

UNVEILING THE RESILIENCE OF SMALLHOLDER FARMERS IN SENEGAL AMIDST
EXTREME CLIMATE CONDITIONS

By

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ABSTRACT

Agriculture plays a critical role in the livelihoods of Senegal's population. However, due to a lack of resources in the agricultural sector, production is significantly affected by extreme climate events such as floods, droughts, and heat waves. This study aims to present a novel resilience approach for assessing various agricultural interventions. We characterize the resilience approach as one that fulfills nutritional requirements affordably and reduces risks for the farmer. The focus is on smallholder farmers in the Groundnut Basin of Senegal who engage in mixed farming, producing both millet and groundnut crops while also raising livestock, especially in the face of extreme drought conditions. The proposed approach is holistic as it requires considering demographics, economics, consumption behavior, and farm operations for smallholder farmers. This information was originally collected across government and non-government organizations reports, scientific papers, organization databases, and surveys. The proposed interventions consider the impacts of three planting dates, three plant densities, and six nitrogen (N) fertilizer rates on pearl millet crop yield in extreme drought conditions. The impacts of these interventions were evaluated within mixed farming. Initially, a multi-objective optimization was employed to meet nutritional needs while maintaining a healthy diet at the lowest cost. The interventions that met the nutritional requirement thresholds were then evaluated against several economic indicators. At the last stage, the economically viable options were ranked based on the risk tolerance level of farmers. The study concludes N fertilizer rates of 0, 20, and 100 kg N ha⁻¹ were generally economically not feasible. Additionally, medium and late planting dates generally performed better than early planting dates, while plant densities of 3.3 and 6.6 pl m⁻² performed better than 1.1. The robust resilience metric introduced in this study is easily transferable to farmers with different characteristics in other regions.

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LIST OF ABBREVIATIONS

APSIM	Agricultural Production Systems sIMulator
ARAC	Alternative Risk Aversion Coefficients
CABO	Centre for Agrobiological Research
CE	Certainty Equivalent
CFA	West African CFA franc
CLIFS	Crop Livestock Farm Simulation
cm	Centimeter
CO ₂	Carbon Dioxide
CoBRA	Community Based Resilience Assessment
COSA	Committee on Sustainability Assessment
CRiSTAL	Community-based Risk Screening Tool-Adaptation and Livelihood
CSIRO	Commonwealth Scientific and Industrial Research Organization
CVCA	Climate Vulnerability and Capacity Analysis
DAPSA	Direction de l'Analyse, de la Prévision et des Statistiques Agricoles
DSSAT	Decision Support System for Agrotechnology Transfer
E	Early
EAA	L'Enquete Agricole Annuelle
EC	Ending Cash Reserves
FAO	Food and Agriculture Organization
FARMSIM	Farm Income Simulator
g	grams
GDP	Global Domestic Product

GLEAM	Global Livestock Environmental Assessment Model
ha	Hectare
IFPRI	International Food Policy Research Institute
IFSIM	Integrated Farm System Model
IRR	Internal Rate of Return
kg	Kilogram
KOV	Key Output Variable
L	Late
M	Medium
m	Meter
MAER	Ministère de l'Agriculture et de l'Équipement Rural
mm	millimeter
N	Nitrogen
NCFI	Net Cash Farm Income
NGOs	Non-Governmental Organizations
NPV	Net Present Value
pl	Plants
RATA	Resilience, Adaptation, and Transformation Assessment
RIMA	Resilience Index Measurement and Analysis Model
RP	Risk Premiums
SERF	Stochastic Efficiency with Respect to a Function
SHARP	Self-evaluation and Holistic Assessment of climate Resilience of farmers and Pastoralists
SGS	Sustainable Grazing Systems

Simetar	Simulation & Econometrics to Analyze Risk
USDA-ARS	United States Department of Agriculture Agricultural Research Service
WOFOST	WOrld FOod STudies
USDA-ARS	United States Department of Agriculture Agricultural Research Service

1.0 INTRODUCTION

Senegal's agriculture and livestock sectors contribute 17% of the gross domestic product (GDP) and employ 70% of the population (CIAT & BFS/USAID, 2016). The majority (around 90%) of agricultural holdings are family farms, which are made up of combinations of cash crops (e.g., cotton, groundnut), subsistence food crops (e.g., maize, sorghum, sesame, and millet), and various livestock that make up a mixed farm system (Blundo-Canto et al., 2021). Unfortunately, many factors have led to the underdevelopment of the agriculture and livestock sectors, leaving the country unable to meet the growing population's food requirements (CIAT & BFS/USAID, 2016). These factors include extreme climate conditions, infertile soil, lack of infrastructure, and poor access to quality fertilizer and seeds (CIAT & BFS/USAID, 2016). In addition, Senegal has a high poverty rate of 46.7% (World Bank, 2020). To combat the high poverty rate, Senegal can greatly increase its economic growth through agriculture (USAID, 2021). Nonetheless, this called for careful planning and understanding of the range of possible results, an approach usually conducted through analysis of large amounts of data and computer-based models due to the complicated nature of the issue being addressed.

Senegal has seen an increase in its number of severely food-insecure people between 2014-16 and 2019-21 (FAO et al., 2022). Additionally, the number of children under 5 years of age who are stunted has remained constant between 2012 and 2020 (FAO et al., 2022). Food security is achieved when individuals have consistent and reliable economic, social, and physical means to access adequate nutritious and safe food that fulfills their dietary preferences and requirements (FAO et al., 2022). A report from the International Food Policy Research Institute determined the total consumption of different nutrients by people in urban and rural settings in 2017/18 (Marivoet et al., 2021). The report found both rural and urban individuals deficient in calories, calcium, iron,

zinc, folate, and vitamin B12, while both groups met their needs for protein and vitamin A (Marivoet et al., 2021).

The impact of climate change (lower crop yields, livestock health, and livestock productivity) and the accompanying extreme events (increasing temperatures, droughts, floods) on Africa has had a significant effect especially on vulnerable communities such as smallholder farmers (Ayanlade et al., 2017; FAO, 2021; Mogomotsi et al., 2020; WMO, 2022). Consequently, this has led to food insecurity, malnutrition, and economic instability in the affected regions (Nhemachena et al., 2020; Schilling et al., 2020; Trisos et al., 2022; Waha et al., 2017). Nevertheless, the effectiveness of strategies during severe events, such as extended droughts, remains inadequately assessed. Therefore, it is crucial to evaluate potential solutions to ensure the resilience of adaptation strategies. However, there is currently no consensus regarding the definition and measurement of resilience, and there is no universally accepted method for quantifying resilience across different scales (Eeswaran et al., 2021b). Therefore, it becomes critical to establish a clear definition and methodology for determining resilience before commencing a study (Davoudi et al., 2013; FAO, 2016).

Overall, there is a need for a resiliency determination approach that utilizes nutrition information, economic data, and risk quantification. The steps outlined in this study accomplish this task. This paper establishes insight into extreme drought mitigation practices for smallholder farmers in the Groundnut Basin in Senegal. Moreover, the proposed approach will establish a method of resilience determination that can be replicated for different technologies, characteristics, and regions. Ultimately, the knowledge gained from this study can be used to improve nutritional and economic security while limiting the risk to the target population through promoting climate-resilient practices.

2.0 LITERATURE REVIEW

2.1 Agriculture and Food Security in West Africa

The food production process, which encompasses activities ranging from farming and processing to packaging, transportation, storage, distribution, and retailing, is responsible for providing employment to 82 million people, which accounts for 66% of total employment in West Africa (Allen et al., 2018). Although the majority of these jobs (78%) are in agriculture, the number and proportion of off-farm jobs in food-related manufacturing and service activities are increasing (Allen et al., 2018). Furthermore, the agricultural sector in West Africa contributes 35% to the gross domestic product (GDP). Meanwhile, many farmers in the region are very poor and produce close to subsistence levels (Jalloh et al., 2013).

West Africa's Agricultural market, in regard to production, effective demand, exports, and imports, is primarily led by four significant players, namely Nigeria, Ghana, Côte d'Ivoire, and Senegal (FAO & AfDB, 2015). Together, these countries represent 66% of the population, more than 80% of the GDP, 75% of agricultural imports, and over 80% of agricultural exports (FAO & AfDB, 2015). In addition, these countries also play a major role in driving demand for agricultural products in their neighboring nation (FAO & AfDB, 2015). West African farmers face agriculture development constraints such as soil acidity, droughts, and nutrient-depleted and degraded soils (Jalloh et al., 2013). Cereals such as sorghum, millet, maize, and rice are widely consumed and cultivated, alongside roots and tubers like cassava, sweet potatoes, yams, and legumes such as cowpeas and groundnuts, which are all important food crops (Jalloh et al., 2013).

2.1.1 Climate of West Africa

The West African region is made up of sixteen countries: Benin, Burkina Faso, Cabo Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, and Togo. Four bioclimatic zones characterize West Africa, the Guinean zone (sub-humid/humid), the Sudanian zone (semi-arid), the Sahelian zone (arid), and the Saharan zone (desert) (Ayantunde et al., 2014; Eeswaran et al., 2022; Kruska et al., 2003). Figure 1 shows a climate zone map of West Africa. The agro-ecological zones of West Africa have variable rainfall, as seen from the humid zone having greater than 1500 mm, sub-humid zone having 1000 mm to 1500 mm, semi-arid zone having 500 mm to 1000 mm, and arid zone, which also contains the Saharan zone, having 0 mm to 500 mm (Eeswaran et al., 2022; Fernández-Rivera et al., 2001).

Agriculture in West Africa is heavily impacted by climate variability, including droughts and floods, and the effects of these challenges will only be amplified by climate change (Sarr, 2012). Other climate change-related challenges include increasing temperatures, water logging, a shorter growing season, new and increasing incidence of plant pests and diseases, and human health concerns (Jalloh et al., 2013). Additionally, West Africa is vulnerable to the effects of climate change due to limited institutional and economic capacity and high reliance on rainfed agriculture (Sultan & Gaetani, 2016). A meta-analysis predicted that crop production in West Africa to decrease by 12.5% by 2050 if no action is taken to mitigate the impacts of climate change (Knox et al., 2012). Meanwhile, another meta-analysis predicted a similar yield loss of around 11% due to climate change (Roudier et al., 2011).

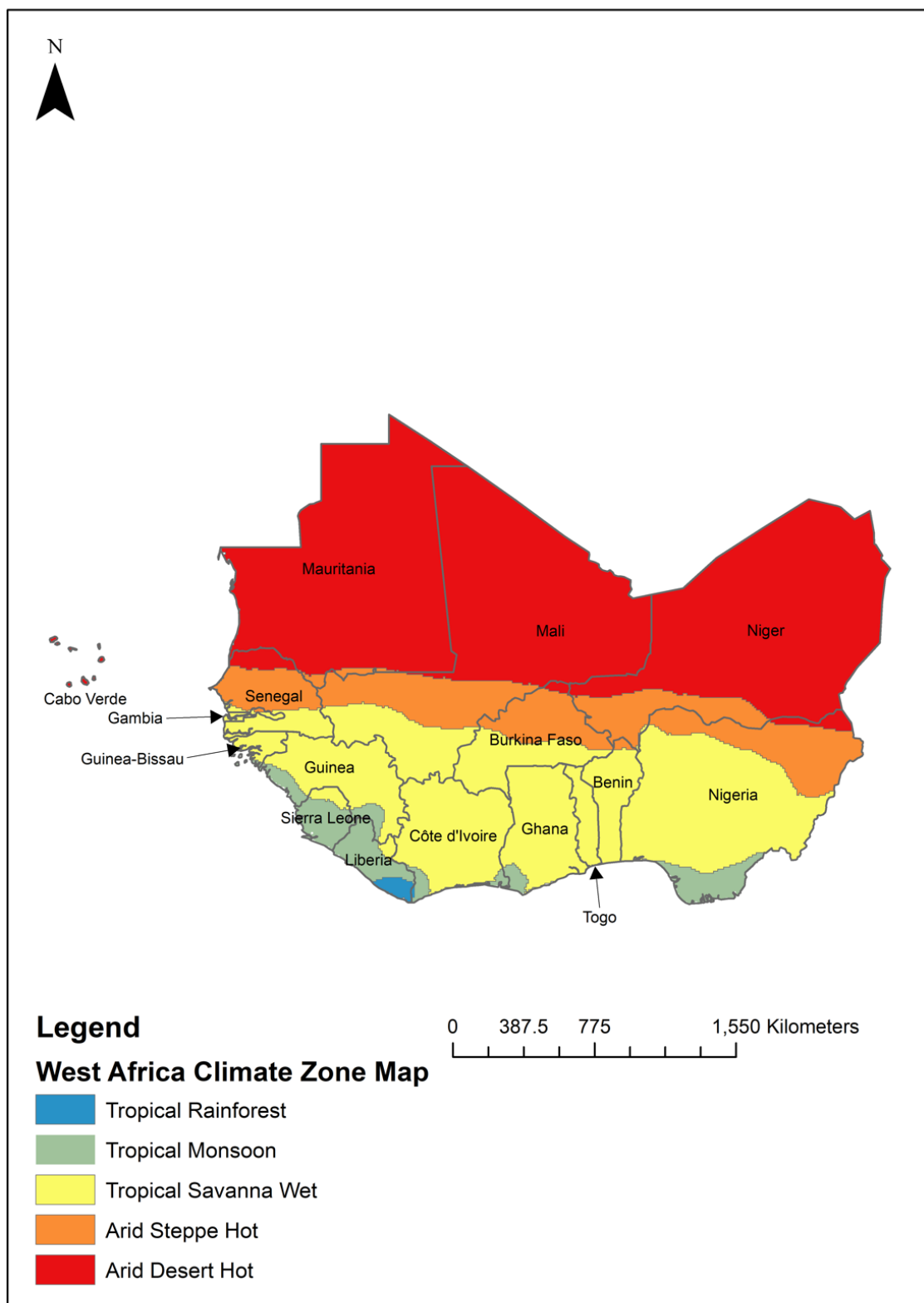


Figure 1. West Africa climate zone map.

2.1.2 Food and Nutritional Security in West Africa

The region of West Africa is inhabited by a populace that encounters one of the most elevated rates of food insecurity worldwide (Brown et al., 2009). West Africa has seen an increase in its number of severely food insecure people from 40.8 million (11.6% prevalence) in 2014-16 to 76.8 million (19.1% prevalence) in 2019-2021 (FAO et al., 2022). Moreover, the number of children who are under 5 years old and are stunted has increased from 1.3 million (34.9% prevalence) in 2012 to 1.8 million (30.9% prevalence) in 2020 (FAO et al., 2022). Furthermore, a survey was conducted in rural communities in Ghana, Liberia, and Senegal to evaluate food insecurity in West Africa, which found that 43% of people in Ghana were food insecure, while 75% of people in Liberia and 78% of people in Senegal were food insecure (Ahn et al., 2022). Additionally, West Africa has seen an increase in total energy (Cal/d), protein (g/d), and fat (g/d) from 1980 to 2020 (FAO, 2023a, 2023b). The primary sources of income for households were the sales of basic crops such as millet, sorghum, maize, cowpea, and groundnut, as well as off-farm earnings (Douxchamps et al., 2016). Although cereals play a crucial role in ensuring food security, households facing food insecurity choose to sell them in smaller quantities compared to households that have access to an ample food supply (Douxchamps et al., 2016). A study highlighted that the critical factors determining food security, which is the availability of food, are the land area per capita and the productivity of the land (Douxchamps et al., 2016). Since it is improbable that the land area per person will increase in the future, this study affirms the importance of intensification as a significant adaptation strategy, as recognized by various scholars (Douxchamps et al., 2016; Jarvis et al., 2011; Thornton & Herrero, 2014; Vermeulen et al., 2012).

2.1.3 Crop Production

Crop production in West Africa plays a vital role in the region's economy and food security (Jalloh et al., 2013). However, crop production in that region primarily relies on rainfall, typically small farms utilizing limited amounts of fertilizer and pesticides (Shimeles et al., 2018; Zougmore et al., 2016). The unpredictability of crop production caused by prolonged droughts and extreme variations in rainfall due to climate change will remain a persistent challenge for farmers who grow rainfed crops (Salack et al., 2016; Sultan et al., 2019; Sultan & Gaetani, 2016; Zougmore et al., 2016). West Africa is home to a wide range of crops, including staple crops like maize, millet, sorghum, rice, and cassava and cash crops like cotton, coffee, cocoa, cashew nuts, sesame, palm oil, and groundnut (FAO & AfDB, 2015; Mechiche-Alami & Abdi, 2020; Sultan & Gaetani, 2016).

Smallholder farmers are the backbone of crop production in West Africa as smallholder agriculture is the dominant economic activity and is critically important to the livelihoods of the local population (Giller et al., 2021; Gollin, 2014; Tarchiani et al., 2017). However, challenges such as limited access to agricultural technologies, resources to invest in new technologies, pests, diseases, desertification, soil fertility, soil degradation, climate variability, and future climate change effects on extreme climatic events hinder smallholder farmers' agriculture production and livelihoods (FAO & AfDB, 2015; Giller et al., 2021; Gollin, 2014; Sultan et al., 2005; Sultan & Janicot, 2003; Tarchiani et al., 2017). A meta-analysis predicted that crop production in West Africa to decrease by 12.5% by 2050 if no action is taken to mitigate the impacts of climate change (Knox et al., 2012). Meanwhile, another meta-analysis predicted a similar yield loss of around 11% due to climate change (Roudier et al., 2011). To overcome these challenges, various initiatives, including agricultural research, farmer training programs, strengthening stakeholder organizations, and infrastructure development, are being undertaken to enhance productivity,

improve crop yields, and promote sustainable farming practices (FAO & AfDB, 2015; Giller et al., 2021; Tarchiani et al., 2017).

2.1.4 Livestock Production

There are three livestock systems that are used in West Africa: the pastoral system, the agropastoral system, and the off-land system (Fernández-Rivera et al., 2001; Kamuanga et al., 2008). The pastoral system is predominantly practiced in arid and semi-arid zones and is defined by moving herbivorous livestock of different animal species in mixed or individual herds (de Haan et al., 2016; Eeswaran et al., 2022; Kamuanga et al., 2008). The agropastoral system is a mixed farming system that involves crop and livestock integration and is generally practiced in sub-humid savannah zones, where the farmers raise livestock for cash reserves, traction, and manure (Eeswaran et al., 2022; McIntire et al., 1992). Peri-urban and urban areas contain the off-land system where the farmers utilize stall-feeding in landless livestock farming (Fernández-Rivera et al., 2001; Kamuanga et al., 2008). Livestock in West Africa, particularly the countries in the Sahel, is constrained by drought (Hiernaux et al., 2009). Additional constraints to livestock in West Africa include water shortages in the dry season, high cost of veterinary services, and insufficient quantity and quality of feed (Ayantunde & Amole, 2016). Moreover, smallholder farmers in the mixed crop and livestock systems are constrained by climate change and variability, limited access to credit, high production and market risks, declining natural resource base, limited use of external inputs, weak agricultural extension systems, insecure land tenure, and low adoption of technologies to improve productivity (Aune & Bationo, 2008; Ayantunde et al., 2020; Pretty et al., 2011).

2.2 Agriculture and Food Security in Senegal

Agriculture contributed to 15% of the GDP in Senegal in 2020, employing 77% of the workforce, with the majority being smallholder farmers (Bousso, 2021). However, there is a

significant variability of agricultural workforce employment in the country, with engagement in crop production ranging from 27.7% in the Saint-Louis region to 95.8% in the Kaolack region, which is the central area of Senegal's groundnut production (Kazybayeva et al., 2006). Additionally, the percentage of rural households engaged in livestock production ranges from 22.6% in Saint-Louis to 73.2% in Louga (Kazybayeva et al., 2006).

Nevertheless, despite a significant proportion of the Senegal population being involved in agriculture, the country depends on imports to fulfill 70% of its food requirements owing to the generally unproductive soils and unpredictable rainfall patterns in the Sahel region of Senegal (Bousso, 2021; ITA, 2023). Senegal is characterized by agro-pastoralism, where more than 2/5 of households combine crop and livestock farming (DAPSA, 2020a). The average family size ranges from 6.6 people in the Saint-Louis district to 11.7 people in the Sedhiou district, with an average of 9.6 (DAPSA, 2021). Additionally, the average cultivated area per household is 3.36 ha; however, strong regional disparities can range between 0.85 ha in the Saint-Louis district and 8.21 ha in the Kaffrine district (DAPSA, 2021).

2.2.1 Climate of Senegal

Senegal contains 3 bioclimatic zones: the Guinean zone (sub-humid/humid), the Sudanian zone (semi-arid), and the Sahelian zone (arid) (Ayantunde et al., 2014; Eeswaran et al., 2022; Fernández-Rivera et al., 2001; Kruska et al., 2003). The annual rainfall in these zones is variable as the humid zone has greater than 1500 mm rainfall, sub-humid zone has 1000 mm to 1500 mm rainfall, and the semi-arid zone has 500 mm to 1000 mm rainfall (Eeswaran et al., 2022; Fernández-Rivera et al., 2001). Additionally, rainfall typically occurs between May and November in Senegal (World Bank, 2021). The mean annual temperature in Senegal in 1991-2020 was 28.91 °C where the mean temperature can range from 25.23 °C in January to 32.07 °C in May (World

Bank, 2021). Senegal is vulnerable to floods, droughts, sea-level rise, and coastal erosion, with floods and droughts projected to increase in magnitude, extent, and unpredictability due to climate change (USAID, 2017; World Bank, 2011). Figure 2 shows a climate zone map of Senegal.

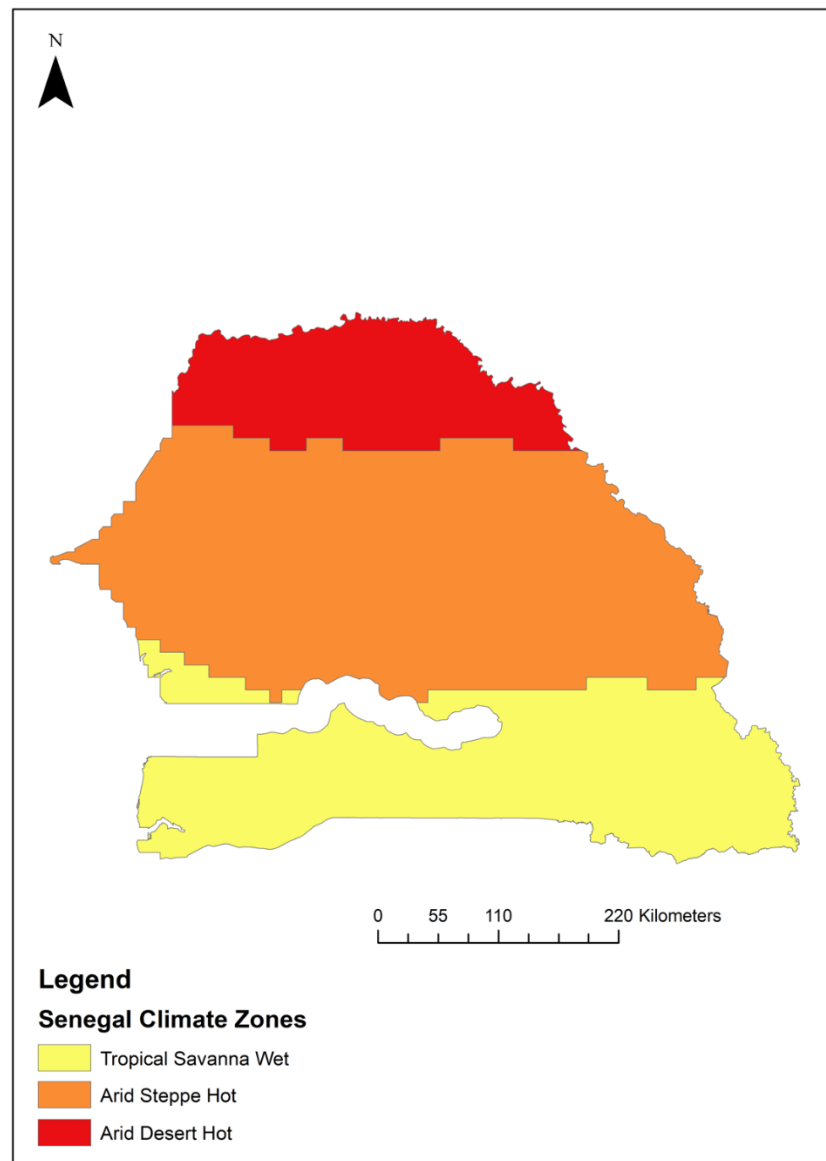


Figure 2. Senegal climate zone map.

2.2.2 Food and Nutritional Security in Senegal

Senegal has seen an increase in its number of severely food-insecure people from 1.1 million people (7.5% prevalence) in 2014-16 to 1.9 million people (11.2% prevalence) in 2019-21 (FAO et al., 2022). Moreover, the number of children under five years old who are stunted has remained constant at 0.5 million (19.8% prevalence in 2012 to 17.2% prevalence in 2020) from 2012 to 2020 (FAO et al., 2022). Meanwhile, chronic malnutrition affects children in rural areas (21%) more than urban areas (12%), with the economics of the family playing a role with 27% in the lowest quantile, 21% in the second quantile, and 9% in the highest quantile (Agence Nationale de la Statistique et de la Démographie (ANSD) & ICF, 2019).

Livestock is a crucial and necessary resource for the nutrition of people living in rural poverty as they not only provide a source of income that allows them to buy essential and nourishing food but also offers a local and cost-effective option for meeting their nutritional needs (IRI, 2019; Roland-Holst & Otte, 2007). Furthermore, in light of the heightened risks linked to crop cultivation amidst progressively unpredictable climate patterns, livestock serves as a safeguard and even a means of reserving and exchanging value to obtain necessary provisions such as sustenance (Kazybayeva et al., 2006; Roland-Holst & Otte, 2007).

2.2.3 Crop Production

In Senegal, peanut (or groundnut) and millet represent the predominant crops, accounting for more than 50% of cultivated plots, with respective proportions of 36% and 27% (DAPSA, 2020a), where groundnut and pearl millet are often grown in rotation (CIAT & BFS/USAID, 2016; HEA SAHEL, 2017a). Cash crops in Senegal include groundnut, sesame, and cotton, while staple crops include rice, maize, sorghum, millet, cowpea, cassava, fonio, taro, and potato (Beye et al., 2022; CIAT & BFS/USAID, 2016; Wood, 2018). Crops are usually rainfed, with less than 5% of

cultivated land under irrigation (CIAT & BFS/USAID, 2016; Eeswaran et al., 2022; Eldon et al., 2020; Nyong et al., 2007). Millet, rice, groundnuts, and sorghum are all very sensitive to annual precipitation changes, where years with more rain are associated with high crop production, while years with less precipitation have lower crop production (WFP, 2013). As a result, crop production in Senegal is vulnerable to climate change, especially in the Groundnut Basin (Eeswaran et al., 2022; WFP, 2013). Millet is a critical crop when considering future climate change as it has a higher temperature ceiling when compared to other cereal crops, which is relevant as temperatures are expected to increase 1.0-1.4°C by mid-century in Senegal due to climate change and heat waves are expected to increase in severity and frequency (Aissatou et al., 2017; Djanaguiraman et al., 2018; Lowe et al., 2011).

A significant challenge to crop production in Senegal is its vulnerability to climate change, which results in erratic rainfall patterns, droughts, and desertification (IPCC, 2007; Raile et al., 2018; WFP, 2013). These factors pose risks to crop yields and agricultural productivity (WFP, 2013). Insufficient access to agricultural technologies, such as improved seeds, fertilizers, and irrigation systems, impedes the potential for improved crop production (CIAT & BFS/USAID, 2016; Raile et al., 2018). Additionally, limited infrastructure, low investment, lack of crop storage facilities, and post-harvest losses contribute to the challenges faced by farmers in Senegal (CIAT & BFS/USAID, 2016; Raile et al., 2018; Steenwerth et al., 2014). However, there are several opportunities to address these challenges and improve crop production. The government and other partners can invest in initiatives to promote climate-smart agriculture, including encouraging the adoption of sustainable practices and resilient crop varieties (CIAT & BFS/USAID, 2016; IPCC, 2007; Steenwerth et al., 2014). Moreover, Senegal's crop production can benefit from strengthening research and development, improving farmer education and extension services, and

enhancing access to credit and markets (CIAT & BFS/USAID, 2016; IPCC, 2007; Raile et al., 2018; WFP, 2013).

2.2.4 Livestock Production

In Senegal, 60% of the population is engaged in livestock farming, which accounts for 4.2% of the country's overall GDP (CIAT & BFS/USAID, 2016; Eeswaran et al., 2022; Habanabakize et al., 2022; Molina-flores et al., 2020). The traditional livestock of Senegal are cattle and small ruminants. On average, a household engaged in pastoralism usually possesses 15.8 cattle, 14.1 sheep, and 11.7 goats (Kazybayeva et al., 2006). Other household animals include 21.5 hens and 11.3 pigs (Kazybayeva et al., 2006). The districts with the most cattle in Senegal in 2021 were Tambacounda, Kolda, Louga, and Saint-Louis. Furthermore, the districts with the smallest ruminant include Tambacounda, Louga, Kaolack, Matam, Fatick, and Saint-Louis. In the sub-humid savannah zones of Senegal, the agropastoral system is the main system in sub-humid savannah zones, while the pastoral system is the dominant system in the arid and semi-arid zones (Eeswaran et al., 2022). In the northern region of Senegal, the agropastoral system mainly comprises the pearl millet-groundnut-livestock system, while Groundnut Basin is characterized by the rice-groundnut-livestock system (Eeswaran et al., 2022; Fernández-Rivera et al., 2001). In Senegal, cattle serve a multitude of purposes, including but not limited to meat and milk production, draft power, meat processing, and are often associated with particular ethnic groups (Habanabakize et al., 2022; Somda et al., 2004).

2.3 Challenges for Agriculture and Food Security in Senegal

The inclusion of multiple traits within the agricultural populace contributes to the observed diversity of farming systems, including livestock breeds and assets, cropping, land access, access to markets, off-farm activities, sociocultural traits, and livelihood orientations (Camara, 2013;

Chatellier, 2019; Habanabakize et al., 2022; Somda et al., 2004). The variability found in the farming systems of Senegal makes it challenging to get a complete picture of what is occurring, which leads to an incomplete understanding of reality and inefficient interventions used for project planning and implementation (Habanabakize et al., 2022).

2.3.1 Challenges for Crop Production

Water availability

The practice of farming in the area is marked by minimal usage of inputs, reliance on rainfall for irrigation, and the presence of nutrient-deficient soils (MacCarthy et al., 2021). Moreover, because the primary form of agriculture in Senegal is rainfed, there is a significant agro-climatic risk due to untimely ending of the growing season, unsuccessful sowings, and water stress (typically terminal drought) during the post-flowering and grain-filling periods (MacCarthy et al., 2021). The interannual variability of rainfall in Senegal affects crops, as was particularly evident in 2014 when the country experienced a drought brought on by a delay in the start of the rainy season and the rainfall deficit that compromised millet and groundnut harvests in Louga, Thiès, and Mbour (Nébié et al., 2021; Sagna et al., 2021). Moreover, the south (Ziguinchor) and the center (Kaolack) of Senegal experienced milder rain deficits and less severe yield decreases (Diop et al., 2016; Sagna et al., 2021). The expansion of irrigation is constrained in multiple regions in Senegal as salinity affects the irrigation of the Gambia and Kayanga/Anambe rivers (World Bank, 2022a).

Meanwhile, the minimum guaranteed dry season flow of the Senegal river basin has been exceeded over the last ten years (World Bank, 2022a). Therefore, irrigation in the rainy season has no constraint on water availability; however, the irrigable land is underutilized because of the inadequate management of the crop calendar, where the irrigated surface is utilized 52% of the time (World Bank, 2022a). In addition, a further obstacle arises in western Senegal, where surface

waters often contain high levels of salt content. The salination of fifty thousand hectares of both irrigated and non-irrigated farmland in the Casamance River basin has had a significant detrimental effect on agricultural output (World Bank, 2022a).

Marketing and International Trade

The smallholder farmers who make up the majority of producers in Senegal, face numerous obstacles that hinder their ability to increase their yields and income. These farmers lack machinery access, market access, fertilizer, high-quality seeds, climate information, financial services, and market access (CIAT & BFS/USAID, 2016; DAPSA, 2021; Eeswaran et al., 2022; MacCarthy et al., 2021). Boosting production and replenishing soils is constrained by smallholder farmers' lack of access to and efficient use of fertilizers (CIAT & BFS/USAID, 2016). Households in Senegal experience food insecurity and vulnerability to climate change due to high food prices and price volatility, which affect both consumers and producers in the country (CIAT & BFS/USAID, 2016; Jha et al., 2021). Moreover, the private sector's limited investment in production and post-harvest activities has resulted in limited rural infrastructure including poor road conditions, irrigation, transformation equipment, storage/warehouses for post-harvest (CIAT & BFS/USAID, 2016; Eeswaran et al., 2022; Ollenburger et al., 2016). The insufficient infrastructure leads to a significant loss of vegetable and fruit production, estimated at 20–50% (CSE, 2013). Inadequate physical infrastructure poses a significant constraint to accessing markets, as the majority of markets are located along main paved roads, which impedes remote rural farmers from accessing them (CIAT & BFS/USAID, 2016; A. Faye et al., 2021). Additionally, smallholder farmers face challenges in term of processing, storage, or distribution of their products, while processors in Dakar have inadequate knowledge on crop varieties and production quality (Bousso, 2021; CIAT & BFS/USAID, 2016; Kamuanga et al., 2008).

Climate Change and Climate Variability

Between 1950 and 2000, Senegal experienced a 30% reduction in rainfall, with significant variability across different regions and years (CIAT & BFS/USAID, 2016). While there has been some improvement in precipitation trends since 2000, though this does not necessarily indicate the dry cycle has ended (CIAT & BFS/USAID, 2016; Nouaceur & Murarescu, 2020). Crop production in the main staple crops of millet, sorghum, rice, and groundnut are very sensitive to variations in annual precipitation, where years with lower rainfall result in lower crop production (WFP, 2013). Moreover, crop production in the groundnut basin is highly responsive to rainfall variability (WFP, 2013). Additionally, the country is expected to face more frequent and intense floods, droughts, and heatwave events (CIAT & BFS/USAID, 2016; Eeswaran, 2017; IPCC, 2007; Thornton et al., 2009). Furthermore, sea-level rise is predicted to reach one meter by 2100, resulting in the destruction of over 6,000 km² of land and causing environmental degradation and soil erosion (CIAT & BFS/USAID, 2016). The agriculture sector is highly sensitive to temperature and precipitation changes, which are likely to have adverse effects on crop yields and livestock (CIAT & BFS/USAID, 2016; IPCC, 2007; Thornton et al., 2009). Crop models indicate groundnut yields could potentially decline by 5–25%, while rainfed rice and maize yields in their current cultivation regions may improve 5–25% in regions where they are currently grown (Jalloh et al., 2013).

Other Constraints

The sector's reliance on natural resources is threatened by the deteriorating conditions where approximately 34% of the territory used for the natural resources is affected by land degradation; where 50% of farmlands within the inner Casamance region, the Niayes, the Sine-Saloum, and the River Valley areas are affected by acidification, while 9% of degraded lands, primarily in the River Valley, are affected by salinization (CIAT & BFS/USAID, 2016). While

some degradation can occur from natural processes, most of the degradation can be attributed to human activities such as improper use of mineral and organic fertilizers, excessive land clearing for peanuts, cash cropping, and charcoal production, overgrazing, poor water management, and unplanned urbanization (CIAT & BFS/USAID, 2016; Eeswaran et al., 2022; Powell et al., 2004).

2.3.2 Challenges for Livestock Production

Feed and pasture availability

In the sub-humid and semi-arid zones of Senegal, livestock production is largely reliant on crop residues' availability, while livestock in the arid zone's rangelands region are dependent on the seasonal availability of pastureland (Eeswaran et al., 2022). Therefore, livestock's potential productivity and stocking capacity rely on crops in the agropastoral system and grasses in the rangelands. The rangelands provide vital functions to the Sahelian ecosystem's equilibrium and the local communities (Hiernaux et al., 2018; Lo et al., 2022). Moreover, in Senegal, the majority of the land consists of savannah areas where livestock plays a significant role in supporting the rural population's nutritional needs, livelihoods, economy, and environmental well-being (Sircely, 2022). There is a sizeable interannual variation in biomass production for annual grasses in the Sahel region due to topography, geomorphology, soil fertility, variable rainfall, and drought intensity, duration, and timing (Fernandez-Rivera et al., 2005; Hiernaux et al., 2009). Climate change will further impact the livestock in the Sahel region by altering herbage growth and quality, changing the floristic composition of vegetation, and altering the importance of crop residues as animal feed (Thornton et al., 2009).

