meet their water needs from rainfall alone, though this does not account for intra-seasonal dry spells that may cause periodic water stress. Rice, however, presents a markedly different situation. Its higher water demand (714.2 mm baseline CWR) already exceeds effective rainfall (487.5 mm) under current conditions, creating a baseline irrigation deficit of 226.7 mm per season. Under climate change, this deficit widens substantially. The NIR increases to 260.5 mm (+14.9%) under SSP2-4.5 and to 276.3 mm (+21.9%) under SSP5-8.5, driven by both rising CWR and declining effective rainfall. This finding highlights the acute vulnerability of irrigated rice production to climate change in The Gambia.

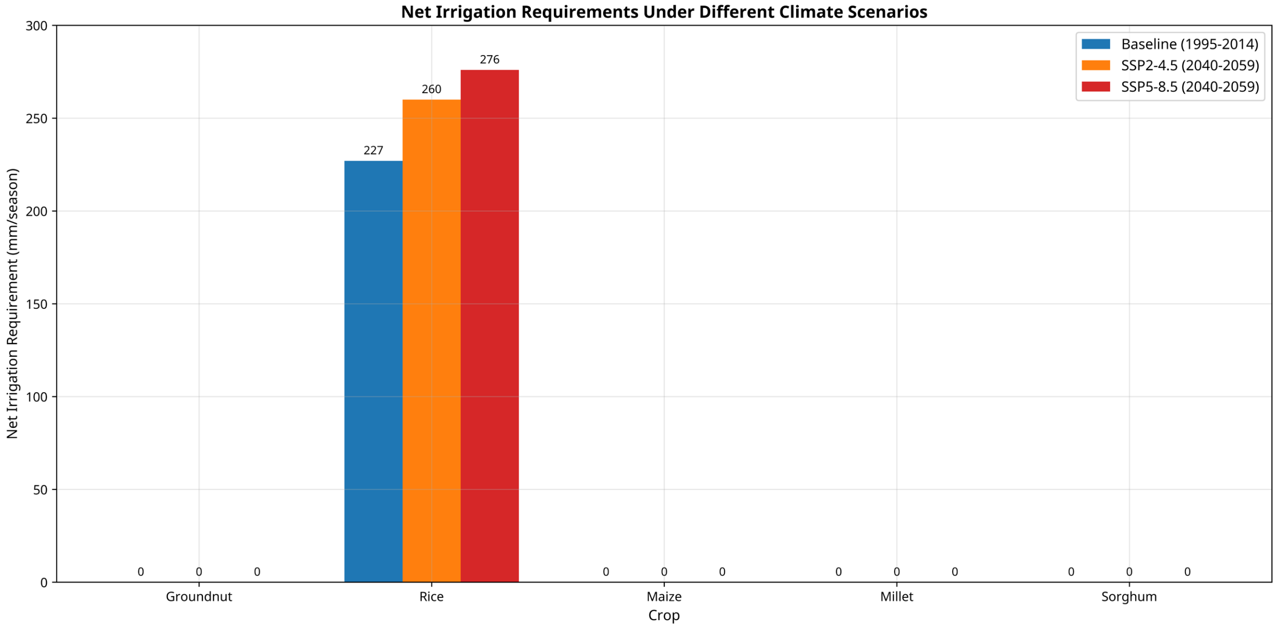

Figure 7. Net irrigation requirements under different climate scenarios.

Table 2. Comparative summary of CWR and NIR (mm/season).

Crop	Scenario	CWR (mm)	Peff (mm)	NIR (mm)	CWR Change (%)	NIR Change (%)
Groundnut	Baseline	485.4	528.7	0.0	-	-
	SSP2-4.5	501.5	518.3	0.0	+3.3%	0.0%
	SSP5-8.5	506.2	507.3	0.0	+4.3%	0.0%
Rice	Baseline	714.2	487.5	226.7	-	-
	SSP2-4.5	738.6	478.1	260.5	+3.4%	+14.9%
	SSP5-8.5	744.9	468.6	276.3	+4.3%	+21.9%
Maize	Baseline	437.6	507.4	0.0	-	-
	SSP2-4.5	452.0	497.5	0.0	+3.3%	0.0%
	SSP5-8.5	456.4	487.3	0.0	+4.3%	0.0%

Continued

Millet	Baseline	325.0	498.2	0.0	-	-
	SSP2-4.5	335.7	488.4	0.0	+3.3%	0.0%
	SSP5-8.5	339.0	478.5	0.0	+4.3%	0.0%
Sorghum	Baseline	401.2	512.6	0.0	-	-
	SSP2-4.5	414.4	502.5	0.0	+3.3%	0.0%
	SSP5-8.5	418.5	492.3	0.0	+4.3%	0.0%

While all crops exhibit increased water demand, the most severe impact is observed in the Net Irrigation Requirement (NIR) for rice, the only crop in this study cultivated under irrigated conditions. **Figure 8** reveals a dramatic projected increase in the irrigation water needed to supplement rainfall and avoid yield loss for rice. Under the SSP2-4.5 scenario, the NIR for rice is projected to increase by a substantial 14.9% compared to the baseline period.

