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FACULTY OF CIVIL AND GEO ENGINEERING

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Cattle corralling for improved soil fertility, maize production and for climate change resilience in the Sudano-Savanna area of Benin, West Africa

by

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(MPhil. Agronomy-Soil Science)

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DECLARATION

I, Awouminassi Marcellin ATAKOUN, hereby declare that this Ph.D. thesis is the result of my own original research. To the best of my knowledge, it contains no material previously published by others nor any material that has been submitted for the award of another degree at this university, except where due acknowledgment has been made.

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DEDICATION

This work is dedicated to

God,

my father, Mr. Lucien ATAKOUN (of blessed memory),

my mother, Leonie DOHOUHEHO (of blessed memory),

my wife Loukaiya ZOROBOURAGUI,

and my sisters and brothers

ABSTRACT

Cattle corralling is an essential traditional soil fertility management practice with potential for enhancing agricultural productivity and climate resilience in resource-constrained farming systems. This study aimed to investigate the socio-cultural and biophysical dimensions of cattle corralling in northern Benin and its implications for maize productivity under current and future climate scenarios. The research was structured around four objectives: (i) assess the socio-cultural benefits, constraints, and determinants of corralling-based strategies, (ii) evaluate the impact of traditional corralling on soil physical and chemical properties, (iii) assess the contribution of corralling to maize production under different water management systems, and (iv) model the effects of corralling under projected climate conditions. To achieve the first objective, a socio-economic survey was conducted among 392 smallholder farmers spanning three distinct agroecological zones in Benin. Descriptive statistics, factorial correspondence analysis (FCA), and binary logistic regression were employed to characterize corralling practices and identify adoption drivers. For the second objective, a field experiment assessed the impact of corralling on soil physical and chemical properties over time, using laboratory analysis of soil bulk density, hydraulic conductivity, macronutrient levels (N, P, K), and soil organic carbon (SOC). The third objective involved on-farm trials to evaluate maize growth, yield, water-use efficiency, and nutrient factor productivity under deficit and additional irrigation. Finally, for the fourth objective, the DSSAT crop simulation model was calibrated and validated to simulate the long-term impacts of cattle corralling on maize productivity under future climate scenarios (RCP 8.5). The results revealed that 71% of farmers adopted cattle corralling practices, with key determinants including agroecological zone, education level, access to credit, and extension services. Corralling improved soil fertility by reducing bulk density (up to 12%) and enhancing NPK and SOC levels (up to 25%). Maize yields increased significantly, with corralling and additional irrigation resulting in yield improvements of up to 55% compared to control plots. The crop model projections showed that corralling could sustain maize productivity under future climate conditions, with increased resilience to heat and water stress, contributing to soil carbon sequestration. This study underscores the relevance of cattle corralling as a sustainable land management strategy for enhancing soil health, crop productivity, and climate resilience. It provides critical insights for policymakers, extension agents, and researchers aiming to promote sustainable agriculture in the Sudano-Savanna region.

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BD: Bulk Density

CCLU: Climate Change and Land Use

CMIP6: Coupled Model Intercomparing Project Phase 6

DSSAT: Decision Support System for Agrotechnology Transfer

FAO: Food and Agriculture Organization

MAEP: Ministry of Agriculture, Livestock, and Fisheries

NPK: Nitrogen, Phosphorus, Potassium

RMSE: Root Mean Square Error

SLM: Sustainable Land Management

SOC: Soil Organic Carbon

SOM: Soil Organic Matter

SSP: Shared Socioeconomic Pathway

WASCAL: West African Science Service Center on Climate Change and Adapted Land Use

WUE: Water Use Efficiency

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CHAPTER 1: GENERAL INTRODUCTION

1.1 Background

Within the current state of demographic growth, climate change, and economic challenges, there is an increasing demand for food. Smallholders are responsible for producing most of the food consumed in sub-Saharan Africa (FAO, 2017) with 70 % being produced by women. Approximately 53 % of these smallholders are poor, and about 28 % suffer from undernourishment (Dawson et al., 2016). Climate change and climate variability pose a major challenge to agricultural production and rural livelihoods (Makate et al., 2018). This is because many of the smallholders relying on rainfed agriculture, are climate dependent and suffer low crop yields (Biazin et al., 2012). However; crop production strongly relies on soil fertility which is usually maintained by the addition of nutrients from external sources (Bisson et al., 2019a). In intensive high-yield agriculture, mineral fertilizers are used (Tilman et al., 2011). These inputs are not affordable to farmers because of their relatively high costs and may cause environmental hazards and health problems if not appropriately used (Kumar et al., 2019). Thus, for efficient agriculture, promoting environmental sustainability and respect, scientists endorse responsible ecological approaches, including the utilization of bioresources. The Figure 1.1 illustrates the possible interactions between livestock and soil productivity in mixed farming systems of the Sahel (Powell and Williams, 1993). This confirms the importance of livestock in agroecosystem. However, in traditional mixed farming systems, engaged by most smallholders in developing countries (FAO, 2011), the addition of fertilizers coming from external sources is usually too challenging (Dugué, 2015) and soil fertility is rather maintained by the addition of organic matter from animal manure (Manlay et al., 2004; Powell et al., 1996). Therefore, increasing crop production mostly relies on the optimization of agricultural practices, which are the driving forces of a proper functioning of agroecosystem (Bisson et al., 2019a). In the context of increasing demand for food and land use, challenges such as low soil fertility (Bationo et al., 2007), suboptimal agronomic practices (e.g., inadequate plant density and insufficient fertilizer application), and limited integration of crop-livestock systems for effective nutrient recycling persist as significant issues in West Africa and beyond (Abdul Rahman et al., 2019)

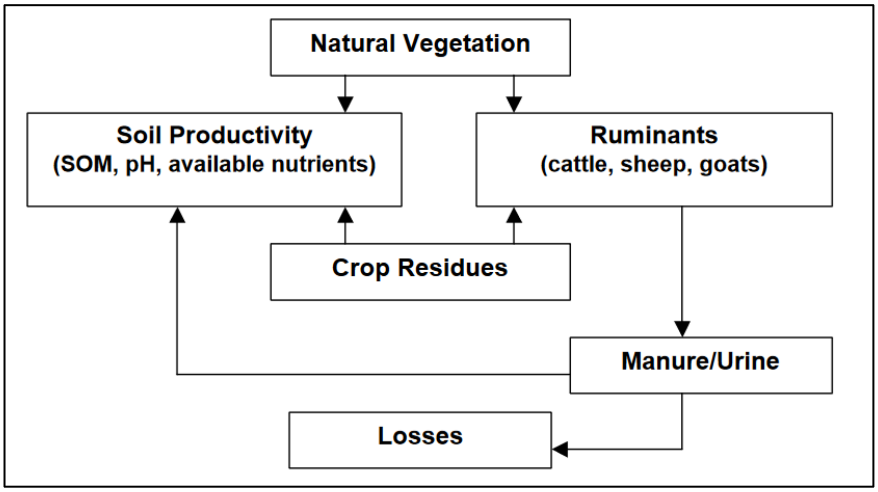


Figure 1.1 Ruminant-soil productivity linkages in mixed farming systems of the Sahel (Powell and Williams, 1993)

Maize (Zea mays L.) is a key cereal crop in West Africa, contributing over 20% to the region's gross domestic product (Bandyopadhyay et al., 2019). However, grain yields on farmers' fields remain low due to various biophysical and socio-economic challenges, such as inconsistent and low rainfall, poor soil fertility, and suboptimal agronomic practices (Zingore, 2023).

In Benin, maize serves as the primary staple food and the most widely cultivated crop. It holds a significant role in agricultural production systems across all agro-ecological zones of the country (Akossou et al., 2016). Approximately 85% of farmers in Benin grow maize (WFP, 2014), with nearly one-third of the country's harvested agricultural land dedicated to its production (Adeguelou et al., 2018). It accounts for approximately 82 % of total cereal land area and approximately 84 %

of cereal production (MAEP, 2017). Its average consumption is estimated to be 85 kg/year/inhabitant, but it can reach 100 kg/year/inhabitant in southern Benin's major urban centers, particularly Cotonou and Porto-Novo (PSDSA, 2017).

The Government of Benin has recognized maize as a strategic crop for intensive development, channelling significant resources, including financial and technical support, the introduction of modern technologies, and the provision of agricultural inputs, to advance this sector. As part of the strategic plan for strengthening the agricultural sector adopted in May 2017, the Government of Benin has promoted maize as one of the strategic crops for improving the livelihoods of smallholder farmers.

Despite its importance in the country, (for food security and the rural economy), maize yield has decreased (Figure 1.2) from 1.42 kg/ha in 2011 to 1.20 kg/ha in 2021 (FAOSTAT, 2021). Average maize yield in Benin remains relatively low, with current yields significantly below the potential achievable range of 3 to 5 t/ha. This gap is attributed to various factors, including limited access to inputs, insufficient capital, and weak institutional frameworks affecting farmers (Amegnaglo, 2018). Additionally, between 1996 and 2016, the United States Department of Agriculture (Bakoye et al., 2017) reported an annual increase of 5% in mean maize consumption in Benin. Thus, increasing maize productivity would be strategically important for improving national and domestic food security.

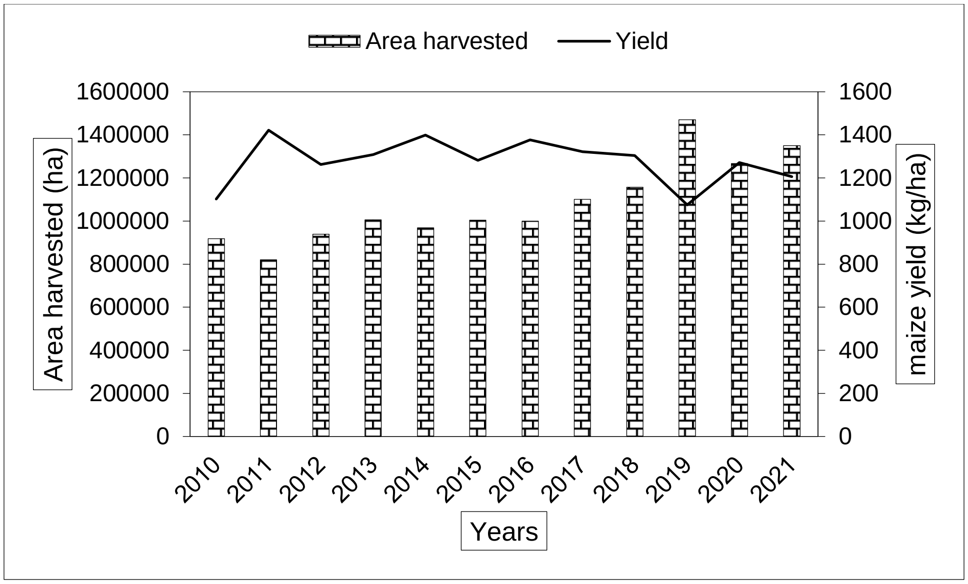


Figure 1.2. Maize yield (kg ha-1) and area harvested (ha) in Benin between 2010 and 2021 (Amegnaglo, 2018; FAOSTAT, 2021).

The need to improve the performance of agricultural production in Benin has become an emergency due to the rapid increase in population and thereby food demand. Several strategies have been suggested to enhance on-farm maize grain yields in small-scale crop-livestock farming systems. These include improved integration of crops and livestock to enhance nutrient cycling, such as corralling livestock on fallow lands before cropping (Schiere et al., 2006), increasing planting densities (Yu et al., 2019), and applying optimal nitrogen fertilizer rates (Abdul Rahman et al., 2019c). In the case of corralling, cows are tied to standing wooden sticks at night (Shinjo et al., 2008) to allow animal releasing their excreta. However, there is lack of empirical field results on the effect of corralling on maize grain yield (Abdul Rahman et al., 2019).

Figure 1.3 Livestock excreta corralled on cropland during the dry season by (Shinjo et al., 2008).

Although the characteristics of semi-arid climates limit soil organic carbon (SOC) storage, there is both an opportunity and a pressing need to enhance the quality and long-term stability of SOC in croplands within these agroecosystems. Reintegrating livestock into cropland presents a promising approach to improving the functionality of semi-arid agroecosystems by influencing biogeochemical processes and supporting multiple ecosystem services, including those related to carbon and nutrient cycling and their efficient utilization (Brewer et al., 2023; Brewer and Gaudin, 2020). In northern Benin, livestock management practices are centred on the collaboration between farmers and sedentary pastoralists to optimize the use of livestock excreta by employing corralling techniques, a traditional practice that is nowadays neglected in favour of mineral fertilization (Shinjo et al., 2008). However, smallholder farmers with low economic income hardly can afford to purchase mineral fertilizers in the context of the global economic crisis (Covid pandemic, and the Russia-Ukraine geopolitical war which limits mineral fertilizer production). Therefore, farmers need to adopt nature-based solutions driven by conservation agriculture, or sustainable crop-livestock integration, etc) to sustain crop productivity, for food security. Managing soil fertility through corralling practices represents a viable option in terms of carbon transfer, carbon sequestration, and resilience to climate change (Dupar, 2020; Mrunalini et al., 2022; Paul et al., 2023; Sharma et al., 2021).

1.2 Problem Statement

In the Sudano-Savanna region of Benin, West Africa, the challenge of maintaining and improving agricultural productivity amidst climate change and resource constraints is increasingly pressing. Smallholder farmers, who constitute a significant proportion of the agricultural sector, experience low crop yields mainly due to poor soil fertility, restricted access to inorganic fertilizers, and reliance on rain-fed agricultural practices. Maize, a crucial staple crop in Benin, suffers from declining yields despite its economic and food security importance. Efforts to increase maize production through the use/application of high-cost inorganic fertilizers are often unsustainable for smallholders, particularly within the context of economic instability driven by global crises (COVID-19 pandemic, geopolitical tensions affecting fertilizer availability).

An alternative, sustainable practice is cattle corralling, a traditional livestock management approach that enhances soil fertility through natural nutrient cycling, specifically via livestock excreta. Although livestock integration has shown promise in improving soil organic content and carbon sequestration, research on the full biophysical and socio-economic impacts of cattle corralling, especially on soil biological properties and maize productivity, remains limited in West Africa. Past studies have predominantly focused on smaller ruminants such as sheep and goats, leaving a critical gap in understanding the potential of cattle corralling for maize yield improvements and soil quality enhancement under changing climate conditions.

This research thus addresses this gap by investigating the implications of cattle corralling on soil health, maize productivity, and climate resilience. It seeks to assess the viability of cattle corralling as a soil amendment practice to enhance sustainable productivity, strengthen food security, and contribute to climate change mitigation in the region.

Previous studies on livestock corralling covered mostly issues on the effects of sheep and goat corralling on soil physicochemical properties, different types of corralling, and the contractual agreement between farmers and pastoralists in doing so. There is also paucity of data on the effect of cattle corralling on soil biological properties, maize productivity, and climate mitigation (Ikpe and Powell, 2002; Sangaré *et al*., 2002; Powell *et al*., 2004). This research intends to bridge the knowledge gap on cattle corralling and provide data on its full potential as a soil fertility amendment practice by small-scale crop-livestock farmers.

1.3 Research Objectives

This study aimed to investigate how and to what extent cattle corralling-based practices improve maize productivity, soil quality, and climate change effects mitigation. Specifically, the research sought to:

1. Assess the socio-economic benefits, constraints, and determinants of corralling-based strategies in northern Benin
2. Evaluate the biophysical impact of traditional cattle corralling practice on soil health in northern Benin
3. Assess the effect of cattle corralling on maize production under two water systems
4. Investigate how the implementation of cattle corralling-based methods affects maize yield within the context of anticipated shifts in rainfall patterns and temperature.

1.4 Research Questions

1. What are the existing corralling practices in the study areas and how do these affect productivity, biophysical, social, and economic trade-offs as perceived by various actors?
2. What is carbon, nitrogen, phosphorus, and potassium dynamics under traditional cattle corralling management practices?
3. To what extent do cattle corralling-based strategies affect maize growth and productivity under different water systems?
4. How does the DSSAT model project the effect of cattle corralling practice on maize productivity under future shifts in rainfall patterns and temperature?

1.5 Structure of the thesis report

The thesis is organized into seven chapters. Chapter one focuses on background of the study, statement of problem, research objectives, and research questions, the outlined assumptions and the significance of the study. Chapter two contains the literature review relevant to the study as well as the conceptual ramifications of the study which have been sectioned into relevant themes. Chapter three focuses on assessing the socio-cultural benefits, constraints, and determinants of corralling-based strategies in northern Benin. Chapter four involves the evaluation of traditional cattle corralling practice impact on soils health in northern Benin. Chapter five assesses the contribution of cattle corralling on maize production under deficit and additional irrigation in northern Benin. Chapter six focuses on modelling the effects of cattle corralling-based amendment on maize growth and development under future climate conditions. A summary of the key findings of the study, conclusions and recommendations are presented in chapter seven.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The Sudano-Savanna region of Benin, located in West Africa, is characterized by a semi-arid climate with a marked dry season and erratic rainfall patterns (Owusu et al., 2022). This agroecological zone is a transitional belt between the dry Sahel to the north and the more humid Guinean savannas to the south. The region's agricultural system is predominantly rain-fed, with subsistence farming centered on staple crops like maize, sorghum, and millet. Livestock farming, particularly cattle, is equally vital to the livelihoods of rural communities. However, the region faces significant agricultural challenges, including soil degradation, reduced rainfall, and the growing impacts of climate change, which threaten both crop yields and food security.

Cattle corralling, a traditional practice where livestock are confined to specific areas overnight, has gained attention as a sustainable agricultural technique for enhancing soil fertility (Powell et al., 2004). The manure deposited by cattle enriches the soil with organic matter, enhancing its structure, nutrient levels, and water retention capacity. This practice is particularly relevant for maize production, a key crop in Benin, as it requires fertile soils and consistent water availability. In the context of the Sudano-Savanna, where declining soil quality and unpredictable weather patterns are prevalent, cattle corralling presents a viable strategy for improving maize yields and promoting agricultural sustainability.

Moreover, with the increasing vulnerability of the region to climate change, manifesting in more frequent droughts and extreme weather events, there is a pressing need to explore farming systems that enhance resilience. Integrating cattle corralling into maize production systems offers potential benefits for both soil health and climate adaptation, helping farmers to sustain productivity under changing environmental conditions (Shinjo et al., 2008). Reviewing the literature on this topic is essential to understand the current state of knowledge, assess the efficacy of cattle corralling, and identify gaps that this thesis aimed to address.

2.2 Agroecological systems in the Sudano-Savanna Region

The Sudano-Savanna region of Benin is characterized by a semi-arid climate with distinct wet and dry seasons, where rainfall patterns are irregular and range from 600 to 1200 mm annually, often concentrated in a few months. The soils are predominantly ferruginous, with limited organic matter and nutrient content, which poses challenges for agriculture (Igué et al., 2004). Traditional farming systems in this region are predominantly subsistence-based, with staple crops including maize, sorghum, millet, and cowpea. Shifting cultivation and slash-and-burn techniques are commonly practiced, although these methods contribute to long-term soil degradation (Bationo et al., 2007). Land management practices have a significant impact on crop productivity in the Sudano-Savanna. Research has demonstrated that practices such as fallowing, manure application, and crop rotation can enhance soil fertility and boost crop yields (Saïdou et al., 2004). However, with increasing population pressure and reduced access to land, fallow periods have become shorter, leading to soil exhaustion. Modern interventions such as agroforestry, conservation agriculture, and the integration of livestock into cropping systems have been proposed as strategies to sustain productivity (Pretty et al., 2010). Research highlights that proper land management not only enhances soil structure and water retention but also mitigates the effects of erratic rainfall, which is crucial for maize production in this climate (Branca et al., 2013; Keesstra et al., 2018; Lal, 2000; Tefera and Sterk, 2010).