Water availability

Water is a limiting factor in livestock farming in Senegal, where lakes, rivers, and ponds are available in the rainy season, and wells and boreholes are utilized during the dry season

(GAFSP, 2012). Therefore, groundwater primarily feeds livestock watering (Faye et al., 2019). Unfortunately, national groundwater levels are annually falling by 0.3 m to 0.67 m due to over-abstraction and low recharge rates brought about by worsening droughts (DGPRES, 2019; SIE-SEE, 2009; Taithe et al., 2013; USAID & SWP, 2021). Another challenge to Senegal livestock farming includes mining operations polluting water resources, which endangers livestock, people, and wildlife (World Bank, 2022a).

Management and Breeding of Livestock Species

West Africa has a wide range of native breeds and ecotypes that are well-adapted to local conditions (Eeswaran et al., 2022). Additionally, some regions have intensified livestock production by introducing pure and crossbred exotic breeds (Eeswaran et al., 2022). However, most crossbreeding programs and imported breeds were unsuccessful in West Africa (Blench, 1999). In addition to their natural immunity to parasitic worms and tick-borne illnesses, endemic ruminant livestock exhibit resistance to trypanosomiasis. (Blench, 1999; Murray & Trail, 1984). Furthermore, endemic ruminant livestock are well suited for the agropastoral system in Senegal due to their smaller body size compared to zebu breeds, which means they have lower requirements for water, feed, nutritional intake, and animal husbandry (Eeswaran et al., 2022). Some management challenges that are minimizing livestock farming's potential production in Senegal include animal healthcare, poor infrastructure (e.g., roads), limited water resources, and market access (Eeswaran et al., 2022). In addition, reasons for inadequate adaptation of new equipment and infrastructure are limited extension services, socioeconomic constraints, and the risky environment for foreign investment (Ollenburger et al., 2016). Furthermore, climate extremes and demographic changes have caused farmers to abandon traditional practices and regulations for

pasture access and water points, which has led to more livestock competing for water and pasture resources and caused land degradation (Eeswaran et al., 2022).

Marketing and International Trade

The primary goal of livestock farmers is to satisfy the subsistence needs of their households and relatives, with live animals serving as a reserve for cash in case of emergency, despite some limited small-scale animal trading (Ayantunde et al., 2011). The pastoral system produces most of the local raw milk with an irregular production that sees high production in the short rainy season and then can spoil because of a lack of processing opportunities and poor access to markets (Eeswaran et al., 2022). Moreover, traditional methods of milk collection by pastoralists are constrained to rural regions (Eeswaran et al., 2022). There are many limitations in marketing opportunities facing pastoralists, including spread-out markets used to feed city's meat demand and irregular livestock production (FAO, 2004). Alternatively, agropastoralists located in the Groundnut Basin are comparatively more connected to Dakar (Senegal's capital), leaving the agropastoralists in a better position than pastoralists for market access (FAO, 2004).

Climate Change and Climate Variability

Climate change is directly affecting Senegal through seawater intrusion, increasing temperature, rainfall variability, and extreme events like heatwaves, floods, and droughts (Eeswaran et al., 2022; Thornton et al., 2009; Thornton & Herrero, 2015). Furthermore, since 1950 the mean annual temperature has risen by 1.6°C, while a 3°C rise occurred in the northern Senegal Sahelian region (CIAT & BFS/USAID, 2016). Livestock farming has both direct and indirect effects from climate variability and change. Decreased production and overall performance are the main direct effect of climate change, which is seen through adverse impacts on animal health, immune response, reproductive performance, weight gain, feed conversion efficiency, and animal

metabolism (Baumgard et al., 2012; Nardone et al., 2010). Indirect impacts of climate variability and change affect water and feed availability as well as the management of livestock species and the livestock food supply chain (Baumgard et al., 2012; Godde et al., 2021; Ickowicz et al., 2012).

Other Constraints

Resource competition in Senegal has intensified due to deforestation, an increasing population, and unplanned crop cultivation expansion (Eeswaran et al., 2022; Moritz et al., 2009). West African pastoral areas are severely restricted by the provision of animal health care is because of the insufficient number of qualified personnel and the lack of locally produced veterinary products (Eeswaran et al., 2022). Moreover, in Senegal the quality of animal health services has declined since the privatization of veterinary care (Molina-flores et al., 2020). This limitation has led to various zoonotic, animal, and avian exposure in livestock species (Eeswaran et al., 2022). Additionally, the transmission of diseases from livestock to humans, including Ebola, can pose significant risks to human health, particularly in densely populated intensive urban and peri-urban systems (Latino et al., 2020; Machalaba et al., 2015). Insufficient investment and inadequate funding for capacity development have resulted in weak institutional capacities for research and extension in the livestock sector, contributing to its challenges (de Haan et al., 2016; Meltzer, 1995; Ollenburger et al., 2016). Furthermore, the sector's growth and development are not being adequately supported by existing policies that are ineffective and outdated (Eeswaran et al., 2022).

2.4 Interventions to Improve Agricultural Production in Senegal

A report utilizing a survey found that 25.8% of households reported experiencing at least one extreme event or environmental shock (DAPSA, 2021). The most severe events reported include torrential rains or violent winds (36.1%), soil degradation (30.0%), floods (23.7%), and rainfall disruptions (19.5%) (DAPSA, 2021). Additionally, the survey found the most effective

adaptation practices, as cited by the households, to be the diversification of crops, the use of practices, knowledge, and traditional heritages, the use of adapted crop varieties and animal species, and the use of seeds adapted to local conditions and stresses (DAPSA, 2021).

Planting Density

In Senegal, millet is a vital staple crop, and optimizing planting density can play an important role in increasing yields as millet is currently sown at low planting densities with the opportunity to increase planting density and yield (A. Faye et al., 2023). The most significant benefit of higher planting densities for millet occurs when there is a high evaporative demand, where drought stresses can be avoided, and water use efficiency and yield improve (Pilloni et al., 2022). Moreover, other possible explanations for high planting densities and associated increased yield include increased soil cover, reduced water loss, limited evaporation, and increased soil moisture (Bastos et al., 2022; A. Faye et al., 2023; Pilloni et al., 2022).

One study looked at planting densities for millet of 7 plants/m² (low) and 15 plants/m² (high) and found millet yield performed better under a low plant density (an increase of 5% to 50%) compared with the high plant density (an increase of 5% to 40%) (Araya et al., 2022). Moreover, all locations except Kanel had an increase in millet yield compared to the baseline under both low and high plant density scenarios (Araya et al., 2022). Peanut yield was not substantially impacted by lower and higher plant densities (Araya et al., 2022). Another study found that the responses of millet grain and fodder yield varied across different environments and exhibited an increase with increased sowing density (A. Faye et al., 2023). Additionally, a different study on pearl millet yields in Senegal found that greater planting density improved yield (Bastos et al., 2022). This was also confirmed in another study that found increasing planting density increased pearl millet yield (Vieira Junior et al., 2023). Moreover, planting densities of 1.1 plants/m², 3.3

plants/m², and 6.6 plants/m² were analyzed, and found the plant density of 1.1 to produce the lowest yielding scenario for all districts (Vieira Junior et al., 2023). Furthermore, a separate study conducted in Senegal investigated the optimal planting density for pearl millet of 3.2 plants/m² (low), 6.4 plants/m² (medium), 12.8 plants/m² (high) (Pilloni et al., 2022). The majority of the genotypes tested showed a positive response to increased sowing densities in trials conducted during seasons with high evaporative demand (Pilloni et al., 2022). These findings suggest that existing pearl millet cultivars have the potential to increase productivity with intensified cultivation, particularly in areas with anticipated high evaporative demand (Pilloni et al., 2022a).

Planting Date

The planting date or sowing date for millet, an important cereal crop, is crucial for optimizing yields and ensuring successful cultivation (Santos et al., 2017; Vieira Junior et al., 2023). Generally, millet is sown at the onset of the rainy season, typically between June and September (Bacci et al., 1999; USAID, 2015). However, because several dry days follow the first rain suitable for planting, due to unpredictable rainfall patterns in the Sahel regions, failure of the initial sowing can occur and requires the farmer to sow again, increasing associated costs of replanting (Bacci et al., 1999; Santos et al., 2017). To avoid this issue, the sowing process could be delayed; however, late sowing would result in missing the nitrogen peak, which occurs in the soil during the onset of the rainy season due to the activity of microbial flora and shortens the growing season (Badianee, 1993; Birch, 1958; Sparling & Ross, 1988). These consequences could be mitigated with nitrogen fertilizer use (Bacci et al., 1999). Overall, choosing the appropriate millet planting date in Senegal is a critical decision that farmers make based on a combination of factors to optimize their yields and adapt to local climate conditions.

Planting date adjustments can be critical to increasing yield when matching planting dates to precipitation to coordinate with the period of greater crop water demand (Vieira Junior et al., 2023). Planting crops in the first and second week of June resulted in improved yield for all crops (millet, groundnut, sorghum) in most locations in Senegal (Araya et al., 2022). Especially, the southern regions of Senegal typically experience an early onset of rainfall. In contrast, the northern regions experience a delayed onset of rainfall by at least one to three weeks, which should be considered when designing management practices for specific regions (Araya et al., 2022). Moreover, the length of the rainy season decreased by 1 to 3 weeks compared to the baseline under a midcentury climate change scenario, which may have a major effect on varietal or crop choice (Araya et al., 2022). A study found that millet in the groundnut basin in Senegal the delayed planting date by 20 days resulted in the highest yield; however, in the Kolda district the delay of 40 days in planting time had the highest yield (Vieira Junior et al., 2023).

Nitrogen Fertilizer

Nitrogen fertilizer use in Senegal significantly affects agricultural productivity and food security (Bado et al., 2022; Bagayoko et al., 2011). Senegal has a largely agrarian economy; however, nitrogen and other fertilizer use remain limited (DAPSA, 2021). Farmers in Senegal utilize nitrogen to enhance their soils' nitrogen content, promoting healthy plant growth, improving crop quality, and increasing overall agricultural productivity (Bado et al., 2022; Bagayoko et al., 2011). According to a study, applying nitrogen fertilizer increased yield for sorghum and millet crops (Araya et al., 2022). For the majority of the locations examined, the yield increased up to 68 kg N/ha. However, specific locations showed an increase of up to 115 kg N/ha, and dry locations did not exhibit any response during the baseline period (Araya et al., 2022). A different study in Nigeria found that the best nitrogen fertilizer rate was 120 kg/ha (Isah et al., 2020). Additionally,

another study found 102 kg N ha⁻¹ to be the optimized treatment for Senegal (Bastos et al., 2022). Alternatively, another study found 100 kg N/ha to be the best nitrogen rate for all districts in Senegal except for Louga and Matam, which had 40 kg N/ha as the nitrogen rate (Vieira Junior et al., 2023).

Irrigation

A study demonstrated that the millet yield was significantly enhanced by irrigation compared to rainfed yield (Araya et al., 2022). Specifically, the location of Kanel exhibited a positive response to irrigation, suggesting that water stress played a significant role in millet yield in the region and the entire country (Araya et al., 2022). Irrigation affected the future peanut yield compared to the baseline by slightly narrowing the deviation, but it was not that substantial (Araya et al., 2022). Furthermore, the effects of irrigation on sorghum yield varied slightly across different locations where under a simulated future climate scenario, the impact on sorghum yield ranged from an increase of 15% to 35% and a decrease of 5% to 50% compared to the corresponding irrigated baseline yield (Araya et al., 2022). Although, it has been reported that temperature changes have a greater impact on areas in southern Senegal than water stress, and conversely, crops grown in northern Senegal are more susceptible to water stress than temperature changes (Sultan et al., 2013).

2.5 Agricultural System Models

Modeling provides the only means of recognizing and measuring the nuanced yet highly significant interactions among different elements within smallholders' systems (Thornton & Herrero, 2001). Without this approach, there are constraints on reliably understanding the broader effects of interventions and modifications on production systems (Thornton & Herrero, 2001). Over time, agroecosystem simulation models have been developed into immensely valuable

instruments for quantifying and assessing the impacts of climate, water, soils, crops, and management practices on environmental and agricultural production sustainability (Antle et al., 2017). As a result, agricultural models are pivotal in guiding decision-making processes, ensuring optimal resource utilization, transferring new technologies, and promoting sustainable agricultural practices in regions or countries (Antle et al., 2017; Ascough et al., 2018).

2.5.1 Crop Models

Crop models are powerful tools used to simulate and predict the growth, development, and yield of crop plants (Asseng et al., 2014). These models are designed to represent the complex interactions between various environmental factors, such as weather conditions, soil characteristics, and management practices, that influence crop growth (Holzworth et al., 2014). By incorporating scientific knowledge and mathematical algorithms, crop models provide valuable insights into the behavior of crop systems under different scenarios, aiding in decision-making processes for farmers, researchers, and policymakers (Vieira Junior et al., 2023).

The first crop model of interest that is discussed in this section is WOFOST (WORld FOod STudies), which utilizes data for about 40 input parameters (Kasampalis et al., 2018). The Agricultural University and the Centre for Agrobiological Research (CABO) collaborated with the Wageningen, the Netherlands based Centre for World Food Studies to create a simulation model for crop growth (van Diepen et al., 1989). By incorporating information about soil, crop, weather, and crop management (such as sowing date), WOFOST can calculate attainable crop production, biomass, water usage, and other related factors for a particular location (WUR, 2023). WOFOST is a mechanistic model that provides an explanation of crop growth on a daily basis, considering underlying processes, such as photosynthesis and respiration, and how they are impacted by environmental conditions (WUR, 2021). However, the model has certain limitations, including its

accuracy being influenced by assumptions that simplify the growth process and ignoring certain growth determining factors (van Diepen et al., 1989). The night and day rhythms of plant respiration, transpiration, and assimilation as well as water infiltration, and runoff are simulated processes whose accuracy is constrained by the time interval of one day as they have a smaller time resolution (van Diepen et al., 1989). Moreover, a lack of local-level data and data aggregation when designing estimates at a regional scale can lead to WOFOST reporting large variations in outcomes based on minor parameter changes (Carcedo et al., 2023; de Wit et al., 2019; Hoffmann et al., 2016).

The Agricultural-Production-System-sIMulator (APSIM) is a model that can produce management scenarios to understand the cause and help reduce the yield gap (Carcedo et al., 2023). Its strong mechanistic approach to simulating biophysical processes in farming systems has made it a popular tool among thousands of researchers worldwide (Holzworth et al., 2014, 2015, 2018; Keating et al., 2003). However, APSIM's intricate structure necessitates the meticulous adjustment of numerous parameters, which significantly impact the model's final results (Morel et al., 2021). This can be particularly challenging when using the model to simulate crop production across diverse locations with varying agricultural practices and soil types (Morel et al., 2021). Despite this complexity, a significant advantage of APSIM is its ability to integrate models from various research disciplines and domains, allowing knowledge from one area to benefit another (APSRU, 2007). Meanwhile, a potential drawback of this approach is the lack of studies that adequately calibrate and validate the model (Liben et al., 2018; van Bussel et al., 2016; Vieira Junior et al., 2023).

AquaCrop is a simulation model that uses water as a driving force and is capable of simulating multiple crops, where it is known for striking a balance between simplicity, accuracy,

and robustness (Vanuytrecht et al., 2014). To tackle the challenge of numerous crop models requiring a large amount of parameter values and input variables that are not readily accessible for worldwide environments and diverse crops the Food and Agriculture Organization of the United Nations (FAO) developed AquaCrop (Vanuytrecht et al., 2014). Enhancements to AquaCrop can involve considering the impact of increased CO₂ levels on normalized biomass water productivity, integrating the influence of temperature on crops, and factoring in cultivating forage crops (Vanuytrecht et al., 2014). AquaCrop aims to utilize point simulations in forecasting crop yield at the individual field scale; therefore, high resolution input data on soil, crops, weather, and management practices is needed to extend simulation from the farm or field level to the regional level (Vanuytrecht et al., 2014).

The Decision Support System for Agrotechnology Transfer (DSSAT) models are the most widely employed among the many models used to predict crop growth. DSSAT is initially developed to simulate the growth, development, and yield of crops grown uniformly on a homogenous land area. The model accounts for soil water, carbon, and nitrogen changes over time under the cropping system (J. W. Jones et al., 2003; Thorp et al., 2008). For the past 15 years, DSSAT has been used by researchers worldwide for various purposes, such as sustainability research, climate change impact studies, crop management, and precision agriculture (Thorp et al., 2008). DSSAT has been well-validated for several regions and crops (Thorp et al., 2008). The model contains subroutines for only a limited number of crops, which fail to account for all environmental and management factors where components that can predict how intercropping, pests, tillage, water, excess soil, and other factors impact crop yield are notably absent (Abayechaw, 2021). Additionally, these models may not perform well under extreme environmental stress (Abayechaw, 2021). Presently, the models solely replicate the possible crop

yields in conditions of nitrogen and water constraints, disregarding various other factors that commonly impact productivity in agricultural settings, such as phosphorus availability (Abayechaw, 2021).

2.5.2 Livestock Models

Livestock models are useful tools that can simulate livestock populations' behavior, performance, and dynamic within different production systems (Gouttenoire et al., 2011; van der Linden et al., 2020). These models are designed to capture the complex interactions between animals, their environment, and management practices (Gouttenoire et al., 2011). By incorporating biological, physiological, and economic principles, livestock models provide valuable insights into various aspects of livestock production, including growth, reproduction, nutrition, health, and economics (Gouttenoire et al., 2011; van der Linden et al., 2020). These models allow researchers, farmers, and policymakers to assess the potential impacts of different management strategies, predict animal performance, optimize resource allocation, and evaluate the sustainability of livestock systems (Gouttenoire et al., 2011; Pacini et al., 2004; van der Linden et al., 2020).

The Global Livestock Environmental Assessment Model (GLEAM) was created by the Food and Agriculture Organization of the United Nations with the goal of providing a tool for analyzing the environmental impact of global livestock production in a comprehensive, disaggregated, and consistent manner (MacLeod et al., 2018). This is important because inconsistencies in methodologies between studies can make it difficult to accurately compare results and identify ways to improve (MacLeod et al., 2018). Outputs from the model are livestock commodity production, distribution of production systems spatially, livestock animal numbers, management and production of manure, animal feed quality, composition, and intake, feed intake

land use, and nitrogen use for different levels of production, and greenhouse gas emissions for different levels of production (FAO, 2023c).

The GRAZPLAN grasslands simulations models of the Commonwealth Scientific and Industrial Research Organization (CSIRO) are commonly employed for evaluating simplified livestock grazing scenarios across various stocking rates, where the scenarios are typically tailored to specific farm systems and locations and analyze the associated economic outcomes (Donnelly et al., 2002; Thomas et al., 2019). The suite of models has been parameterized for China (Donnelly et al., 2005) and Canada (Cohen et al., 2003) livestock systems though they have been mostly used on Australian livestock systems (Donnelly et al., 2002). The ruminant model can be utilized for beef, dairy cattle, and sheep (Snow et al., 2014). The main objective of these tools is to assess management choices that enhance the utilization of farm resources, ensuring both profitability and environmental sustainability (Donnelly et al., 2002).

The SGS Pasture Model (the Sustainable Grazing Systems Pasture Model), a grazing systems model, was created by IMJ Consultants Pty Ltd, University of Melbourne, Dairy Australia, and Meat and Livestock Australia to facilitate the simulation of intricate dynamics among water, nutrients, soil, climate, pasture species, and grazing animal management (Johnson et al., 2003; Smith, 2022; Snow et al., 2014). The EcoMod and DairyMod models incorporate the SGS Pasture Model, sharing a common biophysical structure and identical model code. However, their variations lie in distinct livestock categories and customized management procedures (Johnson et al., 2008; Snow et al., 2014). Modules for animal intake and metabolism, nutrient and water dynamics, and herbage accumulation and utilization are encompassed on a daily time-step by the mechanistic biophysical simulation model (Johnson et al., 2003; Smith, 2022). By integrating these components, it offers a comprehensive framework for examining the dynamics of the pasture

system (Johnson et al., 2003). Understanding the intricate interactions among these elements is crucial for efficient pasture management, optimal utilization, and assessing the environmental impact of management practices, particularly concerning water and nutrient dynamics (Johnson et al., 2003).

2.5.3 Crop-Livestock Integration Models

Crop-livestock integrated models represent an innovative approach combining agricultural practices involving crops and livestock within the same farming system. These models provide the best approach to quantifying the outcomes of the numerous interacting variables in understanding crop-livestock systems (Parsons et al., 2011). This integration fosters a holistic and interconnected approach to agriculture, highlighting the importance of symbiotic relationships between crops and livestock in achieving sustainable and efficient food production systems (Sekaran et al., 2021). It has been noted that crop-livestock systems outperform traditional agricultural models in terms of ecological and social advantages, as seen through mitigating the impacts of climate change, enhancing soil quality, and higher net income and input-output ratio (Yang et al., 2022).

FARMSIM (farm simulation model) evaluates alternative scenarios against a baseline of a farm using a Monte Carlo simulation model (Bizimana et al., 2020; Bizimana & Richardson, 2019). The model uses the Simetar© software to estimate probability distributions for key output variables, simulate random variables, estimate parameters for price and yield probability distributions, and rank agricultural adaptations (Bizimana et al., 2020; Bizimana & Richardson, 2019). FARMSIM assesses the nutritional status of a farm family by simulating nutritional consumption in a stochastic environment (Clarke et al., 2017). FARMSIM repeatedly simulates a 5-year planning horizon for a representative farm in 500 iterations (Bizimana et al., 2020; Bizimana & Richardson, 2019). Economic variables include annual ending cash reserves (EC),

annual net cash income (NCFI), net present value (NPV), and internal rate of return (IRR). Nutrition factors considered are calories, protein, fat, calcium, iron, and vitamin A. FARMSIM can simulate a representative farm with up to 15 crops and five livestock (cattle, goats, chickens, swine, and dairy).

The Integrated Farm System Model (IFSIM) developed by the United States Department of Agriculture from the Agricultural Research Service (USDA-ARS) and is able to simulate and forecast key dairy farm outputs such as greenhouse gases, milk production, crop yields, nutrient losses, and economic returns for different management strategies (Rotz et al., 2007; Snow et al., 2014). Milk production, feeding, and manure handling as well as crop growth, development, establishment, harvest, and storage are utilized by the model in a detailed process-level simulation (Rotz et al., 2022). The outcomes of these simulations can then be used to predict production costs and the net return to management for a representative dairy farm (Ranck et al., 2020).

CLIFS (Crop Livestock Farm Simulator) is a tool that uses various inputs such as input costs, sale prices, manure production, livestock characteristics, family structure, and more (Le Gal, 2021) to calculate food, forage, and manure balances at the farm level for different scenarios (Le Gal et al., 2022). The model analyzes the yearly balance of the supply and demand of organic fertilizer and fodder biomass by accounting for the production levels and requirements of crop and animal units (Ryschawy et al., 2014). In mixed crop-livestock systems animal feeding and organic fertilization are two critical interactions the simulator examines between crops and livestock (Le Gal et al., 2011).

2.6 Resilience Metrics of Agriculture Systems

A consensus on measuring resilience and a universally accepted tool for quantifying resilience at different scales is currently lacking (Eeswaran, et al., 2021a). Additionally, definitions

of resilience may vary across disciplines and groups. A general definition is a system's ability to recover from stressors (Holling, 1973). Resilience metrics help gauge the extent of system improvement towards sustainable conditions, identify critical thresholds for potential issues, and aid in assessing the management of the system (Quinlan et al., 2016). According to the Committee on Sustainability Assessment (COSA), assessing resilience typically requires an extensive process considering a system of interest's interconnected social, economic, and environmental dimensions (COSA, 2017). While there have been many studies on resilience, few studies utilize risk as a metric to evaluate resilience (Slijper et al., 2020).

Conventional risk management methods rely on retrospective knowledge, incident reporting, and risk assessments that use probability calculations based on historical data (Tong & Gernay, 2023). However, these approaches prove insufficient for modern socio-technical systems, particularly because numerous adverse events arise from unforeseen combinations of normal performance variability (Tong & Gernay, 2023). Households have to choose between asset smoothing and consumption smoothing as a means to cope with shocks as a form of risk management, but risk as a metric is not always used to determine resilience (FAO, 2016). Therefore, risk behavior is inherently related to resilience as farmers' risk-management strategies, risk preferences, and risk perceptions impact how farmers cope with risks (Slijper et al., 2020). Due to the intricate relationships and complexity within these dimensions, the assessment of food system resilience is often conducted using qualitative methods (Toth et al., 2016). Nevertheless, qualitative assessments are geographically limited and prone to discrepancies in assumptions (Eeswaran et al., 2021a).

Resilience capacities such as robustness, adaptability, and transformability must be improved by maintaining agricultural systems' structures and provisioning its function against

climate variability and extremes (Eeswaran et al., 2021b; Meuwissen et al., 2019; Tendall et al., 2015; Urruty et al., 2016). Robustness is a system's capacity to withstand extreme climate events (Eeswaran et al., 2021b; Tendall et al., 2015). Adaptability refers to the ability to adjust risk management, marketing strategies, and overall agricultural practices to mitigate the effects of climate extremes while maintaining existing system feedback mechanisms and structures (Callo-Concha & Ewert, 2014; Eeswaran et al., 2021b; Tendall et al., 2015). Transformability is the ability of the systems to undergo significant changes to its functions, feedback mechanisms, and structures in defense of climate extremes (Meuwissen et al., 2019). Therefore, resilience and alternative practices should be analyzed through the lens of robustness, adaptability, and transformability.

Numerous tools have been devised to appraise food production systems in terms of climate resilience across various regions worldwide (Douxchamps et al., 2017). These tools are frequently employed at large socioeconomic scales, such as communities, administrative regions, or even national levels (Eeswaran et al., 2021a). The FAO created a tool called Resilience Index Measurement and Analysis Model (RIMA) (FAO, 2016), to evaluate agricultural regions in multiple African countries (Serfilippi & Ramnath, 2018). Additionally, other organization used tools include the FAO's utilization of the Self-evaluation and Holistic Assessment of climate Resilience of farmers and Pastoralists (SHARP) (Choptiany et al., 2017), the United Nations Development Program's development of the Community Based Resilience Assessment (CoBRA) (UNDP, 2013), The Commonwealth Scientific and Industrial Research Organization's instigation of the Resilience, Adaptation and Transformation Assessment Framework (RATA) (O'connell et al., 2015), the International Institute for Sustainable Development's formation of the Community-based Risk Screening Tool-Adaptation and Livelihood (CRiSTAL) (IISD, 2014), and Care international's creation of the Climate Vulnerability and Capacity Analysis (CVCA) (Care, 2019)

have been introduced to evaluate climate resilience in various contexts. Meanwhile, all of these tools use different metrics to define and measure resilience including revenue (Kandulu et al., 2012; Rigolot et al., 2017; Tibesigwa & Visser, 2015), profit (Browne et al., 2013; Komarek et al., 2015; Seo, 2010), means and variance of agricultural production (Di Falco & Chavas, 2008), agricultural gross domestic product (Hsiang & Jina, 2014), dietary diversity (Dillon et al., 2015), crop yields (Birthal et al., 2015; Martin & Magne, 2015), crop failure (P. G. Jones & Thornton, 2009), social characteristics (FAO, 2016; UNDP, 2013), labor productivity (Komarek et al., 2015), expenditure for meeting food security through food consumption (Alfani et al., 2015).

2.7 Summary of Knowledge Gaps and Potential Solutions

Resiliency is an important characteristic of farmers especially in terms of climate change. Moreover, assessing climate resiliency of agricultural workers is an important part of securing their livelihoods. Resilient farming systems are robust, adaptable, and transformable. Therefore, it is imperative to determine farmer climate resiliency. There are current metrics to determine resiliency of farmers; however, existing frameworks and tools are often unable to fully cover the temporal and spatial dynamics of resilience (Dixon & Stringer, 2015; Douchamps et al., 2017). Moreover, most metrics do not utilize a quantified risk value as a part of their determination of resilience (FAO, 2016). Additionally, qualitative assessments of resilience are region specific and can have varying assumptions. Therefore, it is important to determine climate resilient practices with consideration to spatial, temporal, and risk dynamics.

Crop, livestock, and integrated crop-livestock models are very useful in understanding the complex biological interactions that affect crop and livestock growth and production. Moreover, no papers have modeled the integration of crops and livestock in Senegal, where crops and livestock are grown and reared together. Thus, there is great potential for integrated crop-livestock

modeling research to analyze the current situation and provide input on site-specific best management practices to adapt to climate extremes. The FARMSIM model is well equipped to be used to understand the spatial, temporal, and risk dynamics of the farming systems in the Groundnut Basin of Senegal to determine the climate resiliency of smallholder farmers as the model can be run for each district in the region over a five-year period.

3.0 UNVEILING THE RESILIENCE OF SMALLHOLDER FARMERS IN SENEGAL AMIDST EXTREME CLIMATE CONDITIONS

3.1 Introduction

Extreme events (e.g., high temperatures, floods and prolonged drought), climate change and variability, major natural disasters, mass pandemics, and civil unrest and political instability, including the war in Ukraine, have had a profound impact on global food and nutrition security (FAO et al., 2022; IFPRI, 2023; Kogo et al., 2021; Lin et al., 2022). These events can disrupt agricultural production, damage infrastructure, and compromise supply chains, decrease food availability, access and increase food prices (FAO et al., 2022; IFPRI, 2023; WFP, 2021). Meanwhile, over 50% of the world's malnourished population live in conflict affected regions (Mehrabi et al., 2022; WFP, 2021). Extreme events often exacerbate existing social and economic inequalities, as poor communities are disproportionately affected and often lack the resources to cope with food shortages (FAO et al., 2022; IFPRI, 2023). Ultimately, these events pose significant challenges to food security, jeopardizing the access, availability, and stability of nutritious food for populations worldwide. Therefore, the resilience of communities, households, and individuals must be improved to better adapt these unforeseen events.

Climate change and its associated extreme events have profoundly affected Africa, exacerbating existing vulnerabilities and posing significant challenges across the continent (Trisos et al., 2022; WMO, 2022). Rising temperatures, changing rainfall patterns, and increased frequency and intensity of droughts, floods, and storms have disrupted agricultural systems, decreased crop yields, and affecting livestock health and productivity (FAO, 2021; WMO, 2022). This has resulted in the regions' food insecurity, malnutrition, and economic instability (Nhemachena et al., 2020; Schilling et al., 2020; Trisos et al., 2022; Waha et al., 2017). Vulnerable

communities, including smallholder farmers (Ayanlade et al., 2017; Mogomotsi et al., 2020), pastoralists (Ayanlade & Ojebisi, 2019; Wangui, 2018), and fishing communities (Belhabib et al., 2016; Muringai et al., 2019), bear the brunt of these impacts, often lacking the resources and capacity to adapt and recover (Trisos et al., 2022; WMO, 2022). Meanwhile, multiple climate risks (e.g., temperatures, drought, pest and disease outbreaks) can interact and amplify impacts; therefore, cross-sectoral solutions are critical to support climate-resilient development (Liu et al., 2018). Climate change and extreme events in Africa are intertwined, creating a complex web of challenges that require urgent attention and comprehensive strategies for adaptation and resilience-building. Nonetheless, the extent to which these strategies remain effective during severe occurrences, such as prolonged droughts, has not been adequately evaluated. Therefore, considering the enormity of the issue, it is imperative to assess potential solutions to guarantee the resilience of the adaptation strategies.

Meanwhile, there is no consensus on measuring resilience and no universally accepted tool to quantify resilience across various scales (Eeswaran et al., 2021a). Moreover, definitions of resilience can differ across disciplines and target groups. Therefore, it is necessary to establish a definition and approach for quantifying resilience before embarking on a study (Davoudi et al., 2013; FAO, 2016). A general definition of resilience is the ability of a system to recover from stressors (Holling, 1973). Resilience metrics help to gauge the extent of system improvement towards sustainable conditions, identify critical thresholds for potential issues, and aid in assessing the management of the system (Quinlan et al., 2016). According to the Committee on Sustainability Assessment (COSA), assessing resilience typically requires a comprehensive approach considering social, economic, and environmental dimensions of a system of interest

(COSA, 2017). While there have been many studies on resilience, there are few studies that utilize risk as a metric to evaluate resilience (Slijper et al., 2020).

Conventional risk management methods rely on retrospective knowledge, incident reporting, and risk assessments using historical data probability calculations (Tong & Gernay, 2023). However, these approaches prove insufficient for modern socio-technical systems, particularly because numerous adverse events arise from unforeseen combinations of normal performance variability (Tong & Gernay, 2023). In addition, risk as a metric is not always used to determine resilience (FAO, 2016). Therefore, risk behavior is inherently related to resilience as farmers' risk-management strategies, risk preferences, and risk perceptions impact how they cope with risks (Slijper et al., 2020). Due to the intricate relationships and complexity within these dimensions, the assessment of food system resilience is often conducted using qualitative methods (Toth et al., 2016). Nevertheless, qualitative assessments are subjective and geographically limited, hence prone to discrepancies. Finally, the existing resilience indices can help with ranking different mitigation scenarios. However, they do not necessarily guarantee that all aspects of food and nutritional security are captured.

Therefore, this paper establishes resilience as the state wherein farmers are able to ensure their essential nutritional and economic needs with minimal risk. To achieve this, we propose a new paradigm to limit resilience solutions to those that are economically feasible and meet the nutritional requirements of society at the lowest level of uncertainty. Here, we consider a variety of relevant aspects, including food purchases consumed, donated food consumed, dietary diversity, costs associated for maintenance, insurance, taxes, loans, debt, school expenses, value of cropland and machinery, type of crops grown, crop variety, percent of a grown crop consumed by the farmers' family, and income generated from sales. These inputs cover social, environmental, and

economic aspects of resilience. Subsequently, in contrast to established approaches, we refrained from computing the comprehensive resilience scores through arbitrary weighting of diverse metrics (such as economic and environmental factors) and their summation (Eeswaran et al., 2021a). Our approach guarantees that the proposed solutions meet the nutritional and economic needs with the lowest risk to the smallholder farmers in the target area. This proposed approach is used in a case study to assess the viability of solutions to extreme drought events in Senegal. Specifically, the objectives of the study are to 1) evaluate and rank alternative scenarios based on the nutritional requirement of smallholders at the lowest cost, 2) determine the most feasible alternative systems that meet the economic needs of smallholder farmers, and 3) rank alternative scenarios based on the risk and resilience to extreme drought conditions.

3.2 Methodology

3.2.1 Study Area

The Groundnut Basin in Senegal, containing the districts Thiès, Diourbel, Fatick, Kaolack, Kaffrine, and Kolda, is the target location of this study (Figure 3). This region is known for its high agricultural production (B. Faye & Du, 2021; Malou et al., 2020; Toure & Diakhate, 2020). Located in the central-western part of Senegal, the basin encompasses an extensive area and is primarily dedicated to pearl millet (*Pennisetum glaucum* (L.) R. Br.) (hereafter referred as millet) and groundnut (*Arachis hypogaea* L.) (or peanut) grown in rotation (HEA SAHEL, 2016b; Ricome et al., 2017). This paper aims to study millet farmers in the Groundnut basin, where as the they grow millet and groundnut in rotation it is relevant to study both crops. Mineral fertilizer use is rare, and most agriculture is rainfed (B. Faye & Du, 2021; Ricome et al., 2017). Smallholder farmers typically have horses and oxen for traction power and cattle, goats, sheep, and chickens for their livelihood (HEA SAHEL, 2016b; Ricome et al., 2017). Despite the Groundnut Basin's

historical focus on groundnut production, there has been a lack of growth in recent years, which can be attributed to a challenging environment characterized by unpredictable rainfall patterns and soil degradation (Mills et al., 2021). Groundnuts serve as a lucrative cash crop and a significant export commodity for Senegal, while millet is a fundamental staple crop for local household consumption. Therefore, delving into the study of the Groundnut Basin becomes imperative for comprehending the resilience demonstrated by smallholder farmers engaged in millet and groundnut cultivation within the region.