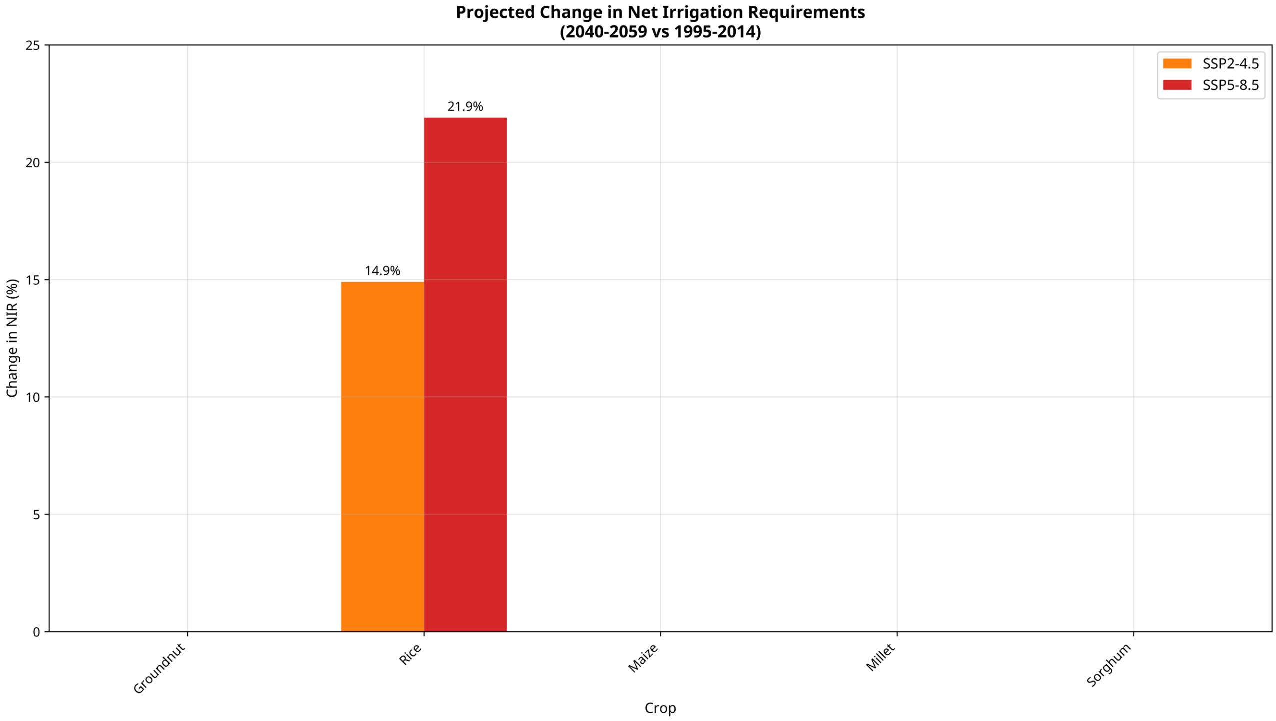

Figure 8. Projected change in net irrigation requirement in 2040-2059, relative to the base period of 1995-2014.

This increases to a 21.9% increase under the more severe SSP5-8.5 scenario. For the other four crops (groundnut, maize, millet, and sorghum), which are modeled as purely rain-fed, the NIR remains zero. This result highlights the acute vulnerability of The Gambia's irrigated rice production, as the widening gap between crop water needs and available effective rainfall will place immense strain on the country's already limited water and irrigation infrastructure.

4.2. System-Level Dynamics and Policy Scenario Analysis

The system dynamics model simulated the long-term (2020-2060) behavior of The Gambia's agricultural system, integrating the biophysical impacts from the CROPWAT analysis with socioeconomic variables. Three policy scenarios were tested against the SSP2-4.5 and SSP5-8.5 climate futures: Business-as-Usual (BAU), Infrastructure Investment, and Crop Diversification.

4.2.1. Food Security Projections

Under the Business-as-Usual (BAU) policy scenario, The Gambia's food security index (defined as the food self-sufficiency ratio) is projected to decline significantly under both climate scenarios. As shown in Figure 9, the index drops from a baseline of 0.65 in 2020 to approximately 0.35 by 2060. This decline is driven by a combination of climate-induced yield stagnation and rapid population growth. The "Infrastructure" and "Diversification" policy interventions show a marginal ability to slow this decline, but neither is sufficient to reverse the trend. The Food Security Index under these improved policy scenarios is only slightly higher, reaching approximately 0.37 by 2060. This indicates that while these interventions help, they are insufficient to counteract the overwhelming pressures of climate change and population growth on the national food system.

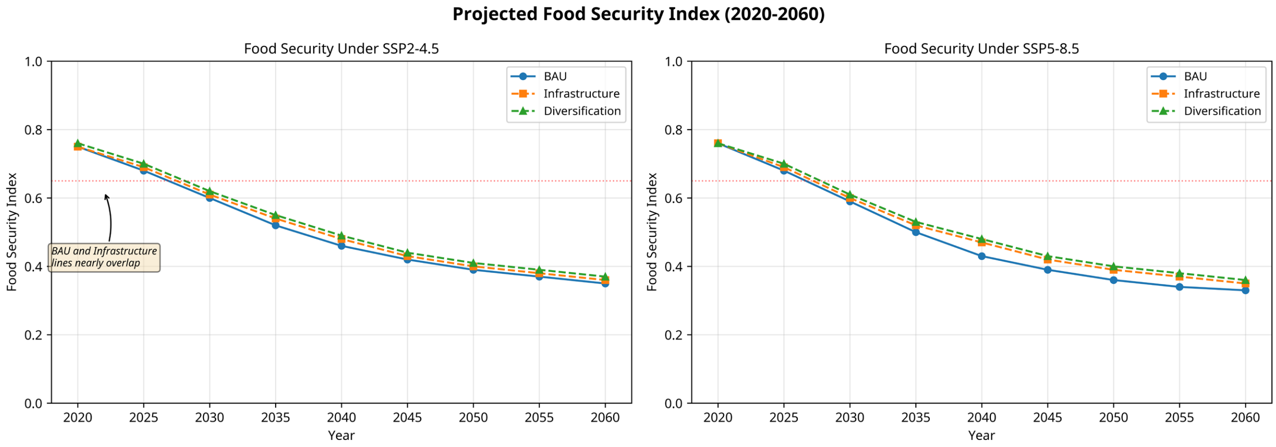

Figure 9. Projected food security index (2020-2060).