Cattle farming is an essential component of the agroecosystems in the Sudano-Savanna. Livestock, particularly cattle, play a dual role in providing food and manure, the latter being a key resource for maintaining soil fertility. Corralling cattle in fields after harvest allows for the deposition of manure, which enriches the soil with organic matter and nutrients, leading to improved crop yields (Hiernaux and Assouma, 2020). This practice is highly valued in the region, as it supports integrated crop-livestock systems, which are more resilient to climate variability. Studies suggest that such systems are more sustainable and productive compared to mono-cropping, especially in semi-arid environments.

2.3 Cattle corralling and soil fertility

Rainfall and soil fertility are the two main determinants of rainfed agriculture in the region of West Africa (Gandah et al., 2003a). According to Hoffmann et al., (2001) the major problems mentioned by the farmers in northwest Nigeria were soil fertility and scarcity of organic and inorganic fertilizers. Concerning soil fertility, livestock accounted for nearly 80% of C, N and P returns to the soil (Manlay et al., 2004).

The study of the carbon (C) cycle and associated nutrient dynamics in agro-ecosystems of the West African savanna (WAS) is of both local and global significance. This importance arises from (1) the heavy reliance of sustainable farming systems in the region on the integration of crop–livestock systems and fallowing practices to recycle on-site organic matter (OM) (Reicosky and Kassam, 2021), and (2) the dual role of farming systems as potential sources or sinks of atmospheric carbon (Manlay et al., 2002). Land degradation and organic matter loss are particularly pressing issues in tropical semi-arid regions, where the risk of desertification is high. These challenges are exacerbated by precipitation variability and temperature increases linked to global warming, which threaten ecosystem integrity. Without effective management, efforts to rehabilitate drylands and conserve organic matter could fail, especially in the face of projected average temperature rises of 1.4–5.8°C (Martius et al., 2001; Malhi et al., 2021; Srivastava, 2022).

In sub-Sahara Africa, traditional soil fertility management practices, particularly the use of manure, have significantly altered soil nutrient content in various ways. For instance, traditional corralling methods employed by Fulani farmers have been shown to enhance soil nutrient status (Eeswaran et al., 2022). According to Gandah et al., (2003), recent dry-season corralling has notably increased nitrogen (N) and phosphorus (P) levels in the top 0–0.10 m of the soil. Even four years after manure application, soil carbon, nitrogen, and pH remained elevated at depths of 0.10–0.40 m in the soil profile. Additionally, recent dry-season corralling resulted in an average grain yield of 1100 kg ha^{-1} under typical rainfall conditions (500 mm). However, adverse weather conditions, such as drought, diminished the impact of manure on grain and straw yields, particularly under very recent dry-season corralling management. The same authors recommended refining these traditional practices to enhance nutrient application efficiency and, consequently, achieve higher yields.

In the Sahel, common herd management practices, such as herding mode (shepherding or free-ranging), night grazing, watering, and corralling, reduce the time animals have to graze. By confining livestock on fields overnight after daytime grazing, faeces and urine (rich in nitrogen and phosphorus) are deposited onto croplands (Powell et al., 1996), leading to a net transfer of nutrients from rangelands and fallows to cultivated fields. Although corralling for manure collection is a vital soil amendment strategy, it limits night-time grazing, especially during the dry season (Eeswaran et al., 2022b; Hiernaux and Assouma, 2020). Hence, a conflict arises between allowing sufficient grazing time for adequate feed intake and enhancing soil fertility on arable land (Fernández-Rivera et al., 2005). In Soudano savanna area, manure application rates exceeding 10

Mg ha^{-1} per year have been documented in typical confined areas (corrals) measuring 10–20 meters in diameter near farmers' homesteads within croplands. In contrast, uncorralled manured fields typically receive an average application rate of 1.5 Mg ha^{-1} (Esse et al., 2001; Powell and Williams, 2022).

Despite significant nutrient losses caused by excessive manure accumulation in concentrated spots on croplands, labour constraints and the inconsistent availability of nomadic livestock often hinder farmers from adopting practices that distribute manure more evenly across their fields, making prolonged corralling on the same spot a common practice (Eeswaran et al., 2022b). Manual spreading of manure from permanent village corrals, unlike prolonged corralling practices, is most effective for maximizing nutrient uptake by plants when applied approximately four weeks after sowing (Asrat et al., 2018). Annual manure applications at rates of 2–3 Mg ha^{-1}, rather than large-scale "once-in-10-years" applications, could help reduce nutrient losses at the field level. Manure application is a proven yield-enhancing method, effectively recycling nutrients from crop residues within short field distances or transferring nutrients from rangelands to croplands (Esse et al., 2001). Additionally, Fernández-Rivera et al., (2005) demonstrated that combining mulching with the corralling of supplemented cattle improves soil chemical properties (e.g., NH_4-N and soil pH) compared to corralling alone. The combined effect of mulching and corralling significantly increased millet grain and stove yields, with enhancements of 67% and 50%, respectively, for supplemented cattle, compared to 30% and 26% for non-supplemented cattle (Fernández-Rivera et al., 2005).

According to Gandah et al., (2003) field corralling of cattle resulted in manure deposits ranging from 1.5 to 17 Mg ha^{-1} over confined sections of the fields. This practice led to a notable increase in millet grain yields, from 500 kg ha^{-1} in areas manured six or more years ago to 1100 kg ha^{-1} in recently manured areas (Gandah et al., 2003a). Materechera et Modiakgotla (2006) examined the quality of cattle manure resources in rural areas and found significant variations in nitrogen, phosphorus, moisture, and soil content between seasons and villages. In addition to seasonal weather differences, these variations were attributed to manure management practices, including feed quality, storage methods, and corralling techniques.

2.4 Maize production in the context of climate variability

Maize is a critical staple crop in Benin, playing a central role in food security, with the majority of farmers (85%) cultivating it, and it accounts for over 80% of the total cereal land area harvested (Akossou et al., 2016; Benjamin et al., 2024; Lihoussou and Limbourg, 2022). Despite its importance, maize yields remain low, with the average yield significantly below the potential (1.2 t/ha compared to 3–5 t/ha) due to several factors, including poor soil fertility, erratic rainfall, and inadequate access to inputs (Amegnaglo, 2018). Climate variability, especially increasing droughts and temperature fluctuations, exacerbates these challenges (Cook et al., 2018; Thornton et al., 2014). Drought stress during critical growth stages, such as flowering and grain filling, can lead to yield losses of up to 90% (Ammani et al., 2013). As climate change progresses, the effects are anticipated to worsen. For example, in Sub-Saharan Africa (SSA), maize yields are predicted to decrease by up to 20% due to rising temperatures and erratic precipitation patterns (Abera et al., 2018; Waha et al., 2013). In the Sudano-Sahelian region, warmer and drier projections are expected to result in median yield losses of 18% by mid-century (Roudier et al., 2011).

To counter these impacts, research has emphasized the importance of developing more resilient maize varieties and adopting sustainable farming practices. Improved germplasm with drought and heat tolerance, coupled with better agronomic management, has shown potential to mitigate yield reductions (Cairns et al., 2012). Simulation models like DSSAT and APSIM have been employed to assess planting dates and crop rotations. Studies indicate that delaying planting and incorporating nitrogen-fixing crops, such as *Sesbania*, can significantly improve maize yields and enhance water-use efficiency (Folberth et al., 2014; Waongo et al., 2015). However, socio-economic factors, such as land tenure, credit access, and extension services, remain critical to farmers' capacity to adopt climate-smart strategies. Addressing these considerations is essential to ensure the long-term sustainability of maize production under changing climate conditions (Yegbemey et al., 2014).

2.5 Climate change resilience through integrated livestock-crop systems

Integrated livestock-crop systems have proven essential in building resilience to climate change, particularly in semi-arid regions like the Sudano-Savanna of Benin (Ayantunde et al., 2020; Tovihoudji et al., 2023). Studies highlight the mutual benefits of integrating livestock into crop systems, as this practice optimizes nutrient cycling and soil health, thereby enhancing the ability of farms to withstand climatic shocks. In West Africa, traditional practices such as corralling cattle on farmlands have improved soil fertility, increased maize yields, and contributed to carbon sequestration, which mitigates climate change impacts (Gandah et al., 2003a; Manlay et al., 2004). These systems buffer against erratic rainfall and rising temperatures by enhancing soil water retention, increasing organic matter, and providing nutrients essential for plant growth (Materechera and Modiakgotla, 2006).

Cattle corralling directly enhances climate resilience by depositing manure that is rich in nitrogen, phosphorus, and other nutrients, thereby improving soil structure, fertility, and water-holding capacity (Powell et al., 1996). This is especially advantageous in drought-prone areas, where preserving soil moisture is crucial for crop survival. Corralling, when practiced during the dry season, also transfers nutrients from rangelands to farmlands, promoting better crop performance

(Powell et al., 1996). However, careful management is required to prevent nutrient loss and soil compaction, which can diminish the long-term benefits (Fernández-Rivera et al., 2005).

Successful models of integrated livestock-crop systems are evident in Mali and Niger, where community agreements between farmers and pastoralists facilitate nutrient transfers through manure contracts (Diarisso et al., 2015; Kasse, 2019; Shinjo, 2017). These systems, when improved with better manure management and mulching techniques, have shown increased yields and enhanced resilience to climate variability (Diogo et al., 2021; Sangaré et al., 2002). These examples underscore the potential for such systems to be adapted across similar climatic zones to promote sustainable agricultural intensification and climate resilience.

2.6 Challenges and opportunities for sustainable agriculture in the Sudano-Savanna

Sustainable agriculture in the Sudano-Savanna region faces multiple challenges, including land degradation, population pressure, and socio-economic constraints. Land degradation, often driven by soil fertility depletion and desertification, is a major issue as the region experiences low and erratic rainfall (Bationo et al., 2007). Population pressure exacerbates these issues, as smallholder farmers are forced to cultivate smaller plots with diminishing soil fertility, often without access to chemical fertilizers, which remain too costly for most (Manlay et al., 2004). Socio-economic factors, such as limited access to credit, inadequate extension services, and poor infrastructure, further impede the adoption of sustainable farming practices (Yegbemey et al., 2017). Climate variability, including increased drought frequency, puts further strain on agricultural systems, reducing crop yields and threatening food security (Yegbemey et al., 2013).

Despite these challenges, there are significant opportunities for improving sustainability and resilience in the Sudano-Savanna. Scaling up cattle corralling practices offers a viable solution for enhancing soil fertility through organic manure application, which improves nutrient cycling and boosts maize yields. Studies have shown that corralling can increase nitrogen, phosphorus, and carbon levels in the soil, leading to better water retention and soil structure (Gandah et al., 2003a). Additionally, integrating livestock with crop production not only enhances soil fertility but also provides resilience against climate shocks, as livestock can serve as a buffer during periods of drought (Peterson et al., 2020). Encouraging the use of manure-based fertilization over chemical inputs can also mitigate socio-economic barriers, making sustainable practices more accessible to smallholders. Promoting these nature-based solutions, alongside improved management practices such as rotational grazing and enhanced corralling methods, could significantly improve productivity and climate resilience in the region.

2.7 Research gaps and future directions

While cattle corralling has been extensively studied as a traditional soil fertility practice, significant research gaps remain, particularly regarding its long-term sustainability and broader application in maize production under changing climatic conditions. One key area requiring further investigation is the long-term effect of corralling on soil biological properties and maize productivity. Existing research predominantly focuses on chemical and physical soil properties, while little is known about how corralling influences soil microbial activity and biodiversity, which are crucial for sustainable soil health (Ikpe and Powell, 2002). Additionally, there is a lack of data on how varying corralling intensities and durations influence nutrient cycling, particularly the balance of carbon (C), nitrogen (N), and phosphorus (P), which are crucial for maintaining crop yields under changing climate conditions (Manlay et al., 2004).

Moreover, the socio-economic factors influencing the adoption of corralling practices need further exploration. While corralling is a low-cost alternative to expensive fertilizers, labour constraints, land tenure issues, and the erratic availability of livestock pose barriers to widespread adoption, especially among smallholder farmers (Powell et al., 1996). Understanding these socio-economic dynamics, particularly how they influence farmers' decision-making in different environmental contexts, is critical for scaling up the practice effectively (Materechera and Modiakgotla, 2006).

Another research gap lies in the impact of climate change on the efficacy of corralling. While studies show that corralling improves soil fertility under current conditions, it is less clear how rising temperatures and erratic rainfall patterns will affect its long-term benefits (Waongo et al., 2015). Research that integrates climate models to simulate future scenarios of maize production with cattle corralling is necessary to identify sustainable adaptations for resilient agricultural systems in the Sudano-Savanna region.

CHAPTER 3: ASSESSING THE SOCIO-ECONOMIC BENEFITS, CONSTRAINTS, AND DETERMINANTS OF CORRALLING-BASED STRATEGIES IN NORTHERN BENIN

Manuscript: Characterizing cattle corralling practices systems for sustainable soil fertility management in northern Benin; A. M. Atakoun, P. G. Tovihoudji, R. V. C. Diogo, W. Amponsah, M. dos Santos Vianna, T. Gaiser, N. Kyei-Bafour, B. Kyereh

ABSTRACT

In the context of climate change and limited access to agricultural inputs, particularly expensive mineral fertilizers, cattle corralling has emerged as a viable alternative for improving soil organic matter and productivity in West Africa. However, further research is required for its sustainable management. This study assessed the benefits, challenges, and factors influencing the adoption of cattle corralling in maize-based farming systems in northern Benin. Data were collected through surveys from 392 smallholder farmers across three agroecological zones. Descriptive statistics, factorial analysis of correspondence (FAC), and ascending hierarchical classification (AHC) were used to analyze cattle corralling typologies, while a binary logistic regression model examined adoption drivers. The results showed that 89% of farmers are familiar with the practice, and 71% have adopted it. Constraints include herd security (44%), water availability (33%), forage availability (27%), and cattle herd ownership (50%). The AHC identified three corralling types: continuous overnight-rotational corralling (CORC), discontinuous overnight-rotational corralling (DORC), and corralling contract (CC). Key adoption factors include agroecological zone, education, ethnicity, access to credit and extension services, field-house distance, breeding strategy, and production objectives. These findings enhance understanding of corralling typologies and socioeconomic drivers, crucial for scaling up sustainable cattle corralling practices in Benin and West Africa.

Keywords: Sustainable Land Management (SLM), Manure Management, Crop-Livestock Integration (CLI), Typology, West Africa

3.1 Introduction

Climate change has emerged as one of the most significant challenges for agricultural sector, particularly in sub-Saharan Africa, where small-scale crop-livestock farming systems predominate (Din et al., 2022; Pörtner et al., 2022; Newell and Taylor, 2018). These systems are particularly vulnerable to adverse consequences of climate change due to their dependence on rainfed agriculture and limited access to infrastructure and resources (Lewis et al., 2018;). The impacts on farming systems include increasing temperatures, changes in growing seasons, soil degradation, and increased climate variability, all of which pose considerable challenges to agricultural productivity and rural livelihoods (Lunyolo et al., 2021; McCarthy et al., 2011).

Among these challenges, the significance of soil and land management in mitigating climate change is increasingly gaining attention (Rahman, 2023). Many studies support that climate is a critical factor that influences soil degradation, leaching, and fertility (Radulov et al., 2023; Rohith, 2023; Vanlauwe et al., 2023, Sharma et al., 2021). Shifts in temperature and rainfall patterns cause soil erosion, nutrient depletion, and compaction, which ultimately diminish soil fertility (Mondal, 2021; Aleminew and Alemayehu, 2020; Yerlikaya et al., 2020; Lal, 2012;).

Adopting climate-smart soil and land management practices is not only essential for food security and agricultural sustainability but also holds the key to combating climate change and its far-reaching consequences (Rahman, 2023). In response to this, there has been a growing interest in adopting environmental-friendly innovations such as conservation agriculture, rainwater harvesting, and the adoption of seed varieties that are drought tolerant, and early maturing for improving agricultural productivity (Patgiri et al., 2023). One such innovation gaining traction in small-scale crop-livestock farming systems in northern Benin is cattle corralling, recognized as an effective soil fertility management strategy (Tovihoudji et al., 2024, 2023; Powell et al., 2004; Buerkert and Hiernaux, 1998).

Cattle corralling entails confining livestock overnight on fallow fields between cropping seasons, ensuring that their manure and urine are deposited back into the soil (Ayantunde et al., 2020; Fernández-Rivera et al., 2005). By doing so, it enhances soil chemical properties, thereby augmenting crop yields. However, while cattle corralling offers economic, social, and environmental benefits, it also presents certain threats to the environment (Abdul Rahman et al., 2019b) if not well-managed by smallholders. The accumulation of manure in specific areas may lead to localized nutrient imbalances and potential water pollution concerns (Sharara et al., 2022; Sakadevan and Nguyen, 2017; Diogo et al., 2010; Shigaki et al., 2006). To ensure the sustainable adoption of cattle corralling practices, it is imperative to conduct comprehensive studies that not only guarantee economic and social well-being of small-holder farmers but also mitigate potential environmental issues, both in the present and future agricultural landscapes (Ichinose et al., 2020). Several studies have investigated various aspects of cattle corralling, focusing on factors such as its impact on soil fertility, crop productivity, and livestock management practices (Galindo et al., 2020; Ayantunde et al., 2018; Shinjo, 2017). Abdul Rahman et al. (2019) found that cattle corralling can enhance soil chemical and biological properties, weed diversity, and grain yield, especially when integrated with complementary measures like higher plant density and nitrogen fertilizer application. Furthermore, when integrated with multi-crop rotation, it can enhance soil productivity and increase beef cattle and crop economic yield (Şentürklü et al., 2016). These studies have explored response variables such as soil nutrient levels, crop yields, and livestock health indicators. It can lead to soil compaction and reduced water infiltration when not homogeneous performed in the field (Botta et al., 2020; Liu et al., 2012). While some findings have highlighted improvement of crop yields under corralling, there are still more aspects to explore for its sustainability. To the best of our knowledge, no studies have explored the sociocultural determinants of cattle corralling adoption and provide a comprehensive understanding of its environmental implications. As such, there remains a gap in the literature necessitating further investigation, which our study aims to address.