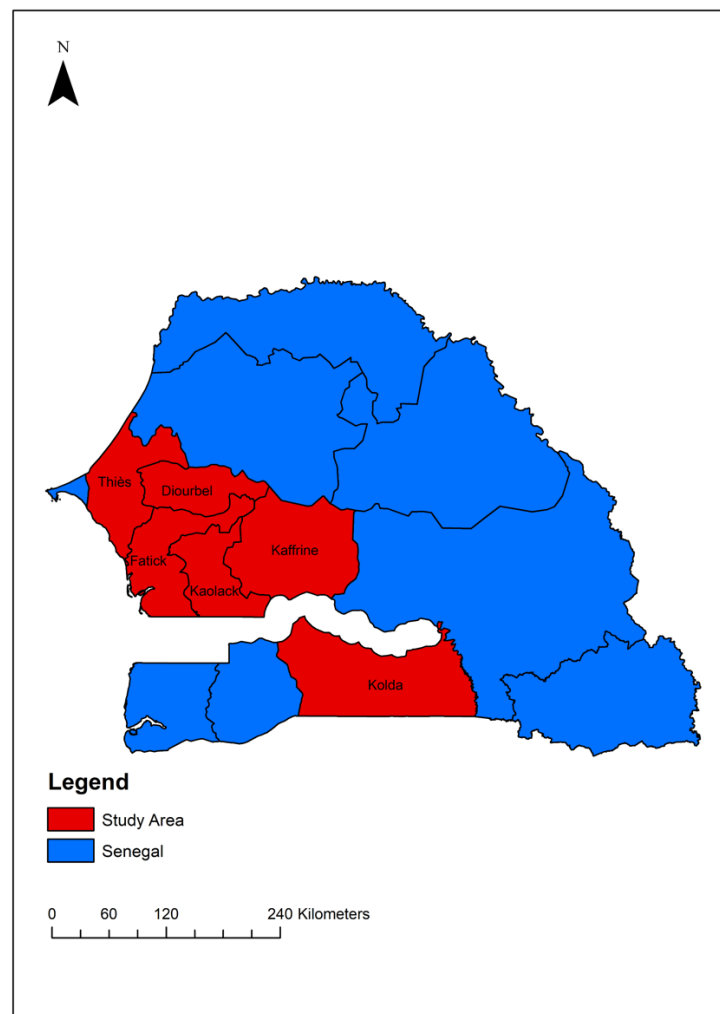


Figure 3. Senegal and the study area.

3.2.2 Modeling Overview

The methodology presented in this study determines resilience employing a holistic approach. Therefore, we utilized two models (FARMSIM, Farm Simulation Model (Texas A&M, 2023); and APSIM, Agricultural Production Systems Simulator (Holzworth et al., 2018)) to obtain the required nutrition, economics, and risk data information. The modeling process started with data collection as FARMSIM requires about 500 inputs to simulate a representative farm for a region. The input data can be seen in Tables S1 to S25. Briefly, some of the main variables include soil moisture (Eeswaran et al., 2021a), climate conditions (FAO, 2016), market price fluctuations (Slijper et al., 2020), crop diversity (FAO, 2016), dietary diversity (Dillon et al., 2015; FAO, 2016), crop yield (Birthal et al., 2015; Martin & Magne, 2015), agricultural assets (FAO, 2016), revenue (Kandulu et al., 2012; Rigolot et al., 2017; Tibesigwa & Visser, 2015), profit (Browne et al., 2013; Komarek et al., 2015; Seo, 2010), and food consumption expenditures to meet food security (Alfani et al., 2015). In addition to regional farming inputs, APSIM was utilized to generate yield data across different districts as inputs to FARMSIM for a baseline management strategy and alternative scenarios. The APSIM model was used to simulate millet yield only as the scope of this paper was to analyze how to improve millet production as millet is one of the most predominate crops across Senegal. Moreover, millet has a higher temperature ceiling than other cereal crops, which is especially relevant as climate change is expected to increase temperatures as well as heat wave frequency and intensity (Aissatou et al., 2017; Djanaguiraman et al., 2018; Lowe et al., 2011). Therefore, increasing millet production is relevant to improving Senegal farmers' livelihoods. However, in regard to FARMSIM millet and groundnut were modeled together as these two crops are typically grown in rotation.

Based on the data obtained to build the aforementioned models, this study aims to analyze how varying planting dates, plant densities, and N fertilizer rates impact millet production and affect the resilience of smallholder farmers under extreme drought. The alternative scenarios have three planting dates, three plant densities, and six fertilizer N rates, resulting in a total of 54 management scenarios and a baseline for each district for a total of 324 simulations (Figure 2). The baseline was defined as an early planting date, 1.1 pl m⁻² plant density, and 30 kg N ha⁻¹ fertilizer rate. All scenarios and the baseline were simulated under rainfed conditions. The first rain higher than 20 mm after May 30 determined the early planting date. Subsequently, the remaining planting dates were spaced 20 days apart (medium and late). The baseline and alternative scenarios were based on Vieira Junior et al., (2023).

As described in the introduction section, resilience was determined when nutritional and economic conditions were satisfied at the lowest risk to the farmer. In the realm of nutrition, this criterion is fulfilled by meeting the minimum requirements for human nutritional needs, achieved through an optimization analysis (Objective 1). The optimization analysis was employed to enhance the deficient nutritional categories, ensuring they meet the minimum nutritional requirements. This demonstrates how farmers can allocate their income towards specific foods in order to fulfill their nutritional needs. A linear optimization was run to examine which solutions meet the minimum nutrition requirements at the lowest cost. Additionally, a multi-objective optimization was used to find minimum nutrition requirements at the lowest cost while maintaining a healthy, balanced diet. Under Objective 1, the alternative scenarios will then be ranked in terms of a nutrition-balanced diet at the lowest cost. The ultimate list comprises solely the solutions that outperformed the baseline scenario, which represents the current practices. After meeting the nutritional requirements for smallholder households, an economic analysis was performed to

identify the most economically feasible solutions. The process starts by filtering out alternative solutions that are not economically feasible (Objective 2). Any alternatives with a negative internal rate of returns (IRR) are eliminated. Subsequently, the remaining options are evaluated according to three economic indicators: net cash farm income (NCFI), ending cash reserves (EC), and net present value (NPV). Finally, the top-ranked economically feasible alternatives were evaluated based on two risk factors, certainty equivalent (CE) and risk premium (RP) to identify the most resilient alternatives (Objective 3). Figure 4 depicts the methodology utilized in this paper.

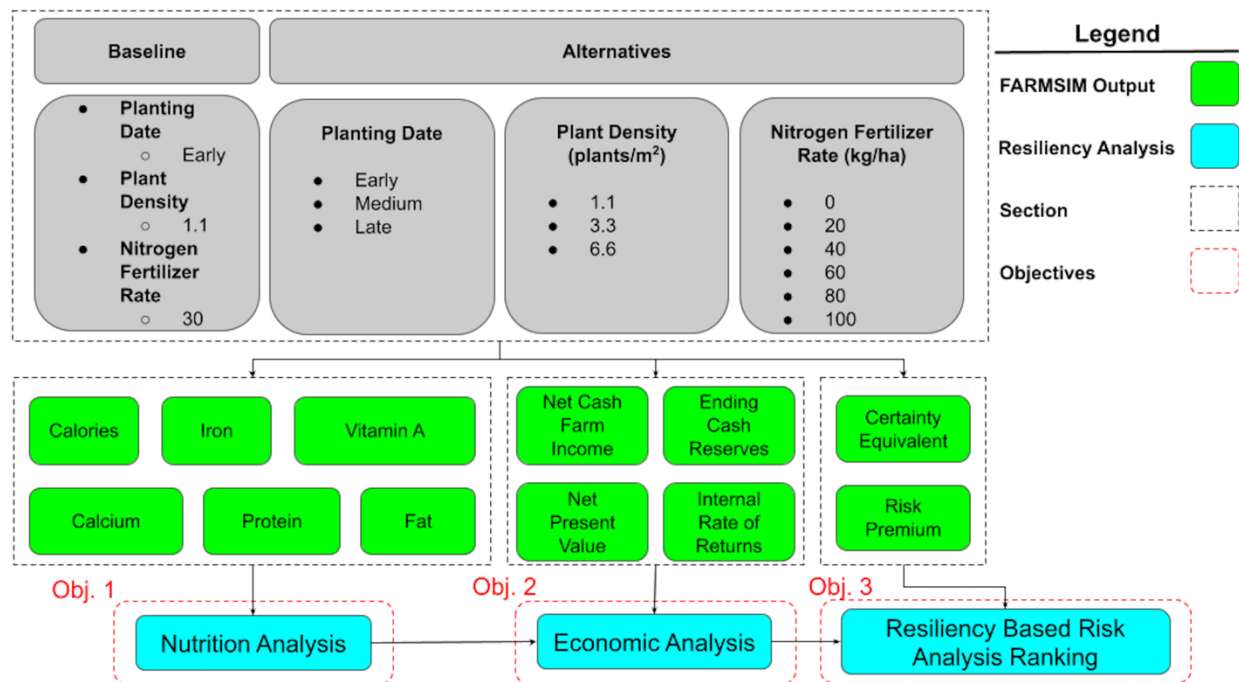


Figure 4. Schematic representation of variables and methodologies used to determine the resilience of smallholders to extreme drought.

3.2.3 Data Collection

Primary and secondary data were utilized in this study. Primary data were obtained through household surveys and experts' opinions. Secondary sources that were utilized include L'Enquete Agricole Annuelle (EAA) reports from the Direction de l'Analyse, de la Prévision et des

Statistiques Agricoles (DAPSA), other government reports, NGOs' reports, and peer-reviewed publications. Crop yield and cultivation extent data were obtained from DAPSA and the Ministère de l'Agriculture et de l'Équipement Rural (MAER) for the years 2016-2020. This data aided our comprehension of agricultural practices for each district and helped to establish representative farm operations, demographics, consumption patterns, and finances. The gathered data encompassed millet and groundnut production details, including crop yield, associated crop production costs, livestock numbers, livestock production costs, milk and egg production, purchased and donated foods, food consumption, fixed costs, alternative scenario costs, and assets. All these data elements were gathered according to the FARMSIM model requirements (Bizimana & Richardson, 2019).

3.2.4 Farm Income and Nutrition Simulator (FARMSIM)

FARMSIM is an integrated farm model, which uses Monte Carlo simulations and is widely employed to predict the potential effects of distinct agricultural interventions on household-level nutrition and financial stability (Bizimana & Richardson, 2019). This model assesses various facets of farming systems, including crop production, livestock rearing, food consumption, market structures, financial systems, and risk management (Richardson et al., 2008). To evaluate the risks associated with agricultural interventions, the model utilizes Simulation and Econometrics to Analyze Risk (Simetar) tools (Richardson et al., 2008). Furthermore, the model incorporates stochastic simulation techniques to account for system uncertainty, generating probabilistic outputs for different agricultural management scenarios. Following the simulation process, the outcome comprises 500 iteration values for each key output variable (KOV) over a five-year planning horizon. Section A of the Supplementary Materials provides the definitions of KOVs used in this study.

The Simetar function of FARMSIM allows for the evaluation of various alternative scenarios utilizing the Stochastic Efficiency with Respect to a Function (SERF). These values establish empirical probability distributions that are instrumental in comparing the baseline farming technologies or interventions with alternative ones. Moreover, decision-makers can quantitatively assess the potential outcomes of introducing alternative technologies through a comparative analysis of the probability distributions. For this study, we are utilizing the following KOVs: NCFI, EC, NPV, IRR, calories, protein, fat, calcium, iron, and vitamin A. Additionally, the CE and RP will be utilized in this study to determine the risk of adapting the alternative scenarios.

The model has been extensively utilized in developing countries such as Ghana (Balana et al., 2020), Ethiopia (Bizimana & Richardson, 2019), Tanzania (Andrew et al., 2019), and Malawi (Chikafa et al., 2023), providing valuable support in decision making. Its credibility and accuracy have been substantiated by its ability to simulate real agricultural data effectively. Notable applications include analyzing household-level food consumption impact in Ethiopia (Bizimana et al., 2020), utilizing farmer's risk factors to assess the adoption potential of technologies (Bizimana & Richardson, 2019), and evaluating the efficacy of farm level agricultural technologies (Bizimana & Richardson, 2019). These abilities empower decision-makers to devise financial and management strategies for the successful implementation, adoption, and sustainability of different technologies (van den Berg et al., 2019).

FARMSIM is comprised of four elements: crops, livestock, nutrition, and economics. The model simulates farming practices at the village, district, or regional level, offering plausible income and nutrition status at the household level. For nutrition analysis, the model accounts for how much a household consumes in terms of the number of livestock, livestock products,

harvested crops, purchases from the market, and food donations. Moreover, FARMSIM utilizes simulations to calculate the potential income for households considering the livestock, livestock products, and crops sold by the household in the market. The model determines the nutritional requirements for families with Calories, protein, fat, calcium, iron, and vitamin A by utilizing the standard nutrient score. Table S2 provides a summary of the minimum nutrient requirements per adult equivalent used by the model for nutrition simulation.

3.2.5 Agricultural Production Systems sIMulator (APSIM)

The simulations in this study were performed utilizing version 7.10 of the APSIM software platform (Holzworth et al., 2014). A previous calibration of the APSIM-Millet model (Van Oosterom, Carberry, & O’Leary, 2001; Van Oosterom, Carberry, Hargreaves, et al., 2001; Van Oosterom et al., 2002) obtained by (Vieira Junior et al., 2023) was employed. This calibration was explicitly developed for the two most commonly adopted millet landraces in Senegal: Sanio and Souna. The model’s performance was assessed by simulating grain yield and crop phenology (Vieira Junior et al., 2023). The soil parameters and initial conditions used in the simulations were defined based on the descriptions provided by Vieira Junior et al. (2023). These soil parameters include depth (0-150 cm), bulk density (1.27-1.64 g/cm³), drained lower limit (0.06-0.17 mm/mm), drained upper limit (0.11-0.28 mm/mm), saturated water content (0.38-0.40), and pH (5.19-6.96).

Grain yield production simulation was conducted at five equidistant points within each of the six millet-producing departments in Senegal, resulting in a total of 95 simulated locations. A total of 54 management scenarios were simulated for the period spanning from 1990 to 2021. The simulated scenarios were defined based on the combination of (i) three planting dates (early (early-June to late-July), medium (early-July to late-August), and late (late-July to mid-September)), (ii) three plant densities (1.1, 3.3, and 6.6 pl m⁻²), and (iii) six N fertilization levels (0, 20, 40, 60, 80,

and 100 kg N ha⁻¹). The simulated nitrogen (N) fertilization source was urea, which was applied at 2 specific dates, 21 days and 45 days after sowing.

3.2.6 Drought determination

Droughts can have devastating effects on crop production and farmers' livelihood. The primary threat to Senegal's agriculture comes from drought and the growing unpredictability of rainfall, which pose the most notable danger to crops and livestock (D'Alessandro et al., 2015). The increased frequency of extreme events, such as prolonged rainy breaks and droughts as well as a delay in the start and duration of the rainy season, have increased the vulnerability of agricultural production systems (IPCC, 2019; Ndiaye et al., 2021). Moreover, floods occur more frequently than droughts; however, droughts have more pronounced impacts and affect more people per event (World Bank, 2011). Droughts will not only decrease crop yields and biomass production but also lead to food shortages, price increases, increases in bushfires, pest infestations, rural-urban migration, and destabilization of poor households' livelihoods (USAID, 2012).

We analyzed farmers' resilience to extreme drought conditions to better understand what combination of interventions better prepares farmers to mitigate the negative impacts of future droughts. We utilized precipitation data from 1990-2021 to determine the driest five-year period within our study area. The growing season was determined by finding the average number of days for each district between the planting date and harvest date. The precipitation was summed over the growing season for each year, and the year with the lowest recorded precipitation was utilized as the third year in the five-year analysis in FARMSIM. The drought period determined for each study district is as follows: Diourbel was 2012-2016, Fatick was 1995-1999, Kaffrine was 2012-2016, Kaolack was 1995-1999, Kolda was 2012-2016, and Thiès was 2012-2016. After finding the drought years, crop yields in those years were utilized in the simulations of FARMSIM. This

drought periods are supported by literature as in 1996-1998 and in 2014 regional droughts were reported (D'Alessandro et al., 2015; Nébié et al., 2021).

3.2.7 Statistical Analysis

A Wilcoxon signed-rank test was used to calculate the adjusted p -value using the Bonferroni method (Wilcoxon, 1945). This test was used to determine the statistical significance between the baseline and alternative indicators. Indicators that had a p -value calculated for them include yield, RP, CE, NPV, NCFI, EC, calories, protein, fat, calcium, iron, and vitamin A. An indicator was determined to be significantly different than the baseline when the p -value was less than 0.05 ($p < 0.05$). The Wilcoxon signed-rank test is a non-parametric statistical test used to compare two related samples or analyze a single sample with a paired difference test of repeated measurements to assess whether the population mean ranks differ (Xia, 2020). The statistical method is the nonparametric equivalent of the parametric paired t-test (Scheff, 2016; Xia, 2020). The Wilcoxon signed-rank test is preferred for dealing with data made up of definite scores, which is the case of this research (Scheff, 2016).

3.2.8 Comparison and Evaluation of Agricultural Alternative Scenarios

In this study, the indicators were categorized into four groups: yield (yield), risk (CE and RP), economics (NPV, NCFI, and EC), and nutrition (calories, protein, fat, calcium, iron, and vitamin A). The p -values obtained from the statistical tests were organized as follows: a value of one was assigned if there was a significant increase in the indicator, a value of minus one was assigned for a significant decrease in the indicator, and a value of zero was assigned if there was no significant difference in the indicator.

A comparison of the baseline and alternatives was conducted using the generated values. The values of -1, 0, and 1 were summed from each district into a table of comparisons with the 54

alternative scenarios. The summed number was averaged for the districts, which resulted in the average *evaluation percentage* for the alternative scenarios versus the baseline current situation. The percentage change (increase, decrease, or no significant difference) can be utilized to see how varying degrees of planting date, plant density, and N fertilizer performed compared to the baseline situation.

Additionally, a comparison using the generated values was conducted between the alternatives to understand better how the alternatives perform when compared to each other. The scenarios were separated into three categories: planting date and plant density, plant density and N fertilizer rate, and planting date and N fertilizer rate. Each category was further divided into four groups: yield, risk, economics, and nutrition. The total values of -1, 0, and 1 were summed for the alternatives and districts and then averaged among the districts. The percent change (increase, decrease, or no significant difference) can be utilized to see how varying degrees of planting date, plant density, and N fertilizer interact.

3.2.9 Meet the Nutritional Requirements of Smallholder Farmers

Here, we proposed two optimization strategies to address the nutritional deficiency of smallholder farmers under the nutrition analysis section to identify 1) the cheapest alternative to meet the nutritional requirements and 2) the most balanced nutritional alternative that also costs the least.

a) Linear Optimization (meet nutritional deficiencies at the lowest cost)

The linear optimization was performed using the Python library Scipy. When a nutrition deficiency is identified at the individual level for each district, a thorough optimization analysis was performed to fulfill the minimum daily requirements as established in Table S2. Based on our knowledge of consumption behavior in each district, the foods considered for purchasing include

fish, beef, milk, eggs, lettuce, peanuts, rice, maize, and millet. Table S26 shows the nutritional values for all considered products. Items included as inputs for the optimization algorithm include nutritional information (Table S26) and prices for crops and food purchases (Table S27) in addition to the minimum daily intake requirement per person (Table S2) and the nutritional data outputs from FARMSIM for calories, protein, fat, calcium, iron, and vitamin A. The objective of the optimization analysis was to fill the nutritional deficits experienced under the baseline and alternative scenarios by utilizing the cost, which will be incorporated into the analysis by adjusting EC and NPV values. Therefore, linear optimization was used to accomplish the objective. Linear programming employs linear equations and inequalities to determine potential solutions for current challenges (Mallick et al., 2020). Linear optimization was used to define decision variables, objective functions, and different constraints where the constraints were recognized and characterized as a collection of linear equations and inequalities. The constraints were defined as a set of inequalities and linear equations with the additional requirement that every decision variable must be positive. Thus, this framework was utilized to meet the required minimum nutrients at the lowest cost. The optimization analysis was completed using Pymoo's implementation of Non-dominated Sorting Genetic Algorithm II (NSGA-II) (Blank & Deb, 2020). The analysis was run for all alternative scenarios for all six districts.

An optimization model (Equation 1) was formulated to minimize the purchasing cost of market goods (C). In this context, the decision variables, denoted as X_i , signify the quantity of consumptive products, while C_i represents the cost per unit of each product (as presented in Table S27). The alternatives were ranked based on cost, with the cheapest alternative being considered the best.

$$C = X_1 \times C_1 + X_2 \times C_2 + X_3 \times C_3 + X_4 \times C_4 + X_5 \times C_5 + X_6 \times C_6 + X_7 \times C_7 + X_8 \times C_8 + X_9 \times C_9 \quad (1)$$

b) Multi-Objective Optimization (meet nutritional deficiencies by achieving a balanced nutritional intake at a minimum cost)

A second optimization analysis was conducted to determine the best use of income while restraining excess nutritional consumption. The multi-objective optimization analysis was completed using Pymoo's implementation of NSGA-II. The two parameters used in this optimization were the cost of additional food purchases to meet minimum nutritional requirements and the percent change in individual consumption above the required nutrition (Table S2). The percentage change in nutritional content was calculated by assessing the percentage change in each nutritional category from the minimum required nutritional values, followed by averaging these changes. After running the optimization, many possible solutions satisfied the criteria, so the chosen solution was at the closest point to the origin as this would be the most balanced position between meeting nutritional needs and cost. The solutions were ranked based on the cost and percent change in nutrition. This was done by normalizing the cost against the minimum cost and the percent change in nutrition values against their minimum, adding the normalized cost and normalized percent change in nutrition, and then ranking them in ascending order.

3.2.10 Economic Analysis to Adjust Cash Income Based on Meeting Nutritional Needs

The economic analysis was performed on scenarios that meet the population's nutritional needs. Therefore, the cost of the optimization solution was subtracted from the EC and NPV to account for the additional food costs. At the start of the economic analysis, the alternative scenarios were filtered using IRR. IRR is a relevant measure of the feasibility of investments and interventions in regard to how they sustain themselves through generated profits from farm produce sales (Chikafa et al., 2023). Again, a negative and zero IRR were not considered

economically feasible solutions. Meanwhile, the remaining alternative scenarios were ranked utilizing the sum of normalized NCFI, EC, and NPV.

3.2.11 Resilience Ranking of Alternative Scenarios Based on Risk

Adaptation of agricultural technologies involves an intrinsic element of risk. Various techniques can be employed to rank risky scenarios, encompassing measures like means, standard deviation, and coefficient of variation (Bizimana & Richardson, 2019). Nonetheless, while these approaches take risk into account, they often lack the resilience to consistently and conclusively prioritize scenarios, as they do not consider the decision maker's risk preferences (Chernobai & Rachev, 2006). Consequently, it is more advisable to integrate utility-based ranking approaches when comparing different farming scenarios, as they offer a superior approach to assist decision-makers in selecting among the options (Geissel et al., 2018). This aids decision-makers in selecting the most favorable technology to adopt.

By employing the Simetar function, diverse alternative scenarios can be assessed. For this study, we utilized the SERF option due to its capacity to evaluate profits or certainty equivalence across various risk aversion levels (ranging from 0, indicating risk neutrality, to 1, indicating risk aversion). Decision-makers can use this approach to evaluate the performance of various alternatives across different risk coefficients and choose the one that consistently yields the largest CE and has a higher RP across all levels of risk (Richardson et al., 2008). Thus, this was the approach utilized in this paper. The CE and RP for the different levels of farmers were averaged over the ARAC (alternative risk aversion coefficients) and were used in the final risk ranking.

The optimization analysis satisfied the nutritional needs of the farmer for the alternatives. The economic analysis ensured economic feasibility and income growth for the alternatives. Finally, the risk analysis eliminated alternative scenarios with a negative RP and determined the

final ranking of the alternatives utilizing CE. The alternative scenarios that are ranked the best after these analyses will provide the farmers with the most resilient options to adapt in extreme drought conditions.

3.3 Results and Discussion

3.3.1 Initial Assessment of Nutritional Deficiency in the Study Region

The FARMSIM model simulated nutrition values for calories, protein, fat, calcium, iron, and vitamin A. The findings of the nutrition analysis (Table 1) indicate that only the baseline scenarios in the Fatick and Kaffrine districts fulfill just half of the population's nutritional needs. In contrast, all the other districts fall short of more than 50% of the required nutritional indicators (e.g., iron, vitamin A). All districts except Thiès had adequate nutrition for protein and fat. All districts were deficient in calcium, iron, and vitamin A. The nutrition values for the alternatives were similar to the baseline as the family consumption of millet was adjusted as yield changed. Several prior studies corroborate our findings. For example, a report from the International Food Policy Research Institute (IFPRI) found rural populations in Senegal deficient in calcium, iron, and vitamin A (Marivoet et al., 2021). Additionally, the rural population was slightly deficient in calories; however, they met their protein intake needs (Marivoet et al., 2021). The rural population was seen to have an excessive fat intake, though not as pronounced as in urban settings (Marivoet et al., 2021). Several other papers also confirm the nutritional results obtained in this study (Fiorentino et al., 2016; Giguère-Johnson et al., 2021).

Table 1. Nutrition per individual for baseline scenarios for all districts*.

Districts	Nutrition					
	Calories (Cal)	Protein (g)	Fat (g)	Calcium (g)	Iron (g)	Vitamin A (g)
Diourbel	<2306.42	>52.10	>73.77	<1.45	<0.0137	<0.009
Fatick	>2306.42	>52.10	>73.77	<1.45	<0.0137	<0.009
Kaffrine	>2306.42	>52.10	>73.77	<1.45	<0.0137	<0.009
Kaolack	<2306.42	>52.10	>73.77	<1.45	<0.0137	<0.009
Kolda	<2306.42	>52.10	>73.77	<1.45	<0.0137	<0.009
Thiès	<2306.42	<52.10	<73.77	<1.45	<0.0137	<0.009

*Red represents not meeting nutritional requirements. Green represents meeting nutritional requirements.

3.3.2 Comparison and Evaluation of Agricultural Baseline and Alternative Scenarios Using Statistical Analysis

a) Comparison of Agricultural Baseline and Alternative Scenarios

The agricultural intervention scenarios were compared against the baseline and evaluated based on *p*-values. The results of this analysis can be seen in Figures 4-7 and Figures A1-A9. The figure shows the percentage of times the *p*-values determined significance for each alternative at each indicator for all six districts. A higher, positive value indicates the percentage of times the districts had a significant increase in the indicator at a particular alternative scenario, while a lower, negative value indicates the percentage of times the districts had a significant decrease in the indicator at a particular alternative scenario. A value of around 0 meant the alternative did not significantly increase or decrease the indicators for a particular alternative scenario from the baseline.

There were some trends of interest in this analysis as seen in Figure 5. Firstly, vitamin A show no significant increase or decrease from the alternatives. Additionally, this was also true for calcium except for two alternative scenarios. A trend occurred within each fertilizer application rate and planting date where a plant density of 1.1 pl m⁻² generally had a lower positive percent

change than plant densities of 3.3 pl m⁻² and 6.6 pl m⁻², which were generally similar. For N fertilizer, it was observed that as the fertilizer rate increased, so did the percent change of yield, calories, protein, fat, and iron for a given plant density and planting date. However, at a plant density of 1.1 pl m⁻², the CE, RP, NPV, NCFI, and EC all decreased with increasing N rate and constant planting date. This could be the result of yields increasing, but not enough to improve risk and economic indicators for smallholder farmers. For the planting date, a trend occurred where at a plant density of 1.1, the CE, RP, NPV, NCFI, EC, calories, protein, fat, and iron increased as the planting date increased, though at varying fertilizer rates. This trend was more pronounced at lower N fertilizer rates (0, 20, and 40 kg N ha⁻¹). Additionally, the late planting date saw a large increase in all the indicators except calcium and vitamin A, especially at the lower N fertilizer application rates of 0, 20, and 40 kg N ha⁻¹. With planting date, there was a relatively small effect on the indicators at high plant densities and N fertilizer rates.

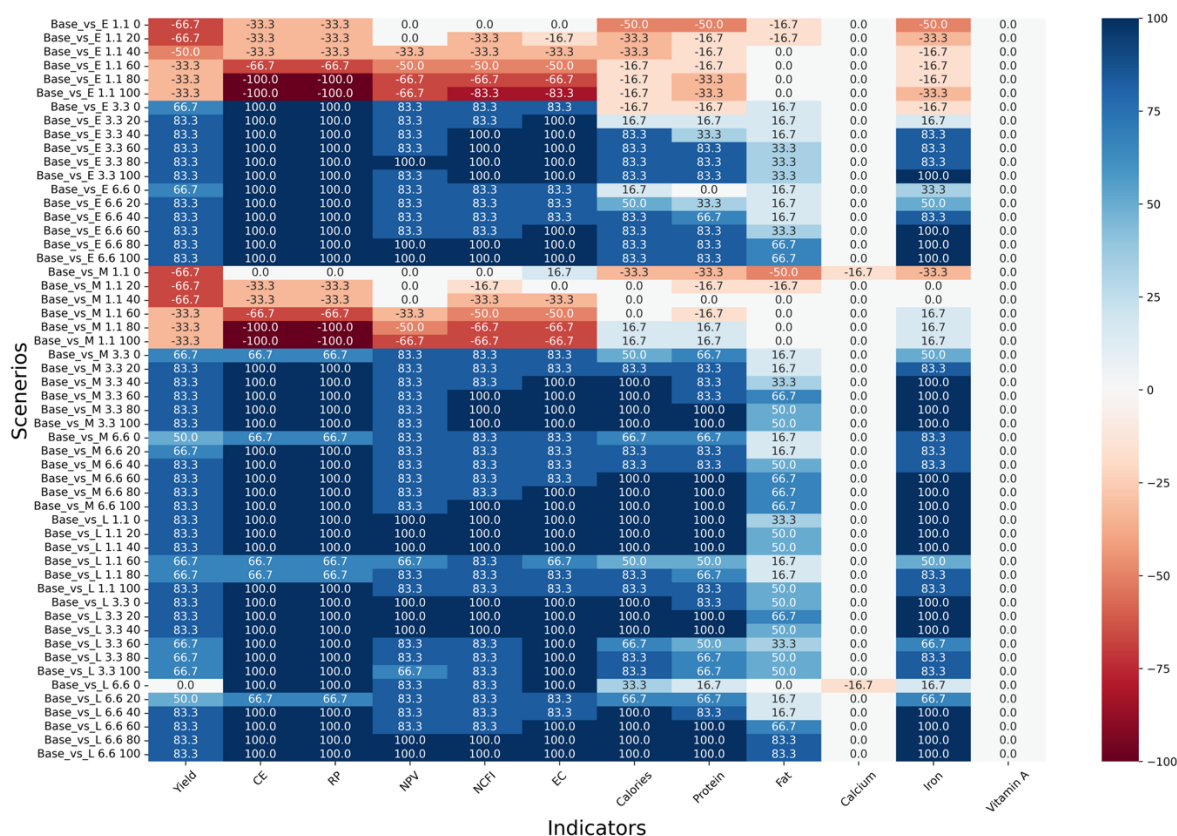


Figure 5. Intervention *evaluation percentage* across six districts for the baseline versus the alternatives. The scenario label shows planting date-plant density-N fertilizer rate). The x-axis scenarios are labeled as planting date (E (Early), M (Medium), L (Late)), plant density (1.1 pl m⁻², 3.3 pl m⁻², 6.6 pl m⁻²), and N fertilizer rate (0 kg N ha⁻¹, 20 kg N ha⁻¹, 40 kg N ha⁻¹, 60 kg N ha⁻¹, 80 kg N ha⁻¹, 100 kg N ha⁻¹).

b) Comparison and Evaluation of Agricultural Alternative Scenarios Against Each Other

After comparing the alternative scenarios against the baseline, a further analysis was conducted to examine how the alternatives compared against each other. The analyses were separated into three comparisons with planting date versus plant density, plant density versus N fertilizer rate, and planting date versus N fertilizer rate. These were further analyzed through four categories: yield, risk, economics, and nutrition. Figures 6-8 provide a practical way to understand

how the alternatives compare. A positive percentage value indicates that the alternative on the side of the figure (y-axis) had a significantly higher performance than the alternative on the bottom (x-axis). Additionally, a negative percentage value indicates that the alternative on the side of the figure (y-axis) had a significantly lower performance than the alternative on the bottom (x-axis). A near 0 percentage value indicated no significant difference in the performance of the two alternatives as assessed by categorical indicators, such as yield.

b1) Effects of Planting Date and Plant Density on Indicators:

Figure 6 can be used to compare how changes in planting date and plant density affect the yield. Generally, alternatives with higher plant densities performed better in terms of yield, with plant densities 3.3 pl m⁻² and 6.6 pl m⁻² performing better than 1.1 pl m⁻², with 3.3 pl m⁻² plant densities performing best with the *evaluation percentage*. The medium and late planting dates generally had higher *evaluation percentages* versus the early planting dates. Additionally, late planting dates usually had higher *evaluation percentages* than early and medium planting dates. Compared to the other alternatives, the two worst alternatives were medium (M) planting date and 1.1 pl m⁻² and early (E) planting date and 1.1 pl m⁻² plant density. The alternative that performed the best was the late (L) planting date with a 3.3 pl m⁻² plant density. These general trends were also observed for nutrition, economics, and risk (Figures A1-A3). This could be due to increased yield, improving nutrition and economic indicators while reducing risk. However, there are still differences between Figures 6, A1, A2, and A3. Figures 6 and A3, which represent yield and risk data, respectively, have similar *evaluation percentages*; however, Figures A1 and A2 (nutrition and economics) have more similar *evaluation percentages*. Figures 6 and A3 have higher positive and lower negative values, indicating more pronounced effects with extreme values at both ends, while Figures A1 and A2 have smaller positive and higher negative *evaluation percentages*. This

can signify that yield and risk data are more volatile when analyzed through changing planting date and plant density where varying dates and densities will have a more significant impact on yield and risk than nutrition and economics. Utilizing a poor performing planting date or density could significantly impact the yield and therefore the risk of the smallholder farmer to this variable yield could increase. Additionally, nutrition and economics had more muted *evaluation percentages* implying less significant impacts due to various planting dates and densities. This could be due to no associated costs for altering the planting date or that even with increasing yield the returns in the form of economics and nutrition were less pronounced and did not vary as much as yield and risk.