4.2.2. Crop Yield and Farmer Income

Average crop yields show a slight decline under the BAU scenario, driven by increasing water and heat stress. The policy interventions, particularly the "Infrastructure" scenario, which promotes irrigation, help to stabilize and slightly increase yields over the long term (Figure 10). By 2060, under the SSP5-8.5 climate scenario, the average yield in the BAU case is 1.15 t/ha, whereas in the Infrastructure and Diversification scenarios, it improves to 1.22 t/ha.

This modest yield improvement does not translate into significant gains in farmer income. Average farmer income is projected to decline across all scenarios, falling from a baseline of around $145 USD/year to below $68 - $75 per year by

2060 (**Figure 11**). The high costs of production and irrigation, coupled with low crop prices and a growing rural population, trap farmers in a cycle of low profitability, even when yields are stabilized.

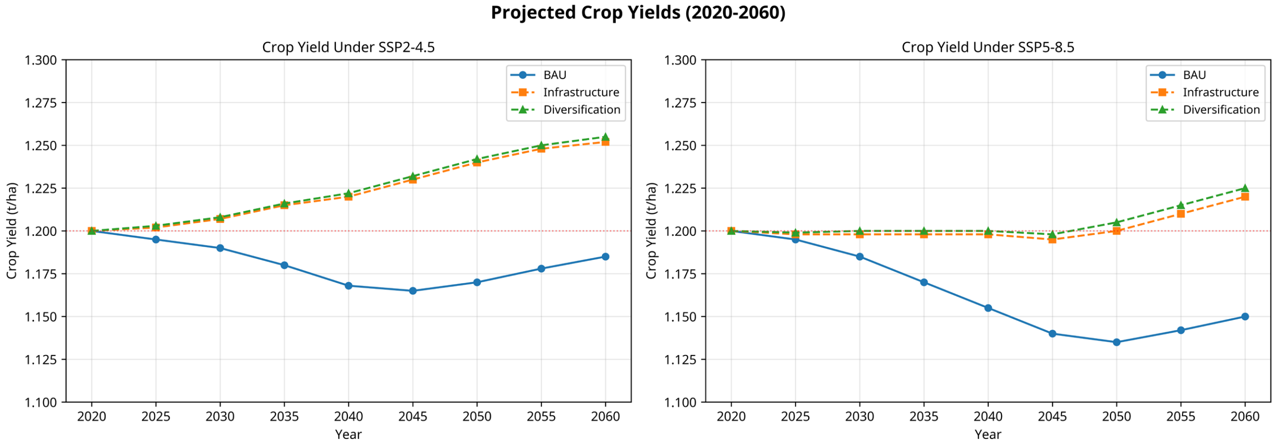

Figure 10. Projected crop yields (2020-2060).

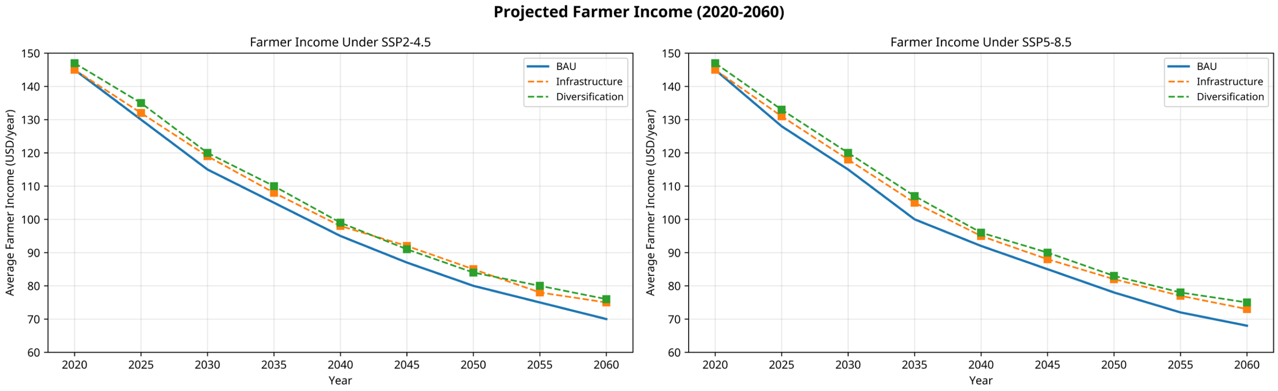

Figure 11. Projected farmer income (2020-2060).