With the intensifying effects of climate change on agricultural systems (Alotaibi et al., 2023; Rahman, 2023; Callo-Concha, 2018), the implementation of climate-smart practices such as cattle corralling becomes ever more critical (Patgiri et al., 2023; Tully et al., 2015; Sanchez et al., 2012). Therefore, understanding the role of cattle corralling in mitigating these challenges and fostering agricultural resilience is paramount. Studies have shown that farm management characterization is crucial for effective policy implementation and extension services in complex agroecosystems (Mohammadi et al., 2020; Goswami et al., 2014). Multivariate statistical methods, such as Principal Component Analysis and Cluster Analysis, have been employed to identify and characterize predominant farm types, which differ in their income sources, farming practices, and resource bases (Goswami et al., 2014). This approach simplifies the diversity of farm types, enabling precise technological interventions and informed policy support. A two-scale approach, integrating both field and farm-level data independently, can provide a more comprehensive understanding of farmers' practices and decision-making processes (Michels et al., 2009). Such characterization methods can serve as decision-support tools for extension agencies, leading to reduced transaction costs in agricultural research and extension systems (Goswami et al., 2014). By elucidating the socio-economic and environmental dimensions of cattle corralling practices, this study seeks to contribute valuable insights into climate-smart agricultural strategies, with the implications for sustainable development and adaptation to future climatic conditions (Ayala et al., 2024).

The aim of this study was to characterize the main types of cattle corralling as a soil fertility management strategy and to identify the factors influencing its adoption in northern Benin. Beyond the local context, our findings provide meaningful guidance for policymakers, researchers, and agricultural practitioners working to strengthen the resilience of small-scale farming systems in the face of climate change.

3.2 Materials and methods

3.2.1. Study area

This study was carried out in three municipalities located in three different agro-ecological zones in northern Benin. These municipalities are Malanville (zone 1), Gogounou (zone 2), and Bembereke (zone 3, Table 3.1). The selection of these zones is based on their heavy reliance on agriculture and livestock farming as primary livelihood activities (Alkoiret et al., 2011). Moreover, climate studies show that these areas are particularly susceptible to rainfall deficits and high levels of solar radiation (Idrissou et al., 2020; Gnanglè et al., 2011).

Table 3.1. Characteristics of the study zones

Features	**Municipalities**		
	Malanville	**Gogounou**	**Bembereke**
Geographical coordinates	11° 52′ 00″ north, 3° 23′ 00″ east	10° 50′ 35″ north, 2° 49′ 42″ east	10°13′ 30″ north, 2° 40′ 05″ east
Altitude (m)	160	305	449
Climate based on Köppen-Geiger classification (Beck et al., 2023)	Aw (Tropical Savannah)	Aw (Tropical Savannah)	Aw (Tropical Savannah)
Rainfall	750 mm per year	1100 mm per year	1100 mm per year
Types of soil and their characteristics	Gneissic type for the most part on the territory, but in the Niger valley and its affluent, sandy-clay, ferruginous soils are encountered.	Soils are tropical ferruginous, moderately fertile, and highly leachable	The main soil types are ferruginous tropical.
Types of vegetation	Wooded savannas where herbaceous formations predominate	wooded savannah dominated by shrubs by Butyrospermum parkii (Shea)	The well-diversified vegetation is made up of wooded, tree, and shrub savannahs with open forests in places

Source: INSAE, (2023)

3.2.2 Data collection

The collection of primary data was carried out from April to May 2023 in two phases: the exploratory phase and the in-depth phase. The exploratory phase was carried out in two stages: interviews with local technicians and identification of households. Semi-structured interviews were first conducted with local technicians to identify villages for the survey, using accessibility and the presence of cattle corralling as key selection criteria. During the subsequent in-depth survey phase, data were collected through semi-structured questionnaires and interviews with the farmers identified in the exploratory phase. The data collection focused on three (3) main areas: a) socio-demographic characteristics of herders (gender, age, ethnicity, household size, farm labour availability, educational level, and contact with agricultural extension services), b) farming characteristics and production objectives, and c) cattle corralling management practices. At the household level, adopters and non-adopters of cattle corralling were sampled in the same or adjacent district whenever possible, as described by Gil et al., (2015). A household in this study context consists of all members who work together in a field, pool resources, share meals, and recognize the authority of a single head (West, 2013). In total, the survey included 392 respondents. This number is determined by using the Danieli (1998) approach (Equation 1). The distribution of the respondent across the study area has been shown in Table 3.2. The snowballing method has been used to select randomly the respondents (Kubiciel-Lodzińska, 2021). The data were collected from the households using a structured questionnaire built under KoboCollect software (version 2023.1.3), digitized on a smartphone tablet, and administered through direct interview.

Danieli's formula: $n = \frac{z^2 p(1-p)N}{z^2 p(1-p)+(N-1)ET^2}$ (1)

Where ***n*** *is the sample size,* ***N*** *is the actual population size (N=117523),* ***ET*** *is the tolerable standard error (margin of error) for the survey (ET = 0.05),* ***Z*** *is the standard normal value of the confidence interval (Z ≈ 1.96),* ***p*** *is the proportion of farm households in the study areas (p=0.72)* (INSAE, 2023).

Table 3.2. Respondents distribution across the three selected municipalities

Municipalities	Agroecological zone	Administrative unit	Number of respondents
Malanville	Zone 1 (South Borgou food zone)	Guéné	46
		Tomboutou	49
		Garou	44
Gogounou	Zone 2 (Cotton zone of North Benin)	Gounarou	36
		Sori	36
		Bagou	37
Bembereke	Zone 3 (South Borgou food zone)	Bouanri	48
		Ina	51
		Beroubouay	45
Total			392

3.2.3 Theoretical framework

Our study is supported by many theories described as following. The Diffusion of Innovations Theory proposed by Rogers, Singhal, and Quinlan (2008) provides a framework for understanding how, why, and at what rate new agricultural practices, such as cattle corralling, are adopted within a community. This theory is particularly relevant to the study as it helps to identify the characteristics of farmers who are innovators and early adopters of cattle corralling practices in northern Benin (Diederen et al., 2003; Agarwal et al., 1998). By analyzing social networks, communication channels, and cultural values, the theory elucidates how information about cattle corralling spreads among farmers (Valente and Fosados, 2006). Also, the agroecological theory emphasizes the application of ecological principles to agricultural systems, promoting sustainability and resilience (Altieri, 1989). This theory is essential for evaluating how cattle corralling practices mimic natural processes, such as nutrient cycling through manure, which enhances soil fertility. By integrating cattle corralling into agroecological practices, farmers can improve soil health and biodiversity. In addition to the previous theories, the systems theory comes here to focus on the interdependence and interactions within a system, whether biological, social, or ecological (van der Werf et al., 2014; Von Bertalanffy, 1972). Applying this theory to cattle corralling practices involves considering the broader context of the farming system, including interactions with crop production, labour dynamics, and market conditions. Systems theory helps to identify positive and negative feedback loops that influence the adoption and outcomes of cattle corralling. For instance, the increased soil fertility resulting from cattle corralling can lead to higher crop yields, which in turn can encourage more farmers to adopt the practice.

3.2.4 Statistical analysis

After tabulation, the survey data were processed using the R software, version 4.2.1. Descriptive statistical analysis was used to summarize the demographic, socio-economic, and institutional characteristics of farm households through mean, standard deviation, percentages, and frequency. For variables reduction and to characterize the corralling types a Factorial Analysis of Correspondence was performed under the packages (Husson, et al., 2007) and FactoExtra (Kassambara, 2016). This allowed the production of the representations of the corralling types in the form of projections on the planes defined by the first factorial axes. Following this, an Ascending Hierarchical Classification (AHC) classification (from the holdings of the coordinates on the main factor axes) was done, which allowed the grouping of corralling types according to their proximity. All individuals were represented in a dendrogram, where the main "branches" corresponded to different typology groups (Pavlopoulos et al., 2010). A non-parametric Kruskal-Wallis test with a Dunn–Bonferroni post hoc was performed on the types-variables matrix of the groups identified by the AHC to compare their mean values (Ahmed and Jena, 2023).

To assess the determinants of cattle corralling adoption a binary logistic regression was performed (Kennedy, 2022; Sarker et al., 2020). The binary model equation is presented as follows: **Yi = Xi**

β + εi. Where: - **Yi** is the variable that takes the value 1 if the farmer adopts cattle corralling and 0 if they do not adopt it; - **Xi** is the set of explanatory variables indicating the factors that influence the adoption of cattle corralling as a soil fertility management strategy (Table 3.3); - **β** represents the vector of coefficients associated with the explanatory variables Xi. These coefficients quantify the influence of each explanatory variable on the probability of the outcome Yi. In other words, β indicates how changes in the explanatory variables affect the likelihood of the farmer adopting cattle corralling as a soil fertility management strategy. - **εi** is the standard error. Before estimating the logistic regression model, the explanatory variables were tested for multicollinearity using the contingency coefficient test (Idrissou et al., 2020). If two variables exhibited collinearity, one was excluded from the model as an explanatory variable.

Table 3.3. Description of explanatory variables used for binary logistic regression

Variable	Description	Modality (ies)	Expected sign
Cattle corralling adoption	This variable assesses whether households have adopted the practice of corralling cattle as a soil fertility management strategy.	Yes/No	Na
Agroecological zone	It categorizes households based on the agroecological zone they belong to, which may influence agricultural practices and climate conditions (Coulibaly et al., 2019).	Zone 1/Zone 2/Zone 3	+/-
Educational level	It indicates the highest level of education attained by the household head, which can influence decision-making and agricultural knowledge (Abu-Shanab, 2011).	Primary/Secondary/ University/None	+/-
Ethnicity	This variable identifies the ethnic background of household members, which may influence cultural practices and agricultural traditions (Jordan and Guerzoni, 2021).	Bariba/Dendi/ Fulani/Other	+/-

Experience	This variable measures the years of experience in agriculture of household members, which can impact farming techniques and decision-making (E. B. Ali et al., 2018).	Numeric	+
Membership in the rural organization	This variable indicates whether household members are affiliated with any rural organization, which may provide access to resources and support networks (Chianu and Tsujii, 2005).	Yes/No	+/-
Access to Credit	It assesses the household's ability to access credit or financial resources for agricultural investment and inputs (Tadesse, 2014).	Yes/No	+/-
Awareness of corralling	This variable measures the level of awareness or knowledge that household members have about the practice of cattle corralling as a soil fertility management strategy (Oyetunde-Usman et al., 2021).	Yes/No	+
Age	This variable represents the age of household members, which can influence labor availability, decision-making, and agricultural practices (Chianu and Tsujii, 2005).	Numeric	+/-
Access to extension services	This variable indicates whether households have access to agricultural extension services, which provide information and support for improved farming practices (Oyetunde-Usman et al., 2021).	Yes/No	+/-
Distance fields-house	It highlights the logistical and practical challenges that distance poses to farmers. Understanding this variable's impact is crucial for developing strategies and interventions that encourage the adoption of beneficial farming practices and technologies (Ajayi et al., 2003).	Far/Medium/Near	+/-
Number of agricultural workers	This variable quantifies the number of individuals engaged in agricultural activities within the household, which can affect farm	Numeric	+/-

	productivity and management (Raut et al., 2011).		
Breeding mode	This variable categorizes the household's approach to livestock breeding, which may influence herd size and productivity (Kaliba et al., 2000).	Sedentary/Semi-Sedentary	+/-
Production objective	This variable identifies the primary objective or goal of agricultural production for the household, such as subsistence, market-oriented, or mixed objectives (Anang, 2016)	Both/For sale	+/-

3.3. Results

3.3.1. Socio-demographic characteristics of respondents

Table 3.4 summarizes the socio-demographic characteristics of the surveyed agricultural households. Most of the heads of household were men (93.4% of the total respondents). Among these, the most prevalent socio-cultural groups were Bariba (32.7%), Dendi (31.9%), and Fulani (28.8%). On average, the surveyed heads of household were 43.3 ± 0.7 years old and 73.5% of them did not attend school. The average household size was 16.3 ± 0.6 individuals and their average experience in agriculture and/or livestock was 26.0 ± 0.7 years. Half of the respondents were members of an agricultural organization (50.5%), and 45.2% were in contact with agricultural extension services. The rate of farmers having access to credit was low (38%) within the study area.

3.3.2 Characterization of cattle corralling practices

The results showed that 89% of the respondents are aware of the corralling practice as a tool for soil fertility management, while 71% practice it (Table 3.5). More than half (51%) of the surveyed population reported manually spreading the excreta after corralling to homogenize the corralled plots. Cattle corralling was predominantly done on generally poor plots (27%), close to the house

(<1 km, 23%). Only 12% of the surveyed population claimed to practice corralling on plots far from the house (>1 km). The majority estimated using the cattle corralling every year (74%), every 2 years (9%), and every 3 years (3%). The average number of cattle corralled on one hectare was estimated at 55.54 ± 1.93, and the corralling period averaged 3.44 ± 0.1 weeks. The fertility level of the soil after corralling is perceived as very high by 75% of the respondents, fertile by 22%, and moderately fertile by 3%.

Table 3.4. Socio-demographic characteristics of farmers surveyed from three municipalities in northern Benin

Variables	Modalities	Zones 1 (n=139, %)	Zones 2 (n=109, %)	Zones 3 (n=144, %)	Study area (N=392, %)	P-values
A) Qualitative variables						$\chi2$
Gender	Male	34.7	24.7	33.9	93.4	0.062
	Female	0.8	3.1	2.8	6.6	
Marital status	Divorced	-	1	0.3	1.3	0.036
	Married	34.7	24.5	34.7	93.9	
	Single	0.8	2.3	1.3	4.3	
	Widow	-	-	0.5	0.5	
Ethnicity	Bariba	-	19.9	12.8	32.7	0.098
	Dendi	31.4	0.3	0.3	31.9	
	Fulani	1.8	7.7	19.4	28.8	
	Other	2.3	0	4.3	6.6	
Religion	Traditional	-	0.3	-	0.3	0.341
	Christian	0.5	2.8	3.6	6.9	
	Muslim	34.9	24.7	33.2	92.9	
Educational level	None	23.5	22.4	27.6	73.5	0.058
	Primary	6.4	1.5	4.3	12.2	
	Secondary	4.6	3.3	3.1	11	
	University	1	0.5	1.8	3.3	
Membership of rural organization	No	21.4	7.9	20.2	49.5	0.052
	Yes	14	19.9	16.6	50.5	
Access to credits	No	18.4	16.6	27	62	0.041
	Yes	17.1	11.2	9.7	38	
Contact with extension services	No	21.7	5.6	27.6	54.8	0.074
	Yes	13.8	87	9.2	45.2	
B) Quantitative variables						*T-test*
Age (years)	Mean	44.7	41.8	43.0	43.3	

	SD	12.3	10.2	11.8	13.7	0.051
	Min	20	22	20	20	
	Max	75	78	91	91	
Agricultural experience (years)	Mean	31.9	21.2	23.8	26.0	
	SD	13.4	9.7	11.2	14.1	0.118
	Min	5	2	2	2	
	Max	71	50	65	71	
Agricultural workers (#)	Mean	17.6	17.0	18.7	17.7	0.041
	SD	4.2	3.9	5.1	8.6	
	Min	0	0	0	0	
	Max	8	11	13	21	

SD: Standard deviation.

Table 3.5. Characteristics and benefits of cattle corralling practices from three municipalities in northern Benin

Variables	Modalities	Zones 1 (n=139, %)	Zones 2 (n=109, %)	Zones 3 (n=144, %)	Study area (N=392, %)	P-value
A) Qualitative variables						χ2 test
Corralling awareness	No	6.9	1.5	3.1	11.5	0.023
	Yes	28.6	26.3	33.7	88.5	
Adoption level	No	17.1	5.1	6.9	29.1	0.033
	Yes	18.4	22.7	29.8	70.9	
Comparison with mineral fertilizer	No	1.5	0.5	0.5	2.6	0.003
	Yes	33.9	27.3	36.2	97.4	
Corralling contracts	No	23.2	25.0	31.4	79.6	0.021
	Yes	12.2	2.8	5.4	20.4	
Corralling charge	No	8.9	13.8	16.8	39.5	0.106
	Yes	26.5	14.0	19.9	60.5	
Goods for corralling contract	No	3.8	12.5	30.1	46.4	0.051
	Yes	31.6	15.3	6.6	53.6	
Manure spread after corralling	No	14.5	19.4	14.8	48.7	0.062
	Yes	20.9	8.4	21.9	51.3	

Corralling method	Overnight	7.4	8.9	10.5	26.8	0.024
	Rotative	18.6	12.0	13.0	43.6	
	Rotative and overnight	5.6	4.8	5.1	15.6	
	Corralling contract	4.6	3.6	5.9	14.0	
Corralling location	Field away from home (>1 km)	5.9	9.2	6.9	21.9	0.034
	Fields near the house (<1 km)	17.1	18.4	15.1	50.5	
	No preference	10.5	8.4	8.7	27.6	
Frequency of corralling	Other	3.3	5.9	4.6	14.3	0.004
	Every year	22.4	23.5	28.6	74.5	
	Every two years	2.3	3.6	2.8	8.7	
	Every three years	1.5	0.8	0.3	2.6	
Soil fertility status after corralling	Fertile	8.2	6.6	7.7	22.4	0.016
	Moderately fertile	0.5	1.3	0.8	2.6	
	Very fertile	23.5	22.2	29.3	75.0	
B) Quantitative variables						*T-test*
Amount paid for corralling (USD)	Mean	32.1	26.2	36.7	31.7	0.101
	SD	11.3	6.3	12.4	10.0	
	Min	0	0	0	0	
	Max	54.6	76.7	82.6	82.6	
Corralling duration (week)	Mean	2.5	4.3	3.1	3.3	0.055
	SD	0.3	0.7	0.4	0.5	
	Min	1	1	1	1	
	Max	5	7	5	7	
Number of cattle corralled per hectare	Mean	47.7	62.4	56.2	55.43	0.081
	SD	3.1	2.3	2.1	2.5	
	Min	0	0	0	0	
	Max	59	70	67	70	

SD: Standard deviation.

3.3.3 Benefits and constraints of cattle corralling practices in northern Benin

The availability of water is considered as a highly constraining factor by 33%, moderately by 27%, and weakly by 17% of the studied populations (Figure 3.1). Forage availability was a major constraint with 27% perceiving it as highly constraining, 34% as moderately constraining, and 15% as weakly constraining (Figure 3.1). The ownership of cattle (50%) and the security of the livestock (44%) were perceived as highly constraining factors to the practice of cattle corralling.