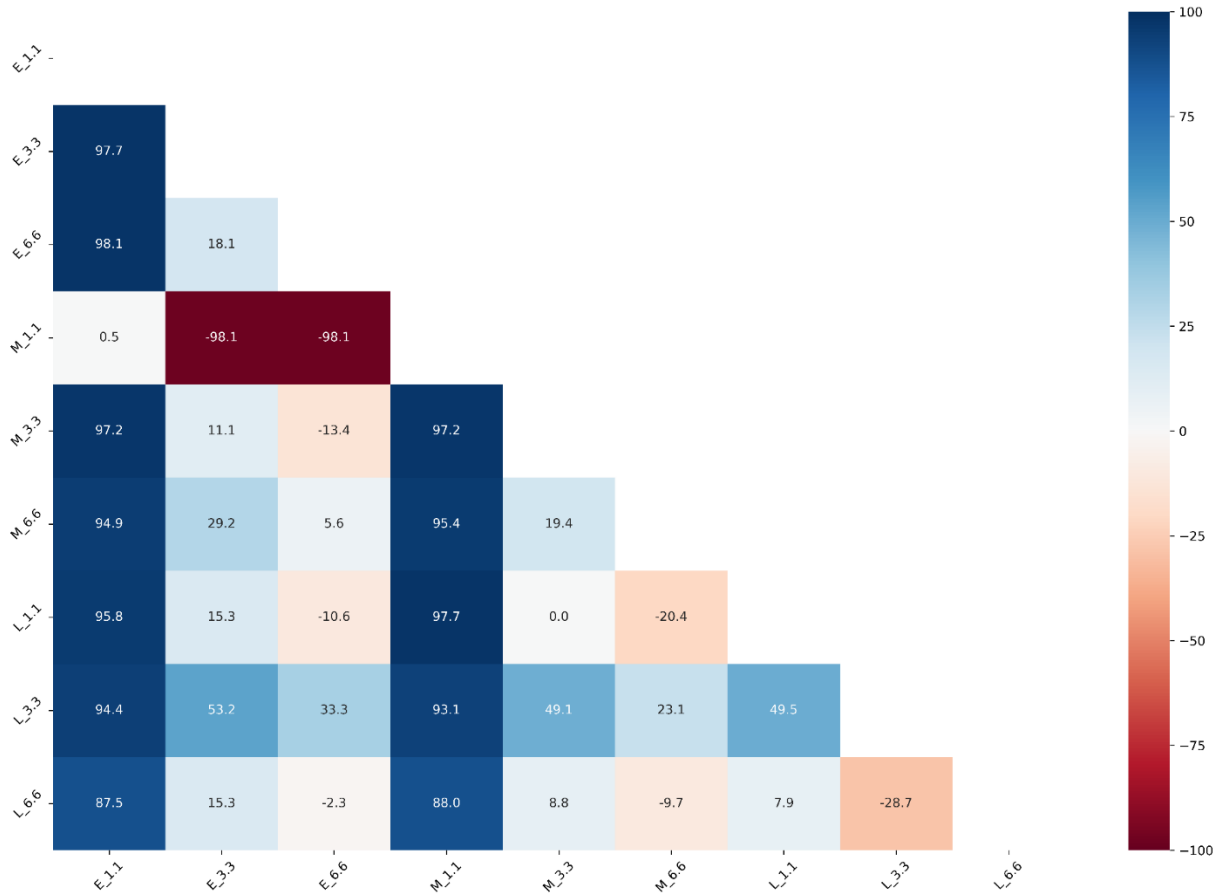


Figure 6. Intervention *evaluation percentage* for yield across six districts for the alternatives versus each other with varying planting dates and plant densities. The alternative labels are (planting date_plant density). The scenarios labeled as planting date (E (Early), M (Medium), L (Late)), plant density (1.1 pl m⁻², 3.3 pl m⁻², 6.6 pl m⁻²), and N fertilizer rate (0 kg N ha⁻¹, 20 kg N ha⁻¹, 40 kg N ha⁻¹, 60 kg N ha⁻¹, 80 kg N ha⁻¹, 100 kg N ha⁻¹).

b2) Effects of Plant Density and N Fertilizer Rate on Indicators:

Figure 7 compares alternative scenarios for all districts against each other concerning yield. Alternatives with different planting dates were compared against each other at different plant densities and N fertilizer rates. In general, as the amount of N fertilizer increased, the percentage of improvement in yield became more evident, indicating the positive impact of a higher N

fertilizer rate. There appears to be a trend where at N rates of 0, 20, and 40 kg ha⁻¹, the *evaluation percentage* increases when plant density increases from 1.1 pl m⁻² to 3.3, but the *evaluation percentage* decreases between plant densities of 3.3 pl m⁻² and 6.6 pl m⁻². Thus, the 3.3 pl m⁻² plant density was superior to the other plant densities. This could be due to the associated costs of utilizing more fertilizer and seeds. However, at higher N fertilizer application rates such as 60 kg ha⁻¹, 80 kg ha⁻¹, and 100 kg ha⁻¹, the *evaluation percentage* increased as plant density increased. Some alternative agricultural scenarios with the lowest *evaluation percentages* include (plant density_N fertilizer rate) 1.1_60, 1.1_80, 1.1_100, 6.6_0, 6.6_20, and 6.6_40. Several of the alternative agricultural scenarios with the highest *evaluation percentages* include (plant density_N fertilizer rate) 3.3_20, 3.3_40, 3.3_100, 6.6_60, 6.6_80, and 6.6_100. These trends were also observed for the risk, economic, and nutrition comparisons in Figures A4-A6. This could be due to increased yield, resulting in improved risk, economics, and nutrition indicators. However, there are still differences between Figures 7 and A4-A6. Figures 7 and A6 (yield and risk, respectively) generally have higher positive and lower negative *evaluation percentages* as compared to Figures A4 (nutrition) and A5 (economics). This can signify that yield and risk data are more volatile when analyzed through changing plant density and N fertilizer rate where varying densities and fertilizer rates will have a more significant impact on yield and risk than nutrition and economics. Opting for an unsuitable planting date or fertilizer rate can substantially impact the crop's output, consequently altering the smallholder farmer's exposure to risk and yield fluctuations. Additionally, nutrition and economics had more muted *evaluation percentages* implying less significant impacts due to various plant densities and fertilizer rates. This could be because even with increasing yield the returns in the form of economics and nutrition were less pronounced and did not vary as much as yield and risk. Figure A6 had negative values for the 1.1 plant density,

which could be attributed to the increased costs of increased fertilizer use not covering the increased yield and economics, thereby putting the farmers at risk.

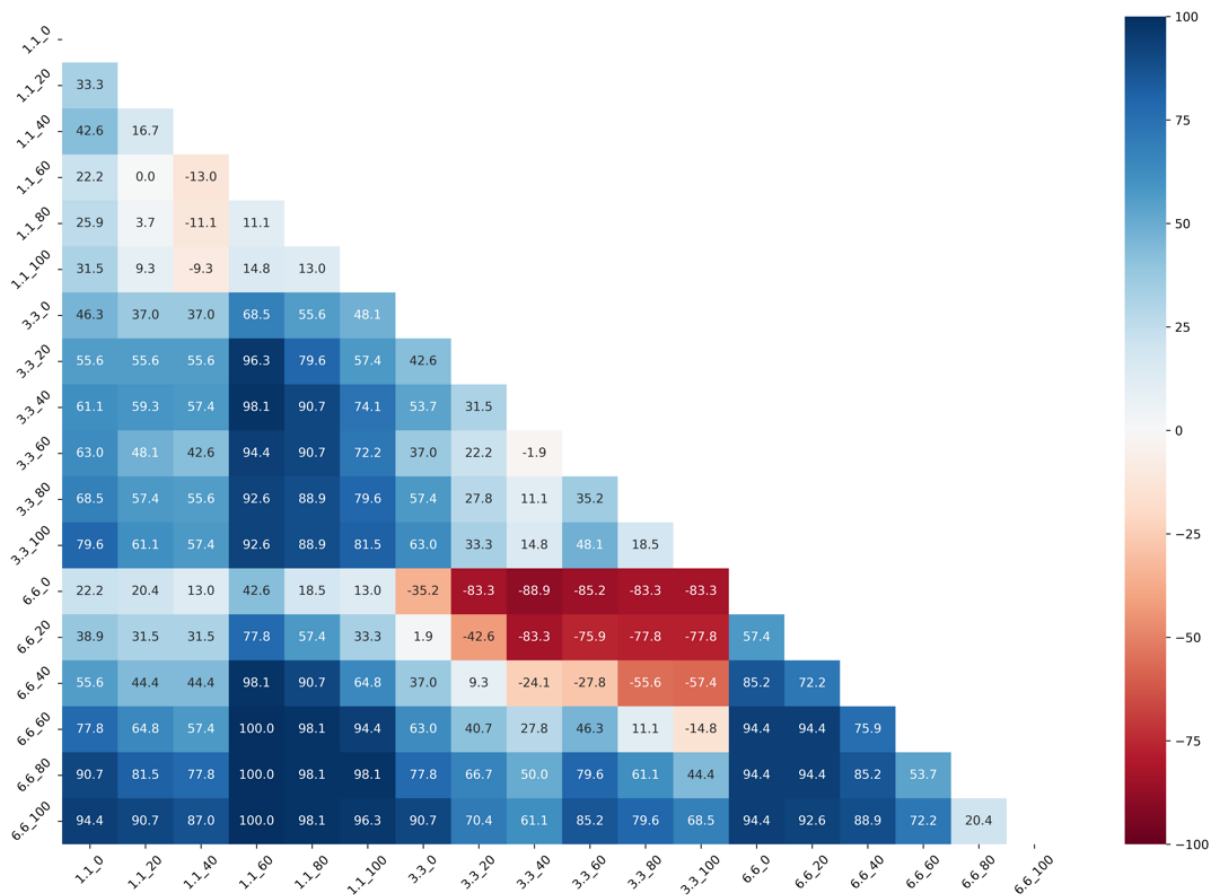


Figure 7. Intervention *evaluation percentage* for yield across six districts for the alternatives versus each other with varying plant densities and N fertilizer rates. The alternative labels are (plant density_N fertilizer application rate). The scenarios labeled as planting date (E (Early), M (Medium), L (Late)), plant density (1.1 pl m⁻², 3.3 pl m⁻², 6.6 pl m⁻²), and N fertilizer rate (0 kg N ha⁻¹, 20 kg N ha⁻¹, 40 kg N ha⁻¹, 60 kg N ha⁻¹, 80 kg N ha⁻¹, 100 kg N ha⁻¹).

b3) Effects of Planting Date and N Fertilizer Rate on Indicators:

Figure 8 compares alternative scenarios for all districts against each other in relation to yield. Alternatives with different plant densities were compared against each other at different planting dates and N fertilizer rates. Generally, as the N fertilizer rate increases so does the

evaluation percentage. Additionally, the *evaluation percentages* are highest at a late planting date. However, the medium planting date at N fertilizer rates of 0-40 generally has lower *evaluation percentages* than the early planting date, but at N fertilizer rates of 60-100 the *evaluation percentages* are generally higher than the early planting date. Some of the alternative agricultural scenarios with the lowest *evaluation percentages* include (planting date_N fertilizer rate) M_0, M_20, M_40, E_0, E_20, and E_40. Several of the alternative agricultural scenarios with the highest *evaluation percentages* include (planting date_N fertilizer rate) L_100, L_80, L_40, M_100, and M_80. These trends were also observed for the risk, economic, and nutrition comparisons in Figures A7-A9. This could be due to increased yield, which can result in improved risk, economics, and nutrition indicators. However, there are still differences between Figure 8 and Figures A7-A9. Figures 8 and A9 (yield and risk, respectively) generally have higher positive and lower negative *evaluation percentages* as compared to Figures A7 (nutrition) and A8 (economics). Figure A8 indicates that there was a muted *evaluation percentage* with less extremes seen in the *evaluation percentage*. This can signify that yield and risk data are more volatile when analyzed through changing planting date and N fertilizer rate where varying dates and fertilizer rates will have a more significant impact on yield and risk than nutrition and economics. Choosing an ineffective planting date or fertilizer rate can greatly influence the crop yield, thereby affecting the smallholder farmer's vulnerability to risk and yield variability. Additionally, nutrition and economics had more muted *evaluation percentages* implying less significant impacts due to various planting dates and fertilizer rates. This could be due to no associated costs for altering the planting date or that even with increasing yield the returns in the form of economics and nutrition were less pronounced and did not vary as much as yield and risk.

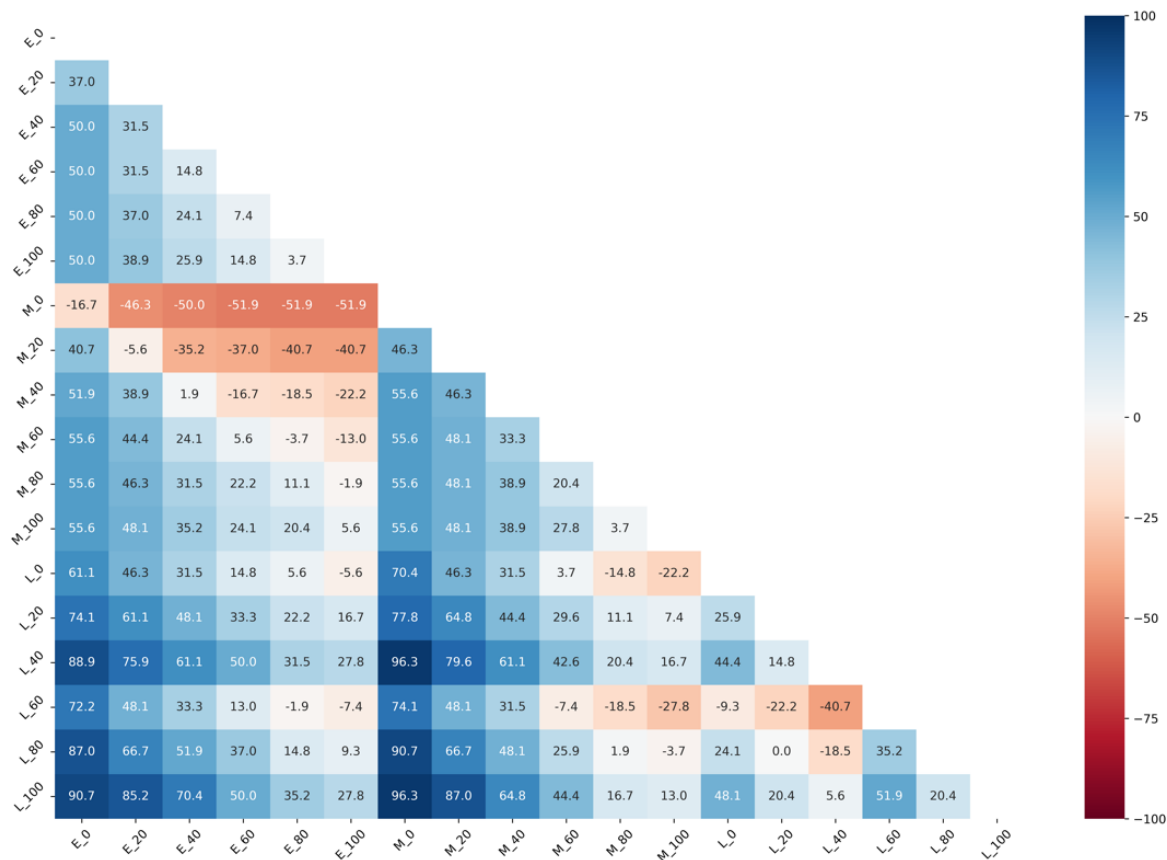


Figure 8. Intervention evaluation for yield across six districts for the alternatives versus each other with varying planting dates and N fertilizer rates. The alternative labels are (planting date_N fertilizer application rate). The scenarios labeled as planting date (E (Early), M (Medium), L (Late)), plant density (1.1 pl m⁻², 3.3 pl m⁻², 6.6 pl m⁻²), and N fertilizer rate (0 kg N ha⁻¹, 20 kg N ha⁻¹, 40 kg N ha⁻¹, 60 kg N ha⁻¹, 80 kg N ha⁻¹, 100 kg N ha⁻¹).

b4) Overall Summary:

Several studies on millet in Senegal found that higher plant densities resulted in higher yields (Bastos et al., 2022; A. Faye et al., 2023; Pilloni et al., 2022; Vieira Junior et al., 2023), which is similarly found in this paper. Additional evidence for the potential benefits of delaying the planting date has on millet yield in Senegal can be seen in other studies, thus confirming our results (Araya et al., 2022; Vieira Junior et al., 2023). Finally, other studies in Senegal on the use

of N fertilizer for millet found the range of the best fertilizer rates to go from 68 kg N/ha to 120 kg/ha (Araya et al., 2022; Bastos et al., 2022; Isah et al., 2020; Vieira Junior et al., 2023), which is in agreement with our results.

3.3.3 Adjustment of Nutrition by Adding Foods to Meet the District Nutrient Requirements at the Lowest Cost

a) Linear Optimization (meet the nutritional deficiency at the lowest costs)

As seen in Table 1, the nutrition for individuals was deficient across the different nutrition values and districts for the alternative agricultural scenarios after running the FARMSIM simulations. Tables A28-A33 depict the recommended food purchases and associated costs to meet the objective of the linear optimization. Additionally, after the linear optimization the final nutrition values as depicted in Tables A34-A39 were above the minimum requirements in Table A2 and the initial nutrition in Table 1. This demonstrates how the excess income from the alternative scenarios can be used to meet nutrition gaps. However, with linear optimization, the process increases all nutrition to meet the minimum requirement, which can be excessively high, as seen especially with calories, protein, and fat. This is further shown in Table 2 as the cheapest cost was chosen as the rating criteria, though this caused the percent change in nutrition to be very high and ranged from 300% to 400%. The percent change in nutrition was largely affected by the excess calories, protein, and fat. Excess calories and fat can lead to obesity (Camacho & Ruppel, 2017; Wang et al., 2020), while excess protein can lead to an increased risk for type 2 diabetes (Fappi & Mittendorfer, 2020). This is important to note as in Senegal, the prevalence of overweight children under 5 years of age in 2020 was 2.1% and the prevalence of adult obesity (18 years and older) in 2016 was 8.8%, where both have increased with time, though have remained below the average for West Africa (FAO et al., 2022). Moreover, regarding food purchases, most alternative

scenarios from all districts utilized only lettuce and peanuts to meet the nutritional gaps in the linear optimization, contributing to the excess nutrients. Therefore, multi-objective optimization may be ideal for understanding how to best utilize the additional income.

Table 2. Linear optimization for identifying the cheapest alternative scenario and percent change in nutrition consumption.

District	Best Alternative Scenario	Cost (CFA/person/day)	Percent Change in Nutrition from Recommend Values (%)
Diourbel	M_3.3 100kg	387.35	384.25
Fatick	L_3.3 40kg	320.30	330.29
Kaffrine	L_3.3 20kg	350.09	366.95
Kaolack	M_3.3 40kg	385.77	394.62
Kolda	L_3.3 40kg	340.42	347.15
Thiès	L_3.3 40kg	394.80	381.92

b) Multi-Objective Optimization (meet nutritional deficiencies by achieving a balanced nutritional intake at a minimum cost)

The multi-objective optimization can determine solutions utilizing more determining parameters. This is important when optimizing scenarios, as multiple criteria need to be satisfied. The cost and percent change in nutrition were utilized in the multi-objective optimization. The results of the multi-objective optimization can be found in Table 3. The alternative scenarios were ranked based on the value of adding the normalized cost and the percent change in nutrition. The costs were relatively close, with Fatick having the lowest cost and Thiès having the highest. The percent change in nutrition varied, with Thiès having the lowest percent change in nutrition and Kolda having the highest change in nutrition. Moreover, food purchases for the alternative scenarios from all districts utilized all food options though primarily milk, lettuce, and peanuts were used to meet the nutritional gaps in the multi-objective optimization. Purchasing a larger variety of foods allowed farmers to meet their nutritional needs, but not in excessive amounts.

To facilitate a clearer comparison between the outcomes of the two optimization approaches, Figure 9 displays the cost and percentage change values for the most optimal scenarios in each district. The linear optimization had lower costs to meet nutritional needs than the multi-objective optimization; however, the percent change in nutrition was much higher in the linear optimization as opposed to the multi-objective optimization. This demonstrates how utilizing a linear optimization would miss a critical aspect of improving agriculture by increasing nutrition excessively. A multi-objective optimization met nutritional needs, while preventing excessive nutritional values and maintaining low costs. Thus, after the optimization analysis, the multi-objective analysis results were utilized in the economic analysis due to more accurately depicting relevant food purchases to meet nutrition.

Table 3. The best alternative scenario in each district was obtained from the multi-objective optimization, associated costs, and percent change in nutrition.

District	Best Alternative Scenario	Cost (CFA/person/day)	Percent Change in Nutrition from Recommended Values (%)
Diourbel	L_3.3 40kg	414.94	36.04
Fatick	E_3.3 40kg	340.40	41.08
Kaffrine	E_1.1 60kg	365.80	41.89
Kaolack	E_6.6 100kg	396.65	35.65
Kolda	M_6.6 80kg	373.36	52.65
Thiès	E_3.3 0kg	440.70	32.13

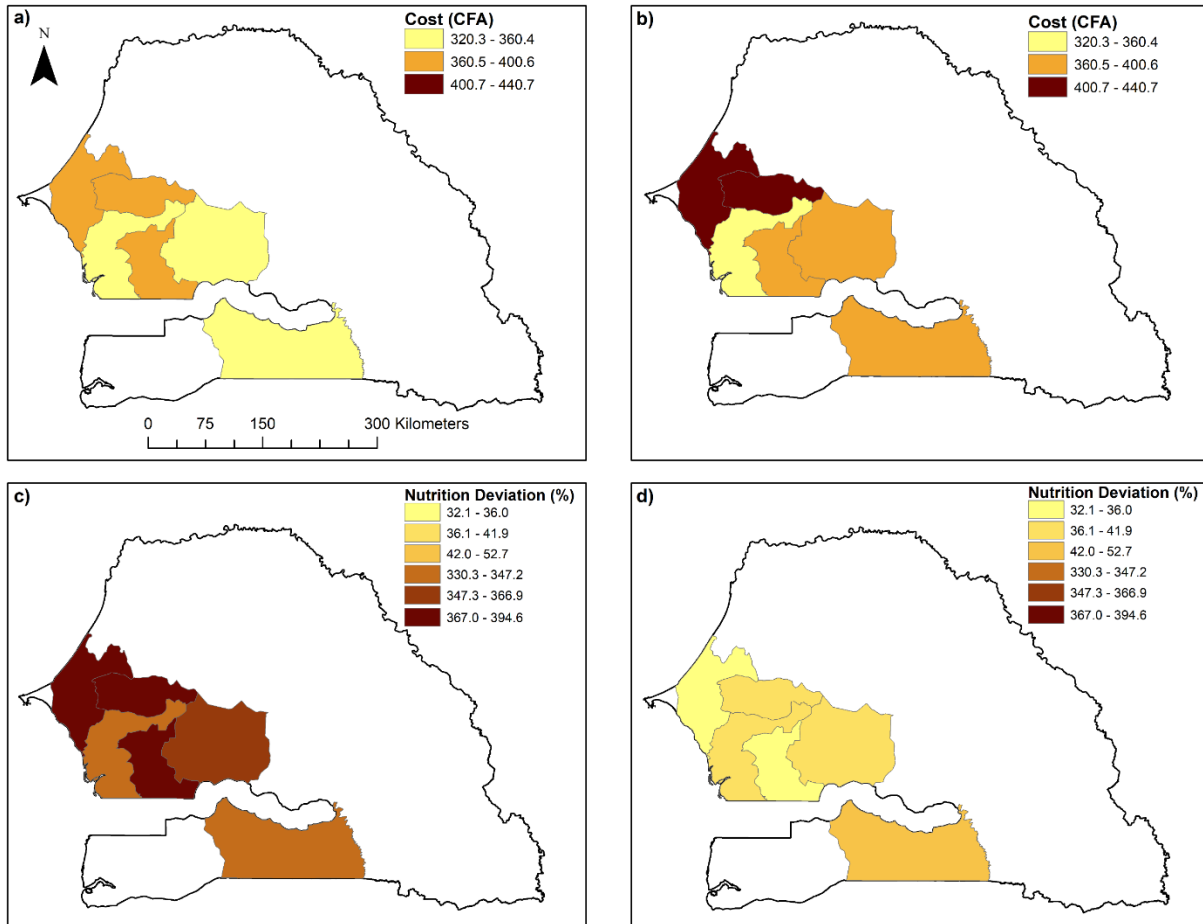


Figure 9. Final optimization maps a) linear optimization cost values, b) multi-objective optimization cost values, c) linear optimization percent change in nutrition values, d) multi-objective optimization percent change in nutrition values.

3.3.4 Economic Analysis to Adjust Cash Income after Meeting the Nutritional Needs of the Population

An economic analysis was used to examine the impact of increased food purchases from the multi-objective optimization on economic indicators. The alternative scenarios were filtered using IRR and ranked utilizing the sum of normalized NCFI, EC, and NPV. Tables A40-A45 show the economic values calculated after adjusting for the increased food purchases for each district in

the study region. Figure 10 depicts the summarized economic ranking for all districts in the study region.

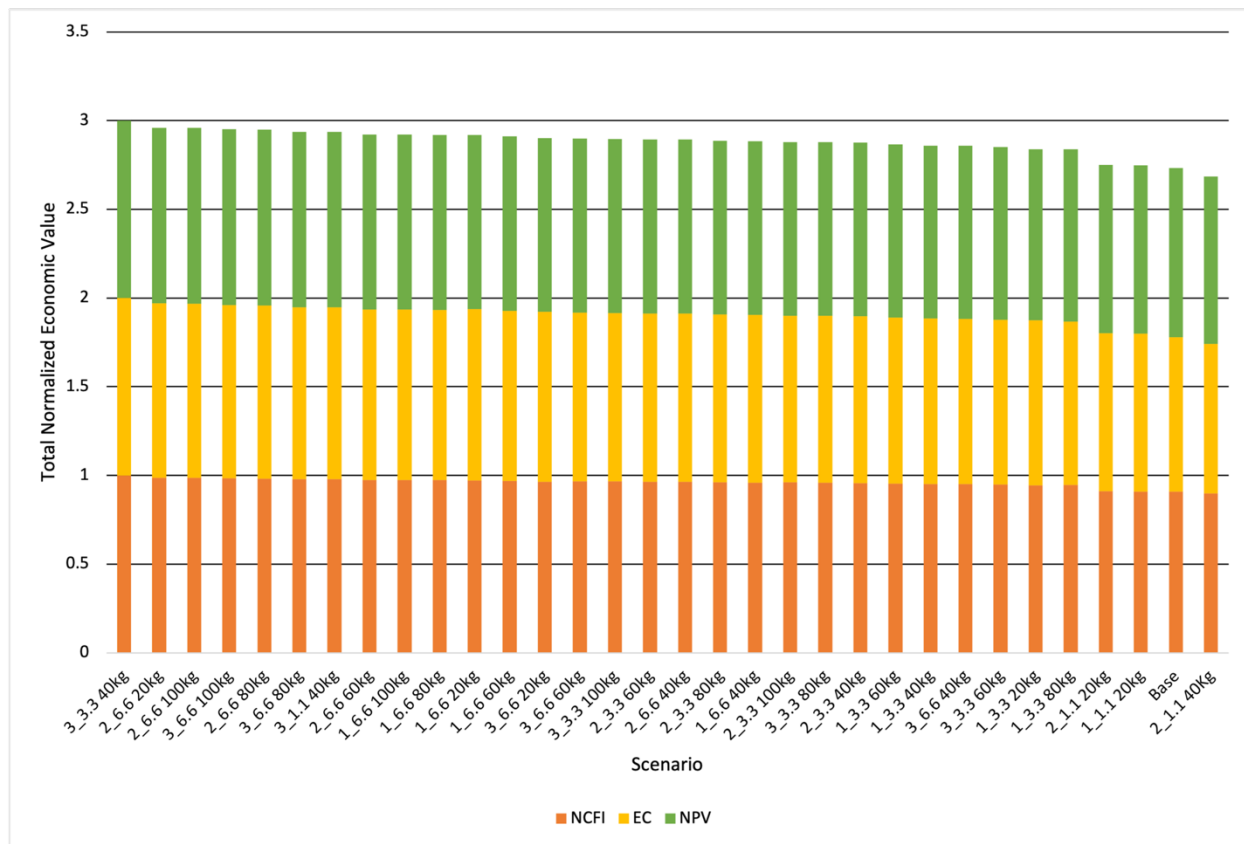


Figure 10. Final economic ranking of alternatives in terms of normalized NCFI, EC, and NPV summarized for all districts.

Based on the results from the economic assessment, only one alternative scenario was worse off than the baseline; therefore, the alternative with a medium planting date, 1.1 plant density, and 40 kg of N fertilizer would not be recommended. The best alternative scenario in terms of economics for 5 of the 6 districts was the late planting date, 3.3 plant density, and 40 kg of N fertilizer. This is further shown in Figure 10, which summarizes the districts in the region.

The alternatives with the highest IRR for 5 out of 6 districts were the alternatives with the late planting date, 3.3 plant density, and 40 kg of N fertilizer, signifying the validity of this

alternative scenario. The Kolda district had the highest NPV, followed by Kaffrine, Fatick, Kaolack, Diourbel, and Thiès. In terms of EC and NCFI, the districts in order of highest to least were Kolda, Kaffrine, Fatick, Diourbel, Kaolack, and Thiès. The variations in economics could be due to the level of groundnut production per hectare, as this is highest in Kolda and lowest in Diourbel and Thiès. This in turn, could be due to Kolda receiving more rainfall, which would boost production in the district.

Generally, alternatives with medium and late planting dates as well as alternatives with 3.3 and 6.6 plant densities, performed better in the ranking. This is a confirmation of the results found in the comparison of agricultural baseline and alternative scenarios comparison, as well as the evaluation of agricultural alternative scenarios against each other. Additionally, in terms of fertilizer scenarios, 0 kg, 20 kg, and 100 kg of fertilizer were generally filtered out as they had zero or negative IRR values. Scenarios that were ranked below the baseline all had 20 kg of fertilizer. For scenarios with 0 kg and 20 kg this could be attributed to lower yield increases due to low amount of fertilizer applications. For scenarios with 100 kg this could be attributed to the increases in yield leveling off in comparison to the costs of the additional fertilizer. These trends were also observed in the resilience ranking based on risk.

3.3.5 Resilience Ranking of Alternative Scenarios Based on Risk

A further analysis was conducted to rank the alternative scenarios based on the CE and RP. Here we first remove all RPs below 0 and then rank the overall risk performance based on the CE. A higher CE and RP signifies a lower risk to the farmer. Here, the risk ranking does not consider alternative scenarios that were removed in the economic analysis through IRR elimination process. The results of this ranking analysis can be seen in Tables A46-A51. The baseline was included in the ranking, showing how some alternative scenarios had a higher risk than the baseline and thus

were not preferred over the baseline. The best alternative scenario in terms of risk for 5 of the 6 districts was the late planting date, 3.3 plant density, and 40 kg of N fertilizer. This is similar to the best scenarios determined in the economic analysis, though not with the same districts. Table A52 contains the final overall ranking of alternative scenarios based on all optimization, economics, and risk analyses. Figure 11 shows the overall best four alternative scenarios for the study region as determined by nutrition, economic, and risk analysis. There is some overlap between the best scenarios from each type of analysis. The economic and risk analyses had the same 3 alternative scenarios in their top four, although these were not necessarily in the same order. The nutrition analysis only had one scenario in its top 4 scenarios, which is also in the other two analyses. The risk analysis was the most durable of the analyses, which is why it was used as the final ranking metric after the previous analyses. To fully understand the resilience of smallholder farmers in Senegal, it is essential to consider multiple facets. While nutritional analysis offers one perspective, it does not capture the economic and risk dimensions. Therefore, an economic analysis is crucial for a deeper understanding of resilience, and a risk analysis further refines this understanding.

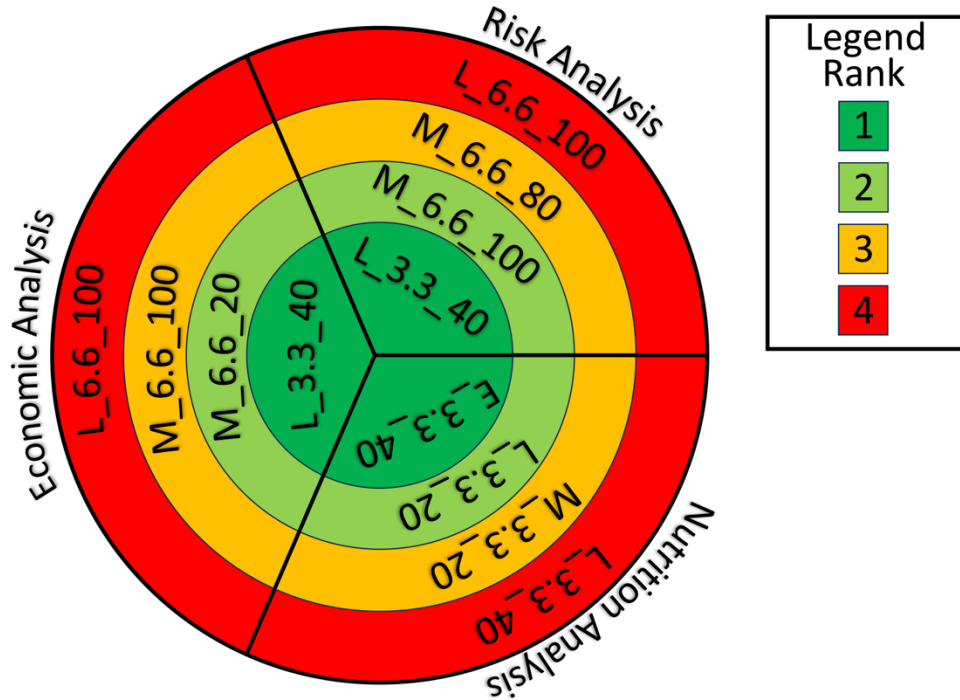


Figure 11. Overall top four ranking of alternatives from each of the nutrition analysis, economic analysis, and risk analysis summarized for all districts. The interior circle contains the highest ranked alternative scenario and proceeds to the outside circle with the fourth ranked alternative scenario.

3.4 Conclusion

Existing metrics for resilience involve a holistic approach that covers nutritional, economic, and environmental aspects; however, there is no guarantee that a high-ranked approach meets the population requirements related to these aspects. In addition, many of the resiliency metrics do not account for risk as a variable. Therefore, the approach taken in this study tries to address these shortcomings, making the approach more robust. Meanwhile, utilizing a qualitative approach with integrated crop and animal models instead of arbitrary weighted metrics is an innovation, as the models can be calibrated for different technologies, practices, climates,

conditions, and regions. The paper presents a novel method for determining farmer resilience to climate extremes. The major findings are as follows:

- Adopting and integrating multi-objective optimization methods in our strategic planning and implementation is recommended to ensure the nutritional well-being of smallholder farmers while maintaining budgetary constraints. This will ultimately guide us in designing a program that meets the population's nutritional requirements in a cost-effective manner while ensuring a balanced diet to combat malnutrition and obesity.
- Scenarios tended to be more resilient for millet production with increasing N fertilizer, plant density, and later planting dates, though this is not always the case, possibly due to diminishing marginal returns from increasing yield and increased costs.
- Considering the economic analysis, it is imperative for millet production to reconsider the promotion or subsidization of N fertilizer rates at 20 kg and 100 kg or promoting no fertilizer application, especially during drought years, given their zero or negative IRR values. Policymakers should prioritize rates that yield positive IRR to ensure economic viability and sustainability of agricultural practices.
- Given that the alternative scenario for millet with a late planting date, 3.3 pl m⁻² plant density, and 40 kg N ha⁻¹ fertilizer rate received the highest overall rating, policymakers should consider endorsing and possibly providing incentives for these specific agricultural practices when utilized together to enhance the resilience of smallholder farmers to extreme drought.
- The comprehensive method employed in this study offers a detailed and multi-faceted assessment of farmers' resilience to climatic extremes. Therefore, it is crucial for the stakeholders to recognize and utilize this approach. By doing so, they can effectively

address farmers' nutritional requirements without overshooting while ensuring affordability and minimizing risks for the farmers.

The novel approach utilized in this paper to determine the resilience of smallholder farmers can be expanded to cover more regions, climate conditions, and demographics in Africa. FARMSIM is well suited to be used for these purposes as it can be developed for different countries with many different alternative interventions. Therefore, more research must analyze specific solutions for specific situations and economic groups. For example, problems affecting very poor and poor farmers may not be the same problems facing middle-class and rich farmers. Therefore, future studies should address these shortcomings.

4.0 OVERALL CONCLUSION

Climate change's effects on agriculture impact crop and livestock production, especially smallholder farmers in developing countries, including Senegal. This has exacerbated food insecurity, malnutrition, and economic instability. Resilience approaches are useful tools for assessing how farmers cope with climate extremes; however, there is no consensus on the measurement. Therefore, a new approach was developed in this paper to determine the resilience of different agricultural practices. The new resilience evaluation approach includes three planting dates, three planting densities, and six N fertilizer rates. The results derived from both the literature review and research modeling provided us with insights into the challenges affecting food security, feasible practices for expanding agricultural production, and the necessary approach for determining the resilience of agricultural technologies to improve food and nutrition security, income, risk, and the overall well-being of rural communities. Results from the model are summarized below:

- A new, robust approach to determining resilience was developed in this study. This method offers promising prospects for further research since it can be tailored for various farmer characteristics and regions.
- While it is essential to enhance agricultural production and the livelihoods of smallholder farmers, they must also employ sustainable practices when implementing different agricultural scenarios. This should be backed by the government and other partner investments in sustainable, climate-smart agriculture.
- Different agricultural interventions, including changes in planting dates, plant densities, and N fertilizer rates, can effectively augment farmers' nutrition, income, and risk mitigation at both household and regional levels.