4.2.3. Effectiveness of Policy Interventions

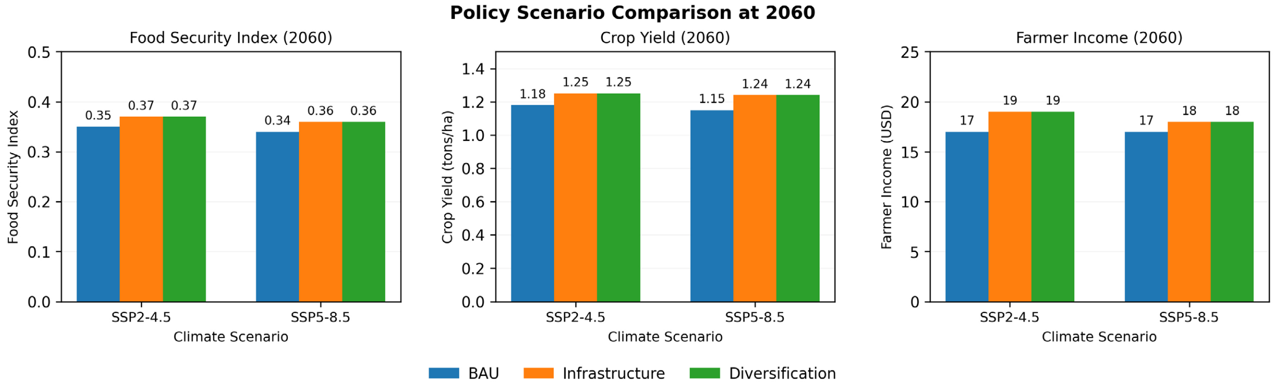

Figure 12. Comparison of key outcome indicators in 2060 under three policy scenarios (Business-as-Usual, Infrastructure Investment, and Crop Diversification) for SSP2-4.5 and SSP5-8.5 climate pathways.

The simulation results highlight the differential impacts of the policy scenarios. The "Infrastructure" scenario, which focuses on expanding irrigation, is the most effective at stabilizing crop yields by mitigating water stress (**Figure 12**). Its high investment cost limits its impact on farmers' income. The "Diversification" scenario shows similar modest benefits to yield but has a lower implementation cost.

Figure 12 shows that while both adaptation policies offer an improvement over the BAU trajectory, the magnitude of this improvement is small. For instance, under the high-emissions SSP5-8.5 scenario, the Infrastructure policy only improves the food security index from 0.34 to 0.36 compared to BAU. This emphasizes the profound challenge facing The Gambia, where even proactive adaptation measures struggle to keep pace with the combined pressures of climate change and socioeconomic trends.

5. Discussion

This study's hybrid modeling approach, integrating biophysical crop water modeling with a wider socioeconomic system dynamics framework, provides a multilayered perspective on the future of agriculture in The Gambia under climate change. The results highlight a dual challenge: a direct, quantifiable increase in the water stress faced by crops, and a more complex, systemic erosion of food security and rural livelihoods that current adaptation strategies may be insufficient to overcome.

5.1. Growing Water Demand and Vulnerability

The CROPWAT analysis confirms a clear trend. Rising temperatures are set to significantly increase atmospheric water demand (ETo) in The Gambia, by as much as 7.4% under a high-emissions scenario (SSP5-8.5) by mid-century. This finding is consistent with the fundamental principles of the Penman-Monteith equation and aligns with regional projections for West Africa (Sultan & Gaetani, 2016; Sylla et al., 2018). The calculated increase in crop-specific water requirements (CWR) of 3% - 4% is a direct consequence of this heightened ETo. While this percentage may seem modest, it represents a substantial new stress on a system already operating at its margins.

The most important finding from this part of the analysis is the projected 21.9% increase in the Net Irrigation Requirement (NIR) for rice under the SSP5-8.5 scenario. This represents a significant new water deficit that, if unmet, will directly translate into yield losses. This result echoes the findings of Gabr (2023), whose work in a different semi-arid region also projected substantial increases in irrigation demand under high-emissions futures. Given that The Gambia currently irrigates just over 1% of its cultivated land (FAO, 2024), and that rice is the primary staple for which the country is already 80% - 90% import-dependent, this escalating water deficit for the one crop that is commonly irrigated presents a formidable challenge to national food security goals.

For the other major rain-fed crops (groundnut, maize, millet, and sorghum), the model did not project a seasonal water deficit, even under future scenarios. This result, however, should be interpreted with caution. It reflects the fact that, on an aggregated monthly basis, total seasonal rainfall still exceeds the total seasonal CWR. This masks the threat of intra-seasonal drought. The West African monsoon is characterized by high variability, and IPCC AR6 highlights that the region is experiencing fewer but more intense rainfall events, alongside an increase in the frequency of meteorological and agricultural droughts (IPCC, 2022). Therefore, while the total volume of water may be sufficient, its temporal distribution is becoming less reliable. A dry spell of just a few weeks during a growth stage, such as flowering, can devastate rain-fed crop yields, a nuance that a monthly water balance model like CROPWAT cannot fully capture but which the system dynamics model begins to address through its yield-stress functions.

5.2. The Socioeconomic Trap, Why Incremental Adaptation Is Not Enough

The system dynamics simulation gave rise to some important results in relation to food security in The Gambia. The model projects a steep decline in The Gambia's food security index, from 0.65 in 2020 to around 0.35 by 2060, across all policy and climate scenarios. This demonstrates that the combined pressures of rapid population growth (projected at over 2% annually for the coming decades) and climate-induced stress on agricultural productivity are set to overwhelm the system's capacity to feed itself. This finding provides a dynamic and quantitative validation of the concerns raised by Carr et al. (2024), who concluded that The Gambia's current cropland will not meet future food demand.

Another important contribution of the system dynamics model simulation is its revelation of a "policy resistance". The simulations showed that even proactive, well-intentioned adaptation strategies, such as the "Infrastructure Investment" and "Crop Diversification" scenarios, had only a marginal impact on the long-term food security trajectory. They slowed the decline but could not reverse it. This suggests that the system is caught in a reinforcing feedback loop, or an "adaptation trap". Climate change suppresses yields and incomes, which in turn limits the capital available for farmers to invest in the very adaptation measures (like irrigation or improved inputs) that could break the cycle. The model shows that farmer income is projected to decline even in the adaptation scenarios, because the high costs of inputs and the small gains in yield are not enough to create a pathway to prosperity. Lamichhane et al. (2022) found that techno-informational, economic, and environmental barriers are strongly and inversely correlated with the adoption of adaptation measures, suggesting that agricultural development policies must consider adaptation measures tailored to specific agroecosystems to effectively alleviate barriers and promote smallholder resilience.