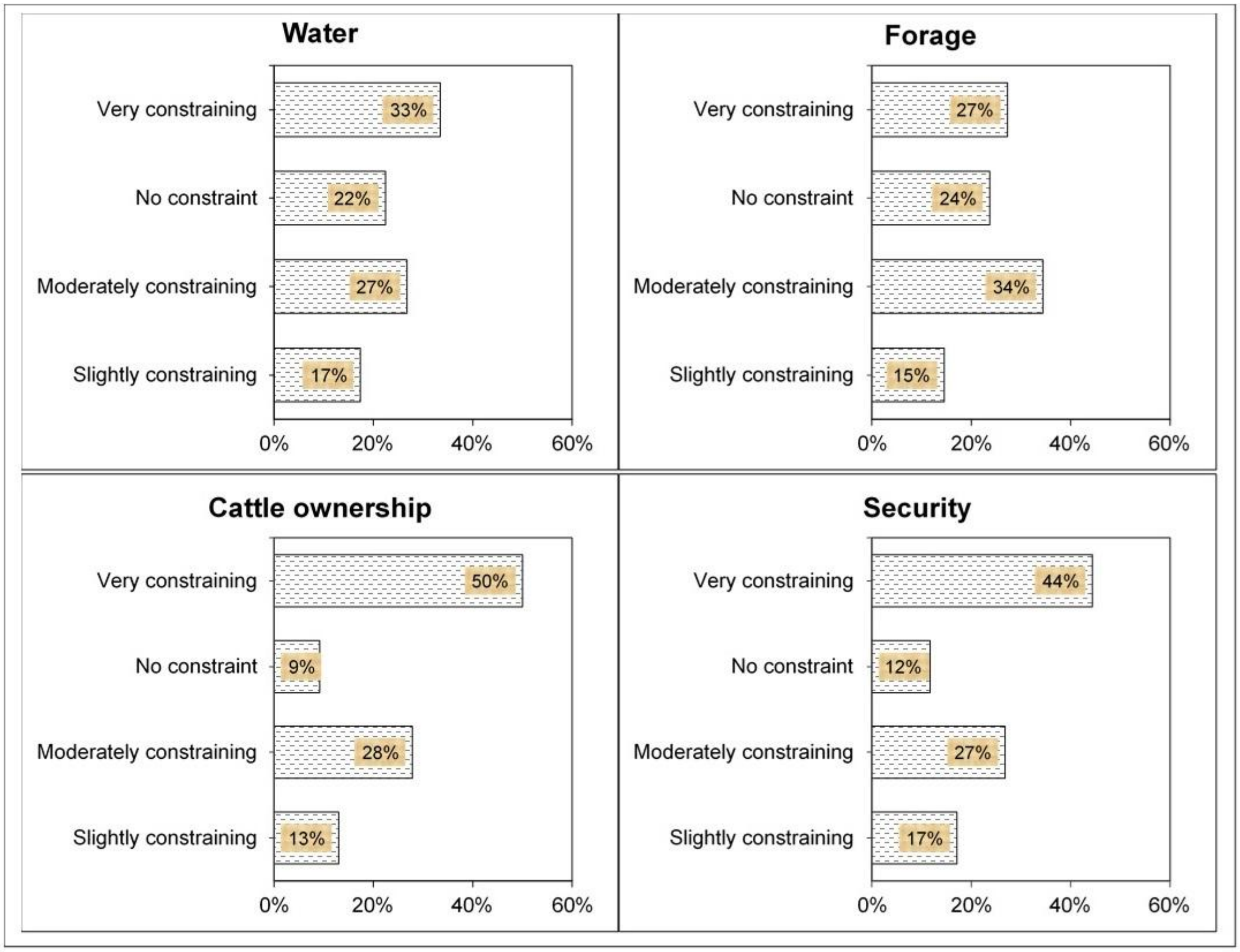


Figure 3.1. Constraints of cattle corralling practices in northern Benin

3.3.4 Typology of cattle corralling practices in northern Benin

The first two factorial axes obtained from the factorial analysis of correspondence allowed for a cumulative percentage of explained variance greater than 50% and were therefore considered for result interpretation (Figure 3.2). Hierarchical clustering indicated 3 cluster cuts of points grouped by structural and functional characteristics of the cattle corralling practices:

Cluster 1 (practitioners of Continuous Overnight-Rotational Corralling, CORC): It was mainly practiced continuously (year after year, 51.2%) by Fulani (31.7%) and Bariba (52.3%) ethnic groups with no educational (67.3%) background (Table 3.6). The methods employed include overnight (53.6%) corralling and rotational (37.1%) corralling. Night corralling was described by respondents as the tethering of animals on a specific plot only during the night, while rotational corralling occurs both day and night, but in a succession from one plot to another. This cluster was characteristic of agroecological zones 2 (44.7%) and 3 (40.1%), and their main production objective was for household consumption (67.1%).

Cluster 2 (practitioners of Discontinuous Overnight-Rotational Corralling, DORC): this type of corralling was practiced intermittently, either every two (37.6%) or three years (30.1%) or according to an indefinite (22.4%) periodicity (Table 6). It was mainly characteristic of agroecological zones 2 (46.5%) and 3 (39.1%), with an education level ranging from primary (34.1%) to secondary (39.3%) school. The characteristic method of this type was overnight (39.2%) - rotational (46.4%) corralling. The production objective was for both household consumption and sale (48.3%) and the farmer's land was near (<1 km, 39%) from their house.

Cluster 3 (practitioners of Corralling contract, CC): This type was characteristic of Dendi (37.4%) and other minorities (34.7%) ethnic in the study area, occurring without a predefined period (undetermined, 41%). It was observed among farmers with a high level of education, potentially reaching a university (44.3%) education, with a preference for land far (57.4%) from the house. This was based on a corralling contract (73.5%) which is an agreement between farmers and herders, where the latter provide corralling services in the fields in exchange for corralling and/or goods in kind (milk, corn, ...). In this group, the production objective was mainly for sale (48.6%).

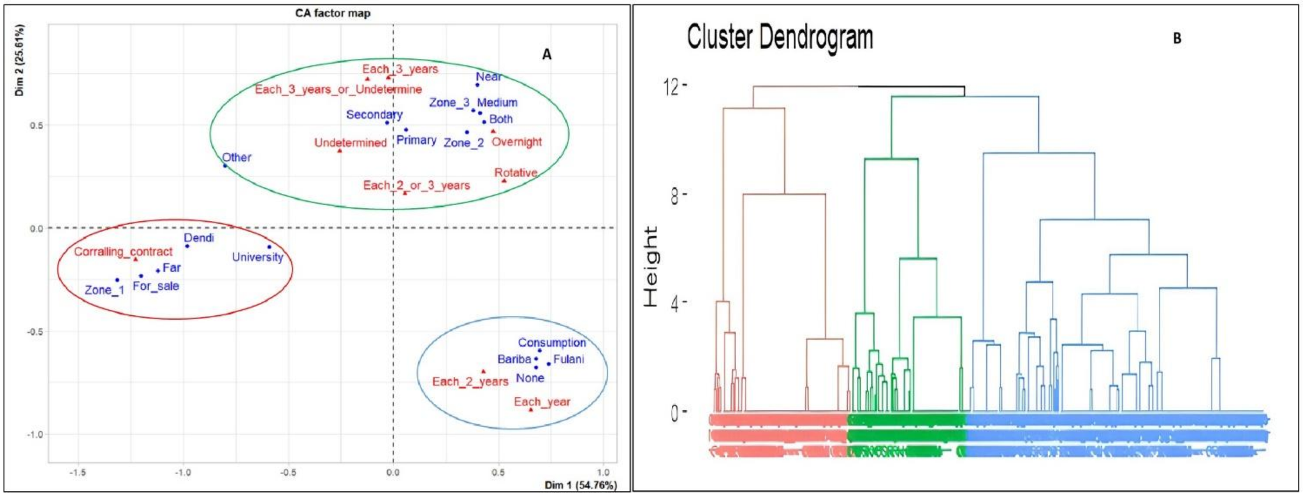


Figure 3.2. Factorial Correspondence Analysis map (A), and Dendrogram of different groups of cattle corralling practices by farmers from northern Benin (B).

The various colours observed on the dendrogram represent the three groups obtained and correspond to the colour of the circles obtained on Fig 2A. Circle red shows cluster 1 (practitioners of Continuous Overnight-Rotational Corralling, CORC), the circle blue shows cluster 2 (practitioners of Discontinuous Overnight-Rotational Corralling, DORC), and the circle green shows the cluster 3 (practitioners of Corralling contract, CC). "Height" on the y-axis (fig 2B) means the proportion weight of each variable group.

Table 3.6. Characteristics of different groups of cattle corralling from northern Benin

Characteristics		Group of cattle corralling				
		CORC	**DORC**	**CC**	**χ2**	**P-value**
Agro-ecological zone (%)	Zone 1	15.2^b	14.4^b	66.9^a	21.6	0.001
	Zone 2	44.7^a	46.5^a	14.7^b		
	Zone 3	40.1^a	39.1^a	18.4^b		
Educational level (%)	None	67.3^a	19.7^b	13.8^c	17.2	0.04
	Primary	18.2^b	34.1^a	21.4^b		
	Secondary	9.1^c	39.3^a	21.2^b		
	University	5.4^c	7.9^c	44.6^a		
Ethnicity (%)	Bariba	52.3^a	49.1^a	11.5^c	9.2	0.01
	Dendi	13.1^c	10.2^c	37.4^a		
	Fulani	31.7^b	28.1^b	17.4^b		
	Other	2.9^d	12.6^c	34.7^a		
Corralling frequency (%)	Each 3 years	14.1^b	30.1^a	21.6^b	31.7	0.001
	Undetermined	8.3^c	22.4^a	41.3^a		
	Each 2 years	26.4^b	37.6^a	22.7^b		
	Each year	51.2^a	9.9^b	14.4^c		
Corralling method (%)	Rotative	37.1^b	46.4^a	11.3^b	23.5	0.02
	Overnight	53.6^a	39.2^a	16.2^b		
	Corralling contract	9.3^c	13.4^b	73.5^a		
Distance fields-house (%)	Near	43.3^a	38.8^a	16.4^c	18.2	0.001
	Medium	41.1^a	47.6^a	26.2^b		
	Far	15.6^b	3.6^b	57.4^a		
Production objective (%)	For sale	16.2^b	29.1^b	48.6^a	16.3	0.05
	Both	16.7^b	48.3^a	27.6^b		
	Consumption	67.1^a	22.6^b	23.8^b		

χ2: represents the Chi-square values; Chi-square was used to compare categorical variables. The values of the same line indicated by different letters are significantly different at the 5% level (p<0,05); CORC: continuous overnight-rotational corralling, DORC: Discontinuous overnight-rotational Corralling, CC: Corralling contract

3.3.5 Drivers of cattle corralling adoption as soil fertility management option in northern Benin

The results of the binary logistic regression analysis conducted to determine the factors influencing the adoption of cattle corralling as a means for soil fertility management are summarized in Table 3.7. The variables agroecological zone (p<0.001), educational level (p<0.001), ethnicity (p<0.001), access to credit (p<0.004), awareness of corralling (p<0.001), access to extension services (p<0.001), distance fields-house (p<0.001), breeding mode (p<0.001), and production objective (p<0.001) significantly influence the adoption. Factors such as experience (p>0.05), membership in rural organizations (p>0.05), age (p>0.05), and number of agricultural workers (p>0.05) do not significantly impact the adoption of cattle corralling.

Table 3.7. Determinants of the adoption of the practice of cattle corralling as a soil fertility management strategy tool in northern Benin

Variable	Modality	B	Sig.	-2 Log likelihood	Model Evaluation
Agroecological zone	Zone 1	0.46	0.000***	435.41	70.9
	Zone 2	-1.39	0.000***		
Educational level	None	2.24	0.000***	427.11	74.2
Ethnicity	Bariba	3.41	0.000***	396.88	72.2
	Other	2.60	0.000***		
Experience	Experience	0.01	0.505*	472.21	70.9
Membership in the rural organization	Yes/No	0.12	0.591*	472.37	70.9
Access to Credit	Yes/No	0.65	0.004**	464.36	70.9
Awareness of corralling	Yes/No	3.65	0.000***	384.03	80.4
Age	Age	0.01	0.121	470.19	70.9
Access to extension services	Yes/No	-1.75	0.000***	416.62	73.2
Distance fields-house	Far	0.74	0.000***	371.65	75.8
	Medium	-2.68	0.000***		
	Near	2.15	0.000***		
Number of agricultural workers	Number of agricultural workers	0.01	0.900	472.64	70.9
Breeding mode	Sedentary	1.56	0.000***	437.81	70.9
	Semi-Sedentary	-3.23	0.001***		
Production objective	Both	0.56	0.000***	119.59	95.9
	For sale	5.58	0.000***		

**** : significative at 1% level (p<0.01); ** : significative at 5% level (0.01 <p< 0.05) ; * : significative at 10% level (0.05 <p <0.10), B : Regression Coefficient*

3.4. Discussion

3.4.1 Characterization, benefits, and constraints of cattle corralling adoption in northern Benin

Understanding the socio-cultural practices related to soil fertility management is essential for developing sustainable agricultural strategies. This study reveals that the practice of cattle corralling as a soil fertility management tool is deeply embedded in the agricultural traditions of northern Benin, as evidenced by its widespread awareness among local populations. Ethnic diversity plays a significant role in this practice, with Fulani, Bariba, and Dendi being the most represented ethnic groups involved. This widespread awareness underscores the traditional nature of cattle corralling in the region, even though not practiced by all farmers. The findings are consistent with those of Shinjo et al., (2008), who indicated that cattle corralling is a common rural practice with significant potential for efficient utilization of livestock excreta.

Rotational and overnight corralling were the most common methods in the study area, and a significant number of respondents opted to manually spread manure after corralling, aiming for a more uniform nutrient distribution across their fields. This practice aligns with the observations of Suzuki et al. (2014), who highlighted the importance of manure transport and corralling for soil fertility improvement. However, the homogenization of nutrients on the plots remains a challenge, particularly on poor plots situated near homesteads, which are chosen for corralling due to security concerns and the availability of water and forage (Huruba et al., 2018). Despite its benefits (75% of respondents perceived their soil as very fertile after cattle corralling), cattle corralling presents several constraints. Security of the herd, water availability, forage availability, and cattle ownership are major limiting factors, as indicated by significant portions of respondents. The necessity of corralling closer to home for safety reasons is particularly emphasized, which also facilitates easier access to water for the animals. In addition, the limited herd size and labour availability affect cattle corralling at large scale. These constraints highlight the need for improved management practices that can address the logistical and resource-related challenges faced by farmers.

The findings indicated that corralling is done annually by 74% of respondents, indicating its ingrained nature in the local agricultural practices. However, the repeated need for corralling could be due to nutrient losses (particularly nitrogen) caused its volatilization from urine and faeces poorly recycled on field plots, coupled with leaching due to heavy rainfall (Bisson et al., 2019b). Addressing these nutrient losses could enhance the effectiveness and sustainability of corralling practices. Adding biochar and mulching to the plots corralled can be an alternative to enhance nutrient loss. Biochar application has shown mixed effects on nutrient retention and leaching in soils. Biochar can improve soil properties, including water retention, pH, and microbial activity (Hossain et al., 2020). It may reduce nitrogen and potassium leaching by up to 30% and phosphorus leaching by 68% in coarse-textured soils (Kuo et al., 2020).

The socio-economic implications of cattle corralling are profound. By providing a traditional yet effective method for enhancing soil fertility, cattle corralling helps improve crop yields, thereby supporting food security and livelihoods (Galindo et al., 2020; Ayantunde et al., 2018). However, the constraints identified, such as water and forage availability, security, labour availability and cattle ownership, pose significant barriers to the wider adoption of this practice. Strategies to alleviate these constraints could include the provision of secure corralling areas, improving water and forage resources, and supporting livestock ownership through credit and extension services.

3.4.2 Typology of cattle corralling in northern Benin

The typology conducted identifies three main groups of cattle corralling practices: Overnight-Rotational Continuous Corralling (ORCC), Discontinuous Overnight-Rotational Corralling (DORC), and Corralling Contract (CC). Each type reflects different socio-economic and cultural contexts, indicating the diverse ways in which cattle corralling is integrated into farming systems in northern Benin. The identification of three distinct cattle corralling practices highlights the adaptability of these practices to different socio-economic and cultural contexts in northern Benin. This diversity in approaches suggests that the effectiveness of cattle corralling as a soil fertility management tool can vary significantly based on the specific method employed. For instance, ORCC may provide more consistent soil fertility benefits due to continuous manure deposition, while DORC and CC might offer flexibility but with potentially less regular nutrient enrichment. Understanding these typologies allows for the development of tailored interventions that optimize the effectiveness of each system, enhancing overall agricultural productivity and sustainability in the region.

The ORCC is practiced continuously over successive years and is widely adopted by major ethnic groups such as the Fulani and Bariba, who generally have no formal education. This type is characterized by overnight corralling, where animals are gathered on a specific plot only during the night, and rotational corralling, which occurs both day and night in succession from one plot to another. The continuous nature of ORCC is likely due to the permanent ownership of cattle by these ethnic groups, which allows for regular manure deposition and soil fertility enhancement (Augustine, 2004). In contrast, DORC is practiced intermittently, either every two or three years or according to an indefinite periodicity, and is characteristic of the farmer group who have a range of educational backgrounds from primary to secondary school. This type typically involves overnight corralling. The irregular nature of DORC suggests that these farmers may not have permanent herds or may use corralling as a supplementary rather than a primary soil fertility management strategy (Duiker and Zampaligre, 2022; Gandah et al., 2003b; Osbahr and Allan, 2003; Place et al., 2003).

The CC type or manuring type, practiced by ethnic minorities in the study area, relies heavily on agreements between herders and farmers. This type is more common among farmers with higher levels of education, potentially reaching the university level. The reliance on corralling contracts indicated a more formalized approach to integrating livestock into crop production, where herders provide corralling services in exchange for goods or payment. This type of arrangement could facilitate access to the benefits of cattle corralling for farmers who do not own cattle, thereby promoting the practice more widely (Suzuki et al., 2014; Shinjo et al., 2008). The diverse typologies of cattle corralling reflect the adaptability of this practice to different socio-economic contexts (Kuivanen et al., 2016). Understanding these typologies informs targeted interventions to promote cattle corralling in ways that are culturally appropriate and socio-economically viable. For instance, supporting the development of corralling and manuring contracts could increase access to these practices for farmers without cattle, while improving security and water resources could benefit all forms of corralling.

3.4.3 Determinants of cattle corralling adoption as a soil fertility management

Understanding the determinants of adopting cattle corralling as a soil fertility management tool in the context of climate change is crucial for better comprehension and promotion of this practice (Martey and Kuwornu, 2021; Mwaura et al., 2021). This study reveals that factors such as agroecological zone, educational level, ethnicity, access to credit, awareness of corralling, access to extension services, distance fields-house, breeding mode, and production objective significantly influences the adoption of cattle corralling. Many previous studies have shown similar results when it comes to adoption drivers (Diro et al., 2022; Jha et al., 2021; Kwadzo and Quayson, 2021; Nguyen et al., 2021; Ado et al., 2020). Educational level impacts corralling adoption ($p<0.001$), where highly educated farmers better organized their operations and leaned towards modern and intensive agriculture with sustained use of chemical inputs. This was not the case for less educated farmers, who turned to nature-based solutions such as cattle corralling to increase their production (Kansanga et al., 2021). Ethnic affiliation ($p<0.001$) determined the possibility of farmers owning livestock and therefore their ability to opt for an integrated agriculture-livestock approach in their production system (Oyetunde-Usman, 2022; Nguyen et al., 2021; Ado et al., 2020). Thus, Fulani and Bariba have a certain ease in adopting cattle corralling.