- Generally, scenarios with medium (early-July to late-August) and late (late-July to mid-September) planting dates yielded the best results concerning nutrition, economic outcomes, and risk.
- Planting densities of 3.3 and 6.6 pl m⁻² typically offered the most substantial improvements in nutrition, economic gains, and risk mitigation.
- In contrast, the least effective scenarios usually involved a 1.1 pl m⁻² plant density, early planting dates (early-June to late-July), and/or N fertilizer rates of 0, 20, and 100 kg N ha⁻¹.
- While certain scenarios can satisfy caloric, protein, and fat requirements, essential nutrients like calcium, iron, and vitamin A cannot be sourced solely from crop and livestock production. As such, agricultural initiatives should be paired with actions to enhance access to a diverse range of food products. This entails infrastructure development, farmer training, improved access to credit and markets, and the bolstering of stakeholder organizations (CIAT & BFS/USAID, 2016; FAO & AfDB, 2015; Giller et al., 2021; Tarchiani et al., 2017).
- Linear optimization analyses might overshoot nutritional requirements; therefore, multi-objective optimization is more desirable, ensuring nutritional needs are met cost-effectively while maintaining a balanced diet.
- Smallholder farmers should be informed about additional food products they can purchase to address any nutritional deficits, thereby maximizing the benefits of interventions.

- Finally, it is crucial to educate smallholder farmers about the economic risks tied to adopting alternative methods and technologies. These risks might severely impact their livelihoods.

5.0 FUTURE RESEARCH

This study sought to assess the resiliency of Senegal farmers to extreme drought conditions. Therefore, other climate change effects such as extreme floods, heatwaves are excluded. Additionally, this research focuses on specific interventions like planting date, planting density, and nitrogen (urea) fertilizer rate, but it does not encompass other strategies such as irrigation, government policies, and crop diversification. This paper does not analyze how global crisis and national policies impact smallholder farmers. Consequently, future studies should tackle these constraints encompassing, but not confined to, the following aspects:

- This study analyzed an average farm in the Groundnut Basin region. Thus, future work should focus on different economic groups, including the very poor, poor, middle class, and wealthy, to better understand how income, nutrition, and risk levels vary. Then, specific policies or projects can be crafted to allocate resources better.
- Investigate how the agricultural intervention irrigation affects the climate resiliency of farmers. This is important as irrigation and applying fertilizer are both good intervention methods but are made even more effective when combined. The effects of irrigation and its collaborative effects with other intervention strategies should be analyzed in future research.
- Determine how other aspects of climate extremes (e.g., heavy rain, high temperature, and plant diseases) impact mixed farming systems and the resiliency of smallholder farmers.
- Explore alternative cropping systems as solutions to alleviate the effects of climate change, especially when current climate-smart strategies prove inadequate for the challenge.

- The Groundnut basin is an important agricultural hub in Senegal. However, other regions of interest in Senegal could benefit from integrated crop-livestock modeling to determine climate resiliency and test alternative technologies and practices.
- Conduct an environmental impact assessment focused on planting date, planting density, and nitrogen fertilizer rate. This can enhance the resilience strategy by evaluating their effects on both the environment and human health.
- Identify the factors impeding smallholder farmers from adopting or adapting practices to a changing climate. Subsequently, these factors can be incorporated into the decision-making process and in ranking the most effective intervention scenarios.
- Determine the best method to disseminate the research findings to policymakers, donors, and local farmers to improve food security at local and national levels.
- Conduct studies on enhancing food product preservation at the regional scale. Higher yields necessitate improved infrastructure and preservation methods to prevent potential wastage of the surplus. It is essential to motivate local investors to advance the production, processing, and storage of food items.

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APPENDIX

Section A: Definition of Key Output Variables of FARMSIM Model

Definitions for the following indicators used in the FARMSIM model came from a relevant paper on the FARMSIM model (Bizimana & Richardson, 2019). Net present value (NPV) is a financial metric that evaluates the viability and profitability of a project or investment within a particular time frame. Annual ending cash reserves (EC) is a key output variable (KOV) used for determining the effects of technology adoption and is the total cash outflows subtracted from the total cash inflows by the end of a calendar year. Cash outflows are the sum of income taxes, family living expenses, principal payments, school expenses, cash purchases of food, and cash flow deficit repayments, while cash inflows are the sum of off-farm income, net cash farm income, interest earned on cash reserves, and beginning cash. Net cash farm income (NCFI) is the profit generated by the farm, where it is the total cash expenses subtracted from the total cash receipts. The total cash expenses include fixed costs, crop and livestock expenses, and interest costs, while the total cash receipts cover the sale of livestock and crops. The internal rate of return (IRR) is the discount rate at which NPV equals zero.

The Simetar function of FARMSIM allows for the evaluation of various alternative scenarios utilizing the Stochastic Efficiency with Respect to a Function (SERF), which generates values for Certainty Equivalent (CE) and Risk Premium (RP). CE and RP were utilized in this paper to determine risk. The certainty equivalent is the threshold at which the decision-maker is indifferent between the risky outcome and the value (Hardaker et al., 2004). The risk premium is the difference between the CE of the alternative scenario and the baseline (Richardson, 2008).

Table A1. Characteristics of millet and groundnut farming households and land holdings (ANSD, 2013a, 2013b; HEA SAHEL, 2016a, 2016b, 2017b, 2017a).

District	Millet and Groundnut Farm Households	Millet and Groundnut Farm Population	Millet and Groundnut Adult Equivalent	Average Family Size	Average Land Holding Size (ha/household)	Millet (ha)	Groundnut (ha)
Diourbel	51,829	639,911	485,808	12	4.3	130,908	91,940
Fatick	46,190	544,116	419,866	12	7.11	141,638	186,864
Kaffrine	32,055	394,922	300,037	12	7.8	121,217	221,115
Kaolack	49,044	577,738	445,810	12	5.94	155,535	135,987
Kolda	24,232	292,294	223,689	12	4.47	39,541	68,800
Thiès	70,541	870,942	661,202	12	3.15	106,502	115,780

Table A2. Minimum nutrient requirements per adult equivalent (ANSD, 2013a; HHS & USDA, 2015; USDA, 2023; USDA & HHS, 2020; World Bank, 2022b, 2022c).

Nutrient	Minimum Nutrient Requirement per Adult Equivalent
Calories (Calorie)	2,306.42
Protein (grams)	52.10
Fat (grams)	73.77
Calcium (grams)	1.45
Iron (grams)	0.0137
Vitamin A (grams)	0.0009

Table A3. Plant density costs (Bastos et al., 2022; Vieira Junior et al., 2023).

Plant Density (plants/m ²)	Associated Cost (CFA/ha)
1.1	900.39
3.3	2,701.16
6.6	5,402.32

Table A4. N fertilizer rate costs (Bastos et al., 2022; Vieira Junior et al., 2023).

N Fertilizer Rate (kg/ha)	Associated Cost (CFA/ha)
0	0
20	12,014.05
40	24,028.09
60	36,042.14
80	48,056.18
100	60,070.23

Table A5. Baseline scenario values and costs (Bastos et al., 2022; Vieira Junior et al., 2023).

Alternative Type	Baseline Scenario	Baseline Scenario Costs (CFA/ha)
Planting date	1 (Early)	0
Plant density (plants/m ²)	1.1	900.39
N fertilizer rate (kg/ha)	30	18,021.07

Table A6. Groundnut production in groundnut basin (DAPSA & MAER, 2020).

Groundnut Production Type	Groundnut Production (kg/ha)
Minimum groundnut production	776.03
Average groundnut production	1316.84
Maximum groundnut production	1876.90

Table A7. Crop market prices (FEWS NET, 2020, 2021; HEA SAHEL, 2016b).

Crop	Minimum Selling Price (CFA/kg)	Maximum Selling Price (CFA/kg)	Average Selling Price (CFA/kg)
Millet	160	300	219.75
Groundnut	175	400	250
Rice	200	360	292.5
Maize	150	250	203.42

Table A8. Costs of millet and groundnut productions (site surveys and (DAPSA, 2020; HEA SAHEL, 2016a, 2016b, 2017b, 2017a).

Costs	Millet (CFA/ha)	Groundnut (CFA/ha)
Seed cost (CFA/ha)	900.39 to 5,402.32	9,520.43
Fertilizer cost (CFA/ha)	0 to 60,070.23	49,449.44
Chemicals cost (CFA/ha)	2,608.28	2,608.28
Land Preparation cost (CFA/ha)	10,500	15,250
Planting cost (CFA/ha)	10,810	13,510
Weeding cost (CFA/ha)	5,875	14,800
Irrigation cost (CFA/ha)	0	0
Harvesting cost (CFA/ha)	24,500	31,625
Other cash cost (CFA/ha)	0	0

Table A9. Crop usage on farm (DAPSA, 2020b; HEA SAHEL, 2016a, 2016b, 2017b, 2017a).

Practice	Millet	Groundnut
Seeds saved in kg/ha planted	36.59	35.52
Fraction of crop consumed by family	0.738	0.064
The annual quantity fed to livestock in kg/head	40.18	0

Table A10. Livestock numbers for each study district (DAPSA/MAER, site surveys, and (HEA SAHEL, 2016a, 2016b, 2017b, 2017a).

District	Cows	Oxen	Hens	Roosters	Ewes	Lambs	Nannies (goat)	Kids (goat)
Diourbel	146,203	58,046	636,503	155,484	246,282	134,408	222,950	155,484
Fatick	222,347	44,342	536,718	138,567	385,375	99,768	322,955	138,567
Kaffrine	165,191	36,224	395,092	96,168	310,956	75,492	204,734	96,168
Kaolack	114,842	47,082	569,882	147,129	864,829	105,933	743,763	147,129
Kolda	237,983	23,264	265,223	72,696	96,400	41,619	79,174	72,696
Thiès	149,000	79,004	866,308	211,620	222,583	182,934	190,855	211,620

Table A11. Cow statistics, expenses, and prices (site surveys and Bizimana & Richardson, 2019; DAPSA, 2020; Selina Wamucii, 2023c).

Cow General Information	Value
Fraction of cows die each year	0.2
Fraction of cows consumed by family each year	0.15
Fraction of cows sold annually	0.17
Sale weight of cows kg/head	250
Manure produced per cow per year in kgs	780
Annual cash expenses per cow	18,333
Price of cows -- Minimum per head	126,355
Price of cows -- Average per head	220,000
Price of cows -- Maximum per head	262,349
Calves born per cow per year - Minimum	0
Calves born per cow per year - Average	1
Calves born per cow per year - Maximum	2

Table A12. Oxen statistics, expenses, and prices (site surveys and Bizimana & Richardson, 2019; DAPSA, 2020; Selina Wamucii, 2023c).

Oxen General Information	Values
Fraction of cows die each year	0.2
Fraction of cows consumed by family each year	0.15
Fraction of cows sold annually	0.17
Sale weight of oxen kg/head	250
Manure produced per cow per year in kgs	860
Annual cash expenses per cow	18,333
Price of cows – Minimum per head	126,355
Price of cows – Average per head	220,000
Price of cows – Maximum per head	262,349

Table A13. Milk and butter prices, consumption, and distribution metrics (site surveys and DAPSA, 2020; Selina Wamucii, 2023a).

Milk Production General Information	Values
Milk price CFA/liter -- Minimum	259
Milk price CFA/liter -- Average	355
Milk price CFA/liter -- Maximum	675
Butter price CFA/liter -- Minimum	559.53
Butter price CFA/liter -- Average	1,188.21
Butter price CFA/liter -- Maximum	1,760.3
Fraction of milk consumed by the family	0.329
Fraction of milk paid to employees	0
Fraction of milk made into butter	0.178
Fraction of butter consumed	0.3

Table A14. Milk production data (DAPSA, 2020; HEA SAHEL, 2016a, 2016b, 2017b, 2017a).

District	Minimum Milk Production (liters per cow per year)	Maximum Milk Production (liters per cow per year)	Average Milk Production (liters per cow per year)
Diourbel	190.29	618.43	237.86
Fatick	198	643.5	643.5
Kaffrine	198	643.5	297
Kaolack	198	643.5	280.5
Kolda	144	468	156
Thiès	190.29	618.43	301.29

Table A15. Chicken general information (site surveys and DAPSA, 2020; Selina Wamucii, 2023d).

Chicken General Information	Values
Sale weight of a hen kgs	3.5
Price of a hen CFA -- Minimum	1,578
Price of a hen CFA -- Average	2,500
Price of a hen CFA -- Maximum	4,375
Fraction of hens die annually	0.05
Fraction of hens consumed by family annually	0.4
Fraction of hens sold annually	0.37
Annual cash expense for hens per head	250

Table A16. Egg metrics: weight, price, consumption, and production (site surveys and Bizimana & Richardson, 2019; Nordhagen et al., 2019; Selina Wamucii, 2023b).

Egg Production General Information	Values
Weight of an Egg in kg	0.035
Price of a dozen eggs CFA -- Minimum	650
Price of a dozen eggs CFA -- Average	1,000
Price of a dozen eggs CFA -- Maximum	1,100
Fraction of eggs consumed by family annually	0.27
Annual cost of production in addition to hen costs	0
Egg production per hen -- Minimum	25
Egg production per hen -- Average	36
Egg production per hen -- Maximum	47

Table A17. Rooster statistics and expenses (site surveys and DAPSA, 2020).

Rooster General Information	Values
Sale weight of a rooster kgs	3
Fraction of roosters die annually	0.05
Fraction of roosters consumed by family annually	0.5
Fraction of roosters sold annually	0.25
Annual cash expense for roosters	550

Table A18. Ewe statistics, expenses, and prices (site surveys and Nordhagen et al., 2019).

Ewe General Information	Values
Sale weight of ewes kg	25
Price of ewes CFA/head -- Minimum	35,000
Price of ewes CFA/head -- Average	75,000
Price of ewes CFA/head -- Maximum	100,000
Fraction ewes die annually	0.27
Fraction ewes consumed by the family annually	0.27
Fraction of ewes sold	0
Annual cash expenses per ewe	29,166.67

Table A19. Lamb statistics, expenses, and prices (site surveys and DAPSA, 2020; Notter et al., 2017).

Lamb General Information	Values
Sale weight of lambs kg	20
Price of lambs CFA/head -- Minimum	20,000
Price of lambs CFA/head -- Average	30,000
Price of lambs CFA/head -- Maximum	40,000
Fraction lambs die annually	0.17
Fraction lambs consumed by the family annually	0.13
Annual cash expenses per lamb	30,833.33
Lambs per ewe annually -- Minimum	1
Lambs per ewe annually -- Average	2
Lambs per ewe annually -- Maximum	3

Table A20. Nannies statistics, expenses, and prices (site surveys and DAPSA, 2020).

Nannies General Information	Values
Sale weight of nannies kg	25
Price of nannies CFA/head -- Minimum	25,000
Price of nannies CFA/head -- Average	30,000
Price of nannies CFA/head -- Maximum	50,000
Fraction nannies die annually	0.22
Fraction nannies consumed by the family annually	0.43
Fraction of nannies sold	0
Annual cash expenses per ewe	2,333.33

Table A21. Kids statistics and prices (site surveys and Sow et al., 2021).

Kids General Information	Values
Sale weight of kids kg	19
Price of kids CFA/head -- Minimum	15,000
Price of kids CFA/head -- Average	20,000
Price of kids CFA/head -- Maximum	25,000
Fraction kids die annually	0.63
Fraction kids consumed by the family annually	0.15
kids per ewe annually -- Minimum	1
kids per ewe annually -- Average	2
kids per ewe annually -- Maximum	4

Table A22. Purchased foods for each family by district (Anderson et al., 2010; Giguère-Johnson et al., 2021; HEA SAHEL, 2016a, 2016b, 2017b, 2017a).

Purchased Foods for each Family	Diourbel	Fatick	Kaffrine	Kaolack	Kolda	Thiès
Fish Meat (kg)	34.85	37.64	40.51	37.64	29.60	34.85
Millet (kg)	240.40	231.50	228.75	231.50	184.13	240.40
Peanuts (kg)	4.59	8.47	9.23	8.47	4.31	4.59
Rice (kg)	636.69	563.97	584.36	563.97	635.85	636.69
Maize (kg)	55.31	48.26	48.86	48.26	24.89	55.31

Table A23. Quantity of international food relief received per family (Anderson et al., 2010; Giguère-Johnson et al., 2021; HEA SAHEL, 2016b, 2016a, 2017a, 2017b).

Purchased Foods for each Family	Diourbel	Fatick	Kaffrine	Kaolack	Kolda	Thiès
Fish Meat (kg)	0.87	1.33	1.34	1.33	1.27	0.87
Millet (kg)	6.66	10.20	9.42	10.20	8.56	6.66
Peanuts (kg)	0.14	0.29	0.29	0.29	0.14	0.14
Rice (kg)	17.03	24.26	23.71	141.35	41.25	17.03
Maize (kg)	1.43	2.13	2.04	2.13	1.09	1.43

Table A24. Fixed costs for the extended family (HEA SAHEL, 2016a, 2016b, 2017b, 2017a).

Purchased Foods for each Family	Diourbel	Fatick	Kaffrine	Kaolack	Kolda	Thiès
Maintenance and repair costs	0	0	0	0	0	0
Liability insurance for farm	0	0	0	0	0	0
Miscellaneous fixed costs	212,090.49	202,219.71	202,107.10	175,370.49	173,469.59	212,091.84
Total cash wages paid to employees	0	0	0	0	0	0
Annual property taxes	54,924.37	59,816.56	59,613.58	14,759.08	8,275.47	54,924.75
Other taxes (cattle, etc.)	0	0	0	0	0	0
Income tax rate (% of income)	0.039	0.039	0.039	0.039	0.039	0.039
Average annual family cash living expenses	0	0	0	0	0	0
Cash expenses for school	27,039.47	24,385.46	24,225.76	24,859.25	23,640.90	27,039.56
Cash costs for fuel, lube, fuel oil	0	0	0	0	0	0
Annual Off-Farm Cash Income per Family	654,367.84	495,312.60	517,916.50	495,303.20	419,418.70	654,368.27
Interest Rate for Cash Reserves	0	0	0	0	0	0
Other Cash Income	0	0	0	0	0	0

Table A25. Assets per family (HEA SAHEL, 2016a, 2016b, 2017b, 2017a).

Purchased Foods for each Family	Diourbel	Fatick	Kaffrine	Kaolack	Kolda	Thiès
Cropland Owned HA	222,848	328,502	342,332	291,522	108,341	222,282
Value of Cropland CFA/HA	700,000	700,000	700,000	700,000	700,000	700,000
Leased Cropland HA	0	0	0	0	0	0
Cropland Rent CFA/HA	0	0	0	0	0	0
Pastureland Owned HA	0	0	0	0	0	0
Value of pastureland CFA/HA	700,000	700,000	700,000	700,000	700,000	700,000
Leased pastureland HA	0	0	0	0	0	0
Pastureland Rent	0	0	0	0	0	0
Value of Machinery Owned	129,598.09	157,200.85	165,051.16	157,197.82	103,677.58	129,599.09
Value of Tools Owned	0	0	0	0	0	0
Value of Buildings Owned	0	0	0	0	0	0
Cash on Hand January 1	0	0	0	0	0	0

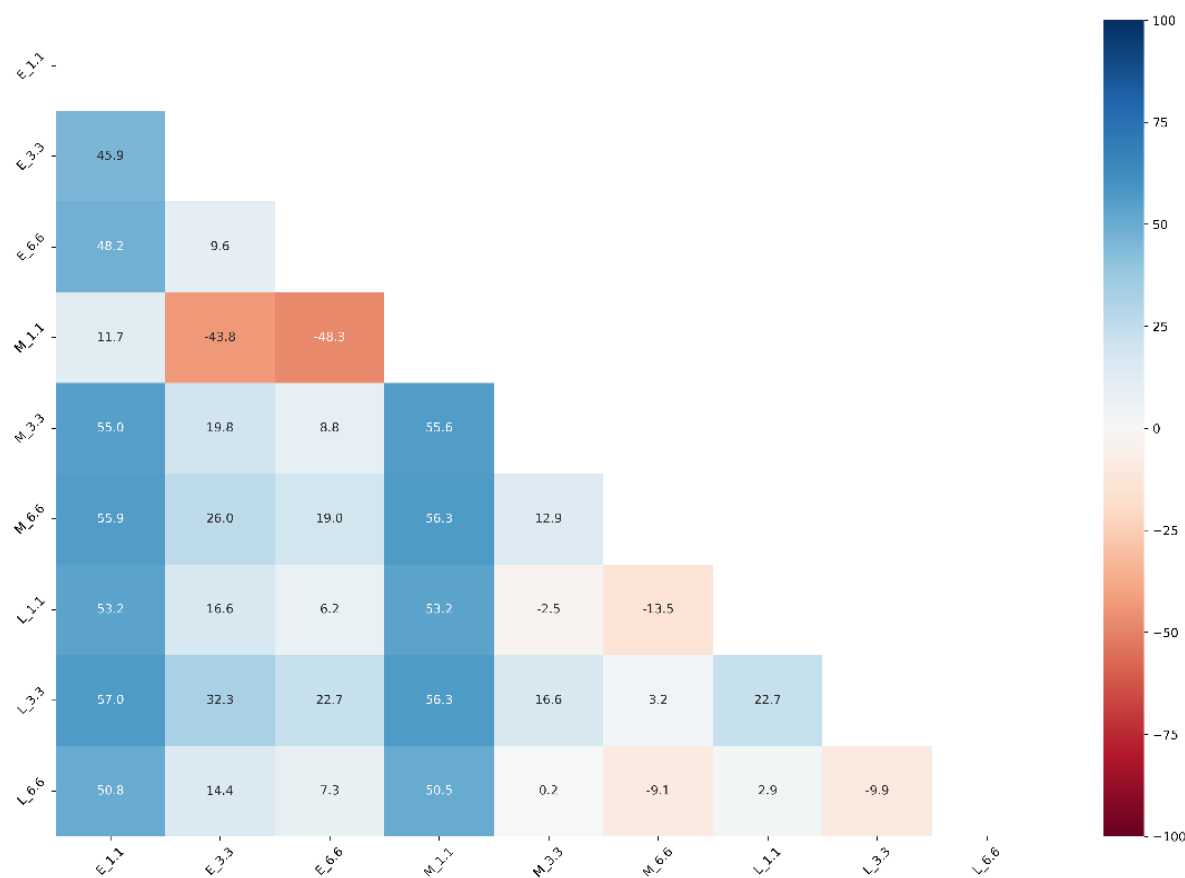


Figure A1. Intervention *evaluation percentage* for nutrition across 6 districts for the alternatives versus each other with varying planting dates and plant densities. The alternative labels are (planting date_plant density). The scenarios are labeled as planting date (E (Early), M (Medium), L (Late)), plant density (1.1 pl m⁻², 3.3 pl m⁻², 6.6 pl m⁻²), and N fertilizer rate (0 kg N ha⁻¹, 20 kg N ha⁻¹, 40 kg N ha⁻¹, 60 kg N ha⁻¹, 80 kg N ha⁻¹, 100 kg N ha⁻¹).

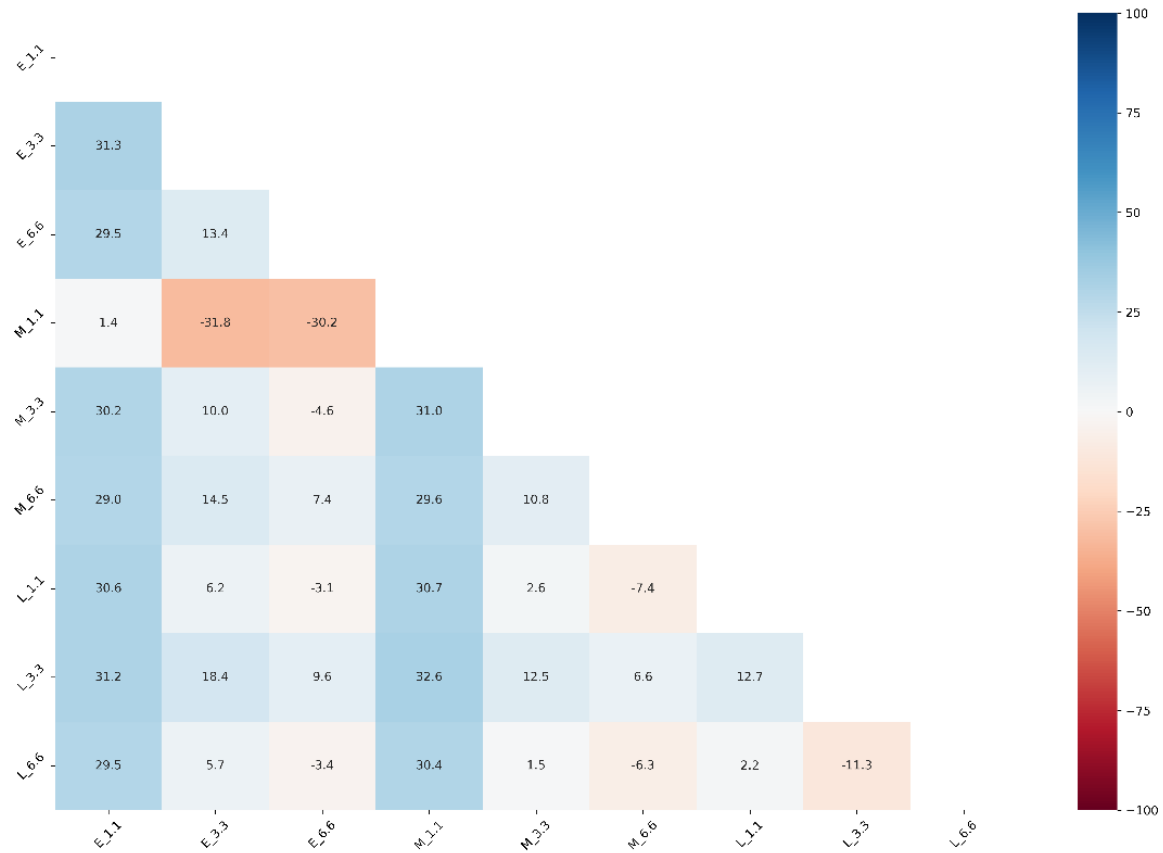


Figure A2. Intervention *evaluation percentage* for economics across six districts for the alternatives versus each other with varying planting dates and plant density. The alternative labels are (planting date_plant density). The scenarios are labeled as planting date (E (Early), M (Medium), L (Late)), plant density (1.1 pl m⁻², 3.3 pl m⁻², 6.6 pl m⁻²), and N fertilizer rate (0 kg N ha⁻¹, 20 kg N ha⁻¹, 40 kg N ha⁻¹, 60 kg N ha⁻¹, 80 kg N ha⁻¹, 100 kg N ha⁻¹).

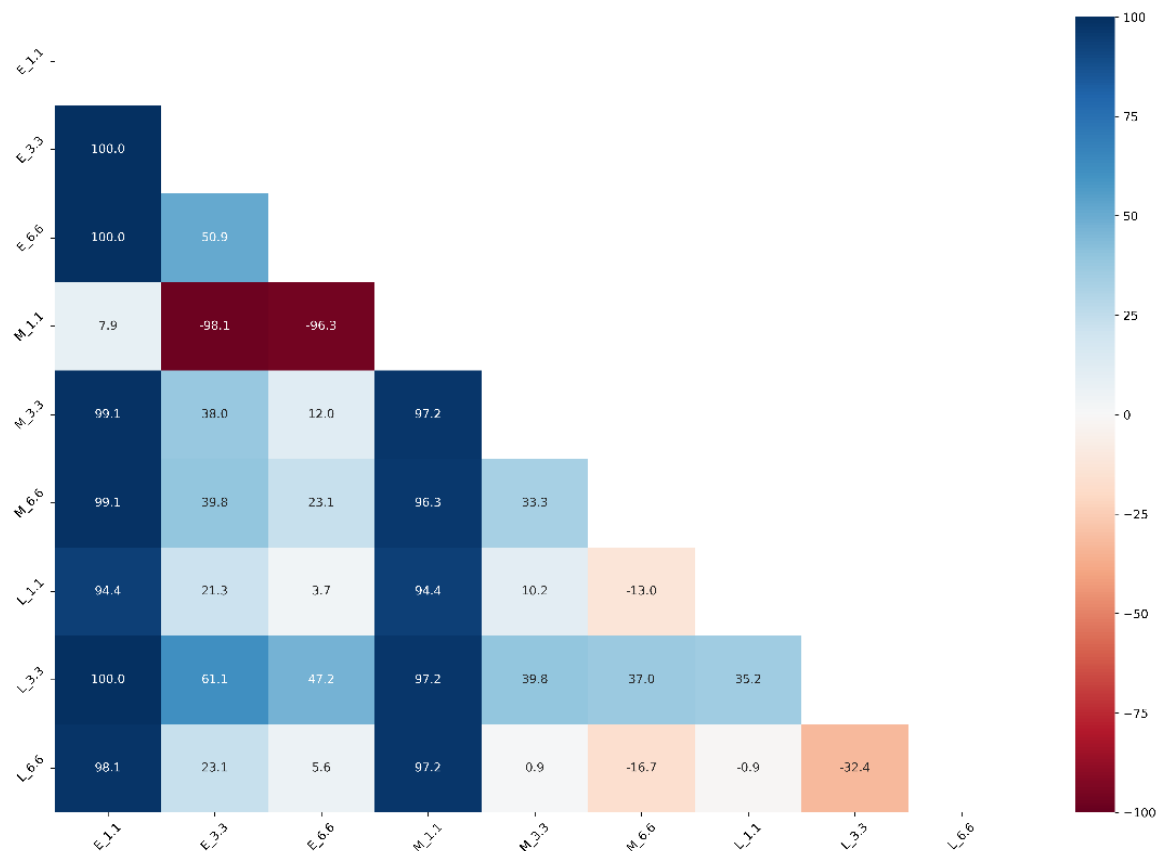


Figure A3. Intervention *evaluation percentage* for risk across 6 districts for the alternatives versus each other with varying planting dates and plant density. The alternative labels are (planting date_plant density). The scenarios are labeled as planting date (E (Early), M (Medium), L (Late)), plant density (1.1 pl m⁻², 3.3 pl m⁻², 6.6 pl m⁻²), and N fertilizer rate (0 kg N ha⁻¹, 20 kg N ha⁻¹, 40 kg N ha⁻¹, 60 kg N ha⁻¹, 80 kg N ha⁻¹, 100 kg N ha⁻¹).

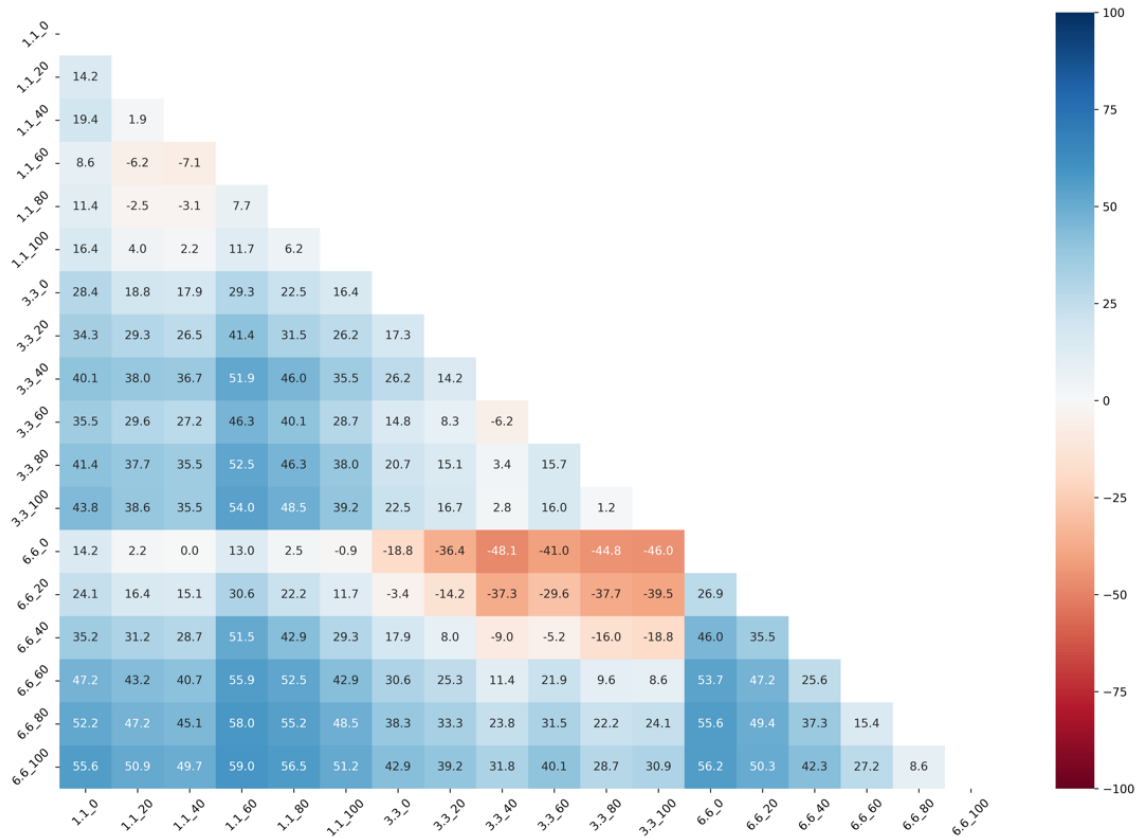


Figure A4. Intervention *evaluation percentage* for nutrition across six districts for the alternatives versus each other with varying plant densities and N fertilizer rates. The alternative labels are (plant density_N fertilizer application rate). The scenarios are labeled as planting date (E (Early), M (Medium), L (Late)), plant density (1.1 pl m⁻², 3.3 pl m⁻², 6.6 pl m⁻²), and N fertilizer rate (0 kg N ha⁻¹, 20 kg N ha⁻¹, 40 kg N ha⁻¹, 60 kg N ha⁻¹, 80 kg N ha⁻¹, 100 kg N ha⁻¹).

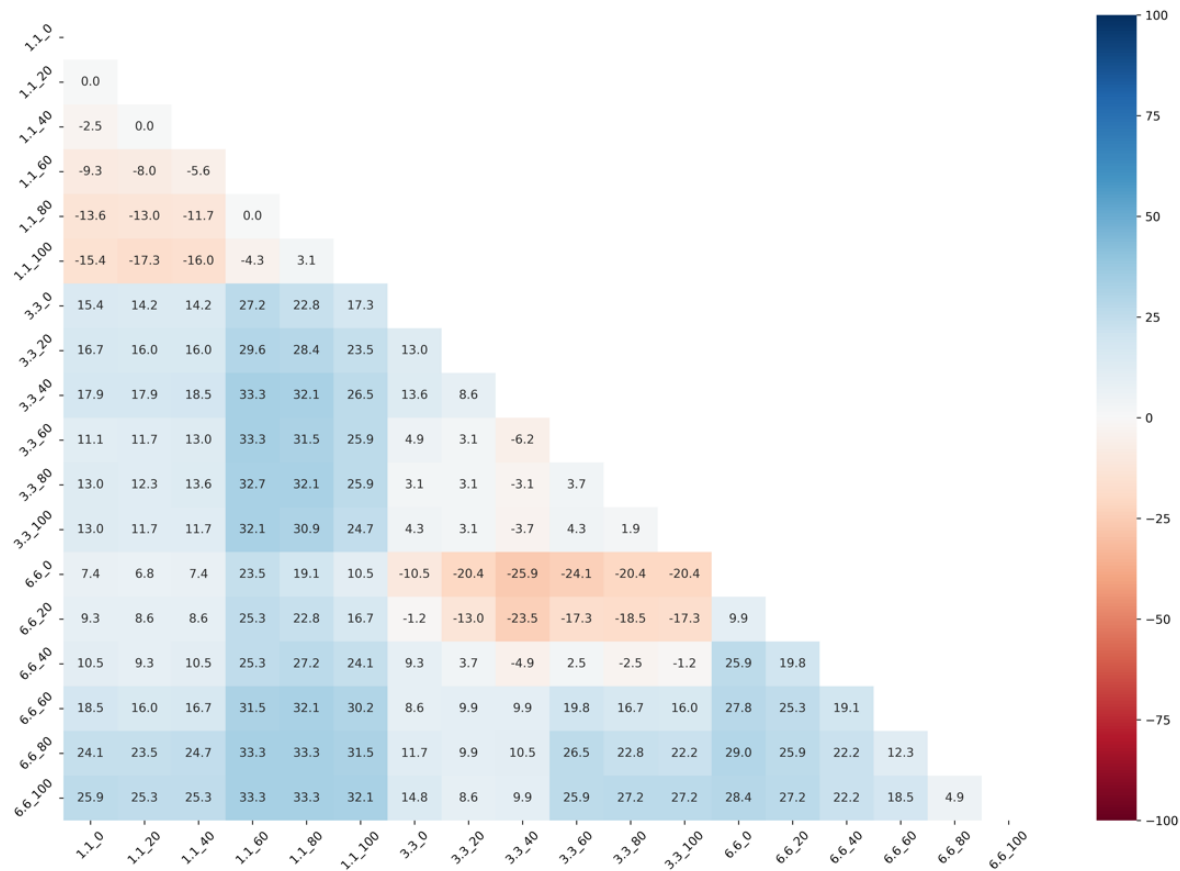


Figure A5. Intervention *evaluation percentage* for economics across six districts for the alternatives versus each other with varying plant densities and N fertilizer rates. The alternative labels are (plant density_N fertilizer application rate). The scenarios are labeled as planting date (E (Early), M (Medium), L (Late)), plant density (1.1 pl m⁻², 3.3 pl m⁻², 6.6 pl m⁻²), and N fertilizer rate (0 kg N ha⁻¹, 20 kg N ha⁻¹, 40 kg N ha⁻¹, 60 kg N ha⁻¹, 80 kg N ha⁻¹, 100 kg N ha⁻¹).