This result challenges the prevailing narrative that simply implementing a checklist of climate-smart agriculture (CSA) practices will be sufficient. The model outputs in this study align with the findings of Segnon et al. (2022), who systematically identified 24 potential adaptation options for The Gambia, but also noted the paucity of evidence for their effectiveness in the local context and the importance of considering barriers to adoption. Results of the simulation in this study suggest that the primary barrier is systemic; the socioeconomic context itself prevents the widespread adoption and success of these technical solutions. The problem is not a lack of knowledge about what to do, but a lack of capacity to do it at the scale and speed required.

5.3. Policy Implications

The findings of this study have profound implications for policymakers in The Gambia and for its international development partners. The results strongly suggest that the country's current adaptation planning, as outlined in its National Adaptation Programme of Action (NAPA) and subsequent strategies, may be necessary but is likely insufficient (Government of The Gambia, 2007). These plans rightly focus on options like water management, crop diversification, and climate information services. Model outputs show that these are helpful, but they are incremental adjustments to a system that is facing an existential threat.

A business-as-usual approach, as simulated in the BAU scenario, leads to a severe decline in national food security and rural welfare. The policy debate, therefore, must shift from a focus on isolated, project-based interventions to one centered on impactful, systemic change. What might this look like? The model points to several high-leverage areas:

1. *De-linking livelihoods from rain-fed agriculture*. With over 90% of agriculture being rain-fed, the entire economy is hostage to the increasingly erratic monsoon. A national strategy focused on creating large-scale employment opportunities outside of traditional agriculture could be the most effective long-term adaptation strategy, as it would reduce the population's significant direct dependence on rain-fed agricultural systems that are vulnerable to a changing climate. Key sectors for labor absorption include the services sector, which already employs over half the workforce (World Bank, 2023c), and the tourism industry, which contributes approximately 20% to GDP and is a growing source of employment (UNCTAD, 2019). Further opportunities exist in the coastal fisheries sector, which provides direct and indirect employment to an estimated 25,000 - 30,000 people and is a significant source of nutrition and export earnings (UNCTAD, 2013), and the emerging digital economy, which offers potential for youth employment and entrepreneurship through initiatives such as the National Youth and Women Development and Empowerment Through ICTs Strategy (Ministry of Information and Communication Infrastructure, 2020).
2. *High levels of state-led irrigation infrastructure*. The model showed that farmer-led, income-dependent irrigation expansion is too slow. Only a large-scale, nationally coordinated program to take advantage of the Gambia River as a key resource for irrigation could potentially alter the trajectory of water availability for agriculture.
3. *Structural economic transformation*. The low profitability of farming is an

essential part of the trap. Policies that address the structural issues, such as input costs, market access, post-harvest losses, and low farm-gate prices, could be more impactful than policies that focus solely on climate resilience. Without a viable economic foundation, climate adaptation becomes an unaffordable luxury for subsistence farmers.

5.4. Limitations of the Study

While this study provides valuable insights, it is essential to acknowledge its limitations. The CROPWAT model uses a monthly time step, which can mask the impact of short-term dry spells that are critical for rain-fed agriculture. A daily-step crop model could provide a more granular assessment of yield impacts. Second, the system dynamics model is an aggregation and simplification of a highly complex reality. The parameters used are based on the best available data, but they carry uncertainties. For example, the coefficients for farmer decision-making, technology adoption rates, and the precise impact of policies are based on literature averages and would benefit from in-country empirical validation. Third, the model does not explicitly account for the impacts of extreme weather events, such as floods or severe storms, which are also projected to increase in frequency and intensity. The policy scenarios tested are stylized representations; real-world policy implementation is far more complex and subject to political, social, and institutional factors not captured in the model.

Notwithstanding these limitations, the study serves its primary purpose, to move beyond a simple impact assessment and explore the dynamic behavior of the entire socio-ecological system. The strength of the model lies not in predicting the exact value of the food security index in 2060, but in revealing the underlying structures and feedback loops that are likely to govern its trajectory.

6. Conclusion

This study set out to assess the impacts of climate change on agriculture in The Gambia using a hybrid modeling approach that connects biophysical crop needs to systemic socioeconomic outcomes. The analysis reveals a future in which rising temperatures will increase the water requirements for all major crops, placing a particular strain on rice, the nation's primary staple. The projected 22% increase in irrigation demand for rice under a high-emissions scenario is a direct and quantifiable threat to the country's food production capacity.

The system dynamics model demonstrates that these biophysical stresses are amplified by socioeconomic factors, creating a negative feedback loop that traps the agricultural system in a state of declining productivity and deepening poverty. The simulations show that even with the implementation of currently favored adaptation strategies, such as modest investments in irrigation and crop diversification, The Gambia faces a decline in its ability to feed itself, with the national food security index projected to fall by nearly half by 2060. The key message is that incremental adjustments are insufficient to counter the powerful, intertwined forces of climate change and population growth.

The primary contribution of this research is the quantification of this “policy resistance” and the demonstration that, without serious interventions, The Gambia’s agricultural sector is on an unsustainable trajectory. The study concludes that the policy focus must be elevated from the field level to the systemic level. The challenge is not merely to help farmers adapt to a changing climate, but to transform the economic and social structures that define their vulnerability. This requires a shift away from isolated agricultural projects and toward integrated, national-level strategies that may include large-scale water infrastructure development, economic diversification to reduce reliance on climate-sensitive livelihoods, and structural reforms to improve the economic viability of farming.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Appendix: System Dynamics Model Specification

1. Overall Model Structure

The SD model integrates five subsystems: Climate, Water Resources, Agricultural Production, Socioeconomic, and Policy. These subsystems interact through feedback loops that govern the long-term behavior of The Gambia's agro-ecological system over a 40-year simulation period (2020-2060).