Access to credit increases farmers' ability to buy chemical fertilizers and therefore reduces the likelihood of adopting corralling as strategy of soil fertility management (Anang et al., 2021; Kwadzo and Quayson, 2021; Mwaura et al., 2021). However, credit can also support the purchase of livestock, thereby facilitating the adoption of cattle corralling. Access to extension services significantly increases corralling awareness among farmers and consequently their chances of adoption (Muhammed et al., 2020). Extension services can provide crucial information and support for best practices in cattle corralling, helping to address some of the constraints identified. Furthermore, extension services can improve cattle corralling systems by promoting sustainable practices, innovative designs, and proper management techniques, thereby reducing their impact on climate change (Andrieu et al., 2015; Eeswaran et al., 2022a). The distance between fields and houses ($p<0.001$) is crucial in terms of corralling adoption, as a shorter distance provides farmers with security guarantees and access to water for corralling practices (Belachew et al., 2020; Wordofa et al., 2020). Fields located far from homes pose significant logistical challenges, making it difficult to manage cattle and ensure their safety. Strategies to facilitate safe and accessible corralling areas closer to farmers' homes could significantly enhance the adoption of this practice. The breeding mode and production objective ($p<0.001$) also play significant roles in adopting cattle corralling. Sedentary breeding modes, where livestock are kept in fixed locations, facilitate regular and systematic manure deposition on fields, supporting soil fertility management. In contrast, semi-sedentary or mobile livestock systems may find it more challenging to implement consistent corralling practices. Similarly, farmers focused on market-oriented production may prioritize short-term yields and chemical fertilizers over long-term soil health practices like corralling. Conversely, subsistence or mixed production objectives may be more aligned with the sustainable benefits of cattle corralling.

Cattle corralling can significantly enhance system resilience and sustainability by promoting the natural recycling of nutrients, which improves soil fertility and structure over time (Hidosa and Meskel, 2022; Mrunalini et al., 2022). This practice reduces dependency on chemical fertilizers, thereby minimizing environmental impacts and fostering long-term agricultural productivity. By integrating livestock into crop production, corralling supports a more diversified and resilient farming system capable of withstanding climate variability (Schiere et al., 2006). Moreover, it encourages sustainable land use by optimizing resource efficiency and reducing land degradation. As a nature-based solution, cattle corralling complements sustainable agricultural practices and reinforces the resilience of farming systems amid climate change challenges.

Ultimately, its adoption as a soil fertility management strategy in northern Benin is governed by a complex interplay of socio-economic, cultural, and environmental factors. Addressing the constraints and leveraging the determinants identified in this study can promote more widespread and effective use of cattle corralling, thereby enhancing soil fertility, agricultural productivity, and resilience to climate change. Future research should focus on developing integrated strategies that combine cattle corralling with other sustainable agricultural practices, supported by policies and programs that address the specific needs and contexts of different farmer groups.

3.5. Conclusion

This study's findings have significant implications for improving food system sustainability and enhancing farmers' livelihoods in northern Benin. The diverse typology of cattle corralling practices, shaped by local socio-economic and environmental factors, suggests that tailored strategies can effectively address the unique challenges faced by different farming communities. By identifying key determinants of adoption, such as access to credit, extension services, and education, targeted interventions can be designed to promote the widespread adoption of cattle corralling, thereby enhancing soil fertility and resilience against climate variability. Additionally, addressing the identified constraints such as security, water availability, and forage resources there is potential to optimize these practices, leading to more sustainable agricultural systems and improved livelihoods for farmers. This research underscores the importance of integrating livestock management into broader agricultural policies to foster long-term sustainability and resilience in farming communities.

These results advocate for continued investment in research and extension services to support farmers in adopting these beneficial practices, ultimately fostering a more sustainable and productive agricultural sector. They form the baseline for further investigation on cattle corralling as a nature-based solution for soil fertility management in the face of climate change.

CHAPTER 4: EVALUATION OF TRADITIONAL CATTLE CORRALLING PRACTICE AND ITS IMPACT ON SOIL HEALTH IN NORTHERN BENIN

Manuscript: Impact of traditional cattle corralling-based practices on soil physico-chemical properties and maize yield in northern Benin; A. M. Atakoun, P. G. Tovihoudji, R. V. C. Diogo, W. Amponsah, M. dos Santos Vianna, T. Gaiser, N. Kyei-Bafour, B. Kyereh

ABSTRACT

Traditional cattle corralling practices are widely used by smallholder farmers in northern Benin as a strategy to improve soil fertility and increase crop yields. This study investigates the effects of cattle corralling on soil physico-chemical properties, maize production, and soil carbon stock. Soil samples were collected from fields corralled every year and at intervals from one to seven years, alongside fields without corralling as control plots. Samples were submitted to laboratory analysis for macronutrients and carbon content assessment. Results show that fields corralled every year significantly enhance maize yields, with yields reaching 2.77 t/ha compared to 1.60 t/ha in non-corralled fields. Additionally, soil organic matter (SOM) and soil organic carbon (SOC) levels were highest in fields corralled every year (EY), with SOM and SOC reaching 2.5% and 1.4%, respectively. Soil carbon stocks (SCS) also increased significantly, peaking at 46.6 Mg/ha in fields corralled every year. The findings reveal a strong positive correlation between maize yield and key soil properties such as SOM, SOC, and potassium content, while an indirect correlation was observed between maize yield and soil pH and hydraulic conductivity. These results highlight the potential of cattle corralling to improve soil health, enhance crop productivity, and contribute to sustainable agricultural practices in semi-arid regions. The study suggests that continuous cattle corralling can be an effective tool for soil fertility enhancement and food security in northern Benin.

Keywords: Carbon sequestration, crop-livestock integration, maize yield, soil fertility, soil hydraulic conductivity

4.1 Introduction

Climate change significantly threatens agricultural systems and food security in sub-Saharan Africa (SSA) by exacerbating soil degradation and reducing productivity (Tully et al., 2015). Extreme weather events, including heavy rainfall and droughts, alongside warming trends, undermine agricultural resilience by depleting soil organic matter and increasing erosion rates (Diacono et al., 2023; Pörtner et al., 2022; Lal, 2015). Healthy soils are vital for sustainable agriculture, supporting plant growth, water retention, and carbon sequestration (Moulik et al., 2024; Lal, 2011). However, with over 33% of croplands moderately or highly degraded globally (Davis, 2023), there is an urgent need to address soil degradation as part of climate change adaptation strategies. Without significant investment in sustainable agricultural practices, improved soil management, and climate adaptation, West Africa faces heightened risks of food insecurity and ecosystem degradation (ten Berge et al., 2019).

Addressing these challenges requires integrating soil health assessments with ecological resilience theories to understand how management practices impact soil functions and agricultural sustainability (Davis, 2023). Strategies for maintaining soil health include managing organic matter inputs, minimizing soil disturbances, enhancing soil biota diversity, and preserving soil cover, with regular monitoring being essential for adaptive management (Moulik et al., 2024; Handayani and Hale, 2022).

In agricultural systems globally, livestock management practices, particularly cattle corralling, significantly impact soil health and crop productivity (Turmel et al., 2015; Lemaire et al., 2014). Cattle corralling involves confining livestock in designated areas overnight, resulting in the accumulation of manure and urine that enriches the soil with nutrients (Schlecht et al., 2004; Schlecht and Buerkert, 2004; Shinjo, 2017; Suzuki et al., 2014). Several studies showed that organic matter from animals serves as the foundation for healthy soils and has far-reaching implications for agricultural sustainability, climate resilience, and ecosystem functioning (Bhogal et al., 2011; Hao et al., 2003; Telo da Gama, 2023). Understanding the effects of these traditional practices on soil properties and crop production is critical for developing sustainable agricultural strategies.

However, in northern Benin, characterized semi-arid climate and prevalence of small-scale farming, there is growing challenges in maintaining soil fertility and crop productivity (Assogbadjo et al., 2022; Callo-Concha et al., 2012). Traditional cattle corralling practices are widespread in the region; but, their specific impacts on soil biophysical and chemical properties, maize production, and soil carbon sequestration remain inadequately understood (Diogo et al., 2021; Jagisso et al., 2019).

Previous studies have shown that traditional cattle corralling can improve soil quality and increase maize yields by utilizing livestock excreta as an organic fertilizer source (Abdul Rahman et al., 2019a; Rahman et al., 2019; Tovihoudji et al., 2017). In northern Benin, soil fertility management strategies such as applying mineral fertilizers, manure, and crop rotations are practiced, though often at suboptimal levels due to limited resources (Tovihoudji et al., 2024, 2023) and their management. The low resource endowment among farmers affects the adoption of these practices, with poorer farmers using less manure and fertilizer inputs (Tovihoudji et al., 2024). Integrated crop-livestock systems have demonstrated potential for soil carbon sequestration, offering significant benefits over other farming systems (Idrissou et al., 2024).

The biophysical and chemical properties of soil are fundamental determinants of soil fertility, nutrient availability, and overall crop productivity (Indoria et al., 2017; Ayala and Rao, 2002). Management practices, including cattle corralling, influence these properties by affecting soil structure, nutrient content, and microbial activity (Mrunalini et al., 2022; Rufino et al., 2006). The application of livestock excreta through corralling is a major practice for soil fertility maintenance among smallholder farmers, especially given the limited use of chemical fertilizers in the region (Rahman et al., 2019; Ayantunde et al., 2018b; Schlecht et al., 2004). As maize is a staple crop in Benin that relies heavily on soil nutrients for optimal growth and yield, understanding soil-maize interactions is crucial for deriving sustainable agricultural strategies in northern Benin.

Despite the significance of these practices, there is a notable gap in knowledge regarding the specific impacts of cattle corralling on soil properties and maize production in northern Benin. Assessing soil nutrients and carbon stocks is essential for understanding ecosystem sustainability and predicting carbon storage potential (Kim and Grunwald, 2016). Soil physicochemical properties, particularly clay content, pH, and iron concentrations, are primary predictors of soil organic carbon (SOC) and nutrient availability across broad geographical scales (Li et al., 2020). Nitrogen (N) and phosphorus (P) availability strongly influence soil carbon sequestration due to stoichiometric links between biogeochemical cycles (Macdonald et al. 2018). Carbon, as a key soil element, plays a vital role in improving soil fertility and enhancing crop productivity (Munghate et al., 2020). Understanding the mechanisms driving interactions between carbon and nutrient cycles is essential for predicting future soil carbon sequestration, especially in the context of human disturbances, global challenges, and changing nutrient availabilities (Macdonald et al. 2018).

This study aims to fill this gap of knowledge by investigating the effects of traditional cattle corralling practices on soil biophysical and chemical properties, maize production, and soil carbon levels in northern Benin. Specifically, it assesses how cattle corralling influences these soil properties and evaluates the subsequent impact on maize yield. The findings will provide valuable insights into the relationship between the region's livestock management practices, soil health, and crop productivity, thereby informing strategies for sustainable agriculture.

4.2 Materials and methods

4.2.1. Study area

The study was carried out in the municipality of Gogounou (in the department of Alibori, Figure 1). Gogounou is located more than 615 km from Cotonou in the north of the Republic of Benin and is situated between 10°33' and 10°57' North latitude and 2°15' and 3°15' East longitude. With a population of 117,523 inhabitants, it covers an area of 4,910 km2, which represents 18.66% of the entire department of Alibori (26,303 km^2) and 4.36% of the entire national territory. The relief is essentially made up of plains and plateaus topped in places by hills whose maximum height is around 300 m. The climate is tropical sub-humid, with a rainy season from May to October and a dry season from November to April, with a harmattan period from December to February. The average annual rainfall is 1058.61mm (MEHU, 2011). The soils are those of the granite-gneissic basement, mostly ferruginous and generally suitable for agriculture. In the alluvial plains, alluvial soils dominate, clay-sand soils that are quite rich due to the contribution of organic matter by the annual flooding of the rivers. The region is considered the main production zone of food and cash crops. Households in the study area are mainly engaged in farming, from which a majority derive their livelihoods. More than 70% of households have farm sizes smaller than 5 hectares. The choice of these zones is based on the fact that agriculture and livestock farming are the main activities of the inhabitants (Alkoiret et al., 2011), and that climate forecasts indicate that they are the most vulnerable to rainfall deficits and high insolation (Idrissou et al., 2020; Gnanglè et al., 2011).

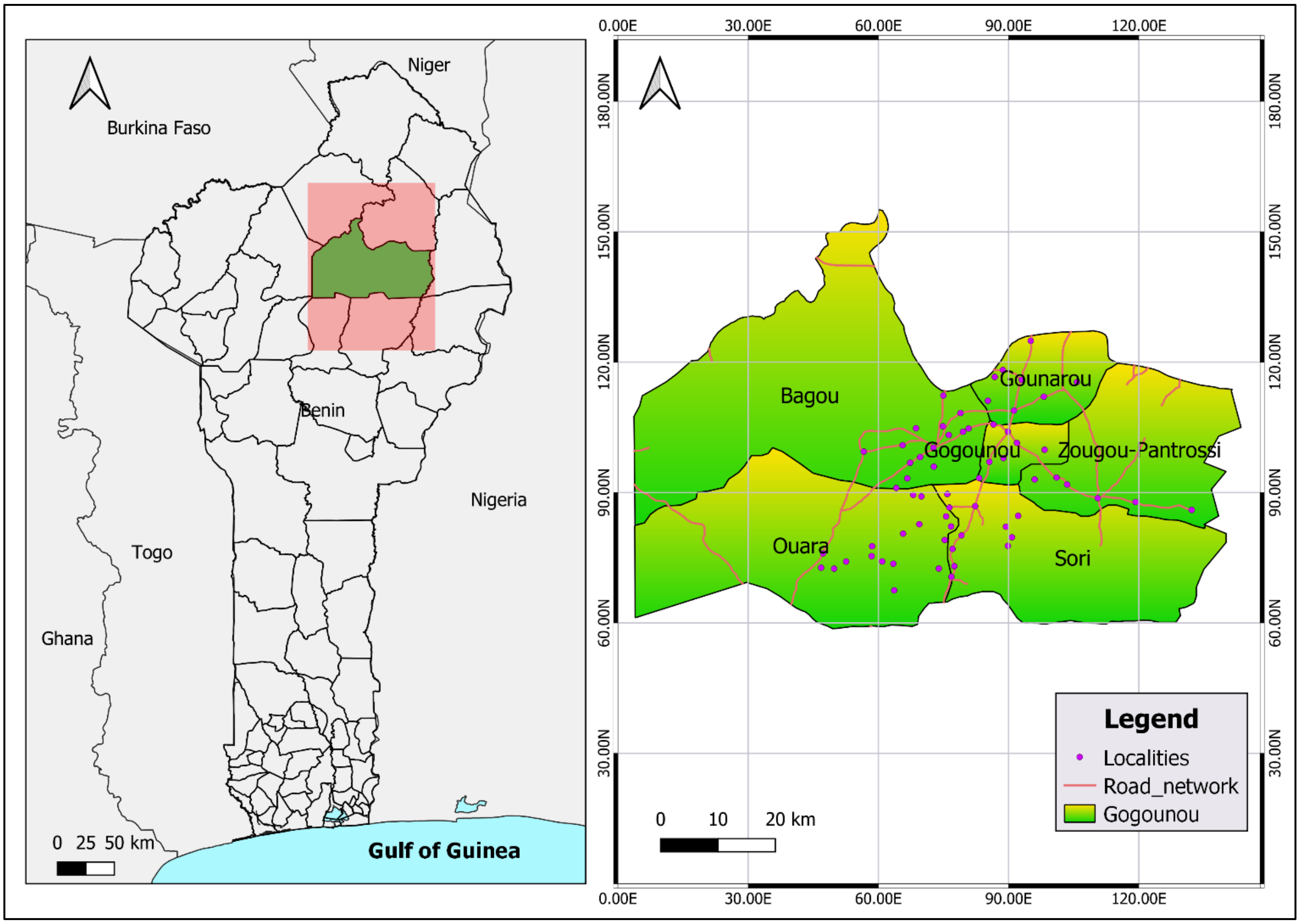


Figure 4.1. A map of Benin showing the study zone (left) and the localities of soil sampling (right) in the municipality of Gofounou.

4.2.2 Data collection

Through an on-farm survey, fields, where cattle were corralled, were identified across the municipality of Gogounou between March and May 2023. A farm survey was also carried out to ensure that cultivation practices were uniform and to obtain comprehensive historical information about each plot. The characteristics considered in the choice of farms were (i) the duration of corralling (1–7 months), (ii) the number and type of livestock corralled, (iii) the density of livestock inside the corral, (iv) the spreading of manure by farmers and tillage practices, (v), and the crop grown (Freschet et al., 2008). Plots were eliminated if trees or bushes surrounded them or if crop residues had previously been burned, or if there was heavy runoff during the rainy season (Freschet et al., 2008). Plots under fallow (short-term grass fallow) were used as control. The samples were classified according to the time since the last corralling. Cultivated control (maize fields without corralling C0), fallow control (CF), and plots corralled every year (EY), last corralling 1 year (C1), last 2 years (C2) or up to last 7 years (C7) before soil sampling were selected for the study. Based on the availability and willingness of the farmers, a short interview was conducted to collect data related to the historical soil management practice and yield of the farms. An estimation of the maize yield was done according to the common traditional method in northern Benin. The farmers in northern Benin estimate the grain yield based on the number of common bags (100 kg) harvested from a hectare. The grain yield is then estimated by computing the weight of one bag (100 kg) times the total number of bags harvested. This method has been chosen since it is the most flexible for the farmers to remember their past production. Also, it is used by rural associations to record the production of each farmer.

4.2.3 Soil sampling

Disturbed samples were taken from the topsoil (0 to 20 cm depth, root and mineralization zone) from each treatment plot. Three farms within the same locality (< 10 km) of each treatment (10 x 3 farms) were considered and three samples were collected from each farm (30 x 3 samples). The snowballing method was used to reach all the farmers and their farms (Parker et al., 2019). The following parameters were assessed:

i) soil chemical properties:

Based on differential pulse anodic stripping voltammetry (ASV), the SA1100 Scanning Analyser developed by Palintest (Gateshead, UK) was used to assess soil pH, water-extractable nitrogen (N), water-extractable phosphorus (P), and water-extractable Potassium (K) (Tang et al., 2018). These chemical analyses were carried out at the Integrated Production Systems Innovation Lab and Sustainable Land Management (InSPIREs-SLM) at the University of Parakou, Faculty of Agronomy, Benin.

ii) soil physical parameters:

Bulk density (BD) was assessed from undisturbed soil samples in the topsoil (0-15 cm), through direct measurement by the core method (in a volumetric cylinder), via the excavation (Al-Shammary et al., 2018; Blake, 1965). It was calculated as the ratio of the dried mass of soil to its total volume (Han et al., 2016; Walter et al., 2016). Water infiltration was measured using the Mini Disk Infiltrometer Model S. Hydraulic conductivity (K) was deducted from water infiltration rate using the method described by Zhang, (1997) coupled with the Van Genuchten mathematical model (Yang and You, 2013). Hydraulic conductivity at the soil surface was the physical parameter used to quantify the infiltration capacity of the soils of the study plots.

iii) Soil Organic Matter (SOM), Soil Organic Carbon (SOC), and Soil Carbon Stock (SCS)

Soil Organic Matter (SOM) was determined by the Loss On Ignition (LOI) method (Hoogsteen et al., 2015; Konare et al., 2010). This method involves burning the soil sample at a very high temperature (usually around 400°C) in a muffle furnace to burn off the organic matter, and the loss in weight is used to estimate the organic matter content as described by Nelson and Sommers, (1996). In summary, fifty-gram soil samples were placed in pre-weighed 50-mL Pyrex beakers, which had been conditioned at 400°C for 2 hours and then cooled. The beakers with soil samples underwent the following steps: 1) heated in a muffle furnace at 105°C for 24 hours; 2) cooled to room temperature in desiccators over CaCl2; 3) soil weight measured to the nearest 0.1 mg; 4) heated in a muffle furnace at 400°C for 16 hours; 5) cooled in desiccators over CaCl2; and 6) weight of ignited soil measured to the nearest 0.1 mg. The percentage mass loss of the soil, relative to its dry weight, was then calculated following equation 1 (McCarty et al., 2010).

$$\mathrm{SOM}\ (\%) = \frac{(\mathrm{Weight105} - \mathrm{Weight400})}{\mathrm{Weight105}}\ x\ 100 \qquad (1)$$

Soil organic carbon (SOC) was obtained from estimated SOM (%) using the conventional conversion equation (2) (Morisada et al., 2004).

$$\mathrm{SOC}\ (\%) = 0.58 \times \mathrm{SOM}\ (\%) \qquad (2)$$

Where SOC is the percentage of soil organic carbon in one gram of carbon per 100 g of soil.