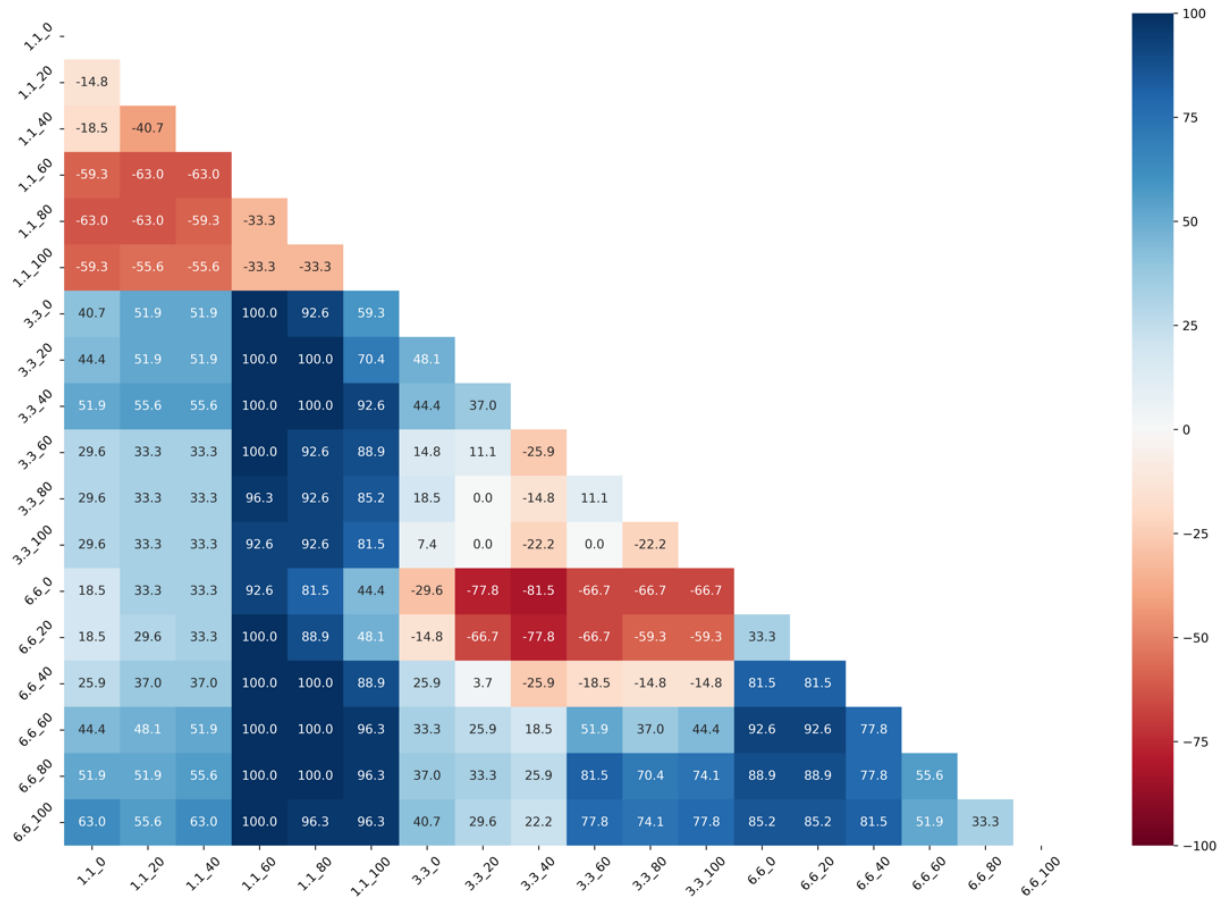


Figure A6. Intervention *evaluation percentage* for risk across six districts for the alternatives versus each other with varying plant densities and N fertilizer rates. The alternative labels are (plant density_N fertilizer application rate). The scenarios are labeled as planting date (E (Early), M (Medium), L (Late)), plant density (1.1 pl m⁻², 3.3 pl m⁻², 6.6 pl m⁻²), and N fertilizer rate (0 kg N ha⁻¹, 20 kg N ha⁻¹, 40 kg N ha⁻¹, 60 kg N ha⁻¹, 80 kg N ha⁻¹, 100 kg N ha⁻¹).

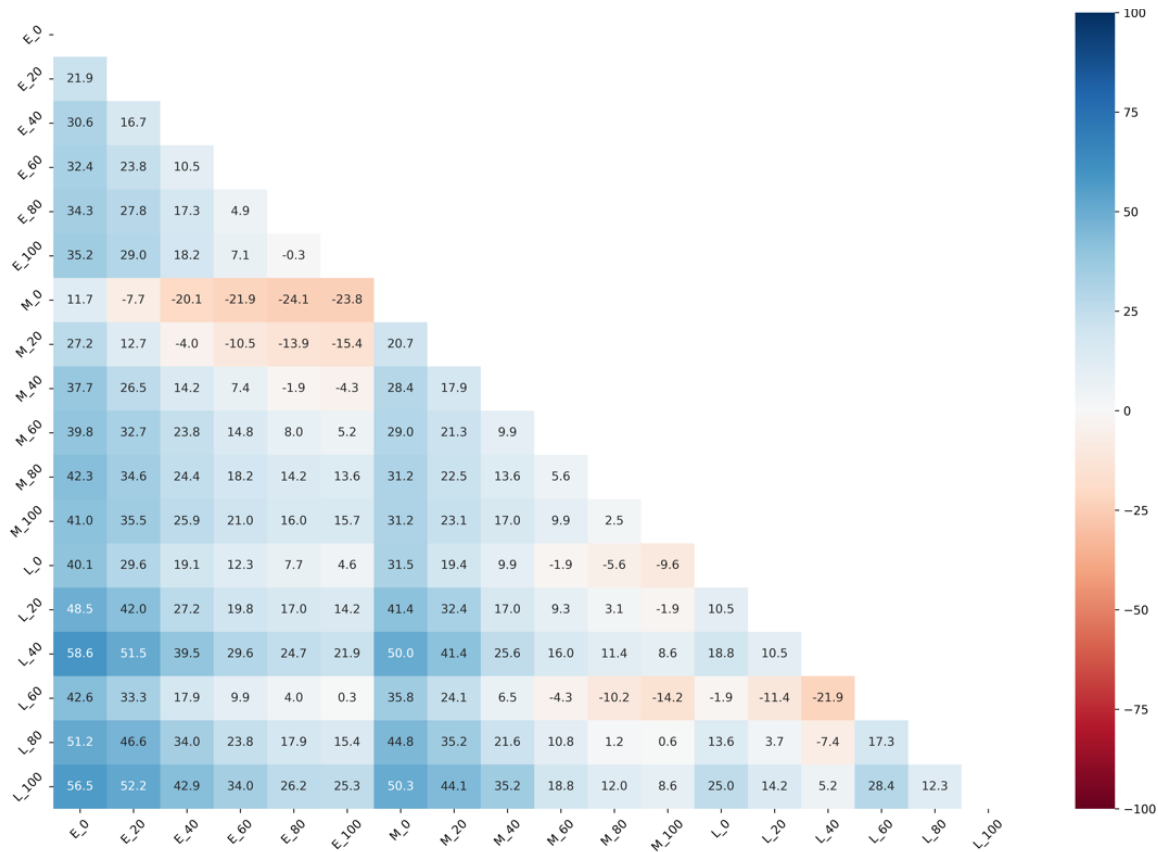


Figure A7. Intervention *evaluation percentage* for nutrition across six districts for the alternatives versus each other with varying planting dates and N fertilizer rates. The alternative labels are (planting date_N fertilizer application rate). The scenarios are labeled as planting date (E (Early), M (Medium), L (Late)), plant density (1.1 pl m⁻², 3.3 pl m⁻², 6.6 pl m⁻²), and N fertilizer rate (0 kg N ha⁻¹, 20 kg N ha⁻¹, 40 kg N ha⁻¹, 60 kg N ha⁻¹, 80 kg N ha⁻¹, 100 kg N ha⁻¹).

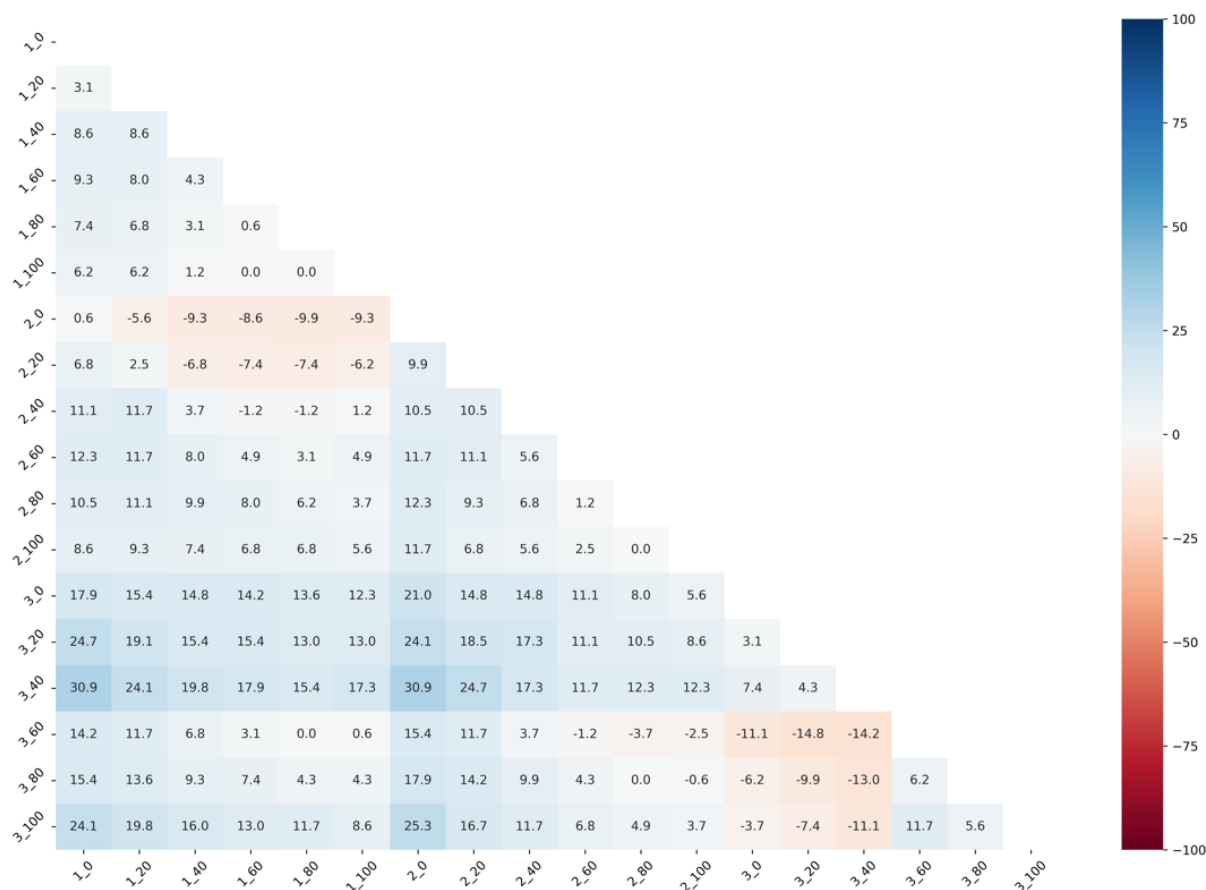


Figure A8. Intervention *evaluation percentage* for economics across six districts for the alternatives versus each other with varying planting dates and N fertilizer rates. The alternative labels are (planting date_N fertilizer application rate). The scenarios are labeled as planting date (E (Early), M (Medium), L (Late)), plant density (1.1 pl m⁻², 3.3 pl m⁻², 6.6 pl m⁻²), and N fertilizer rate (0 kg N ha⁻¹, 20 kg N ha⁻¹, 40 kg N ha⁻¹, 60 kg N ha⁻¹, 80 kg N ha⁻¹, 100 kg N ha⁻¹).

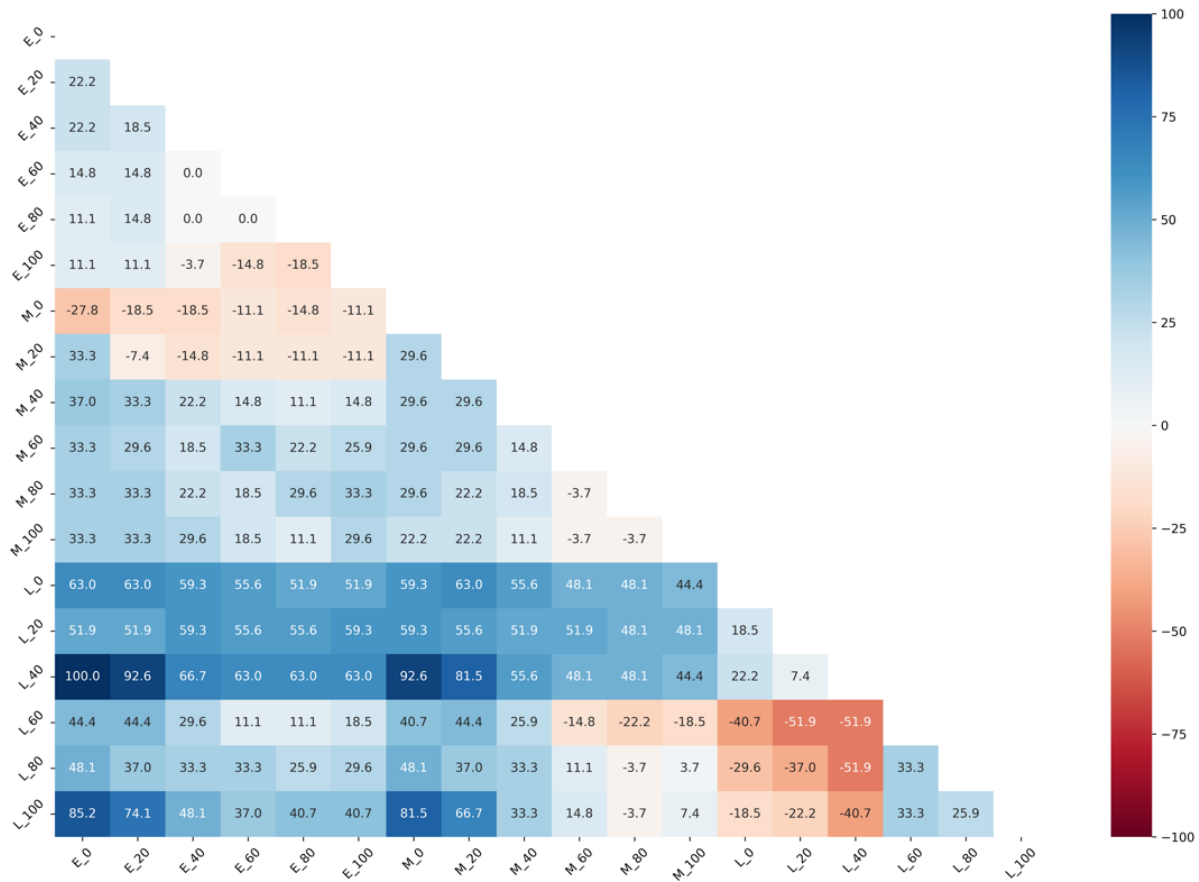


Figure A9. Intervention *evaluation percentage* for risk across six districts for the alternatives versus each other with varying planting dates and N fertilizer rates. The alternative labels are (planting date_N fertilizer application rate). The scenarios are labeled as planting date (E (Early), M (Medium), L (Late)), plant density (1.1 pl m⁻², 3.3 pl m⁻², 6.6 pl m⁻²), and N fertilizer rate (0 kg N ha⁻¹, 20 kg N ha⁻¹, 40 kg N ha⁻¹, 60 kg N ha⁻¹, 80 kg N ha⁻¹, 100 kg N ha⁻¹).

Table A26. Selected foods for optimization analysis nutritional values (Bizimana & Richardson, 2019; Sharma & Katz, 2012).

Food	Units	Calories	Protein	Fat	Calcium	Iron	Vitamin A
Fish	/kg	2500	198	165	0.22	0.015	0.007497
Beef	/kg	6740	82.1	708.9	0.26	0.0072	0
Milk	/Liter	640	32.8	36.6	1.19	0.0005	0.000414
Egg	/kg	1430	125.6	95.1	1.36	0.0175	0.00162
Lettuce	/kg	150	13.6	1.5	0.36	0.0086	0.022215
Peanut	/kg	5670	258	492	0.92	0.0458	0
Rice	/kg	970	20.2	1.9	0.02	0.0014	0
Maize	/kg	3610	69.3	38.6	0.07	0.0238	0
Millet	/kg	1190	35.1	10	0.03	0.0063	0

Table A27. Selected foods for optimization analysis of economic costs (Bousso, 2022; DAPSA, 2020b; FEWS NET, 2020, 2021; HEA SAHEL, 2016b; Rich & Wane, 2021; Selina Wamucii, 2023b, 2023c).

Food	Cost	Cost Units
Fish	2706.19	CFA/kg
Beef	1000	CFA/kg
Milk	355	CFA/Liter
Egg	1000	CFA/dozen eggs
Lettuce	1389.5	CFA/kg
Peanut	250	CFA/kg
Rice	292.5	CFA/kg
Maize	203.42	CFA/kg
Millet	219.75	CFA/kg

Table A28. Diourbel linear optimization recommended quantities (kg/person/day) and cost of food (CFA/person/day) for purchase to meet nutritional needs for each alternative scenario.

Alternative	Fish	Beef	Milk	Egg	Lettuce	Peanut	Rice	Maize	Millet	Cost
Baseline	0	0	0	0	0.04	1.34	0	0	0	387.83
1_1.1 0kg	0	0	0	0	0.04	1.34	0	0	0	387.95
1_1.1 20kg	8.3E-11	4.24E-10	9.06E-11	8.23E-11	0.04	1.34	7.73E-11	8.95E-11	9.03E-11	387.86
1_1.1 40kg	0	0	9.6E-09	0	0.04	1.34	0	0	0	387.90
1_1.1 60kg	5.59E-06	2.06E-06	7.31E-07	4.92E-06	0.04	1.34	6.02E-07	4.18E-07	4.52E-07	387.94
1_1.1 80kg	0	0	0	0	0.04	1.34	0	0	0	387.88
1_1.1 100kg	1.02E-06	3.78E-07	1.34E-07	9E-07	0.04	1.34	1.1E-07	7.65E-08	8.27E-08	387.83
1_3.3 0kg	0	0	0	0	0.04	1.34	0	0	0	387.60
1_3.3 20kg	1.09E-08	3.08E-09	1.01E-09	7.41E-09	0.04	1.34	8.46E-10	5.8E-10	6.26E-10	387.72
1_3.3 40kg	3.16E-10	0	0	4.15E-10	0.04	1.34	0	0	0	387.67
1_3.3 60kg	0	0	0	0	0.04	1.34	0	0	0	387.68
1_3.3 80kg	0	0	0	0	0.04	1.34	0	0	0	387.52
1_3.3 100kg	0	0	0	0	0.04	1.34	0	0	0	387.63
1_6.6 0kg	0	0	0	0	0.04	1.34	0	0	0	387.59
1_6.6 20kg	2.11E-06	7.78E-07	2.76E-07	1.85E-06	0.04	1.34	2.27E-07	1.58E-07	1.7E-07	387.67
1_6.6 40kg	0	0	0	0	0.04	1.34	0	0	0	387.62
1_6.6 60kg	4.01E-07	0	0	4.03E-07	0.04	1.34	0	0	0	387.53
1_6.6 80kg	0	0	0	0	0.04	1.34	0	0	0	387.57
1_6.6 100kg	0	9.3E-07	0	0	0.04	1.34	0	0	0	387.45
2_1.1 0kg	0	0	0	0	0.04	1.34	0	0	0	387.86
2_1.1 20kg	0	0	0	0	0.04	1.34	0	0	0	387.84
2_1.1 40kg	0	0	0	0	0.04	1.34	0	0	0	387.81
2_1.1 60kg	0	0	0	0	0.04	1.34	0	0	0	387.85
2_1.1 80kg	1.84E-05	6.81E-06	2.42E-06	1.62E-05	0.04	1.34	1.99E-06	1.39E-06	1.5E-06	387.95

Table A28. (cont'd)

2_1.1 100kg	0	0	0	0	0.04	1.34	0	3.83E-08	0	387.84
2_3.3 0kg	0	0	0	0	0.04	1.34	0	0	0	387.56
2_3.3 20kg	7.03E-08	0	0	0	0.04	1.34	0	0	0	387.68
2_3.3 40kg	1.09E-10	0	0	0	0.04	1.34	0	0	0	387.51
2_3.3 60kg	0	0	0	0	0.04	1.34	0	0	0	387.59
2_3.3 80kg	0	0	0	0	0.04	1.34	0	0	0	387.41
2_3.3 100kg	0	0	0	0	0.04	1.34	0	0	0	387.35
2_6.6 0kg	2.42E-08	9.96E-09	3.7E-09	2.28E-08	0.04	1.34	3.03E-09	1.98E-09	6.07E-08	387.71
2_6.6 20kg	0	0	0	0	0.04	1.34	0	0	0	387.66
2_6.6 40kg	0	0	0	0	0.04	1.34	0	0	0	387.57
2_6.6 60kg	3.48E-06	1.29E-06	4.55E-07	3.06E-06	0.04	1.34	3.75E-07	2.6E-07	2.82E-07	387.54
2_6.6 80kg	0	0	0	0	0.04	1.34	0	0	0	387.49
2_6.6 100kg	6.75E-06	2.49E-06	8.83E-07	5.94E-06	0.04	1.34	7.27E-07	5.05E-07	5.46E-07	387.50
3_1.1 0kg	0	5.25E-07	0	0	0.04	1.34	0	0	0	387.58
3_1.1 20kg	0	0	0	0	0.04	1.34	0	0	0	387.59
3_1.1 40kg	0	0	0	0	0.04	1.34	0	0	0	387.50
3_1.1 60kg	0	0	0	0	0.04	1.34	0	0	0	387.73
3_1.1 80kg	0	0	0	0	0.04	1.34	0	0	0	387.67
3_1.1 100kg	0	0	0	0	0.04	1.34	0	0	0	387.54
3_3.3 0kg	0	1.47E-08	0	0	0.04	1.34	0	1.52E-08	0	387.54
3_3.3 20kg	0	0	0	0	0.04	1.34	0	0	0	387.47
3_3.3 40kg	0	0	0	0	0.04	1.34	0	0	0	387.47
3_3.3 60kg	6.14E-06	2.27E-06	8.03E-07	5.4E-06	0.04	1.34	6.62E-07	4.59E-07	4.97E-07	387.64
3_3.3 80kg	0	0	0	0	0.04	1.34	0	0	0	387.52
3_3.3 100kg	0	0	0	0	0.04	1.34	0	0	0	387.45
3_6.6 0kg	0	0	0	0	0.04	1.34	0	0	0	387.77

Table A28. (cont'd)

3_6.6 20kg	0	0	0	0	0.04	1.34	0	0	0	387.65
3_6.6 40kg	0	0	0	0	0.04	1.34	0	0	0	387.66
3_6.6 60kg	0	0	0	0	0.04	1.34	0	0	0	387.36
3_6.6 80kg	0	0	0	0	0.04	1.34	0	0	0	387.43
3_6.6 100kg	0	0	0	0	0.04	1.34	0	0	0	387.46

Table A29. Fatick linear optimization recommended quantities (kg/person/day) and cost of food (CFA/person/day) for purchase to meet nutritional needs for each alternative scenario.

Alternative	Fish	Beef	Milk	Egg	Lettuce	Peanut	Rice	Maize	Millet	Cost
Baseline	0	3.21E-06	0.000187	0	0.03	1.09	0	0	0	320.84
1_1.1 0kg	8.15E-06	3.01E-06	1.07E-06	7.17E-06	0.03	1.09	8.78E-07	6.1E-07	6.59E-07	321.27
1_1.1 20kg	0	0	0	1.69E-07	0.03	1.09	0	0	0	321.11
1_1.1 40kg	0	0	0	0	0.03	1.09	0	0	0	321.01
1_1.1 60kg	1.58E-06	5.85E-07	2.07E-07	1.39E-06	0.03	1.09	1.71E-07	1.18E-07	1.28E-07	321.07
1_1.1 80kg	0	0	0	0	0.03	1.09	0	0	0	320.96
1_1.1 100kg	4.1E-06	1.51E-06	5.37E-07	3.61E-06	0.03	1.09	4.43E-07	3.08E-07	3.33E-07	321.11
1_3.3 0kg	1.95E-07	7.24E-08	2.57E-08	1.73E-07	0.03	1.09	2.13E-08	1.48E-08	1.59E-08	321.10
1_3.3 20kg	0	0	0	0	0.03	1.09	0	0	0	321.17
1_3.3 40kg	0	0	0	0	0.03	1.09	0	0	0	321.06
1_3.3 60kg	0	0	0	0	0.03	1.09	0	0	0	321.06
1_3.3 80kg	2.59E-07	9.62E-08	3.42E-08	2.29E-07	0.03	1.09	2.81E-08	1.96E-08	2.11E-08	321.04
1_3.3 100kg	0	2.73E-07	0	0	0.03	1.09	0	0	0	320.94
1_6.6 0kg	0	0	0	0	0.03	1.09	0	0	0	321.00
1_6.6 20kg	0	0	0	0	0.03	1.09	0	0	0	321.06
1_6.6 40kg	0	0	0	0	0.03	1.09	0	0	0	321.13
1_6.6 60kg	0	0	0	0	0.03	1.09	0	4.58E-08	0	321.08
1_6.6 80kg	0	0	0	0	0.03	1.09	0	0	0	321.05
1_6.6 100kg	0	0	0	0	0.03	1.09	0	0	0	321.04
2_1.1 0kg	1E-07	0	7.59E-09	0	0.03	1.09	0	0	0	321.33
2_1.1 20kg	0	3.3E-06	3.36E-06	0	0.03	1.09	0	0	0	321.28
2_1.1 40kg	1.12E-06	4.12E-07	5.41E-06	9.8E-07	0.03	1.09	1.21E-07	8.39E-08	9.05E-08	321.11
2_1.1 60kg	2.54E-08	0	0	0	0.03	1.09	0	0	0	321.05
2_1.1 80kg	1.94E-06	7.17E-07	2.54E-07	1.71E-06	0.03	1.09	2.09E-07	1.45E-07	1.57E-07	321.05

Table A29. (cont'd)

2_1.1 100kg	0	0	0	0	0.03	1.09	0	0	0	320.96
2_3.3 0kg	0	0	0	0	0.03	1.09	0	0	0	320.69
2_3.3 20kg	2.84E-07	1.05E-07	3.72E-08	2.5E-07	0.03	1.09	3.07E-08	2.13E-08	2.3E-08	320.73
2_3.3 40kg	2.23E-07	1.25E-07	2.32E-07	2.24E-07	0.03	1.09	1.25E-07	1.22E-07	1.25E-07	320.67
2_3.3 60kg	4.58E-06	1.69E-06	5.99E-07	4.03E-06	0.03	1.09	4.93E-07	3.43E-07	3.7E-07	320.94
2_3.3 80kg	6.18E-06	2.28E-06	8.09E-07	5.44E-06	0.03	1.09	6.66E-07	4.62E-07	5E-07	320.88
2_3.3 100kg	0	0	0	0	0.03	1.09	0	0	0	320.81
2_6.6 0kg	0	0	0	0	0.03	1.09	0	0	0	320.66
2_6.6 20kg	5.14E-06	1.9E-06	6.73E-07	4.52E-06	0.03	1.09	5.54E-07	3.85E-07	4.16E-07	320.72
2_6.6 40kg	0	0	0	0	0.03	1.09	0	0	0	320.65
2_6.6 60kg	0	0	0	0	0.03	1.09	0	0	0	320.69
2_6.6 80kg	5.5E-06	2.03E-06	7.22E-07	4.84E-06	0.03	1.09	5.95E-07	4.13E-07	4.47E-07	320.82
2_6.6 100kg	3.17E-06	1.17E-06	4.16E-07	2.79E-06	0.03	1.09	1.24E-06	2.38E-07	2.58E-07	320.79
3_1.1 0kg	3.34E-07	0	0	3.36E-07	0.03	1.09	0	0	0	320.62
3_1.1 20kg	0	0	0	0	0.03	1.09	0	0	0	320.56
3_1.1 40kg	0	0	0	0	0.03	1.09	0	0	0	320.72
3_1.1 60kg	0	0	0	0	0.03	1.09	0	0	0	321.07
3_1.1 80kg	0	0	0	0	0.03	1.09	0	0	0	320.34
3_1.1 100kg	0	0	1.32E-05	0	0.03	1.09	0	0	0	320.51
3_3.3 0kg	0	1.07E-10	2.19E-10	0	0.03	1.09	0	0	0	320.58
3_3.3 20kg	0	0	0	0	0.03	1.09	0	0	0	320.62
3_3.3 40kg	0	0	0	0	0.03	1.09	0	0	0	320.30
3_3.3 60kg	0	0	0	0	0.03	1.09	0	0	0	321.24
3_3.3 80kg	0	0	3.04E-05	0	0.03	1.09	0	0	0	320.97
3_3.3 100kg	0	0	0	0	0.03	1.09	0	0	0	320.94
3_6.6 0kg	0	0	0	0	0.03	1.09	0	0	0	321.09

Table A29. (cont'd)

3_6.6 20kg	0	0	0	0	0.03	1.09	0	0	0	321.05
3_6.6 40kg	0	0	0	0	0.03	1.09	0	0	0	320.92
3_6.6 60kg	0	6.74E-07	0	0	0.03	1.09	0	0	0	320.50
3_6.6 80kg	0	0	0	0	0.03	1.09	0	0	0	320.48
3_6.6 100kg	3.25E-06	1.2E-06	4.27E-07	2.86E-06	0.03	1.09	3.52E-07	2.44E-07	2.64E-07	320.49

Table A30. Kaffrine linear optimization recommended quantities (kg/person/day) and cost of food (CFA/person/day) for purchase to meet nutritional needs for each alternative scenario.

Alternative	Fish	Beef	Milk	Egg	Lettuce	Peanut	Rice	Maize	Millet	Cost
Baseline	0	0	0	0	0.04	1.20	0	0	0	351.21
1_1.1 0kg	0	0	0	0	0.04	1.20	0	0	0	351.45
1_1.1 20kg	0	0	0	0	0.04	1.20	0	0	0	351.55
1_1.1 40kg	1.42E-06	5.25E-07	1.86E-07	1.25E-06	0.04	1.20	1.53E-07	1.06E-07	1.15E-07	351.51
1_1.1 60kg	0	0	0	0	0.04	1.20	0	0	0	351.47
1_1.1 80kg	0	0	0	0	0.04	1.20	0	0	0	350.76
1_1.1 100kg	0	0	0	0	0.04	1.20	0	0	0	351.48
1_3.3 0kg	0	0	0	0	0.04	1.20	0	0	0	351.35
1_3.3 20kg	0	0	8.9E-09	0	0.04	1.20	0	0	0	351.29
1_3.3 40kg	0	0	0	0	0.04	1.20	0	0	0	351.13
1_3.3 60kg	0	0	0	0	0.04	1.20	0	0	0	351.17
1_3.3 80kg	0	0	0	0	0.04	1.20	0	0	0	351.12
1_3.3 100kg	0	0	0	0	0.04	1.20	0	0	0	351.04
1_6.6 0kg	0	0	0	0	0.04	1.20	0	0	0	351.39
1_6.6 20kg	0	0	0	0	0.04	1.20	0	0	0	351.30
1_6.6 40kg	0	0	0	0	0.04	1.20	0	0	0	351.23
1_6.6 60kg	0	0	0	0	0.04	1.20	0	0	0	351.01
1_6.6 80kg	1.36E-05	5.02E-06	1.78E-06	1.2E-05	0.04	1.20	1.47E-06	1.02E-06	1.1E-06	351.09
1_6.6 100kg	0	0	0	0	0.04	1.20	0	0	0	350.95
2_1.1 0kg	0	0	0	0	0.04	1.20	0	0	0	351.63
2_1.1 20kg	0	0	0	0	0.04	1.20	0	0	0	351.40
2_1.1 40kg	0	0	0	0	0.04	1.20	0	0	0	351.43
2_1.1 60kg	2.57E-06	9.49E-07	3.37E-07	2.26E-06	0.04	1.20	2.78E-07	1.93E-07	2.09E-07	351.40

Table A30. (cont'd)

2_1.1 80kg	0	0	0	0	0.04	1.20	0	0	0	351.33
2_1.1 100kg	0	0	0	0	0.04	1.20	0	0	0	351.35
2_3.3 0kg	0	0	0	0	0.04	1.20	0	0	0	351.25
2_3.3 20kg	0	0	0	0	0.04	1.20	0	0	0	351.14
2_3.3 40kg	0	0	0	0	0.04	1.20	0	0	0	351.00
2_3.3 60kg	1.59E-08	2.89E-09	3.65E-09	2.14E-09	0.04	1.20	3.7E-09	3.49E-09	3.48E-09	350.94
2_3.3 80kg	0	0	0	0	0.04	1.20	0	0	0	350.86
2_3.3 100kg	0	0	0	0	0.04	1.20	0	0	0	350.78
2_6.6 0kg	0	0	0	0	0.04	1.20	0	0	0	351.25
2_6.6 20kg	0	0	0	0	0.04	1.20	0	0	0	351.17
2_6.6 40kg	0	0	0	0	0.04	1.20	0	0	0	350.93
2_6.6 60kg	3.86E-06	1.42E-06	5.05E-07	3.4E-06	0.04	1.20	4.16E-07	2.89E-07	3.12E-07	350.93
2_6.6 80kg	3.69E-08	4.95E-09	6.5E-09	1.62E-09	0.04	1.20	6.65E-09	6.87E-09	6.83E-09	350.72
2_6.6 100kg	0	0	0	0	0.04	1.20	0	0	0	350.40
3_1.1 0kg	5.15E-06	1.9E-06	6.73E-07	4.53E-06	0.04	1.20	5.55E-07	3.85E-07	4.16E-07	351.02
3_1.1 20kg	0	0	0	0	0.04	1.20	0	0	0	350.82
3_1.1 40kg	0	0	0	0	0.04	1.20	0	0	0	350.93
3_1.1 60kg	2.52E-06	9.3E-07	3.31E-07	2.22E-06	0.04	1.20	2.72E-07	1.89E-07	2.05E-07	351.14
3_1.1 80kg	0	0	0	0	0.04	1.20	0	0	0	351.05
3_1.1 100kg	0	0	0	0	0.04	1.20	0	0	0	350.70
3_3.3 0kg	2.02E-06	7.47E-07	2.65E-07	1.78E-06	0.04	1.20	2.19E-07	1.52E-07	1.64E-07	350.88
3_3.3 20kg	0	0	0	0	0.04	1.20	0	0	0	350.09
3_3.3 40kg	0	0	0	0	0.04	1.20	0	0	0	350.71
3_3.3 60kg	0	0	0	0	0.04	1.20	0	0	0	350.96
3_3.3 80kg	0	0	0	0	0.04	1.20	0	0	0	350.86
3_3.3 100kg	0	0	0	0	0.04	1.20	0	0	0	350.86

Table A30. (cont'd)

3_6.6 0kg	0	0	0	0	0.04	1.20	0	0	0	351.34
3_6.6 20kg	1.22E-05	4.49E-06	1.59E-06	1.07E-05	0.04	1.20	1.31E-06	9.09E-07	9.83E-07	351.26
3_6.6 40kg	0	0	0	0	0.04	1.20	0	0	0	351.03
3_6.6 60kg	0	0	0	0	0.04	1.20	0	0	0	350.98
3_6.6 80kg	0	0	0	0	0.04	1.20	0	0	0	350.86
3_6.6 100kg	0	0	0	0	0.04	1.20	0	0	0	350.68

Table A31. Kaolack linear optimization recommended quantities (kg/person/day) and cost of food (CFA/person/day) for purchase to meet nutritional needs for each alternative scenario.