The model operates on an annual time step (dt = 1 year). At each time step, the Climate Subsystem provides temperature and rainfall values based on the selected climate scenario. These values drive the Water Resources and Agricultural Production subsystems, which calculate water availability and crop yields. The Socioeconomic Subsystem then computes population, food security, and farmer income based on agricultural output. The Policy Subsystem modifies parameters within the other subsystems according to the selected intervention scenario.

2. Climate Subsystem

The Climate Subsystem serves as the primary external driver of the model. It does not contain internal feedback dynamics; rather, it reads projected values of temperature and rainfall from lookup tables based on the selected climate scenario (SSP2-4.5 or SSP5-8.5). These projections are derived from CMIP6 multi-model ensemble means, downscaled to the national level for The Gambia.

Reference Evapotranspiration (ETo)

For the SD model, a simplified temperature-based approximation is used:

$$\text{ETo\_annual} = \text{ETo\_baseline} \times (1 + 0.04 \times \Delta T)$$

where: ETo_baseline = 1825 mm/year (baseline annual ETo for The Gambia), ΔT = Temperature change from baseline [˚C], 0.04 = Sensitivity coefficient (4% increase in ETo per 1˚C warming).

Parameter Values

Parameter	Baseline Value	SSP2-4.5 (2050)	SSP5-8.5 (2050)	Source
Mean Annual Temperature	27.8˚C	29.2˚C (+1.4˚C)	29.6˚C (+1.8˚C)	World Bank CCKP
Annual Rainfall	884 mm	849 mm (−4%)	813 mm (−8%)	World Bank CCKP
Annual ETo	1825 mm	1940 mm (+6.3%)	1960 mm (+7.4%)	Calculated

Assumptions

1. Climate projections follow a linear interpolation between baseline (2020) and mid-century (2050) values.
2. Inter-annual variability is not modeled; the simulation uses smoothed trend values.
3. Wind speed, humidity, and solar radiation are assumed constant at baseline values due to limited projection data.
4. The 4% ETo sensitivity to temperature is based on regional studies (Sylla et

al., 2018).

Data Sources

- Baseline climate data: FAO CLIMWAT 2.0 database for Yundum station, The Gambia (1995-2014 average).
- Future climate projections: World Bank Climate Change Knowledge Portal, CMIP6 ensemble mean for The Gambia, SSP2-4.5 and SSP5-8.5 scenarios (World Bank, 2023a).

Effective Rainfall (Peff)

Effective rainfall is calculated using the USDA Soil Conservation Service method (USDA Soil Conservation Service, 1970):

If $P \le 250$ mm/month:

$$\text{Peff} = P \times (125 - 0.2 \times P)/125$$

If $P > 250$ mm/month:

$$\text{Peff} = 125 + 0.1 \times P$$

where: Peff = Effective rainfall [mm/month], P = Total monthly rainfall [mm/month].

Irrigation Water Supply

$$\text{Irrigation\_Supply} = \text{Irrigation\_Coverage} \times \text{Irrigated\_Area} \times \text{Irrigation\_Efficiency} \times \text{Water\_Availability\_Factor}$$

where:

Irrigation_Coverage = Fraction of agricultural land with irrigation infrastructure [dimensionless];

Irrigated_Area = Total irrigated area [ha];

Irrigation_Efficiency = 0.60 (typical for surface irrigation);

Water_Availability_Factor = MIN (1, Available_Water/Water_Demand).

Water stress Factor

$$\text{Water\_Stress} = 1 - \text{MIN}\left(1, (\text{Peff} + \text{Irrigation\_Supply})/\text{CWR}\right)$$

Stock Equation

$$\text{Irrigation\_Coverage}(t) = \text{Irrigation\_Coverage}(t - dt) + \text{Irrigation\_Investment} \times dt$$

Assumptions

1. The model uses a single, aggregated national water balance; spatial variations are not modeled.
2. Groundwater resources are assumed to be negligible for large-scale irrigation, consistent with current infrastructure limitations.
3. Irrigation efficiency is fixed at 60%, representing typical surface irrigation systems.
4. Water allocation for non-agricultural uses is not explicitly modeled.
5. Rice cultivation is modeled under a supplemental irrigation regime, where rainfall provides the primary water input and irrigation supplements water deficits during dry periods; full water control (paddy flooding) is not assumed, reflecting the limited extent of formal irrigation infrastructure in The Gambia.

Data Sources

- Irrigation coverage: FAO (2024), approximately 1% of cultivated land.
- Irrigation efficiency: FAO Irrigation and Drainage Paper No. 56.

3. Agricultural Production Subsystem

The Agricultural Production Subsystem simulates crop water requirements, calculates actual yields based on water stress, and aggregates total national food production. It is the core biophysical component of the model.

Crop Water Requirement (CWR)

$$CWR = \Sigma\ (Kc\_i \times ETo \times Growing\_Days\_i)$$

where: CWR = Seasonal crop water requirement [mm/season]; Kc_i = Crop coefficient for growth stage i [dimensionless]; ETo = Reference evapotranspiration [mm/day]; Growing_Days_i = Duration of growth stage i [days].