Soil carbon stock (SCS) per unit area was calculated using equation 3 (Pimentel, 1997).

$$\mathrm{SCS} = \mathrm{e\ x\ BD\ x\ SOC}(\%)\mathrm{x}10 \qquad (3)$$

Where SCS indicates the amount of carbon stock in the soil in ton/ha at a certain depth, e is the soil depth (meter), SOC represents the organic carbon mass in gram carbon per 100 g of soil, and BD denotes the soil bulk density in gram per cubic centimetre.

4.2.4 Statistical analysis

All the analyses were performed using R 4.1.2 software. Variables were first investigated for normal distribution using the Anderson-Darling test, and homogeneity of variance was checked using Levene’s test. The analysis of variance (ANOVA) followed by Tukey’s honestly significant difference (HSD) test at an error probability of 5% was used to evaluate the effect of corralling on soil chemical properties, soil physical properties, and maize yield. Correlation analysis was performed to describe the relationship between all the variables. The relationships among soil bulk density (BD), soil macronutrients (NPK), corralling yield (CY, meaning year since when the field has been corralled, here ranging from 0 to 7) soil hydraulic conductivity (HC), SOM, SOC, SCS, and yield variables, were examined by performing Person's multiple correlations and a structural equation modelling (SEM) using the Lavaan package (Rosseel, 2012) in R software version 4.0.5. Given the context of the variables, the Structural Equation Model (SEM) is as follows: i) yield is influenced by all the other variables, ii) there may be correlations among the soil properties (e.g., N, P, K, pH, SCS), and iii) there may also be causal relationships between some of the soil properties. The standardized path coefficients, resulting from the SEM, reflect the change in the dependent variable (in standard deviations) for a one-standard-deviation change in the predictor variable. The values of the standardized path coefficients range from -1 to +1, where positive values indicate a positive relationship; negative values indicate an inverse relationship; and values closer to ±1 indicate stronger relationship between dependent and independent variable. To ensure that each variable contributes equally to the correlation and SEM, standardized values (z-scores) were used to convert all variables to have a mean of zero and a standard deviation of one before analysis. For each variable, the z-score was calculated using the formula: $Z = (X-\mu)/\sigma$, where X is the value of the variable, μ is the mean, and σ is the standard deviation.

4.3. Results

4.3.1. Farms surveyed characteristics and yield estimation

The surveyed fields exhibited identical characteristics (Table 4.1). It appeared that the number of cattle corralled (young and adult) and the duration of corralling did not differ significantly ($p > 0.05$) from one field to another. The fields visited covered an area of 1 ha with a loamy-sandy texture. The control fields had an average maize yield of 1.6 t/ha which was more or less identical to those observed in the corralled fields from 4 years ago (1.5 t/ha), 5 years ago (1.3 t/ha), 6 years ago (1.1 t/ha), and 7 years ago (1.2 t/ha). A progressive yield decrease was observed as the duration of corralling increased. The best yields were observed in fields corralled every year (2.8 t/ha) and fields corralled one year ago (2.5 t/ha).

Table 4.1. Description of corralled farms surveyed in the municipality of Gogounou

Farms surveyed	**Average number of adult cattle**	**Average number of yearling cattle**	**Average corralling duration (week/ha)**	**Area (ha)**	**Yield (t/ha)**	**Topsoil texture**
C0	28.7a	12.0a	2.0a	1.0a	1.6a	Sandy-Loam
C1	32.0a	13.0a	2.0a	1.0a	2.5bc	Sandy-Loam
C2	37.3a	12.7a	2.7a	1.0a	1.8ab	Sandy-Loam
C3	31.3a	13.3a	2.3a	1.0a	1.8ab	Sandy-Loam
C4	27.7a	11.3a	2.3a	1.0a	1.5a	Sandy-Loam
C5	36.0a	10.7a	2.3a	1.0a	1.3a	Sandy-Loam
C6	29.7a	8.3a	2.7a	1.0a	1.1a	Sandy-Loam
C7	26.3a	9.0a	2.7a	1.0a	1.2a	Sandy-Loam
EY	28.0a	9.7a	2.3a	1.0a	2.8c	Sandy-Loam
			ANOVA			
Sd	6.93	2.78	0.74	0	2.21	-
P-value	0.685	0.28	0.937	0.74	< 0.0001	-

Sd: standard deviation of means. Anova: Analysis of variance. Similar letters indicate no significant difference at the 5% level. C0: Cultivated controls, CF: fallow control, EY: farm corralled every year, C1: farm corralled 1 year previously, C2: farm corralled 2 years previously, C3: farm corralled 3 years previously, C4: farm corralled 4 years previously, C5: farm corralled 5 years previously, C6: farm corralled 6 years previously, and C7: farm corralled 7 years previously, -: non-applicable

4.3.2 Cattle corralling impact on soil hydraulic conductivity (K) and soil bulk density (BD)

Soil hydraulic conductivity increased progressively with the number of years since the fields were corralled (Figure 4.2a). The fields corralled in the current year (0.001 cm/s) and the fields corralled every year (0.0013 cm/s) showed the lowest values, while the highest values were observed in the control fields (0.005 cm/s), fields corralled 5 years ago (0.005 cm/s), fields corralled 6 years ago (0.006 cm/s), and fields corralled 7 years ago (0.0067 cm/s). The bulk density of the soil decreased progressively from the recently corralled fields to the older ones. The highest BD were observed in fields corralled every year (1.74 g/cm³) and in fields corralled one year ago (1.66 g/cm³), while the lowest values were recorded in the control fields (1.51 g/cm³) and fields corralled 7 years ago (1.40 g/cm³) (Figure 4.2b).

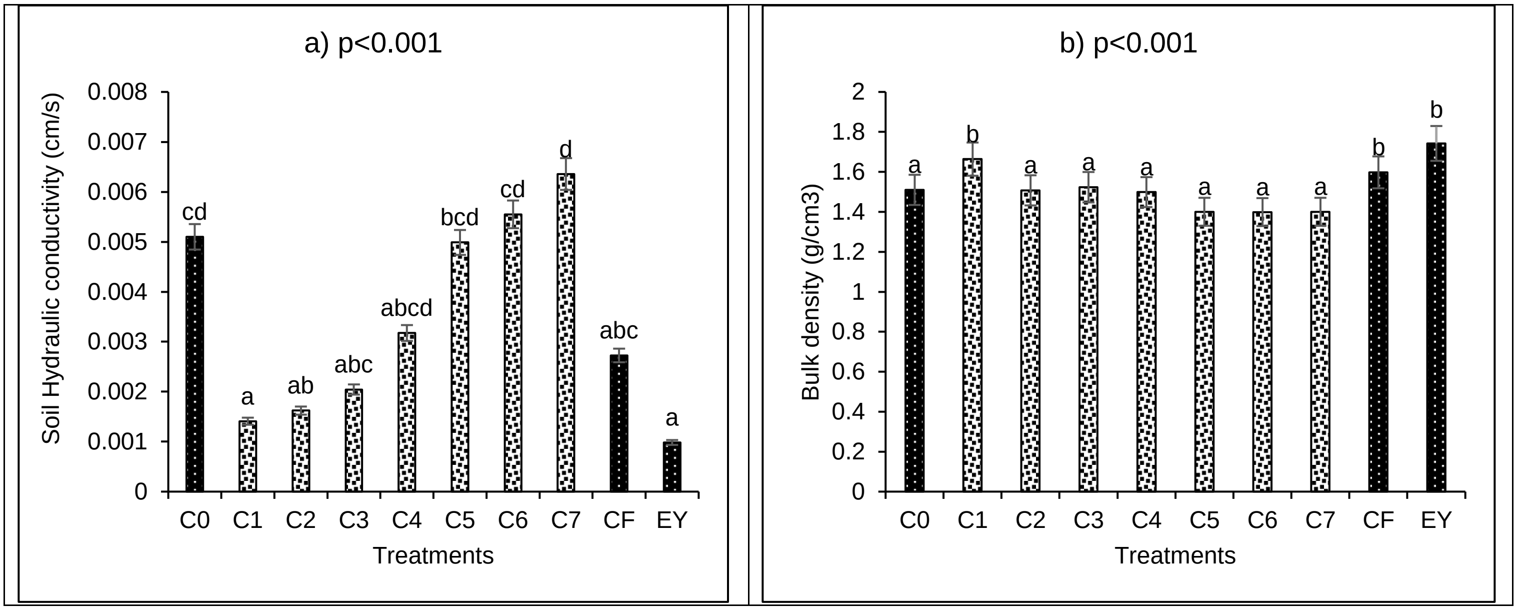


Figure 4.2. Effect of cattle corralling on soil hydraulic conductivity (a), and soil bulk density (b) over years.

Similar letters indicate no significant difference at the 5% level. C0: Cultivated controls, CF: fallow control, EY: farm corralled every year, C1: farm corralled 1 year previously, C2: farm corralled 2 years previously, C3: farm corralled 3 years previously, C4: farm corralled 4 years previously, C5: farm corralled 5 years previously, C6: farm corralled 6 years previously, and C7: farm corralled 7 years previously.

4.3.3 Benin cattle corralling impact on soil macronutrients (N, P, K) and pH over time

Soil macronutrients (NPK) were found to be more abundant in fields corralled every year (0.25 g/kg; 0.34 g/kg; 4.44 g/kg), fields corralled one year ago (0.21 g/kg; 0.24 g/kg; 3.49 g/kg), fields corralled 2 years ago (0.17 g/kg; 0.25 g/kg; 3.2 g/kg), and fields corralled 3 years ago (0.21 g/kg; 0.21 g/kg; 1.32 g/kg). The lowest values were recorded in the control fields (0.02 g/kg; 0.14 g/kg; 1.08 g/kg) and in fields corralled 6 and 7 years ago. The fields corralled every year and those corralled one year ago were found to be more acidic (pH = 5.6 and 6.3, respectively) than the control fields (pH = 7.4) and the other studied fields (pH > 7, Table 4.2).

Table 4.2. Water extractable soil macronutrients (N, P, K) and pH variation over time under cattle corralling practice

Farms surveyed	**Nitrogen (mg/kg)**		**Phosphorus (mg/kg)**		**Potassium (mg/kg)**		**pH**	
	Mean	**Sd**	**Mean**	**Sd**	**Mean**	**Sd**	**Mean**	**Sd**
C0	0.02a	0.02	0.14abc	0.01	1.08bc	0.18	7.4bc	0.28
C1	0.21bcd	0.01	0.24cd	0.04	3.49de	0.01	6.29ab	0.41
C2	0.17abcd	0.05	0.25cd	0.01	3.20d	0.28	7.14bc	0.02
C3	0.21bcd	0.01	0.21bcd	0.01	1.32c	0.09	7.84c	0.04
C4	0.10abc	0.04	0.18abcd	0.03	1.61c	0.01	7.45bc	0.01
C5	0.08abc	0.09	0.11ab	0.01	0.17ab	0.01	7.36bc	0.09
C6	0.04ab	0.04	0.14abc	0.07	0.14a	0.03	7.64c	0.69
C7	0.02a	0.01	0.07a	0.04	1.05bc	0.07	7.36bc	0.09
CF	0.33d	0.05	0.16abc	0.01	2.70d	0.57	7.5bc	0.42
EY	0.25cd	0.03	0.37e	0.01	4.40f	0.23	5.55a	0.21
Anova (P-value)	<0.001		< 0.001		< 0.001		< 0.001	

Anova: Analysis of variance. Similar letters indicate no significant difference at the 5% level. C0: Cultivated controls, CF: fallow control, EY: farm corralled every year, C1: farm corralled 1 year previously, C2: farm corralled 2 years previously, C3: farm corralled 3 years previously, C4: farm corralled 4 years previously, C5: farm corralled 5 years previously, C6: farm corralled 6 years previously, and C7: farm corralled 7 years previously.

4.3.4 Cattle corralling impact on soil organic carbon (SOC) and soil carbon stock (SCS) over time

The analysis of variance (ANOVA) showed significant differences across treatments for SOM, SOC, and SCS ($P < 0.01$; Table 4.3). The fields corralled every year (EY) had the highest SOM (2.5%), significantly higher than other treatments. The control fallow fields (CF) and fields corralled 5 years previously (C5) also exhibited relatively high and similar SOM values ($P>0.05$). The cultivated control fields (C0) and other fields corralled in years 1, 4 and 7 consistently showed lowest SOM percentages, with values ranging from 0.4% to 0.8%. Fields corralled every year raised out with the highest SOC (1.4%), followed by the control fallow fields (0.7%) and the fields corralled 5 years ago (C5, 0.6%). The lowest SOC values were observed in the C0 and C7 fields (0.3% and 0.2%, respectively). The highest carbon stocks were observed in the EY fields of (46.6 Mg/ha). The CF fields and fields corralled 5 years ago (C5) also maintained relatively highest SCS values (21.5 and 20.2 Mg/ha, respectively). In contrast, the C0, C1, and C7 fields exhibited the lowest SCS values (11, 13.3, and 7.6 Mg/ha, respectively).

Table 4.3. Soil organic matter (SOM), soil organic carbon (SOC), and soil carbon stock (SCS) variation over time under cattle corralling practice

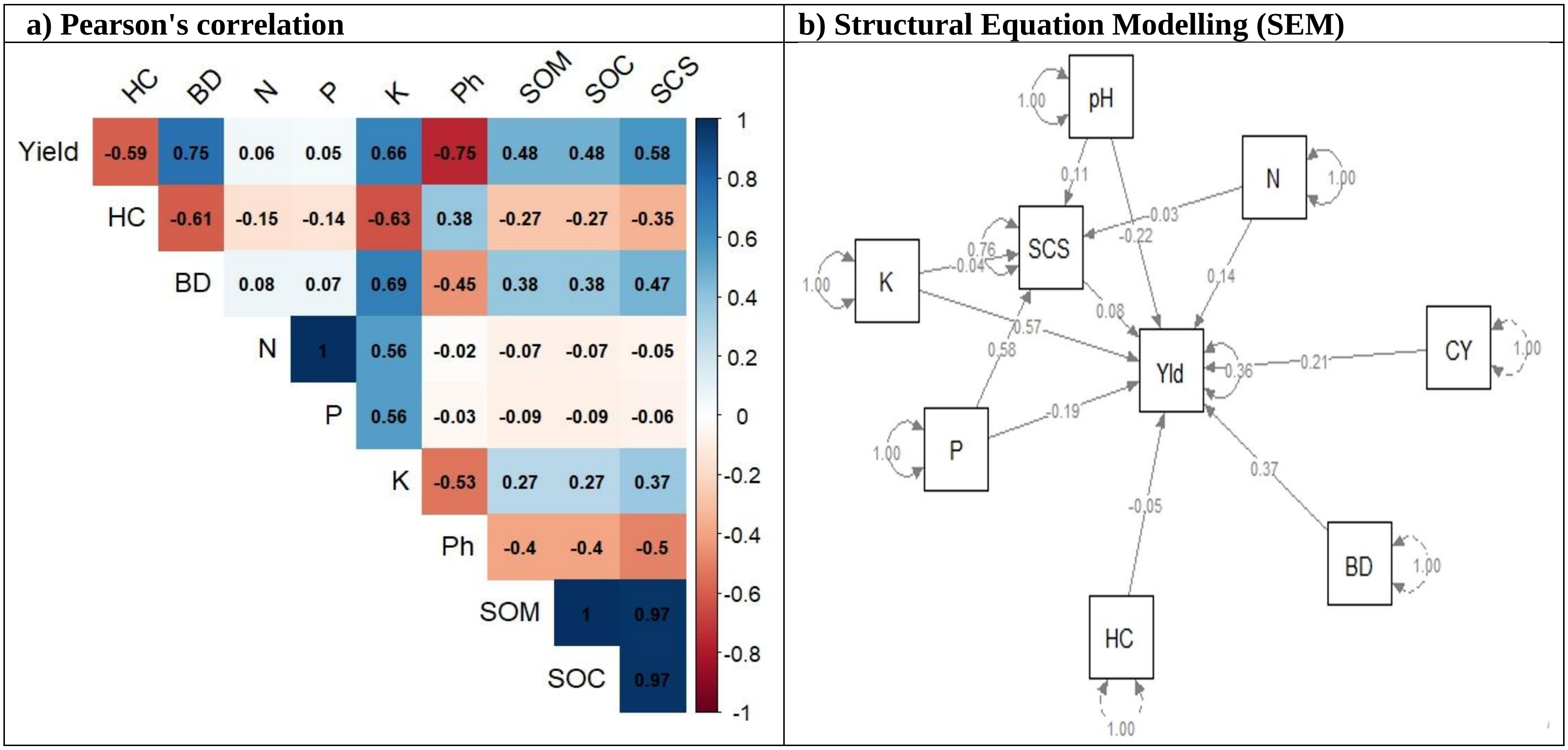
Farms surveyed	SOM (%)		SOC (%)		SCS (Mg/ha)	
	Mean	Sd	Mean	Sd	Mean	Sd
C0	0.6a	0.1	0.3a	0.1	11a	2.2
C1	0.7a	0.1	0.4a	0.1	13.3a	0.1
C2	0.7a	0.1	0.4a	0.1	13.2a	0.1
C3	0.6a	0.1	0.3a	0.1	11.3a	0.1
C4	0.8a	0.3	0.4a	0.2	14.6a	5.3
C5	1.1ab	0.6	0.6ab	0.3	20.2ab	10.9
C6	0.9ab	0.2	0.5ab	0.1	17.6ab	2.9
C7	0.4a	0.1	0.2a	0.1	7.6a	0.1
CF	1.1ab	0.5	0.7ab	0.3	21.5ab	9.4
EY	2.5b	0.5	1.4b	0.9	46.6b	27.7
Anova (P-value)	0.009		0.009		0.008	

SOM: Soil Organic Matter, **SOC**: Soil Organic Carbon, and **SCS**: Soil Carbon Stock. **Sd**: standard deviation of means. **Anova**: Analysis of variance. Similar letters indicate no significant difference at the 5% level. C0: Cultivated controls, CF: fallow control, EY: farm corralled every year, C1: farm corralled 1 year previously, C2: farm corralled 2 years previously, C3: farm corralled 3 years previously, C4: farm corralled 4 years previously, C5: farm corralled 5 years previously, C6: farm corralled 6 years previously, and C7: farm corralled 7 years previously.