Alternative	Fish	Beef	Milk	Egg	Lettuce	Peanut	Rice	Maize	Millet	Cost
Baseline	0	0	0	0	0.04	1.33	0	0	0	386.34
1_1.1 0kg	0	0	0	0	0.04	1.33	0	0	0	386.50
1_1.1 20kg	8.7E-06	3.22E-06	1.14E-06	7.66E-06	0.04	1.33	2.25E-05	6.54E-07	7.07E-07	386.25
1_1.1 40kg	0	0	0	0	0.04	1.33	0	0	0	386.36
1_1.1 60kg	0	0	0	0	0.04	1.33	0	0	0	386.39
1_1.1 80kg	3.13E-06	1.16E-06	4.11E-07	2.75E-06	0.04	1.33	3.38E-07	2.35E-07	2.54E-07	386.41
1_1.1 100kg	1.94E-06	7.18E-07	2.55E-07	1.71E-06	0.04	1.33	2.1E-07	4.83E-06	1.4E-06	386.39
1_3.3 0kg	0	0	0	0	0.04	1.33	0	0	0	386.49
1_3.3 20kg	0	0	0	0	0.04	1.33	0	0	0	386.32
1_3.3 40kg	0	0	0	0	0.04	1.33	0	0	0	386.10
1_3.3 60kg	0	0	0	0	0.04	1.33	0	0	0	385.96
1_3.3 80kg	3.79E-06	1.4E-06	4.96E-07	3.34E-06	0.04	1.33	4.09E-07	2.84E-07	3.07E-07	385.90
1_3.3 100kg	3.63E-07	1.34E-07	4.79E-08	3.21E-07	0.04	1.33	3.93E-08	2.73E-08	2.95E-08	386.03
1_6.6 0kg	0	0	0	0	0.04	1.33	0	0	0	386.15
1_6.6 20kg	0	0	0	0	0.04	1.33	0	0	0	386.07
1_6.6 40kg	0	0	0	0	0.04	1.33	0	0	0	386.07
1_6.6 60kg	0	0	0	0	0.04	1.33	0	0	0	385.99
1_6.6 80kg	9.19E-07	3.39E-07	1.2E-07	8.07E-07	0.04	1.33	9.89E-08	6.87E-08	7.42E-08	385.96
1_6.6 100kg	0	0	0	0	0.04	1.33	0	0	0	385.93
2_1.1 0kg	0	0	0	0	0.04	1.33	0	0	0	386.35
2_1.1 20kg	0	0	7.66E-10	0	0.04	1.33	0	1.42E-09	0	386.37
2_1.1 40kg	0	0	0	0	0.04	1.33	0	0	0	386.27
2_1.1 60kg	0	0	0	0	0.04	1.33	0	0	0	386.28
2_1.1 80kg	0	0	0	0	0.04	1.33	0	0	0	386.26

Table A31. (cont'd)

2_1.1 100kg	0	0	0	0	0.04	1.33	0	0	0	386.32
2_3.3 0kg	0	0	0	0	0.04	1.33	0	0	0	386.15
2_3.3 20kg	0	0	0	0	0.04	1.33	0	0	0	386.13
2_3.3 40kg	0	0	0	0	0.04	1.33	0	0	0	385.77
2_3.3 60kg	0	0	0	0	0.04	1.33	0	0	0	386.04
2_3.3 80kg	0	0	0	0	0.04	1.33	0	0	0	385.95
2_3.3 100kg	0	0	0	0	0.04	1.33	0	0	0	386.05
2_6.6 0kg	0	0	0	0	0.04	1.33	0	0	0	386.16
2_6.6 20kg	4.93E-06	1.82E-06	6.44E-07	4.33E-06	0.04	1.33	5.31E-07	3.69E-07	3.98E-07	386.22
2_6.6 40kg	0	0	0	0	0.04	1.33	0	0	0	385.95
2_6.6 60kg	0	0	0	0	0.04	1.33	0	0	0	386.00
2_6.6 80kg	0	0	0	0	0.04	1.33	0	0	0	385.82
2_6.6 100kg	0	4.54E-09	0	0	0.04	1.33	0	0	0	385.91
3_1.1 0kg	3.87E-07	1.28E-07	5.28E-08	3.56E-07	0.04	1.33	4.36E-08	9.39E-09	3.28E-08	386.14
3_1.1 20kg	0	0	0	0	0.04	1.33	0	0	0	386.18
3_1.1 40kg	3.25E-07	1.21E-07	4.28E-08	2.88E-07	0.04	1.33	3.52E-08	2.44E-08	2.64E-08	386.19
3_1.1 60kg	0	0	0	0	0.04	1.33	0	0	0	386.22
3_1.1 80kg	0	0	0	0	0.04	1.33	0	0	0	386.08
3_1.1 100kg	0	0	0	0	0.04	1.33	0	0	0	386.04
3_3.3 0kg	0	0	0	0	0.04	1.33	0	0	0	386.05
3_3.3 20kg	1.54E-06	5.67E-07	2.01E-07	1.35E-06	0.04	1.33	1.66E-07	1.15E-07	1.25E-07	386.12
3_3.3 40kg	0	0	0	0	0.04	1.33	0	0	0	386.07
3_3.3 60kg	1.85E-06	6.84E-07	2.42E-07	1.63E-06	0.04	1.33	2E-07	1.39E-07	1.5E-07	386.40
3_3.3 80kg	0	0	0	0	0.04	1.33	0	0	0	386.23
3_3.3 100kg	0	0	0	0	0.04	1.33	0	0	0	386.28
3_6.6 0kg	0	0	0	0	0.04	1.33	0	0	0	386.28

Table A31. (cont'd)

3_6.6 20kg	0	0	0	0	0.04	1.33	0	0	0	386.14
3_6.6 40kg	0	0	0	0	0.04	1.33	0	5E-08	0	386.11
3_6.6 60kg	0	0	0	0	0.04	1.33	0	0	0	386.03
3_6.6 80kg	0	0	0	0	0.04	1.33	0	0	0	386.02
3_6.6 100kg	0	0	0	0	0.04	1.33	0	0	0	386.00

Table A32. Kolda linear optimization recommended quantities (kg/person/day) and cost of food (CFA/person/day) for purchase to meet nutritional needs for each alternative scenario.

Alternative	Fish	Beef	Milk	Egg	Lettuce	Peanut	Rice	Maize	Millet	Cost
Baseline	0	0	0	0	0.04	1.16	0	0	0	340.77
1_1.1 0kg	0	0	0	0	0.04	1.16	0	0	0	340.83
1_1.1 20kg	8.52E-06	3.15E-06	1.12E-06	7.5E-06	0.04	1.16	9.2E-07	6.4E-07	6.92E-07	340.86
1_1.1 40kg	0	0	0	0	0.04	1.16	0	0	0	340.74
1_1.1 60kg	1.29E-06	4.77E-07	1.69E-07	1.1E-06	0.04	1.16	1.4E-07	9.71E-08	1.05E-07	340.81
1_1.1 80kg	1.37E-06	5.06E-07	1.79E-07	1.2E-06	0.04	1.16	1.48E-07	1.03E-07	1.11E-07	340.80
1_1.1 100kg	0	0	0	0	0.04	1.16	0	0	0	340.77
1_3.3 0kg	3.97E-06	1.47E-06	5.2E-07	3.5E-06	0.04	1.16	4.29E-07	2.98E-07	3.22E-07	340.87
1_3.3 20kg	0	0	0	0	0.04	1.16	0	0	0	340.74
1_3.3 40kg	0	0	0	0	0.04	1.16	4.89E-06	0	5.23E-06	340.68
1_3.3 60kg	1.12E-06	4.12E-07	1.46E-07	9.8E-07	0.04	1.16	1.2E-07	8.35E-08	9.03E-08	340.70
1_3.3 80kg	0	0	0	0	0.04	1.16	0	0	0	340.54
1_3.3 100kg	0	0	0	0	0.04	1.16	0	0	0	340.60
1_6.6 0kg	0	0	0	0	0.04	1.16	0	0	0	340.79
1_6.6 20kg	0	0	0	0	0.04	1.16	0	0	0	340.73
1_6.6 40kg	0	0	1.12E-05	0	0.04	1.16	1.43E-05	1.92E-05	1.06E-05	340.65
1_6.6 60kg	0	0	0	0	0.04	1.16	0	0	0	340.68
1_6.6 80kg	3.91E-07	1.45E-07	5.15E-08	3.5E-07	0.04	1.16	4.23E-08	2.95E-08	3.19E-08	340.64
1_6.6 100kg	0	0	0	0	0.04	1.16	0	0	0	340.62
2_1.1 0kg	0	0	0	0	0.04	1.17	0	0	0	343.23
2_1.1 20kg	1.9E-07	7.19E-08	3.76E-08	1.7E-07	0.04	1.16	3.87E-08	7.46E-08	1.22E-08	340.81
2_1.1 40kg	7.02E-06	2.59E-06	9.19E-07	6.2E-06	0.04	1.16	7.56E-07	5.25E-07	5.68E-07	340.85
2_1.1 60kg	0	0	0	0	0.04	1.16	0	8.51E-07	0	340.79

Table A32. (cont'd)

2_1.1 80kg	1.47E-05	5.41E-06	1.92E-06	1.3E-05	0.04	1.16	1.58E-06	1.1E-06	1.19E-06	340.90
2_1.1 100kg	0	0	0	0	0.04	1.16	0	0	0	340.74
2_3.3 0kg	0	0	0	0	0.04	1.16	0	0	0	340.79
2_3.3 20kg	0	0	0	0	0.04	1.16	0	0	0	340.76
2_3.3 40kg	1.22E-05	4.49E-06	1.59E-06	1.1E-05	0.04	1.16	1.31E-06	9.09E-07	9.83E-07	340.79
2_3.3 60kg	7.04E-06	2.6E-06	9.23E-07	6.2E-06	0.04	1.16	7.61E-07	5.29E-07	5.71E-07	340.73
2_3.3 80kg	0	0	0	0	0.04	1.16	0	0	0	340.65
2_3.3 100kg	0	0	0	0	0.04	1.16	0	3.74E-08	0	340.63
2_6.6 0kg	0	0	4E-06	0	0.04	1.16	0	0	1.44E-05	340.75
2_6.6 20kg	0	0	0	0	0.04	1.16	0	0	0	340.79
2_6.6 40kg	0	0	0	0	0.04	1.16	0	0	0	340.58
2_6.6 60kg	0	0	0	0	0.04	1.16	0	0	0	340.63
2_6.6 80kg	4.24E-07	1.41E-07	5E-08	3.7E-07	0.04	1.16	4.11E-08	2.86E-08	3.09E-08	340.66
2_6.6 100kg	1.73E-06	6.39E-07	2.27E-07	1.5E-06	0.04	1.16	1.87E-07	1.3E-07	1.41E-07	340.63
3_1.1 0kg	4.75E-06	1.75E-06	6.23E-07	4.2E-06	0.04	1.16	5.13E-07	3.57E-07	3.85E-07	340.72
3_1.1 20kg	0	0	0	0	0.04	1.16	0	0	0	340.53
3_1.1 40kg	8.25E-08	2.71E-07	1.12E-07	2.4E-07	0.04	1.16	1.13E-07	1.14E-07	1.14E-07	340.67
3_1.1 60kg	0	0	0	0	0.04	1.16	0	0	0	340.70
3_1.1 80kg	0	0	0	0	0.04	1.16	0	0	0	340.78
3_1.1 100kg	0	0	0	0	0.04	1.16	0	0	0	340.75
3_3.3 0kg	0	0	0	0	0.04	1.16	0	0	0	340.66
3_3.3 20kg	2.84E-06	1.05E-06	3.73E-07	2.5E-06	0.04	1.16	3.07E-07	2.14E-07	2.31E-07	340.70
3_3.3 40kg	2.58E-09	3.92E-10	4.83E-10	1.2E-10	0.04	1.16	5.12E-10	5.1E-10	5.23E-10	340.42
3_3.3 60kg	0	0	0	0	0.04	1.16	0	0	0	340.61
3_3.3 80kg	0	0	0	0	0.04	1.16	0	0	0	340.57
3_3.3 100kg	2.24E-06	1.69E-06	1.48E-06	2.1E-06	0.04	1.16	1.46E-06	1.43E-06	1.44E-06	340.67

Table A32. (cont'd)

3_6.6 0kg	0	0	0	0	0.04	1.17	0	0	0	343.24
3_6.6 20kg	2.08E-09	1.03E-09	5.87E-10	2.4E-09	0.04	1.16	3.8E-08	2.63E-10	1.76E-10	340.82
3_6.6 40kg	0	0	0	0	0.04	1.16	0	0	0	340.66
3_6.6 60kg	0	0	0	0	0.04	1.16	0	0	0	340.68
3_6.6 80kg	0	0	2.08E-09	0	0.04	1.16	0	0	2.42E-09	340.64
3_6.6 100kg	0	0	0	0	0.04	1.16	0	0	0	340.60

Table A33. Thiès linear optimization recommended quantities (kg/person/day) and cost of food (CFA/person/day) for purchase to meet nutritional needs for each alternative scenario.

Alternative	Fish	Beef	Milk	Egg	Lettuce	Peanut	Rice	Maize	Millet	Cost
Baseline	7.61E-06	2.81E-06	9.97E-07	6.69E-06	0.04	1.36	8.22E-07	5.72E-07	6.17E-07	395.26
1_1.1 0kg	5.09E-06	1.88E-06	6.66E-07	4.48E-06	0.04	1.36	5.48E-07	3.81E-07	4.11E-07	395.23
1_1.1 20kg	0	0	0	0	0.04	1.36	0	0	0	395.15
1_1.1 40Kg	0	0	0	0	0.04	1.36	0	0	0	395.17
1_1.1 60kg	0	0	4.83E-07	0	0.04	1.36	0	0	0	395.17
1_1.1 80kg	1.4E-05	5.18E-06	1.84E-06	1.23E-05	0.04	1.36	1.51E-06	1.05E-06	1.13E-06	395.26
1_1.1 100kg	0	0	0	0	0.04	1.36	0	0	0	395.01
1_3.3 0kg	4.04E-07	2.99E-07	2.63E-07	3.83E-07	0.04	1.36	2.6E-07	2.55E-07	2.57E-07	395.12
1_3.3 20kg	0	0	0	0	0.04	1.36	0	0	0	395.07
1_3.3 40kg	2.49E-06	9.19E-07	3.26E-07	2.19E-06	0.04	1.36	2.69E-07	1.87E-07	5.98E-06	395.05
1_3.3 60kg	0	0	0	0	0.04	1.36	1.7E-06	2.98E-06	0	395.01
1_3.3 80kg	0	0	0	0	0.04	1.36	0	0	0	394.99
1_3.3 100kg	0	0	0	0	0.04	1.36	0	0	0	395.03
1_6.6 0kg	0	0	0	0	0.04	1.36	0	0	0	395.00
1_6.6 20kg	0	0	2.61E-06	0	0.04	1.36	6.26E-06	2.62E-06	1.04E-05	395.03
1_6.6 40kg	0	0	0	0	0.04	1.36	0	0	0	394.99
1_6.6 60kg	5.09E-07	1.89E-07	6.71E-08	4.5E-07	0.04	1.36	5.52E-08	3.84E-08	4.14E-08	395.03
1_6.6 80kg	0	0	0	0	0.04	1.36	0	0	0	395.01
1_6.6 100kg	2.98E-06	1.1E-06	3.9E-07	2.62E-06	0.04	1.36	3.22E-07	2.24E-07	2.42E-07	395.02
2_1.1 0kg	0	0	0	0	0.04	1.36	0	0	0	395.18
2_1.1 20kg	0	0	0	0	0.04	1.36	0	2.56E-05	0	395.16
2_1.1 40Kg	6.18E-06	2.28E-06	8.09E-07	5.44E-06	0.04	1.36	6.66E-07	4.62E-07	5E-07	395.21
2_1.1 60kg	2.85E-06	1.05E-06	3.74E-07	2.51E-06	0.04	1.36	3.09E-07	2.14E-07	2.32E-07	395.20
2_1.1 80kg	0	0	0	0	0.04	1.36	0	0	0	395.16

Table A33. (cont'd)

2_1.1 100kg	0	0	0	0	0.04	1.36	0	0	0	395.17
2_3.3 0kg	6.79E-07	5.11E-07	4.46E-07	6.45E-07	0.04	1.36	4.39E-07	4.34E-07	4.33E-07	395.15
2_3.3 20kg	0	0	0	0	0.04	1.36	0	0	0	395.07
2_3.3 40kg	0	0	0	0	0.04	1.36	0	0	0	395.05
2_3.3 60kg	0	0	0	0	0.04	1.36	0	0	0	395.00
2_3.3 80kg	0	0	0	0	0.04	1.36	0	0	0	394.89
2_3.3 100kg	6.32E-06	4.76E-06	1.32E-05	6.02E-06	0.04	1.36	1.27E-05	1.51E-05	1.5E-05	395.03
2_6.6 0kg	0	0	0	0	0.04	1.36	0	0	0	395.14
2_6.6 20kg	0	0	0	0	0.04	1.36	0	0	0	395.05
2_6.6 40kg	0	0	0	0	0.04	1.36	0	0	0	395.04
2_6.6 60kg	0	0	0	0	0.04	1.36	0	1.3E-09	0	394.99
2_6.6 80kg	0	0	0	0	0.04	1.36	0	0	0	394.95
2_6.6 100kg	0	0	0	0	0.04	1.36	0	0	0	394.93
3_1.1 0kg	0	0	0	0	0.04	1.36	0	0	0	395.03
3_1.1 20kg	0	0	0	0	0.04	1.36	0	0	0	394.86
3_1.1 40kg	0	0	0	0	0.04	1.36	0	0	0	394.99
3_1.1 60kg	0	0	0	0	0.04	1.36	0	0	0	395.08
3_1.1 80kg	0	0	0	0	0.04	1.36	0	0	0	395.08
3_1.1 100kg	0	0	0	0	0.04	1.36	0	0	0	395.01
3_3.3 0kg	0	0	0	0	0.04	1.36	0	0	0	395.00
3_3.3 20kg	0	0	0	0	0.04	1.36	0	5.74E-08	0	394.96
3_3.3 40kg	0	0	0	0	0.04	1.36	0	0	0	394.80
3_3.3 60kg	1.8E-07	2.62E-07	1.62E-07	3.03E-07	0.04	1.36	1.6E-07	1.61E-07	1.57E-07	394.98
3_3.3 80kg	0	0	0	0	0.04	1.36	0	0	0	394.90
3_3.3 100kg	6.64E-07	2.46E-07	8.72E-08	5.84E-07	0.04	1.36	7.17E-08	4.98E-08	5.39E-08	394.99
3_6.6 0kg	0	0	0	0	0.04	1.36	0	0	0	395.16

Table A33. (cont'd)

3_6.6 20kg	0	0	0	0	0.04	1.36	0	0	0	395.12
3_6.6 40kg	0	0	0	0	0.04	1.36	0	0	0	395.08
3_6.6 60kg	0	0	0	0	0.04	1.36	0	0	0	395.02
3_6.6 80kg	0	0	0	0	0.04	1.36	0	0	0	394.98
3_6.6 100kg	0	0	0	0	0.04	1.36	0	0	0	394.88

Table A34. Diourbel linear optimization final nutrition values.

Alternative	Calories	Protein	Fat	Calcium	Iron	Vitamin A
Baseline	9377.19	403.83	739.05	1.45	0.0707	0.0009
1_1.1 0kg	9375.53	403.79	739.05	1.45	0.0707	0.0009
1_1.1 20kg	9381.54	403.95	739.01	1.45	0.0708	0.0009
1_1.1 40kg	9381.65	403.95	739.01	1.45	0.0708	0.0009
1_1.1 60kg	9381.87	403.96	739.01	1.45	0.0708	0.0009
1_1.1 80kg	9382.13	403.96	739.01	1.45	0.0708	0.0009
1_1.1 100kg	9382.47	403.97	739.01	1.45	0.0708	0.0009
1_3.3 0kg	9400.58	404.45	738.88	1.45	0.0709	0.0009
1_3.3 20kg	9404.91	404.57	738.87	1.45	0.0709	0.0009
1_3.3 40kg	9408.56	404.66	738.85	1.45	0.0709	0.0009
1_3.3 60kg	9409.32	404.68	738.84	1.45	0.0709	0.0009
1_3.3 80kg	9413.99	404.81	738.83	1.45	0.0709	0.0009
1_3.3 100kg	9414.75	404.83	738.81	1.45	0.0709	0.0009
1_6.6 0kg	9409.50	404.69	738.85	1.45	0.0709	0.0009
1_6.6 20kg	9413.12	404.79	738.82	1.45	0.0709	0.0009
1_6.6 40kg	9416.90	404.88	738.80	1.45	0.0709	0.0009
1_6.6 60kg	9420.50	404.98	738.78	1.45	0.0709	0.0009
1_6.6 80kg	9422.01	405.02	738.77	1.45	0.0710	0.0009
1_6.6 100kg	9428.92	405.21	738.73	1.45	0.0710	0.0009
2_1.1 0kg	9387.88	404.11	738.97	1.45	0.0708	0.0009
2_1.1 20kg	9390.52	404.18	738.96	1.45	0.0708	0.0009
2_1.1 40kg	9389.35	404.15	738.97	1.45	0.0708	0.0009
2_1.1 60kg	9388.96	404.14	738.96	1.45	0.0708	0.0009
2_1.1 80kg	9390.39	404.18	738.97	1.45	0.0708	0.0009
2_1.1 100kg	9388.82	404.14	738.97	1.45	0.0708	0.0009

Table A34. (cont'd)

2_3.3 0kg	9400.23	404.45	738.92	1.45	0.0708	0.0009
2_3.3 20kg	9407.84	404.64	738.85	1.45	0.0709	0.0009
2_3.3 40kg	9416.00	404.86	738.81	1.45	0.0709	0.0009
2_3.3 60kg	9421.33	405.00	738.77	1.45	0.0710	0.0009
2_3.3 80kg	9423.43	405.06	738.77	1.45	0.0710	0.0009
2_3.3 100kg	9426.88	405.15	738.76	1.45	0.0710	0.0009
2_6.6 0kg	9406.06	404.60	738.86	1.45	0.0709	0.0009
2_6.6 20kg	9411.12	404.73	738.83	1.45	0.0709	0.0009
2_6.6 40kg	9420.11	404.97	738.78	1.45	0.0709	0.0009
2_6.6 60kg	9429.92	405.23	738.72	1.45	0.0710	0.0009
2_6.6 80kg	9433.57	405.33	738.70	1.45	0.0710	0.0009
2_6.6 100kg	9436.58	405.41	738.68	1.45	0.0710	0.0009
3_1.1 0kg	9419.63	404.96	738.79	1.45	0.0709	0.0009
3_1.1 20kg	9420.68	404.99	738.77	1.45	0.0709	0.0009
3_1.1 40kg	9422.56	405.04	738.77	1.45	0.0710	0.0009
3_1.1 60kg	9403.09	404.52	738.88	1.45	0.0709	0.0009
3_1.1 80kg	9410.04	404.70	738.84	1.45	0.0709	0.0009
3_1.1 100kg	9420.19	404.97	738.78	1.45	0.0709	0.0009
3_3.3 0kg	9427.27	405.16	738.73	1.45	0.0710	0.0009
3_3.3 20kg	9429.66	405.22	738.72	1.45	0.0710	0.0009
3_3.3 40kg	9432.66	405.30	738.70	1.45	0.0710	0.0009
3_3.3 60kg	9420.07	404.97	738.78	1.45	0.0709	0.0009
3_3.3 80kg	9426.79	405.15	738.74	1.45	0.0710	0.0009
3_3.3 100kg	9425.06	405.10	738.76	1.45	0.0710	0.0009
3_6.6 0kg	9398.45	404.40	738.91	1.45	0.0708	0.0009
3_6.6 20kg	9402.92	404.52	738.89	1.45	0.0709	0.0009

Table A34. (cont'd)

3_6.6 40kg	9412.46	404.77	738.82	1.45	0.0709	0.0009
3_6.6 60kg	9427.55	405.17	738.74	1.45	0.0710	0.0009
3_6.6 80kg	9435.87	405.39	738.69	1.45	0.0710	0.0009
3_6.6 100kg	9436.94	405.42	738.68	1.45	0.0710	0.0009

Table A35. Fatick linear optimization final nutrition values.

Alternative	Calories	Protein	Fat	Calcium	Iron	Vitamin A
Baseline	8515.58	358.14	643.89	1.45	0.0614	0.0009
1_1.1 0kg	8485.47	357.38	644.23	1.45	0.0613	0.0009
1_1.1 20kg	8498.72	357.73	644.15	1.45	0.0613	0.0009
1_1.1 40kg	8504.71	357.89	644.11	1.45	0.0613	0.0009
1_1.1 60kg	8504.72	357.89	644.11	1.45	0.0613	0.0009
1_1.1 80kg	8504.63	357.88	644.11	1.45	0.0613	0.0009
1_1.1 100kg	8502.59	357.83	644.13	1.45	0.0613	0.0009
1_3.3 0kg	8500.58	357.78	644.14	1.45	0.0613	0.0009
1_3.3 20kg	8488.55	357.46	644.21	1.45	0.0613	0.0009
1_3.3 40kg	8496.71	357.67	644.16	1.45	0.0613	0.0009
1_3.3 60kg	8505.48	357.91	644.11	1.45	0.0613	0.0009
1_3.3 80kg	8508.52	357.99	644.09	1.45	0.0614	0.0009
1_3.3 100kg	8514.15	358.14	644.06	1.45	0.0614	0.0009
1_6.6 0kg	8496.00	357.65	644.17	1.45	0.0613	0.0009
1_6.6 20kg	8496.30	357.66	644.16	1.45	0.0613	0.0009
1_6.6 40kg	8495.52	357.64	644.17	1.45	0.0613	0.0009
1_6.6 60kg	8499.98	357.76	644.14	1.45	0.0613	0.0009
1_6.6 80kg	8499.12	357.74	644.14	1.45	0.0613	0.0009
1_6.6 100kg	8501.13	357.79	644.13	1.45	0.0613	0.0009
2_1.1 0kg	8471.47	357.00	644.31	1.45	0.0612	0.0009
2_1.1 20kg	8466.87	356.88	644.32	1.45	0.0612	0.0009
2_1.1 40kg	8497.12	357.68	644.16	1.45	0.0613	0.0009
2_1.1 60kg	8504.24	357.87	644.12	1.45	0.0613	0.0009
2_1.1 80kg	8508.48	357.99	644.09	1.45	0.0614	0.0009
2_1.1 100kg	8510.35	358.04	644.08	1.45	0.0614	0.0009

Table A35. (cont'd)

2_3.3 0kg	8550.43	359.10	643.84	1.45	0.0616	0.0009
2_3.3 20kg	8545.95	358.98	643.87	1.45	0.0615	0.0009
2_3.3 40kg	8539.50	358.81	643.90	1.45	0.0615	0.0009
2_3.3 60kg	8523.97	358.40	644.00	1.45	0.0614	0.0009
2_3.3 80kg	8531.82	358.61	643.95	1.45	0.0615	0.0009
2_3.3 100kg	8532.45	358.62	643.95	1.45	0.0615	0.0009
2_6.6 0kg	8548.76	359.06	643.85	1.45	0.0616	0.0009
2_6.6 20kg	8551.34	359.13	643.84	1.45	0.0616	0.0009
2_6.6 40kg	8551.29	359.12	643.83	1.45	0.0616	0.0009
2_6.6 60kg	8542.92	358.90	643.88	1.45	0.0615	0.0009
2_6.6 80kg	8538.80	358.79	643.91	1.45	0.0615	0.0009
2_6.6 100kg	8536.14	358.72	643.92	1.45	0.0615	0.0009
3_1.1 0kg	8549.20	359.07	643.85	1.45	0.0616	0.0009
3_1.1 20kg	8546.53	359.00	643.86	1.45	0.0615	0.0009
3_1.1 40kg	8543.27	358.91	643.88	1.45	0.0615	0.0009
3_1.1 60kg	8496.30	357.66	644.16	1.45	0.0613	0.0009
3_1.1 80kg	8515.51	358.02	643.30	1.45	0.0614	0.0009
3_1.1 100kg	8548.59	359.05	643.84	1.45	0.0616	0.0009
3_3.3 0kg	8557.01	359.27	643.80	1.45	0.0616	0.0009
3_3.3 20kg	8559.55	359.34	643.78	1.45	0.0616	0.0009
3_3.3 40kg	8554.72	359.17	643.60	1.45	0.0616	0.0009
3_3.3 60kg	8482.77	357.30	644.24	1.45	0.0612	0.0009
3_3.3 80kg	8506.29	357.92	644.06	1.45	0.0613	0.0009
3_3.3 100kg	8513.39	358.12	644.06	1.45	0.0614	0.0009
3_6.6 0kg	8501.10	357.79	644.13	1.45	0.0613	0.0009
3_6.6 20kg	8505.06	357.90	644.11	1.45	0.0613	0.0009

Table A35. (cont'd)

3_6.6 40kg	8522.30	358.35	644.01	1.45	0.0614	0.0009
3_6.6 60kg	8567.17	359.55	643.74	1.45	0.0616	0.0009
3_6.6 80kg	8571.12	359.65	643.71	1.45	0.0617	0.0009
3_6.6 100kg	8577.95	359.83	643.67	1.45	0.0617	0.0009

Table A36. Kaffrine linear optimization final nutrition values.

Alternative	Calories	Protein	Fat	Calcium	Iron	Vitamin A
Baseline	9312.05	390.79	699.57	1.45	0.0676	0.0009
1_1.1 0kg	9274.44	389.79	699.80	1.45	0.0675	0.0009
1_1.1 20kg	9279.59	389.93	699.76	1.45	0.0675	0.0009
1_1.1 40kg	9287.48	390.14	699.72	1.45	0.0675	0.0009
1_1.1 60kg	9289.58	390.19	699.70	1.45	0.0675	0.0009
1_1.1 80kg	9276.33	389.58	698.52	1.45	0.0674	0.0009
1_1.1 100kg	9289.51	390.19	699.70	1.45	0.0675	0.0009
1_3.3 0kg	9297.92	390.41	699.66	1.45	0.0676	0.0009
1_3.3 20kg	9305.83	390.62	699.61	1.45	0.0676	0.0009
1_3.3 40kg	9317.33	390.93	699.54	1.45	0.0677	0.0009
1_3.3 60kg	9327.45	391.20	699.48	1.45	0.0677	0.0009
1_3.3 80kg	9333.55	391.36	699.44	1.45	0.0678	0.0009
1_3.3 100kg	9337.53	391.47	699.42	1.45	0.0678	0.0009
1_6.6 0kg	9299.30	390.45	699.65	1.45	0.0676	0.0009
1_6.6 20kg	9306.30	390.64	699.61	1.45	0.0676	0.0009
1_6.6 40kg	9319.27	390.98	699.53	1.45	0.0677	0.0009
1_6.6 60kg	9335.51	391.41	699.43	1.45	0.0678	0.0009
1_6.6 80kg	9348.51	391.76	699.36	1.45	0.0678	0.0009
1_6.6 100kg	9355.28	391.94	699.31	1.45	0.0679	0.0009
2_1.1 0kg	9270.07	389.67	699.82	1.45	0.0674	0.0009
2_1.1 20kg	9299.53	390.46	699.64	1.45	0.0676	0.0009
2_1.1 40kg	9291.79	390.25	699.69	1.45	0.0676	0.0009
2_1.1 60kg	9300.86	390.49	699.64	1.45	0.0676	0.0009
2_1.1 80kg	9300.86	390.49	699.64	1.45	0.0676	0.0009
2_1.1 100kg	9300.75	390.49	699.64	1.45	0.0676	0.0009

Table A36. (cont'd)

2_3.3 0kg	9311.71	390.78	699.57	1.45	0.0676	0.0009
2_3.3 20kg	9326.87	391.18	699.48	1.45	0.0677	0.0009
2_3.3 40kg	9342.56	391.60	699.39	1.45	0.0678	0.0009
2_3.3 60kg	9351.19	391.83	699.34	1.45	0.0678	0.0009
2_3.3 80kg	9356.17	391.96	699.30	1.45	0.0679	0.0009
2_3.3 100kg	9360.53	392.08	699.28	1.45	0.0679	0.0009
2_6.6 0kg	9316.35	390.90	699.54	1.45	0.0677	0.0009
2_6.6 20kg	9327.94	391.21	699.47	1.45	0.0677	0.0009
2_6.6 40kg	9345.61	391.68	699.37	1.45	0.0678	0.0009
2_6.6 60kg	9360.78	392.08	699.28	1.45	0.0679	0.0009
2_6.6 80kg	9373.08	392.41	699.21	1.45	0.0679	0.0009
2_6.6 100kg	9374.31	392.43	699.17	1.45	0.0679	0.0009
3_1.1 0kg	9350.43	391.81	699.34	1.45	0.0678	0.0009
3_1.1 20kg	9356.37	391.97	699.31	1.45	0.0679	0.0009
3_1.1 40kg	9357.22	391.99	699.30	1.45	0.0679	0.0009
3_1.1 60kg	9329.07	391.24	699.46	1.45	0.0677	0.0009
3_1.1 80kg	9342.06	391.59	699.39	1.45	0.0678	0.0009
3_1.1 100kg	9358.81	392.03	699.30	1.45	0.0679	0.0009
3_3.3 0kg	9365.65	392.21	699.25	1.45	0.0679	0.0009
3_3.3 20kg	9371.19	392.35	699.17	1.45	0.0679	0.0009
3_3.3 40kg	9376.01	392.49	699.19	1.45	0.0680	0.0009
3_3.3 60kg	9351.47	391.84	699.33	1.45	0.0678	0.0009
3_3.3 80kg	9358.73	392.03	699.29	1.45	0.0679	0.0009
3_3.3 100kg	9354.95	391.93	699.31	1.45	0.0679	0.0009
3_6.6 0kg	9307.01	390.66	699.60	1.45	0.0676	0.0009
3_6.6 20kg	9325.93	391.16	699.49	1.45	0.0677	0.0009

Table A36. (cont'd)

3_6.6 40kg	9341.24	391.56	699.40	1.45	0.0678	0.0009
3_6.6 60kg	9351.25	391.83	699.33	1.45	0.0678	0.0009
3_6.6 80kg	9357.62	392.00	699.30	1.45	0.0679	0.0009
3_6.6 100kg	9376.74	392.51	699.18	1.45	0.0680	0.0009

Table A37. Kaolack linear optimization final nutrition values.