Actual Yield (Ya)

The FAO 33 water-yield relationship (Steduto et al., 2012):

$$Ya = Yp \times (1 - Ky \times (1 - ETa/ETc))$$

where: Ya = Actual yield [t/ha]; Yp = Potential yield [t/ha]; Ky = Yield response factor [dimensionless]; ETa = Actual crop evapotranspiration [mm]; ETc = Crop evapotranspiration under no stress (= CWR) [mm].

Implementation

$$Ya = Yp \times (1 - Ky \times Water\_Stress) \times Technology\_Index$$

Total Food Production

$$Total\_Production = \Sigma\ (Ya\_crop \times Area\_crop)$$

Crop Parameters

Crop	Growing Period (Days)	Kc (Average)	Ky	Potential Yield (t/ha)	Cultivated Area (ha)
Groundnut	120	0.70	0.70	1.2	120,000
Rice	150	1.10	1.10	2.5	50,000
Maize	120	0.80	1.25	1.8	40,000
Millet	90	0.55	0.90	0.8	80,000
Sorghum	120	0.65	0.90	1.0	60,000

Stock and Flow Structure

Element	**Type**	**Initial Value**	**Units**
Technology_Index	Stock	1.0	Dimensionless
Arable_Land	Stock	350,000	Ha
Technology_Adoption	Flow	Varies by Scenario	Index/Year
Land_Degradation	Flow	0.005	Fraction/Year

Stock Equations

$$\text{Technology\_Index}(t) = \text{Technology\_Index}(t - dt) + \text{Technology\_Adoption} \times dt$$

$$\text{Arable\_Land}(t) = \text{Arable\_Land}(t - dt) - \text{Land\_Degradation} \times \text{Arable\_Land}(t - dt) \times dt$$

Assumptions

1. Crop coefficients (Kc) and yield response factors (Ky) are representative of varieties commonly grown in The Gambia.
2. The relationship between water stress and yield loss is linear (FAO 33 methodology).
3. Pests, diseases, and nutrient limitations are implicitly captured in the Potential Yield parameter.
4. Land degradation occurs at a constant rate of 0.5% per year under BAU.
5. Technology improvements increase potential yield linearly.

Data Sources

- Crop coefficients (Kc): FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998).
- Yield response factors (Ky): FAO Irrigation and Drainage Paper No. 66 (Steduto et al. 2012).
- Baseline yields and cultivated areas: FAOSTAT database (2018-2022 average).

4. Socioeconomic Subsystem

Population Dynamics

$$\text{Population}(t) = \text{Population}(t - dt) + (\text{Births} - \text{Deaths}) \times dt$$

$$\text{Births} = \text{Population} \times \text{Birth\_Rate}$$

$$\text{Deaths} = \text{Population} \times \text{Death\_Rate}$$

where: Birth_Rate = Base_Fertility × Fertility_Modifier/1000 [per year]; Death_Rate = Base_Mortality × Mortality_Modifier/1000 [per year]; Fertility_Modifier = f (Food_Security) decreases with food insecurity; Mortality_Modifier = f (Food_Security) increases with food insecurity.

Food Security Index

Food_Security_Index = MIN (1, Total_Food_Supply/Total_Food_Demand);
Total_Food_Demand = Population × Per_Capita_Requirement;
Per_Capita_Requirement = 180 kg grain equivalent/person/year.

Farmer Income

$$\text{Farmer\_Income} = (\text{Total\_Production} \times \text{Crop\_Price} - \text{Production\_Costs}) / \text{Farm\_Households}$$

Investment Capacity

$$\text{Investment\_Capacity} = \text{MAX}(0, \text{Farmer\_Income} - \text{Subsistence\_Threshold}) \times \text{Savings\_Rate}$$

Parameter values

Parameter	Value	Units	Source
Initial Population (2020)	2,417,000	Persons	World Bank WDI
Base Fertility Rate	36.8	per 1000/year	World Bank WDI
Base Mortality Rate	7.5	per 1000/year	World Bank WDI
Per Capita Food Requirement	180	kg/person/year	FAO
Average Crop Price	250	USD/tone	FAOSTAT
Savings Rate	0.10	Fraction	Estimated

Stock and Flow Structure

Element	Type	Initial value	Units
Population	Stock	2,417,000	Persons
Births	Flow	~89,000	Persons/year
Deaths	Flow	~18,000	Persons/year

Assumptions

1. Population growth follows modified exponential growth, with fertility and mortality rates influenced by food security.
2. Per capita food demand is constant at FAO minimum requirements (2,100 kcal/day ≈ 180 kg grain equivalent/year).
3. Crop prices are exogenous and based on 5-year historical averages; market dynamics are not modeled.
4. The savings rate (10%) represents the fraction of income above subsistence available for investment.

Data sources

- Population data: World Bank World Development Indicators (2020).
- Fertility and mortality rates: World Bank WDI (2020).
- Crop prices: FAOSTAT producer prices (2018-2022 average).

5. Policy Subsystem

Policy Scenario Definitions

Scenario 1. Business-as-Usual (BAU).

Parameter	Value	Affected Subsystem
Irrigation_Investment_Rate	0.0	Water Resources
Technology_Adoption_Rate	0.01 (1%/year)	Agriculture
Crop_Diversification	None	Agriculture

Scenario 2. Infrastructure investment.

Parameter	Value	Affected Subsystem
Irrigation_Investment_Rate	0.0005 (0.05%/year increase in coverage)	Water Resources
Technology_Adoption_Rate	0.01 (1%/year)	Agriculture
Crop_Diversification	None	Agriculture

Scenario 3. Crop diversification.