4.3.5 Relationship between maize yield and soil properties

Figure 4.3.a) shows a strong positive correlation between maize grain yield and soil parameters such as bulk density (BD), potassium (K), SOM, SOC, and SCS, while hydraulic conductivity and pH showed a strong negative correlation with yield. The structural equation model showed a direct positive path correlation of BD, corralling year (CY), K, SCS, and nitrogen on maize yield. The

negative standardized path coefficients were observed with HC, pH, and phosphorus on yield (Figure 4.3.b). An indirect positive correlation was found from N, P, K, and pH on maize yield through SCS.


a) Pearson's correlation

b) Structural Equation Modelling (SEM)

Figure 4.3. Relationship between maize yield and the soil properties parameters

a) shows Pearson's correlation b) shows Structural Equation Modelling (SEM) HC: Hydraulic conductivity, BD: bulk density, N: nitrogen, P: phosphorus, K: potassium, pH, SOM: soil organic matter, SOC: soil organic carbon, SCS: soil carbon stock, CY: corralling year. Model fit statistics: Chi-square ($\chi 2$): 63.71; P-value: 0.001; Degree of freedom (df): 11; Root Mean Square Error of Approximation (RMSEA): 0.076; Comparative fit index (CFI): 0.66. The numbers above the arrows denote the standardized path coefficients. It reflects the change in the dependent variable (in standard deviations) for a one-standard-deviation change in the predictor variable. Values range from -1 to +1; Positive values indicate a positive relationship; Negative values indicate an inverse relationship, and Values closer to ±1 indicate stronger relationships.

4.4 Discussion

4.4.1 Impact of cattle corralling on soil physicochemical properties

Cattle corralling has notable effects on the physicochemical properties of soil, particularly enhancing soil fertility and carbon stocks. The study revealed significant effects on soil organic matter (SOM) and, consequently, on soil organic carbon (SOC) levels in fields corralled every year (EY) comparable to the SOC levels in control fallow fields (CF), and alongside higher soil carbon stocks (SCS). These results align with previous research that highlights the positive impact of annual rotations receiving manure on soil health (Augarten et al., 2023). For instance, Verma et al. (2020) and Rayne et Aula, (2020) noted that manure application contributes to soil organic carbon, which is crucial for maintaining soil health. Manure application can improve soil fertility, physical properties, and biological characteristics, although effects may vary depending on manure type and environmental conditions (Rayne and Aula, 2020). Grazing strategies also influence soil health, with rotational grazing showing substantial benefits over continuous grazing in terms of soil organic carbon and bulk density (Byrnes et al., 2018). Soil health management practices, including crop rotations, cover crops, and organic amendments, generally have positive effects on soilborne disease management by increasing microbial biomass, activity, and diversity (Larkin, 2015). However, the findings also contrast with those by Folberth et al. (2014), who observed limited effectiveness of green manure under highly adverse climatic conditions. This study contributes to the existing literature by providing specific data on soil organic carbon dynamics in the sub-humid context of northern Benin, thus filling a critical knowledge gap.

The analysis of key results shows that fields corralled annually (EY) and control fallow fields (CF) had the highest SOM and SOC levels, indicating enhanced soil fertility. These findings suggest that continuous organic input from livestock excreta significantly boosts soil carbon content. Long-term studies show that SOC and total nitrogen increase linearly with cumulative manure additions, regardless of whether applications are recent or historic (Bhogal et al., 2011; Hao et al., 2003). These improvements persist even after the cessation of applications. Manure additions enhance soil fertility, water retention, and microbial biomass while reducing bulk density (Yan et al., 2023; Bhogal et al., 2011). The quality and quantity of organic materials applied influence the extent of soil improvements, with bulky materials like compost and farmyard manure having greater impacts than low dry matter content materials (Bhogal et al., 2018). Continuous manure application also positively affects soil microbial community diversity and abundance, particularly benefiting fungi (Yan et al., 2023). However, excessive manure application through cattle corralling can lead to nitrate accumulation, potentially risking water pollution and increased N2O emissions (Hao et al., 2003). However, the need of continuous corralling may be unrealistic for smallholder farmers. Integrating biochar and cover crop to cattle corralling practice, could sustainably contribute to nutrient retention (Arif et al., 2021; Atakoun et al., 2023; Tovihoudji et al., 2022).

Moreover, the high SCS in EY and CF fields underscores the role of cattle corralling in carbon sequestration. Traditional pastoral practices, including corralling, contribute to cropland biodiversity conservation and soil carbon restoration, mitigating climate change (Seid et al., 2016). Silvopastoral systems, which integrate trees with pastures, have shown higher carbon storage potential above and belowground than single-species grazing systems (Nair et al., 2011). In the Chilean Patagonia, silvopastoral systems demonstrated a positive net carbon flux of 1.8 Mg C ha^{-1} $year^{-1}$, outperforming natural prairies regarding carbon sequestration (Dube et al., 2011). These systems can help offset carbon losses from cattle-based livestock operations while maintaining biodiversity and ecosystem services (Seid et al., 2016; Dube et al., 2011). However, the effectiveness of these practices may be compromised by factors limiting traditional management techniques and livestock mobility, potentially leading to rangeland degradation (Seid et al., 2016).

The practical implications of this study are profound for smallholder farmers in Northern Benin. The findings advocate for annual cattle corralling practices to enhance soil fertility and maize yields. By integrating livestock management with crop production, farmers can achieve sustainable agriculture that improves food security and resilience against climate change. The study's results also suggest that extension services and agricultural policies should support these practices, providing training and resources to help farmers implement effective cattle corralling techniques. While the study provides significant insights, there are methodological limitations that must be acknowledged. The reliance on farmer-reported data for yield estimation, although practical, may introduce biases. Additionally, the study's focus on a specific region and soil type limits the generalizability of the findings to other contexts.

4.4.2 Impact of cattle corralling on maize yield

The findings from this study provide strong evidence that cattle corralling has a significant positive impact on maize yield in Northern Benin. Fields corralled every year (EY) exhibited higher maize yields, primarily due to the enhanced soil fertility resulting from continuous organic matter inputs. The study revealed positive correlations between maize yield and key soil parameters such as bulk density (BD), potassium (K), soil organic matter (SOM), soil organic carbon (SOC), and soil carbon stocks (SCS). These correlations indicate that cattle corralling improves soil properties thereby enhancing crop productivity.

The continuous application of manure through cattle corralling is a major contributor to this improvement, as it boosts the soil’s organic matter content and fertility, making it more conducive to higher maize yields (Abdul Rahman et al., 2019a; Ayantunde et al., 2018b). This finding is consistent with previous research by Verma et al. (2020) and Rayne and Aula (2020), who observed that proper manure management can enhance soil fertility and increase crop yields. Manure application improves soil structure, nutrient availability, and microbial activity, all of which are crucial for supporting robust crop growth (Ayantunde et al., 2018b; Rayne and Aula, 2020).

The positive correlations between maize yield and soil parameters such as bulk density (BD), potassium (K), and SCS highlight the multifaceted benefits of improved soil health on crop productivity. This could be explained by the fact that management practices affect soil properties primarily in the upper 10 cm, with intensive management leading to denser soils and lower organic matter content (Northup and Daniel, 2010). In this study, the management practice corresponds to cattle corralling particularly in C1 (field corralled one year ago) and CY, where higher BD, SOM, and maize yield were recorded. However, the study also identified certain negative correlations, particularly with hydraulic conductivity (HC) and pH, suggesting that excessive soil compaction and soil acidity, limiting crop productivity. Compaction, caused by livestock trampling, increases bulk density and reduces soil porosity, thereby impairing root development and water infiltration, which are critical for plant growth (Shaheb et al., 2021). This leads to significant yield reductions, particularly in situations where compaction is severe, potentially reducing crop yields by up to 50% (Shaheb et al., 2021). This could be observed under CY treatment but the nutrient inputs each year may alleviate this effect, whereas the effect was more visible under C3 (field corralled three years ago) and C4 (field corralled four years ago). The practical implications of these findings are significant for smallholder farmers in the region. By adopting regular cattle corralling practices, farmers can improve their soil quality and, consequently, maize yields. This integrated approach to livestock and crop management aligns with sustainable agricultural practices, contributing to enhanced food security and resilience to climate change. Extension services and agricultural policies should support these practices by offering training (on their proper practice) to farmers, as the study suggests, to promote the successful implementation of cattle corralling as a strategy for improving maize yield. Future research should employ more precise yield measurement techniques and expand the study area to include diverse agroecological zones to validate and broaden the applicability of the results.

4.5. Conclusion

This study assesses the influence of cattle corralling-based practices on soil properties, and nutrient content, as well as their impact on maize production in northern Benin. It reveals that fields corralled every year (EY) and control fallow fields (CF) exhibited the highest levels of soil organic matter (SOM) and soil organic carbon (SOC), significantly outperforming control fields (C0). EY and CF fields also demonstrate superior soil carbon stocks (SCS), while fields corralled several years ago (C3 to C7) had the lowest SCS. There is a strong positive correlation between maize grain yield and soil parameters such as bulk density (BD), potassium (K), SOM, SOC, and SCS, while hydraulic conductivity (HC) and pH show negative correlations. Annual corralling (EY) led to the highest maize yields, underscoring the benefits of regular livestock corralling for soil fertility and crop production. The study confirms that cattle corralling-based practices significantly improve soil health, by enhancing organic matter, carbon content, and carbon stock, supporting sustainable agricultural productivity and resilience against climate change impacts in semi-arid regions like Northern Benin. Further research must focus on i) studying the effects of cattle corralling on soil microbial biodiversity and ecosystem functions, including nutrient cycling and disease suppression, and ii) exploring the optimal duration and intensity of cattle corralling to maximize soil fertility and crop productivity without causing soil compaction or degradation.

CHAPTER 5: ASSESSING THE CONTRIBUTION OF CATTLE CORRALLING ON MAIZE PRODUCTION UNDER DEFICIT AND ADDITIONAL IRRIGATION

Manuscript: Effect of cattle corralling-based fertilization on maize production under deficit and full irrigation in Northern Benin; A. M. Atakoun, P. G. Tovihoudji, R. V. C. Diogo, W. Amponsah, M. dos Santos Vianna, T. Gaiser, N. Kyei-Bafour, B. Kyereh

ABSTRACT

The study investigates the combined impact of cattle corralling-based fertilization and irrigation management on maize (Zea mays L.) production in Northern Benin, a semi-arid region prone to water scarcity. Conducted over two seasons (2023–2024), the experiment utilized a strip plot design to assess the impacts of organic soil amendments (including control, cattle corralling, cattle corralling+biochar, and cattle corralling+biochar+maize straw mulching) combined with two irrigation modalities (full irrigation and deficit irrigation). The primary outcomes evaluated included maize growth, yield performance, nutrient factor productivity (NFP), water use efficiency (WUE), and soil carbon inputs. Results revealed that cattle corralling-based fertilization significantly enhanced maize growth and yield, with the highest performance observed under full irrigation conditions. The treatment combining cattle corralling, biochar, and mulching (T8) yielded 3.97 t/ha of biomass and 4.29 kg/ha/mm WUE in 2023. In contrast, under deficit irrigation, yields were markedly lower (e.g., 2.18 t/ha for T8 in 2024), underscoring the critical role of water availability. Soil carbon inputs were highest in T8, contributing up to 0.05 t C/ha aboveground and 0.12 t C/ha belowground in 2023, confirming the potential of organic amendments for carbon sequestration. Water use efficiency and nutrient productivity declined under water stress, with WUE dropping by approximately 36% for T8 between 2023 (4.29 kg/ha/mm) and 2024 (2.73 kg/ha/mm). This highlights the sensitivity of maize to water scarcity, even with enhanced soil fertility. Biochar and cattle corralling synergistically improved soil water retention, resulting in increased WUE and sustainable nutrient cycling. This research underscores the importance of integrating organic fertilization with precise irrigation to achieve sustainable agricultural intensification in water-limited environments. The findings provide actionable insights for policymakers and practitioners aiming to enhance food security and climate resilience in sub-Saharan Africa.

Keywords: Soil fertility management, Biochar, Mulching, Water use efficiency (WUE), Nutrient factor productivity (NFP), Soil carbon input

5.1 Introduction

Maize (Zea mays L.) is a key cereal crop globally, ranking as the third most important after wheat and rice (Foley et al., 2020). It holds particular importance in Sub-Saharan Africa, including Northern Benin, where it serves as a staple food and plays a pivotal role in food security (Ekpa et al., 2018; ten Berge et al., 2019; Tesfaye et al., 2015). However, maize production is highly vulnerable to climate variability, particularly droughts, which have become more severe, prolonged, and frequent due to climate change (Ayanlade et al., 2018; Cairns et al., 2012; Omoyo et al., 2015; Thornton et al., 2014). Drought stress poses a significant challenge to maize production, impacting both the yield and quality of the crop (Wossen et al., 2017). Given that maize requires approximately 450-600 mm of water per season, with each plant consuming up to 250 liters of water by maturity, ensuring adequate soil moisture is essential for optimal productivity (Du Plessis, 2003). This context highlights the critical need for sustainable strategies to enhance maize drought tolerance, especially in regions prone to water scarcity.

Cattle corralling, a traditional practice of confining livestock overnight to deposit manure, offers a potential solution for enhancing soil fertility (Diarisso et al., 2015; Hoffmann et al., 2001b; Powell, 2014; Powell et al., 2004). Corralling-based fertilization is an accessible method for many smallholder farmers and has shown promise in enhancing soil nutrient content, water retention, and soil health generally (Abdul Rahman et al., 2019; Duiker and Zampaligre, 2022; Mason et al., 2015; Rahman et al., 2019). Despite its traditional use in various West African farming systems, limited research exists on the interaction between cattle corralling-based fertilization and irrigation strategies under drought conditions in maize cultivation, particularly in Northern Benin. Given the agroecological challenges faced in this region, there is an opportunity to explore how this organic fertilization method might optimize maize production when combined with specific water management approaches.

Water availability is a key determinant of crop yield, particularly in semi-arid regions (Lamptey, 2022; Golla, 2021). Deficit irrigation, which involves applying less water than the full crop requirement (Wang et al., 2023; Zou et al., 2021), and additional irrigation, which aims to ensure full water supply (Cakmakci and Sahin, 2021), are two strategies used to manage limited water resources. The effectiveness of these strategies can be influenced by soil fertility, with cattle corralling-based fertilization potentially playing a crucial role in improving water use efficiency and yield outcomes. The integration of organic fertilization and appropriate irrigation could thus provide a sustainable means of enhancing maize production in water-limited environments.

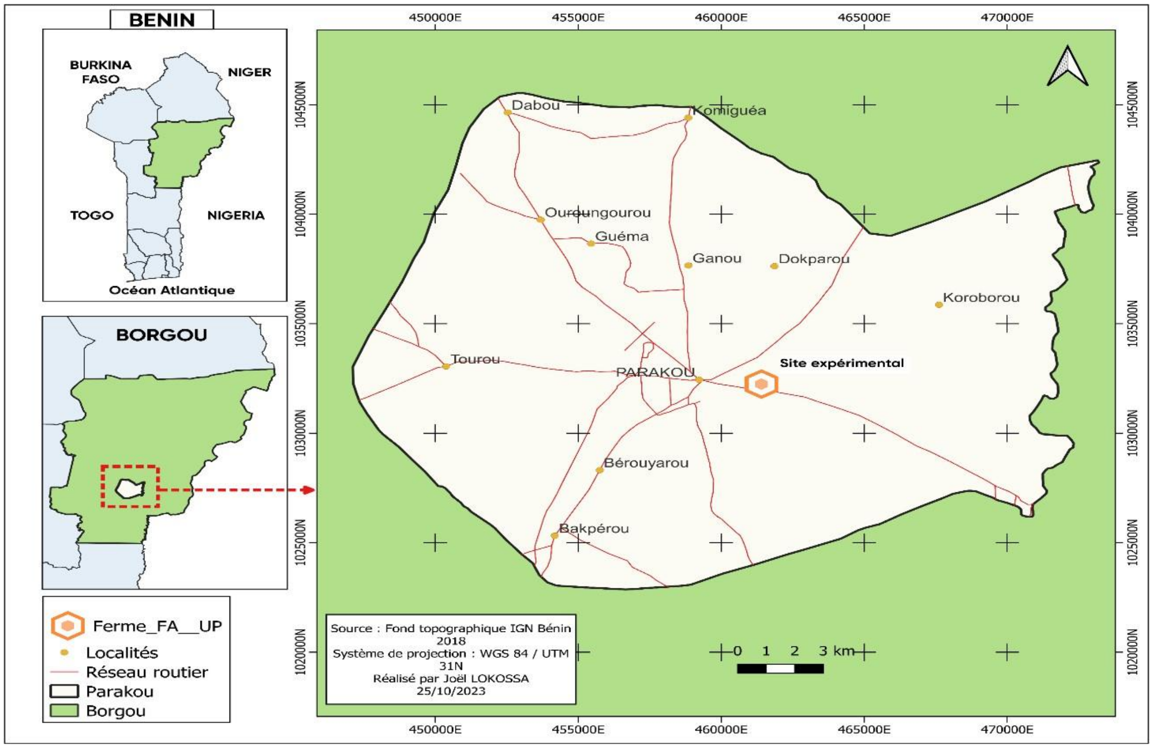
Studies have shown that fertilization can mitigate deficit irrigation stress and improve maize performance (Wang et al., 2023; Li et al., 2022; Zamora-Re et al., 2020). In West Africa, nitrogen application has significantly increased maize yields under drought conditions, especially in cultivars tolerant to both drought and Striga (Badu-Apraku et al., 2013; Kamara et al., 2012, 2003). Additionally, animal manure amendments, such as cattle manure, improve soil structure and water-holding capacity, leading to better crop growth and resilience (Iqbal et al., 2019; Sánchez-Báscones et al., 2019). The use of biochar, derived from organic matter like manure, is also growing rapidly and shows potential for enhancing soil fertility and water retention (Abiola et al., 2023; Davis, 2023). However, there remains a knowledge gap regarding the specific effects of cattle-based corralling on maize yield and water stress mitigation under varying irrigation regimes (Li et al., 2023).

Therefore, this study aims to evaluate the effect of cattle corralling-based fertilization on maize production under deficit and additional irrigation conditions in Northern Benin. By assessing this traditional fertilization method within the context of water management practices, the research seeks to contribute to sustainable agricultural strategies that enhance maize productivity, improve drought tolerance, and address food security challenges in water-limited environments.

5.2 Materials and methods

5.2.1. Study site

The two-year experiment was conducted in research station conditions during the rainy season (June-September 2023) and dry seasons (February-May 2024) at the Agronomic Research Station, University of Parakou, Benin. It is located on the northeast side of the university at coordinates (9°33’77’N; 2°64’87’99 E) with an altitude of 369 meters (Figure 5.1). The region's climate is Sudanese, characterized by two seasons: a rainy season from May to October and a dry season from November to April. The site receives an annual rainfall average of 1000-1200mm. The average soil properties of the field experiment indicate suitability for agricultural production (Table 5.1). The selection of this site for the trial was based on water availability, site security, and easy access to tools and equipment essential for the trial's proper execution.