Alternative	Calories	Protein	Fat	Calcium	Iron	Vitamin A
Baseline	9670.87	421.66	737.67	1.45	0.0735	0.0009
1_1.1 0kg	9652.00	421.16	737.78	1.45	0.0734	0.0009
1_1.1 20kg	9661.53	421.41	737.72	1.45	0.0735	0.0009
1_1.1 40kg	9664.07	421.48	737.71	1.45	0.0735	0.0009
1_1.1 60kg	9665.64	421.52	737.70	1.45	0.0735	0.0009
1_1.1 80kg	9666.00	421.53	737.70	1.45	0.0735	0.0009
1_1.1 100kg	9665.52	421.52	737.70	1.45	0.0735	0.0009
1_3.3 0kg	9650.34	421.12	737.79	1.45	0.0734	0.0009
1_3.3 20kg	9674.51	421.76	737.65	1.45	0.0735	0.0009
1_3.3 40kg	9701.19	422.47	737.49	1.45	0.0737	0.0009
1_3.3 60kg	9718.04	422.91	737.38	1.45	0.0737	0.0009
1_3.3 80kg	9729.43	423.22	737.32	1.45	0.0738	0.0009
1_3.3 100kg	9710.05	422.70	737.43	1.45	0.0737	0.0009
1_6.6 0kg	9680.10	421.91	737.62	1.45	0.0736	0.0009
1_6.6 20kg	9691.88	422.22	737.55	1.45	0.0736	0.0009
1_6.6 40kg	9703.37	422.52	737.47	1.45	0.0737	0.0009
1_6.6 60kg	9712.97	422.78	737.42	1.45	0.0737	0.0009
1_6.6 80kg	9719.30	422.95	737.38	1.45	0.0737	0.0009
1_6.6 100kg	9721.40	423.00	737.36	1.45	0.0738	0.0009
2_1.1 0kg	9668.74	421.61	737.68	1.45	0.0735	0.0009
2_1.1 20kg	9667.16	421.56	737.69	1.45	0.0735	0.0009
2_1.1 40kg	9666.79	421.55	737.70	1.45	0.0735	0.0009
2_1.1 60kg	9670.63	421.66	737.68	1.45	0.0735	0.0009
2_1.1 80kg	9668.10	421.59	737.69	1.45	0.0735	0.0009
2_1.1 100kg	9668.45	421.60	737.69	1.45	0.0735	0.0009

Table A37. (cont'd)

2_3.3 0kg	9692.46	422.24	737.54	1.45	0.0736	0.0009
2_3.3 20kg	9697.19	422.36	737.51	1.45	0.0736	0.0009
2_3.3 40kg	9700.29	422.37	737.13	1.45	0.0736	0.0009
2_3.3 60kg	9708.14	422.65	737.44	1.45	0.0737	0.0009
2_3.3 80kg	9702.25	422.50	737.49	1.45	0.0737	0.0009
2_3.3 100kg	9702.47	422.50	737.48	1.45	0.0737	0.0009
2_6.6 0kg	9687.20	422.10	737.57	1.45	0.0736	0.0009
2_6.6 20kg	9690.06	422.17	737.56	1.45	0.0736	0.0009
2_6.6 40kg	9709.23	422.68	737.45	1.45	0.0737	0.0009
2_6.6 60kg	9713.58	422.80	737.41	1.45	0.0737	0.0009
2_6.6 80kg	9713.50	422.80	737.43	1.45	0.0737	0.0009
2_6.6 100kg	9714.01	422.81	737.42	1.45	0.0737	0.0009
3_1.1 0kg	9696.52	422.34	737.51	1.45	0.0736	0.0009
3_1.1 20kg	9688.43	422.13	737.56	1.45	0.0736	0.0009
3_1.1 40kg	9690.16	422.17	737.55	1.45	0.0736	0.0009
3_1.1 60kg	9686.33	422.07	737.58	1.45	0.0736	0.0009
3_1.1 80kg	9696.85	422.35	737.52	1.45	0.0736	0.0009
3_1.1 100kg	9706.24	422.60	737.46	1.45	0.0737	0.0009
3_3.3 0kg	9702.93	422.51	737.48	1.45	0.0737	0.0009
3_3.3 20kg	9700.42	422.45	737.49	1.45	0.0737	0.0009
3_3.3 40kg	9701.86	422.49	737.48	1.45	0.0737	0.0009
3_3.3 60kg	9665.37	421.52	737.70	1.45	0.0735	0.0009
3_3.3 80kg	9675.06	421.77	737.65	1.45	0.0735	0.0009
3_3.3 100kg	9673.62	421.74	737.66	1.45	0.0735	0.0009
3_6.6 0kg	9678.57	421.87	737.62	1.45	0.0735	0.0009
3_6.6 20kg	9693.27	422.26	737.54	1.45	0.0736	0.0009

Table A37. (cont'd)

3_6.6 40kg	9698.94	422.41	737.50	1.45	0.0736	0.0009
3_6.6 60kg	9704.46	422.55	737.47	1.45	0.0737	0.0009
3_6.6 80kg	9710.97	422.73	737.43	1.45	0.0737	0.0009
3_6.6 100kg	9710.72	422.72	737.43	1.45	0.0737	0.0009

Table A38. Kolda linear optimization final nutrition values.

Alternative	Calories	Protein	Fat	Calcium	Iron	Vitamin A
Baseline	8696.21	359.98	710.97	1.45	0.0616	0.0009
1_1.1 0kg	8690.71	359.84	711.00	1.45	0.0616	0.0009
1_1.1 20kg	8692.71	359.89	710.99	1.45	0.0616	0.0009
1_1.1 40kg	8693.86	359.92	710.98	1.45	0.0616	0.0009
1_1.1 60kg	8693.48	359.91	710.98	1.45	0.0616	0.0009
1_1.1 80kg	8694.67	359.94	710.98	1.45	0.0616	0.0009
1_1.1 100kg	8695.24	359.96	710.97	1.45	0.0616	0.0009
1_3.3 0kg	8688.86	359.79	711.01	1.45	0.0616	0.0009
1_3.3 20kg	8700.76	360.10	710.94	1.45	0.0616	0.0009
1_3.3 40kg	8704.58	360.20	710.91	1.45	0.0616	0.0009
1_3.3 60kg	8707.72	360.29	710.90	1.45	0.0617	0.0009
1_3.3 80kg	8710.20	360.35	710.89	1.45	0.0617	0.0009
1_3.3 100kg	8710.24	360.36	710.88	1.45	0.0617	0.0009
1_6.6 0kg	8692.86	359.89	710.99	1.45	0.0616	0.0009
1_6.6 20kg	8698.38	360.04	710.95	1.45	0.0616	0.0009
1_6.6 40kg	8706.56	360.25	710.90	1.45	0.0617	0.0009
1_6.6 60kg	8708.59	360.31	710.89	1.45	0.0617	0.0009
1_6.6 80kg	8713.83	360.45	710.86	1.45	0.0617	0.0009
1_6.6 100kg	8715.73	360.50	710.85	1.45	0.0617	0.0009
2_1.1 0kg	8393.92	351.96	712.78	1.45	0.0602	0.0009
2_1.1 20kg	8692.88	359.89	710.99	1.45	0.0616	0.0009
2_1.1 40kg	8693.66	359.92	710.99	1.45	0.0616	0.0009
2_1.1 60kg	8693.53	359.91	710.98	1.45	0.0616	0.0009
2_1.1 80kg	8692.92	359.90	711.00	1.45	0.0616	0.0009
2_1.1 100kg	8692.84	359.89	710.99	1.45	0.0616	0.0009

Table A38. (cont'd)

2_3.3 0kg	8688.38	359.77	711.02	1.45	0.0616	0.0009
2_3.3 20kg	8698.51	360.04	710.95	1.45	0.0616	0.0009
2_3.3 40kg	8704.65	360.21	710.92	1.45	0.0616	0.0009
2_3.3 60kg	8707.87	360.29	710.90	1.45	0.0617	0.0009
2_3.3 80kg	8710.65	360.37	710.88	1.45	0.0617	0.0009
2_3.3 100kg	8711.50	360.39	710.88	1.45	0.0617	0.0009
2_6.6 0kg	8689.31	359.80	711.00	1.45	0.0616	0.0009
2_6.6 20kg	8694.18	359.93	710.98	1.45	0.0616	0.0009
2_6.6 40kg	8702.51	360.15	710.93	1.45	0.0616	0.0009
2_6.6 60kg	8708.43	360.31	710.89	1.45	0.0617	0.0009
2_6.6 80kg	8711.07	360.38	710.88	1.45	0.0617	0.0009
2_6.6 100kg	8715.84	360.50	710.85	1.45	0.0617	0.0009
3_1.1 0kg	8707.37	360.28	710.90	1.45	0.0617	0.0009
3_1.1 20kg	8707.78	360.29	710.90	1.45	0.0617	0.0009
3_1.1 40kg	8709.37	360.33	710.89	1.45	0.0617	0.0009
3_1.1 60kg	8692.09	359.87	710.99	1.45	0.0616	0.0009
3_1.1 80kg	8695.06	359.95	710.97	1.45	0.0616	0.0009
3_1.1 100kg	8699.92	360.08	710.94	1.45	0.0616	0.0009
3_3.3 0kg	8704.81	360.21	710.92	1.45	0.0616	0.0009
3_3.3 20kg	8708.47	360.31	710.89	1.45	0.0617	0.0009
3_3.3 40kg	8712.03	360.40	710.88	1.45	0.0617	0.0009
3_3.3 60kg	8708.85	360.32	710.89	1.45	0.0617	0.0009
3_3.3 80kg	8711.51	360.39	710.88	1.45	0.0617	0.0009
3_3.3 100kg	8711.94	360.40	710.87	1.45	0.0617	0.0009
3_6.6 0kg	8392.15	351.91	712.79	1.45	0.0602	0.0009
3_6.6 20kg	8691.76	359.86	710.99	1.45	0.0616	0.0009

Table A38. (cont'd)

3_6.6 40kg	8707.28	360.28	710.90	1.45	0.0617	0.0009
3_6.6 60kg	8707.46	360.28	710.90	1.45	0.0617	0.0009
3_6.6 80kg	8713.43	360.44	710.86	1.45	0.0617	0.0009
3_6.6 100kg	8713.88	360.45	710.86	1.45	0.0617	0.0009

Table A39. Thiès linear optimization final nutrition values.

Alternative	Calories	Protein	Fat	Calcium	Iron	Vitamin A
Baseline	9189.77	400.36	743.52	1.45	0.0703	0.0009
1_1.1 0kg	9191.06	400.39	743.51	1.45	0.0703	0.0009
1_1.1 20kg	9195.87	400.52	743.47	1.45	0.0703	0.0009
1_1.1 40kg	9195.43	400.50	743.48	1.45	0.0703	0.0009
1_1.1 60kg	9194.53	400.48	743.48	1.45	0.0703	0.0009
1_1.1 80kg	9194.44	400.48	743.49	1.45	0.0703	0.0009
1_1.1 100kg	9193.61	400.46	743.50	1.45	0.0703	0.0009
1_3.3 0kg	9200.22	400.63	743.45	1.45	0.0703	0.0009
1_3.3 20kg	9206.87	400.81	743.41	1.45	0.0704	0.0009
1_3.3 40kg	9209.03	400.87	743.40	1.45	0.0704	0.0009
1_3.3 60kg	9212.13	400.95	743.38	1.45	0.0704	0.0009
1_3.3 80kg	9212.90	400.97	743.38	1.45	0.0704	0.0009
1_3.3 100kg	9211.58	400.93	743.38	1.45	0.0704	0.0009
1_6.6 0kg	9197.87	400.57	743.48	1.45	0.0703	0.0009
1_6.6 20kg	9201.88	400.67	743.43	1.45	0.0703	0.0009
1_6.6 40kg	9208.65	400.86	743.40	1.45	0.0704	0.0009
1_6.6 60kg	9212.45	400.96	743.38	1.45	0.0704	0.0009
1_6.6 80kg	9214.59	401.01	743.36	1.45	0.0704	0.0009
1_6.6 100kg	9216.06	401.05	743.35	1.45	0.0704	0.0009
2_1.1 0kg	9189.95	400.36	743.51	1.45	0.0703	0.0009
2_1.1 20kg	9193.80	400.45	743.45	1.45	0.0703	0.0009
2_1.1 40kg	9195.09	400.50	743.48	1.45	0.0703	0.0009
2_1.1 60kg	9193.94	400.47	743.49	1.45	0.0703	0.0009
2_1.1 80kg	9195.78	400.51	743.48	1.45	0.0703	0.0009
2_1.1 100kg	9194.34	400.48	743.48	1.45	0.0703	0.0009

Table A39. (cont'd)

2_3.3 0kg	9197.75	400.57	743.46	1.45	0.0703	0.0009
2_3.3 20kg	9203.57	400.72	743.43	1.45	0.0704	0.0009
2_3.3 40kg	9209.70	400.88	743.39	1.45	0.0704	0.0009
2_3.3 60kg	9214.33	401.01	743.37	1.45	0.0704	0.0009
2_3.3 80kg	9218.00	401.10	743.34	1.45	0.0704	0.0009
2_3.3 100kg	9218.41	401.11	743.34	1.45	0.0704	0.0009
2_6.6 0kg	9197.52	400.56	743.46	1.45	0.0703	0.0009
2_6.6 20kg	9203.37	400.72	743.43	1.45	0.0704	0.0009
2_6.6 40kg	9210.65	400.91	743.39	1.45	0.0704	0.0009
2_6.6 60kg	9217.10	401.08	743.35	1.45	0.0704	0.0009
2_6.6 80kg	9221.71	401.20	743.32	1.45	0.0704	0.0009
2_6.6 100kg	9224.87	401.29	743.30	1.45	0.0705	0.0009
3_1.1 0kg	9211.85	400.94	743.38	1.45	0.0704	0.0009
3_1.1 20kg	9214.56	401.01	743.35	1.45	0.0704	0.0009
3_1.1 40kg	9215.92	401.05	743.35	1.45	0.0704	0.0009
3_1.1 60kg	9200.08	400.63	743.45	1.45	0.0703	0.0009
3_1.1 80kg	9202.29	400.69	743.44	1.45	0.0703	0.0009
3_1.1 100kg	9208.81	400.86	743.40	1.45	0.0704	0.0009
3_3.3 0kg	9215.83	401.05	743.35	1.45	0.0704	0.0009
3_3.3 20kg	9219.44	401.14	743.33	1.45	0.0704	0.0009
3_3.3 40kg	9222.64	401.23	743.33	1.45	0.0704	0.0009
3_3.3 60kg	9210.27	400.90	743.39	1.45	0.0704	0.0009
3_3.3 80kg	9215.05	401.03	743.37	1.45	0.0704	0.0009
3_3.3 100kg	9217.37	401.09	743.35	1.45	0.0704	0.0009
3_6.6 0kg	9194.92	400.49	743.48	1.45	0.0703	0.0009
3_6.6 20kg	9200.65	400.64	743.45	1.45	0.0703	0.0009

Table A39. (cont'd)

3_6.6 40kg	9205.72	400.78	743.41	1.45	0.0704	0.0009
3_6.6 60kg	9212.46	400.96	743.37	1.45	0.0704	0.0009
3_6.6 80kg	9218.58	401.12	743.34	1.45	0.0704	0.0009
3_6.6 100kg	9219.67	401.15	743.34	1.45	0.0704	0.0009

Table A40. Diourbel district ranking based on economic variables.

Scenario	Food Cost (CFA/year/household)	NPV (CFA)	EC (CFA)	NCFI (CFA)	IRR	Rank
3_3.3 40kg	1393382.99	40226628.73	22611458.55	6485933.68	9.3307	1
2_6.6 100kg	1325953.96	39890945	22052478.05	6374137.58	0.4542	2
2_6.6 80kg	1328238.01	39763041.84	21860426.09	6335727.19	0.9884	3
3_6.6 100kg	1326577.81	39654516.7	21669808.62	6297603.7	0.238	4
3_1.1 40kg	1386334.93	39572983.31	21606408.17	6284923.61	9.3426	5
1_6.6 100kg	1359871.53	39578403.55	21585225.71	6280687.12	0.1646	6
2_6.6 60kg	1386986.89	39528036.83	21499289.78	6263499.93	1.7895	7
3_6.6 80kg	1345029.37	39524533.02	21465651.5	6256772.27	0.7664	8
1_6.6 80kg	1342451.81	39431990.81	21381461.73	6239934.32	0.6586	9
1_6.6 60kg	1328701.04	39334423.03	21231778.37	6209997.65	1.5281	10
2_3.3 80kg	1326465.98	39283088.53	21135813.79	6190804.73	0.675	11
2_3.3 100kg	1329903.78	39264872.72	21090787.06	6181799.39	0.009	12
3_6.6 60kg	1326288.65	39200937.12	20983539.52	6160349.88	1.3612	13
3_3.3 80kg	1326358.02	39192413.38	20973410.55	6158324.08	0.5761	14
2_3.3 60kg	1326336.29	39146988.37	20925901.28	6148822.23	1.6027	15
2_6.6 40kg	1326555.00	39127168.91	20899815.9	6143605.15	3.8028	16
3_3.3 60kg	1387793.85	39103887.65	20862565.23	6136155.02	1.537	17
1_6.6 40kg	1374944.75	39056479.83	20800871.65	6123816.3	3.6088	18
2_3.3 40kg	1327691.68	38964989.4	20658333.15	6095308.6	4.8288	19
1_3.3 80kg	1326526.38	38923159.91	20600197.28	6083681.43	0.2089	20
1_3.3 60kg	1411578.63	38855517.52	20512716.62	6066185.3	1.1512	21
1_3.3 40kg	1327298.59	38803646.37	20432914.09	6050224.79	4.2365	22
3_6.6 40kg	1326610.88	38740107.95	20312253.77	6026092.73	2.7572	23
Baseline	1494788.72	37388600.3	18301686.06	5623979.19	0	24

Table A41. Fatick district ranking based on economic variables.

Scenario	Food Cost (CFA/year/household)	NPV (CFA)	EC (CFA)	NCFI (CFA)	IRR	Rank
3_6.6 100kg	1096956.93	63016071.71	44956103.44	10779367.84	0.3801	1
3_6.6 80kg	1097139.11	62915894.21	44826568.61	10753460.88	0.9555	2
3_3.3 40kg	1097454.32	62865876.32	44811813.89	10750509.93	7.4236	3
3_6.6 60kg	1097223.2	62655254.99	44425726.19	10673292.39	1.77	4
2_6.6 80kg	1098076.46	62262925.61	43926624.97	10573472.15	0.3735	5
2_6.6 60kg	1113956.51	62250644.31	43887495.73	10565646.3	1.3251	6
3_1.1 40kg	1132080.7	62176055.28	43765709.5	10541289.05	7.256	7
2_6.6 40kg	1097536.77	62140840.15	43671523.38	10522451.83	3.7034	8
3_6.6 40kg	1099295.42	61653511.02	43022262.64	10392599.68	2.7214	9
2_3.3 60kg	1350513	61571244.8	42882527.89	10364652.73	0.7555	10
2_3.3 40kg	1106388.36	61553257.75	42780540.22	10344255.2	3.5453	11
1_6.6 60kg	1099138.13	61456406.11	42809344.13	10350015.98	0.4253	12
1_6.6 40kg	1099603.38	61391789.21	42726351.03	10333417.36	2.1293	13
1_6.6 20kg	1102712.19	61226361.99	42456427.22	10279432.6	0.0597	14
3_6.6 20kg	1128948.91	60954969.51	41977913.9	10183729.94	0.1546	15
3_3.3 60kg	1103030.19	60901793.03	41996835.17	10187514.19	0.1194	16
1_3.3 20kg	1099199.16	60833517.1	41860175.26	10160182.21	0.0285	17
1_3.3 40kg	1143047.85	60850150.28	41848586.87	10157864.53	1.4394	18
1_3.3 60kg	1142076.71	60757957.98	41658830.05	10119913.17	0.0076	19
Baseline	1173435.04	60077795.43	40509113.15	9889969.784	0	20
2_1.1 20kg	1129143.18	59685751.29	40109797.26	9810106.607	0.3539	21
1_1.1 20kg	1193701.26	59735806.58	40044876.8	9797122.515	0.886	22

Table A42. Kaffrine district ranking based on economic variables.

Scenario	Food Cost (CFA/year/household)	NPV (CFA)	EC (CFA)	NCFI (CFA)	IRR	Rank
3_3.3 40kg	1201662.28	77558513.07	49640266.29	11783013.1	7.6725	1
2_6.6 100kg	1325214.41	76992018.87	48734022.26	11601764.29	0.0285	2
2_6.6 80kg	1201770	76879186.14	48559220.78	11566804	0.5267	3
3_6.6 100kg	1219158	76833396.79	48468931.97	11548746.23	0.0151	4
3_1.1 40kg	1203109.69	76661422.95	48277216.37	11510403.11	7.4203	5
1_6.6 80kg	1202905.5	76469902.64	48006955.05	11456350.85	0.1924	6
2_6.6 60kg	1201785.44	76451308.77	47923598.84	11439679.61	1.1046	7
3_6.6 80kg	1246418.87	76406023.93	47864088.11	11427777.46	0.1523	8
1_6.6 60kg	1203940.07	76169574.16	47579532.69	11370866.38	0.8241	9
2_3.3 80kg	1201930.01	76118842.77	47408189.83	11336597.81	0.0687	10
3_6.6 60kg	1223542.51	76019974.31	47269972.23	11308954.28	0.679	11
3_3.3 80kg	1202181.47	76036373.22	47264174.17	11307794.67	0.0239	12
2_3.3 60kg	1210592.34	75993617	47228260.08	11300611.86	0.9238	13
3_3.3 60kg	1211713.21	75907702.45	47088486.56	11272657.15	0.8292	14
2_6.6 40kg	1202238.77	75834848.81	46996687.01	11254297.24	2.3919	15
1_6.6 40kg	1202813.66	75693685.59	46883650.04	11231689.85	2.1352	16
2_3.3 40kg	1202446.63	75689794.75	46776476.14	11210255.07	3.1796	17
1_3.3 60kg	1206258.6	75632783.53	46749945.12	11204948.86	0.4704	18
1_3.3 40kg	1202910.73	75455133.13	46508085.47	11156576.93	2.6204	19
3_6.6 40kg	1213971.26	75448479.33	46393155.42	11133590.92	1.6963	20
Baseline	1210072.22	74014196.91	44210894.17	10697138.67	0	21

Table A43. Kaolack district ranking based on economic variables.

Scenario	Food Cost (CFA/year/household)	NPV (CFA)	EC (CFA)	NCFI (CFA)	IRR	Rank
3_3.3 40kg	1322778.87	44148161.27	19693649.91	5677262.15	5.8691	1
2_6.6 80kg	1323184.43	43948815.71	19324165.63	5603365.29	0.2635	2
3_6.6 80kg	1324625.44	43935411.57	19312861.2	5601104.4	0.2406	3
1_6.6 80kg	1324009.7	43827421.83	19103370.87	5559206.34	0.1691	4
2_6.6 60kg	1328363.96	43762705.59	19023589.33	5543250.03	0.999	5
1_6.6 60kg	1322221.77	43656500.33	18854938.58	5509519.88	0.883	6
3_6.6 60kg	1322429.75	43575998.34	18761679.27	5490868.02	0.7742	7
3_1.1 40kg	1322797.54	43435734.86	18595699.03	5457671.97	5.267	8
2_6.6 40kg	1324519.98	43395888.07	18451693.73	5428870.91	2.518	9
1_6.6 40kg	1325065.28	43328033.26	18366631.31	5411858.42	2.3861	10
2_3.3 60kg	1322348.58	43323761.98	18339592.85	5406450.73	0.7259	11
2_3.3 40kg	1322360.94	43208997	18171450.36	5372822.23	3.1668	12
1_3.3 60kg	1325990.19	43225309.83	18141586.59	5366849.48	0.56	13
1_3.3 40kg	1325561.84	43093855.97	17998907.96	5338313.76	2.844	14
3_6.6 40kg	1330315.26	43016468.05	17883326.95	5315197.55	1.7218	15
3_3.3 60kg	1323416.13	42884122.08	17811950.7	5300922.3	0.1813	16
Baseline	1323290.94	41813733.31	16065890.3	4951710.22	0	17

Table A44. Kolda district ranking based on economic variables.

Scenario	Food Cost (CFA/year/household)	NPV (CFA)	EC (CFA)	NCFI (CFA)	IRR	Rank
3_3.3 40kg	1165489.97	109751906.66	93735035.14	20948703.55	4.8091	1
3_1.1 40kg	1192917.14	109637319.84	93562925.83	20914281.68	5.6585	2
1_3.3 60kg	1164966.22	109426539.06	93231231.63	20847942.84	0.4521	3
1_3.3 40kg	1164894.73	109385388.00	93179739.61	20837644.44	2.755	4
2_3.3 60kg	1204961.79	109377293.02	93151477.76	20831992.07	0.2849	5
1_6.6 60kg	1168185.01	109322544.99	93059470.41	20813590.6	0.0357	6
2_3.3 40kg	1313767.58	109265534.65	92986902.17	20799076.95	2.0722	7
1_6.6 40kg	1166046.57	109180202.85	92839905.62	20769677.64	0.8949	8
3_6.6 40kg	1164842.26	109030881.79	92595963.89	20720889.3	0.2052	9
1_6.6 20kg	1165358.4	108972915.68	92544802.49	20710657.02	0.0052	10
2_6.6 40kg	1214133.06	108950150.14	92488640.76	20699424.67	0.0157	11
2_6.6 20kg	1165238.59	108741802.71	92192335.9	20640163.7	0.4046	12
Baseline	1165122.27	108738353.67	92177522.57	20637201.03	0	13
3_6.6 20kg	1165210.79	108633901.50	92030009.58	20607698.43	2.578	14

Table A45. Thiès district ranking based on economic variables.

Scenario	Food Cost (CFA/year/household)	NPV (CFA)	EC (CFA)	NCFI (CFA)	IRR	Rank
3_3.3 40kg	1350830.94	28709845.67	15496147.03	4872088.20	9.5280	1
2_6.6 100kg	1352052.19	28569172.53	15258204.67	4824499.73	0.5849	2
2_6.6 80kg	1440181.75	28448180.68	15078587.63	4788576.32	1.0591	3
3_1.1 40kg	1408955.88	28424420.06	15068195.72	4786497.94	10.3870	4
3_6.6 100kg	1350891.07	28426950.43	15054544.40	4783767.68	0.3694	5
1_6.6 100kg	1375124.85	28370596.04	14980825.85	4769023.96	0.2720	6
1_6.6 80kg	1351036.79	28316918.85	14901385.08	4753135.81	0.8428	7
3_6.6 80kg	1362005.91	28286748.56	14833622.50	4739583.30	0.8023	8
2_6.6 60kg	1350972.74	28251960.45	14784762.78	4729811.35	1.7629	9
1_6.6 60kg	1383190.49	28195798.49	14716677.63	4716194.32	1.6310	10
3_3.3 100kg	1412936.72	28190128.05	14683924.76	4709643.75	0.1148	11
2_3.3 100kg	1351339.67	28190296.54	14679593.37	4708777.47	0.1208	12
2_3.3 80kg	1455247.53	28185860.99	14673883.85	4707635.57	0.8067	13
3_3.3 80kg	1360390.92	28144281.49	14621685.17	4697195.83	0.7264	14
2_3.3 60kg	1360369.71	28090687.12	14538473.37	4680553.47	1.7402	15
3_3.3 60kg	1376169.47	28042308.45	14480246.82	4668908.16	1.6119	16
3_6.6 60kg	1351198.26	28042502.55	14469762.01	4666811.20	1.2948	17
1_3.3 80kg	1351221.52	28008508.05	14412977.95	4655454.39	0.4576	18
1_6.6 40kg	1431452.52	27990403.12	14404537.59	4653766.31	3.6390	19
2_6.6 40kg	1496833.34	27973454.02	14367294.73	4646317.74	3.5720	20
1_3.3 60kg	1449479.03	27971399.60	14356797.47	4644218.29	1.4413	21
2_3.3 40kg	1351402.13	27939579.68	14317367.47	4636332.29	4.9009	22
1_3.3 40kg	1396287.34	27882378.22	14228427.58	4618544.31	4.5586	23
3_6.6 40kg	1351970.54	27765593.95	14056228.13	4584104.42	2.6276	24
2_1.1 40Kg	1396359.68	27103903.18	13042169.01	4381292.60	0.0196	25
Baseline	1351652.40	26985801.18	12877455.58	4348349.91	0	26

Table A46. Diourbel district final ranking based on risk variables.

Scenario	CE	RP	Rank
3_3.3 40kg	4190343.6	591576.64	1
2_6.6 100kg	4091760.08	492993.12	2
2_6.6 80kg	4085607	486840.35	3
3_1.1 40kg	4069939.04	471171.79	4
2_6.6 60kg	4068251.68	469485.12	5
3_6.6 100kg	4055684.32	456917.75	6
3_6.6 80kg	4046016.8	447249.58	7
2_3.3 80kg	4006713.8	407946.27	8
2_3.3 60kg	4001534.32	402767.58	9
3_6.6 60kg	3999463.92	400697.07	10
2_6.6 40kg	3997119.88	398353.04	11
3_3.3 80kg	3996115.04	397348.48	12
2_3.3 100kg	3996069.08	397302.34	13
1_6.6 60kg	3984786.16	386019.11	14
3_3.3 60kg	3975135.48	376368.15	15
2_3.3 40kg	3974258.12	375490.78	16
1_6.6 100kg	3973476.76	374709.92	17
1_6.6 40kg	3962960.64	364193.71	18
1_6.6 80kg	3953483.76	354716.54	19
3_6.6 40kg	3915819.08	317051.74	20
1_3.3 40kg	3907193	308426.14	21
1_3.3 80kg	3881488.04	282721.21	22
1_3.3 60kg	3880390.76	281623.44	23
Baseline	3598766.84	0	24

Table A47. Fatick district final ranking based on risk variables.

Scenario	CE	RP	Rank
3_6.6 100kg	6991135.04	790514.64	1
3_6.6 80kg	6938326.92	737706.62	2
3_6.6 60kg	6919997.28	719377.77	3
3_3.3 40kg	6882705.52	682085.99	4
2_6.6 40kg	6773880.48	573260.18	5
2_6.6 60kg	6770481.84	569862.23	6
3_1.1 40kg	6756399.72	555780.1	7
2_6.6 80kg	6689886.08	489266.08	8
2_3.3 40kg	6616719	416099.19	9
2_3.3 60kg	6605756.68	405136.76	10
3_6.6 40kg	6575612.16	374991.85	11
1_6.6 40kg	6487183.72	286563.82	12
1_6.6 20kg	6481613.48	280993.36	13
1_6.6 60kg	6464893.12	264273.02	14
1_3.3 20kg	6401291.44	200671.34	15
3_6.6 20kg	6396734.48	196113.99	16
1_3.3 40kg	6390278.76	189659.02	17
3_3.3 60kg	6355260.24	154640.24	18
1_3.3 60kg	6349739.56	149119.27	19
Baseline	6200619.92	0	20

Table A48. Kaffrine district final ranking based on risk variables.

Scenario	CE	RP	Rank
3_3.3 40kg	7759951.56	1009024.1	1
2_6.6 100kg	7619787.68	868859.36	2
2_6.6 80kg	7590188.32	839260.47	3
3_6.6 100kg	7547916.24	796987.82	4
3_1.1 40kg	7533727.8	782799.47	5
1_6.6 80kg	7491229.4	740300.97	6
2_6.6 60kg	7480551.68	729623.43	7
3_6.6 80kg	7460792.04	709863.54	8
1_6.6 60kg	7418932.88	668004.47	9
2_3.3 80kg	7396210.8	645282.75	10
3_3.3 80kg	7365101.88	614173.15	11
2_3.3 60kg	7363936.16	613007.82	12
3_6.6 60kg	7359465.04	608536.43	13
3_3.3 60kg	7335356.2	584428.16	14
2_6.6 40kg	7320554.92	569627.18	15
1_6.6 40kg	7301248.4	550320.26	16
2_3.3 40kg	7284551	533623.15	17
1_3.3 60kg	7276526.28	525597.94	18
1_3.3 40kg	7235827.56	484899.61	19
3_6.6 40kg	7209066.84	458138.8	20
Baseline	6750928.44	0	21

Table A49. Kaolack district final ranking based on risk variables.

Scenario	CE	RP	Rank
3_3.3 40kg	3655706.48	704731.32	1
3_6.6 80kg	3600386.24	649411.58	2
2_6.6 80kg	3594130.12	643155.45	3
1_6.6 80kg	3539508.08	588532.93	4
2_6.6 60kg	3529758.48	578783.7	5
1_6.6 60kg	3488694.08	537719.01	6
3_6.6 60kg	3483395.68	532421	7
3_1.1 40kg	3438097.92	487123.43	8
2_6.6 40kg	3414600.92	463626.24	9
1_6.6 40kg	3392871.44	441896.78	10
2_3.3 60kg	3391162.36	440187.38	11
2_3.3 40kg	3356025.2	405050.34	12
1_3.3 60kg	3349865	398890.44	13
1_3.3 40kg	3318859.92	367885.13	14
3_6.6 40kg	3295062.32	344087.91	15
3_3.3 60kg	3293425.68	342451.01	16
Baseline	2950974.96	0	17

Table A50. Kolda district final ranking based on risk variables.

Scenario	CE	RP	Rank
3_3.3 40kg	13243823.68	317482.53	1
3_1.1 40kg	13211457.04	285116.57	2
1_3.3 60kg	13145219.80	218879.34	3
1_3.3 40kg	13132266.40	205925.38	4
2_3.3 60kg	13129920.64	203579.61	5
1_6.6 60kg	13104668.12	178327.46	6
2_3.3 40kg	13092556.04	166215.68	7
1_6.6 40kg	13058435.76	132094.71	8
3_6.6 40kg	13006872.36	80531.74	9
1_6.6 20kg	12997799.08	71458.42	10
2_6.6 40kg	12987074.92	60733.79	11
2_6.6 20kg	12926648.48	307.38	12
Baseline	12926340.84	0.00	13

Table A51. Thiès district final ranking based on risk variables.

Scenario	CE	RP	Rank
3_3.3 40kg	3232608.64	415105.28	1
2_6.6 100kg	3190115.36	372611.59	2
3_1.1 40kg	3183658.00	366155.10	3
2_6.6 80kg	3174940.80	357437.34	4
2_6.6 60kg	3143986.04	326482.30	5
3_6.6 100kg	3134385.28	316882.38	6
2_3.3 80kg	3132131.04	314628.13	7
3_6.6 80kg	3131505.24	314002.26	8
3_3.3 100kg	3126117.28	308613.80	9
3_3.3 80kg	3118687.20	301184.11	10
2_3.3 100kg	3117414.76	299911.12	11
1_6.6 80kg	3115234.88	297731.60	12
1_6.6 60kg	3112395.92	294892.85	13
2_3.3 60kg	3112311.40	294808.24	14
1_6.6 100kg	3106678.40	289175.41	15
3_6.6 60kg	3104450.36	286947.00	16
3_3.3 60kg	3086923.04	269419.48	17
1_6.6 40kg	3085029.04	267525.68	18
2_6.6 40kg	3082818.80	265315.42	19
2_3.3 40kg	3073501.92	255998.37	20
1_3.3 60kg	3071518.16	254014.32	21
1_3.3 80kg	3067203.12	249699.28	22
1_3.3 40kg	3051726.08	234223.20	23
3_6.6 40kg	3022280.96	204778.08	24
2_1.1 40Kg	2854557.00	37053.33	25
Baseline	2817503.28	0	26

Table A52. The overall ranking based on risk variables in the Groundnut Basin.

Scenario	Rank
3_3.3 40kg	1
2_6.6 100kg	2
2_6.6 80kg	3
3_1.1 40kg	4
2_6.6 60kg	5
3_6.6 100kg	6
3_6.6 80kg	7
2_3.3 80kg	8
2_3.3 60kg	9
3_6.6 60kg	10
2_6.6 40kg	11
3_3.3 80kg	12
2_3.3 100kg	13
1_6.6 60kg	14
3_3.3 60kg	15
2_3.3 40kg	16
1_6.6 100kg	17
1_6.6 40kg	18
1_6.6 80kg	19
3_6.6 40kg	20
1_3.3 40kg	21
1_3.3 80kg	22
1_3.3 60kg	23
Base	24