Parameter	Value	Affected Subsystem
Irrigation_Investment_Rate	0.0	Water Resources
Technology_Adoption_Rate	0.03 (3%/year, drought-resistant varieties)	Agriculture
Crop_Diversification	20% shift from rice/maize to millet/sorghum	Agriculture

Assumptions

1. Policy parameters are implemented consistently throughout the simulation period.
2. The model does not account for political, social, or financial barriers to policy implementation.
3. Policy effects are additive and do not interact with each other.
4. Infrastructure investments begin immediately in 2020 and continue at a constant rate.

6. Model Validation

Validation Approach: The system dynamics model was validated to ensure its structural integrity, parameter credibility, and behavioral realism in relation to its intended purpose. In line with established best practices in the field of system dynamics (Sterman, 2000; Barlas, 1996), the validation process was multifaceted. The primary goal was not to achieve point-by-point historical replication, which is inconsistent with the model's design as a long-term strategic tool, but rather to assess its ability to endogenously generate behaviors that are broadly consistent with historical patterns and to transparently evaluate its structural limitations.

Data Sources for Validation: Historical data for the validation period (2010-2020) were obtained from two primary sources. Data for the national population were sourced from the World Bank's World Development Indicators (WDI) database (World Bank, 2024). Time-series data for area harvested and production for the five specific crops included in the model (maize, millet, groundnut, rice, and sorghum) were obtained from the Food and Agriculture Organization's Statistical Database (FAOSTAT) (FAO, 2024).

Behavioral Validation Results: The behavioral validation was conducted by running the model from 2010 to 2020 using the baseline parameters documented in the main appendix, without fitting or calibration to the historical data. Simulated production was calculated by multiplying the observed area harvested for each year (from FAOSTAT) by the model's potential yield (Yp) parameters. This approach provides an objective assessment of the model's structural performance. The results for population and total crop production are presented in **Figure S1**.

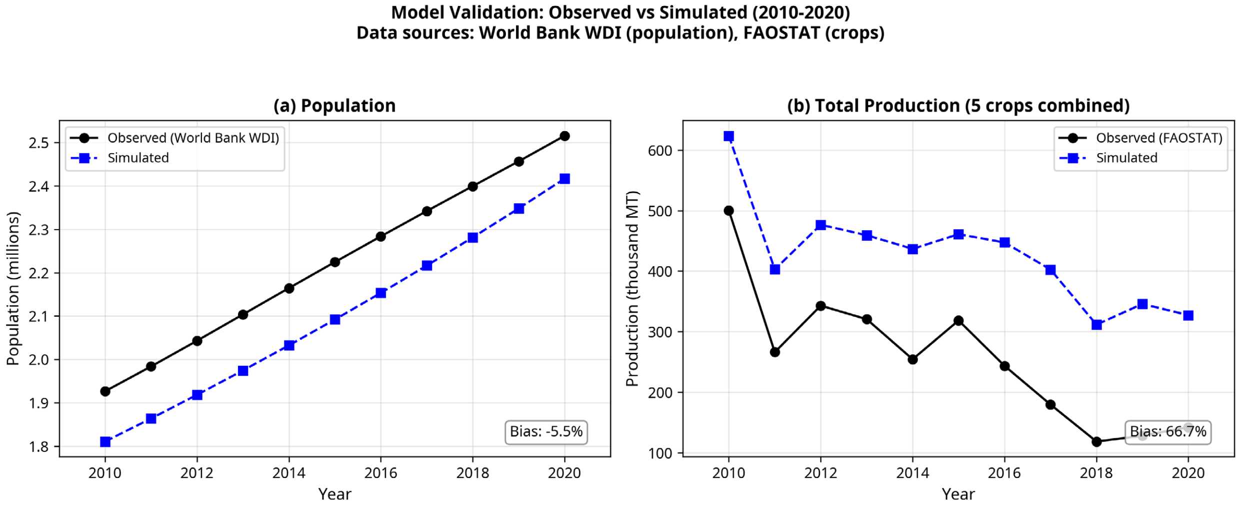

Figure S1. Comparison of simulated model output against observed historical data (2010-2020).

Summary of statistical performance metrics for the validation period (2010-2020).

Variable	Observed Mean	Simulated Mean	Bias (%)	NRMSE (%)
Population	2,222,232	2,100,759	−5.5	5.5
Total Production (5 Crops)	256,162 MT	426,924 MT	66.7	68.0

Definition of Metrics and Interpretation

Bias measures the systematic difference between the mean of the simulated values and the mean of the observed values, expressed as a percentage of the observed mean. A positive bias indicates the model, on average, overestimates the variable. It is calculated as:

$$\text{Bias (\%)} = (\text{Mean (Simulated)} - \text{Mean (Observed)})/\text{Mean (Observed)} * 100$$

Normalized Root Mean Square Error (*NRMSE*) measures the magnitude of the error relative to the mean of the observed values, providing a standardized measure of the model's predictive accuracy. It is calculated as:

$$\text{NRMSE (\%)} = [\text{sqrt (mean ((Simulated} - \text{Observed})^2))]/\text{Mean (Observed)} * 100$$

The validation results highlight the model's capabilities and limitations. The demographic module performs well, with a low bias (−5.5%), indicating that the assumed fertility and mortality rates provide a reasonable basis for long-term population projections. In contrast, the agricultural module shows a significant positive bias (+66.7%) for total production. This discrepancy is an expected outcome of the model's design. The simulated production is based on the model's potential yields (Yp) multiplied by observed harvested area, whereas observed production is consistently lower and more volatile. This is due to a host of factors not explicitly modeled, including intra-seasonal droughts, pest outbreaks, and constraints on access to inputs. The model's purpose is not to simulate these high-frequency, stochastic events but to analyze the long-term impact of structural changes.