Source : Fond topographique IGN Bénin 2018
Système de projection : WGS 84 / UTM 31N
Réalisé par Joël LOKOSSA
25/10/2023

Figure 5.1. Location map of the study site

Table 5.1. Soil characteristics (horizon 0-20cm)

Characteristics	Initial soil	Biochar
Sand, %	80	-
Silt, %	12	-
Clays, %	8	-
Nitrogen (N), %	0.05	0.31
Phosphorus (P), %	0.89	0.28
Potassium (K), %	0.16	2.14
Sodium (Na), mg/kg	0.43	961.28
pH water	5.74	10.21
Ash, %	-	13.76
MS, %	-	89.00
Organic carbon, %	0.30	50.03
OM (%)	0.7	-

5.2.2 Experimental design and treatments

A strip plot design was used for the trial due to a superimpose cattle corralling application on the site, and each treatment was repeated thrice. The experiment included two water application modalities: full crop water needs (I0) and water stress (I1). For the rainy season experiment (2023) the full crop water needs application was rainfall plus additional irrigation to reach the maize water need, while the water stress application was only rainfall without additional irrigation.

Four levels of soil amendment with one control (F0 = control, F1 = cattle corralling, F2 = cattle corralling under maize straw mulching, F3= cattle corralling under biochar, F4= cattle corralling under biochar + maize straw) were applied on each plot. Therefore, we had ten treatments ($\mathbf{T_1}$=I_0F_0, $\mathbf{T_2}$=I_0F_1, $\mathbf{T_3}$=I_0F_2, $\mathbf{T_4}$=I_0F_3, $\mathbf{T_5}$=I_0F_4, $\mathbf{T_6}$=I_1F_0, $\mathbf{T_7}$=I_1F_1, $\mathbf{T_8}$=I_1F_2, $\mathbf{T_9}$=I_1F_3, $\mathbf{T_{10}}$=I_1F_4). For mulching, the variety has a potential yield ranging from 4 to 5.1 t/ha, with a corresponding harvest index of 0.51 (Abadassi, 2001), and biomass production is estimated at approximately 9 t/ha. For our plots (9 m²), we applied 7.8 kg per plot (8.67 t/ha). Regarding biochar, 4 t/ha was used based on the literature (Houben et al., 2017). Both mulching and biochar applications were done before corralling. Knowing that a LU (Livestock Unit) with an average weight of 317 kg produces an average of 1.44 kg of dry matter per night and 3.40 litters of urine per night (Ayantunde et al., 2018b; Kasse, 2019), the computation was done to determine the number of cattle that was confined on the single plot to have 8.2t of dry manure per hectare (Tovihoudji, 2018). Corralling was performed on a given plot from 6-7 pm to 8-9 am. The net plot size was 3 × 3 m, and a buffer plot was kept to avoid the effect of soil moisture from neighbouring plots (Farhad et al., 2018; Khalili et al., 2013). Five overnight corralling with two cattle confined per plot was enough to reach 8.2 t ha^{-1} from these conditions. After the corralling treatment application, the real quantity of cattle dung deposited was determined using three quadrats (0,5m x 0,5m) for each plot before sowing. The dung was weighted from each quadrat for total estimation (13.2 t/ha of fresh dung in 2023, and 14,6 t/ha of fresh dung in 2024). Cattle dung nutrient content was assumed to be 3.0 g/kg of N, 0.6 g/kg of P, and 4.1 g/kg of K (Gbenou et al., 2017).

5.2.3 Crop management

The maize variety DMR-ESR-W (Downy Mildew Resistant, Early-Streak Resistant – White) was used (for the 2023 and 2024 experiments), known for its sensitivity to drought and a 90-day growth cycle. Certified seeds were procured from the Agricultural Research Center of INA.

Maize was planted on 07 June 2023 and 17 February 2024, with three seeds per hole. After two weeks, the seedlings were thinned to two plants per hole, resulting in a final density of 62,500 plants per hectare (using 0.8 m × 0.4 m spacing). During the dry season, the full crop water needs were supplied through full irrigation, while for the water stress application, irrigation was reduced to 50% during two weeks at two growth periods: vegetative (20 to 60 days after sowing) and flowering (60 to 80 days after sowing) stages. Stress was introduced at the vegetative stage, starting 21 days after planting and lasting two weeks. It was then reapplied at the flowering stage, following the emergence of flower buds (65 days after sowing), for another two-week period (Ge et al., 2012). These irrigation treatments were randomly distributed across the plots. In all treatments, the plants were well-watered twice daily (morning and evening) up to 21 days after planting to prevent water stress, ensure uniform germination, and support robust seedling establishment. The FAO Penman-Montheith methodology through the CROPWAT 8.0 Windows program and CLIMWAT 2.0 Windows program was used for water-supplying scheduling at 2 mm depletion.

5.2.4 Data collection

5.2.4.1 Maize growth and yields

The data were collected at 15 Days After Sowing (DAS), 30 DAS, 45 DAS, 60 DAS, 75 DAS, and 90 DAS. Biomass was measured by destructively sampling entire plants from two planting holes on each sampling date. Leaf area measurements were obtained in each experimental plot by randomly tagging three plants from three different planting holes in the three middle rows designated for final biomass measurement. Every two weeks, green leaf length and maximum width were measured with a ruler, and leaf area (LA) was calculated using the formula: (LA) = Leaf length * maximum width * k, where k is a shape factor with the value of 0.75. The leaf area index (LAI) was calculated as the ratio of LA to the soil surface area of the hill. Final harvesting was carried out by hand, and aboveground biomass plus grain yields were recorded as described by Tovihoudji et al. (2017).

5.2.4.2 Water use efficiency (WUE)

Maize total evapotranspiration (ET, in mm) was determined over the course of the growing season by applying the water balance equation, expressed as follows:

$$\mathrm{ET} = \mathrm{P} + \mathrm{I} + \mathrm{Cr} - \mathrm{Rf} - \mathrm{Dp} \pm \Delta\mathrm{S} \ (1)$$

where ET is the total evapotranspiration (mm) during the growing season, P is the total precipitation (mm), I is the irrigation water amount (mm), Cr is the capillary rise (mm), Rf is the runoff (mm), Dp is the percolation (mm), and ΔS is the change in soil water storage at planting and harvesting (mm).

In Equation (1), Cr is considered to be zero because the groundwater table depth is consistently below 20 m; runoff is also considered to be insignificant because all the experimental plots were flat, and D p is assumed negligible because the soil water content below 80 cm did not reach field capacity (FC) on any sampling date.

The soil water storage was calculated as the product of the soil volumetric moisture by the soil depth according to Eq. 2. Soil volumetric moisture measurements were taken in three quadrats of 0.25m-2 located midway between two lines of or maize, using a calibrated portable moisture meter (Lutron PMS-714, Taiwan) at 30cm depth. These measurements were taken at sowing, and 75 DAS of maize.

$$\Delta S = \Theta\text{v x h x } 10 \quad (2)$$

Where SWS is the soil water storage at a specific depth (mm), θv is the soil volumetric moisture at a particular depth (cm3 cm3), and h is the soil depth increment (cm). Water-use efficiency (WUE, kg ha^{-1} mm^{-1}) was calculated as the ratio of grain yield and the total water consumption for the whole season: $\text{WUE} = \frac{Y}{ET} \quad (3)$

Where Y is the maize yield (kg ha^{-1}), ET is the total evapotranspiration for the whole growing period season (mm).

5.2.4.3 Nutrients (NPK) factor productivity

Factor productivity (FP) referring to the efficiency with which plants convert applied nutrients (like nitrogen, phosphorus, and potassium) into yield or biomass, has been determined here as followed:

$$FP_{\{N,P,K\}} = \frac{Y_{T\ \{N,P,K\}}}{N,P,K_{(applied)}} \quad (4)$$

Where $FP_{\{N,P,K\}}$ refers to factor productivity for N, P, or K. Y_T refers to maize grain yields (kg ha^{-1}) in the treatments with mineral (N, P, K) fertilizer. $N, P, K_{(applied)}$ is the amount of mineral (N, P, K) fertilizer applied (kgN ha^{-1}, kgP ha^{-1}, kgK ha^{-1}).

5.2.4.4 Quantities of biomass and rhizodeposition

The inputs of C to the soil from aboveground and belowground crop biomass (AGB and BGB) were calculated from data on crop yields, C content in biomass, and information on crop residue management, using average values for the harvest index (HI=Yield/(ABG+Yield)), the root:shoot ratio (RSR). We used a HI of 0.51 and RSR of 0.16 for maize to calculate total AGB and BGB (Cao et al., 2011; Craufurd et al., 2002; Diels et al., 2004; Gregory and Reddy, 1982; Wang et al., 2020). The C contents were considered to be 20% for maize AGB residues (Solomon et al., 2007), 45% of BGB in the topsoil for rhizodeposition (Balesdent and Balabane, 1992; Qian et al., 1997), 1.7% of cattle dung dry matter (Gbenou et al., 2017).

5.2.5 Statistical analysis

The data collected during the experimentation were entered using Microsoft Excel version 2016 and analysed using R.4.1.2 software. A variance analysis was conducted on these data. The homogeneity of variance was assessed using the Levene test to examine the differences between the effects of treatments on growth and yield parameters. Mean separations were performed using the Tukey test at a significance level ($p < 0.05$) to identify significant relationships between the treatments.

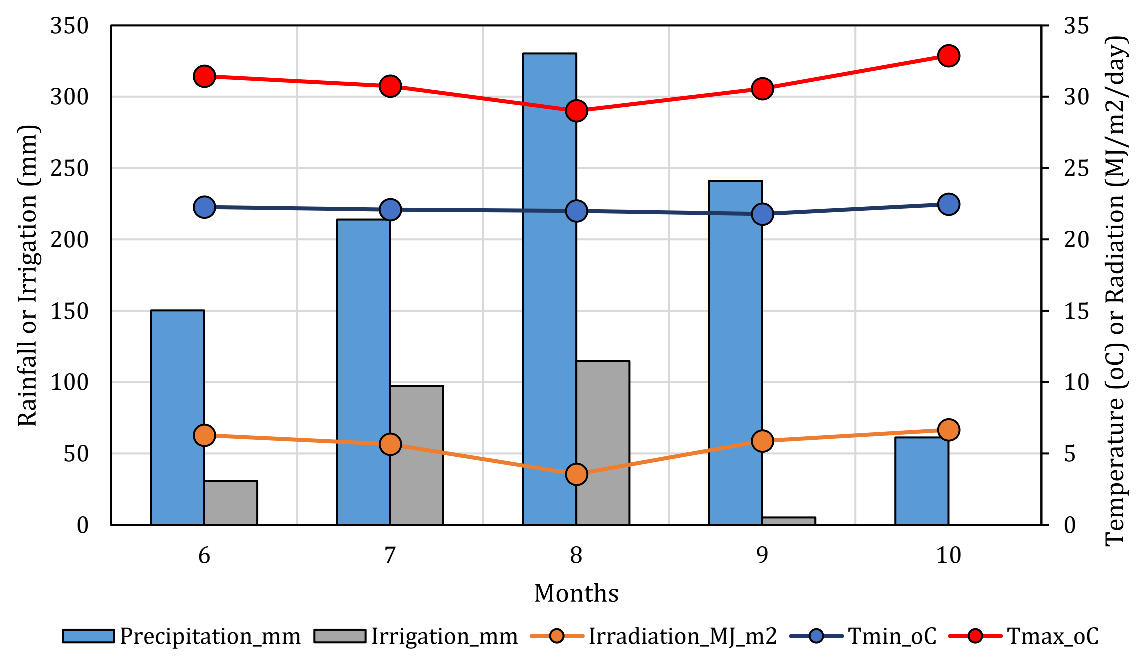
5.3 Results

5.3.1. Rainfall and Irrigation

During the 2024 field experiment, the total rainfall gradually increased from very low levels in the early months (0.02 mm in January) to moderate levels in May (27.38 mm). The precipitation for these five months was relatively low. However, irrigation was substantial in the same period, particularly in April (460.00 mm) and March (252.69 mm), compensating for the lack of rainfall during this period (Figure 5.2a).

For the 2023 experiment, the rainfall increased significantly in mid-year, peaking in August (330.3 mm), then gradually declining in September (241.20 mm) and further in October (61.2 mm). Irrigation significantly decreased as natural precipitation increased, with the highest irrigation in July (97.33 mm) and August (114.97 mm), and minimal irrigation in September (5.25 mm) (Figure 5.2b).

a) Weather conditions during 2023 experiment



b) Weather conditions during 2024 experiment

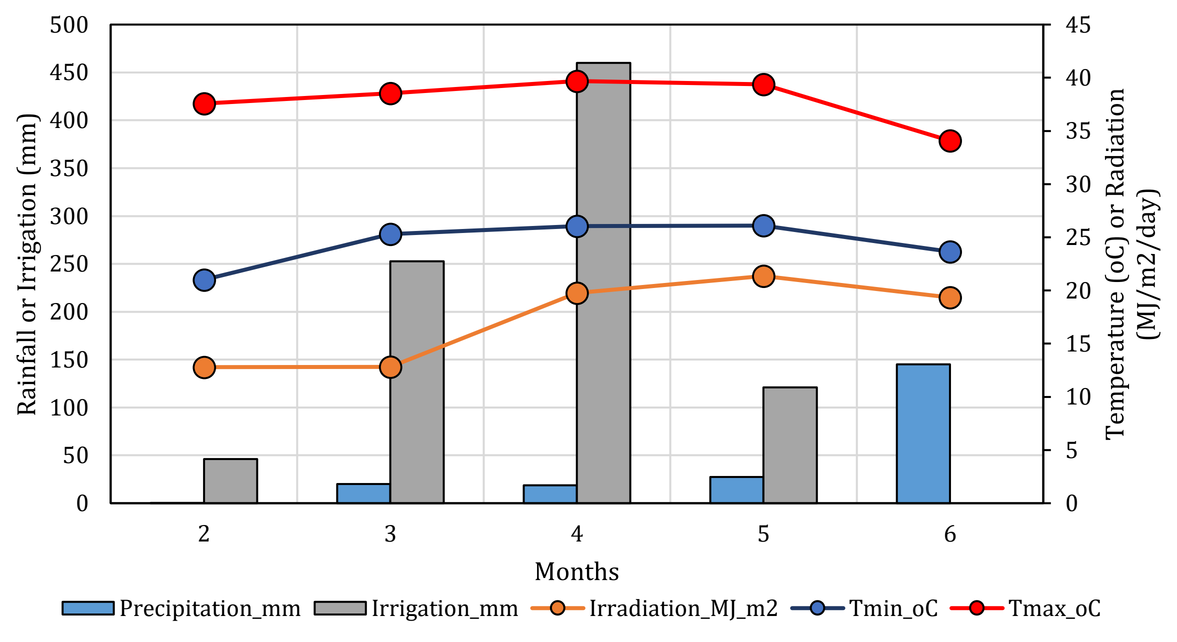


Figure 5.2. Weather condition during the experimentation

5.3.2 Effect of cattle corralling-based amendment and water management on maize growth

In 2023 and 2024, the LAI for each treatment generally increased from 15 DAS to a peak at day 45 DAS, followed by a decline towards day 75 DAS (Figure 5.3). The highest LAI values were consistently observed around day 45 DAS, with treatments such as T2, T3, and T4 (all the cattle-based treatments without water deficit or additional) exhibiting relatively higher LAI peaks.

Biomass production was generally higher in 2023 than in 2024. In 2023, there was no significant difference ($p>0.05$) among the cattle corralling-based treatments (T2, T3, T4, T5, T7, T8, T9, and T10). However, a significant difference ($p<0.05$) was found between the controls and the cattle corralling-based treatments. The highest biomass production was observed with the cattle pen + mulching + additional irrigation treatment (T8 =3.97 t/ha), while the lowest value was observed with the control without stress (T1 = 1.25 t/ha). Water management did not affect biomass production. The same trends were observed in 2024, but with lower values (T8= 2.51 t/ha, and T1= 1.44 t/ha).

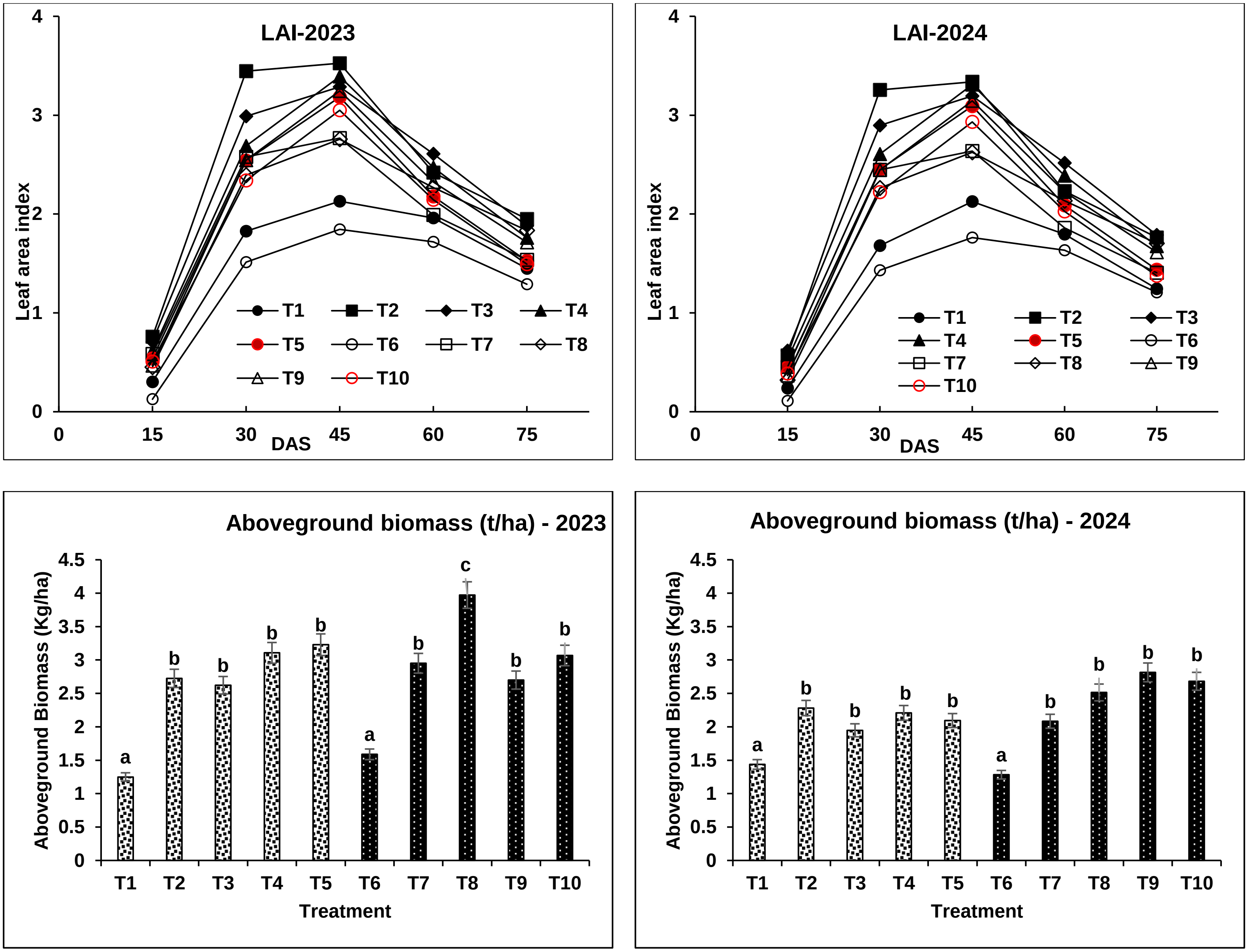
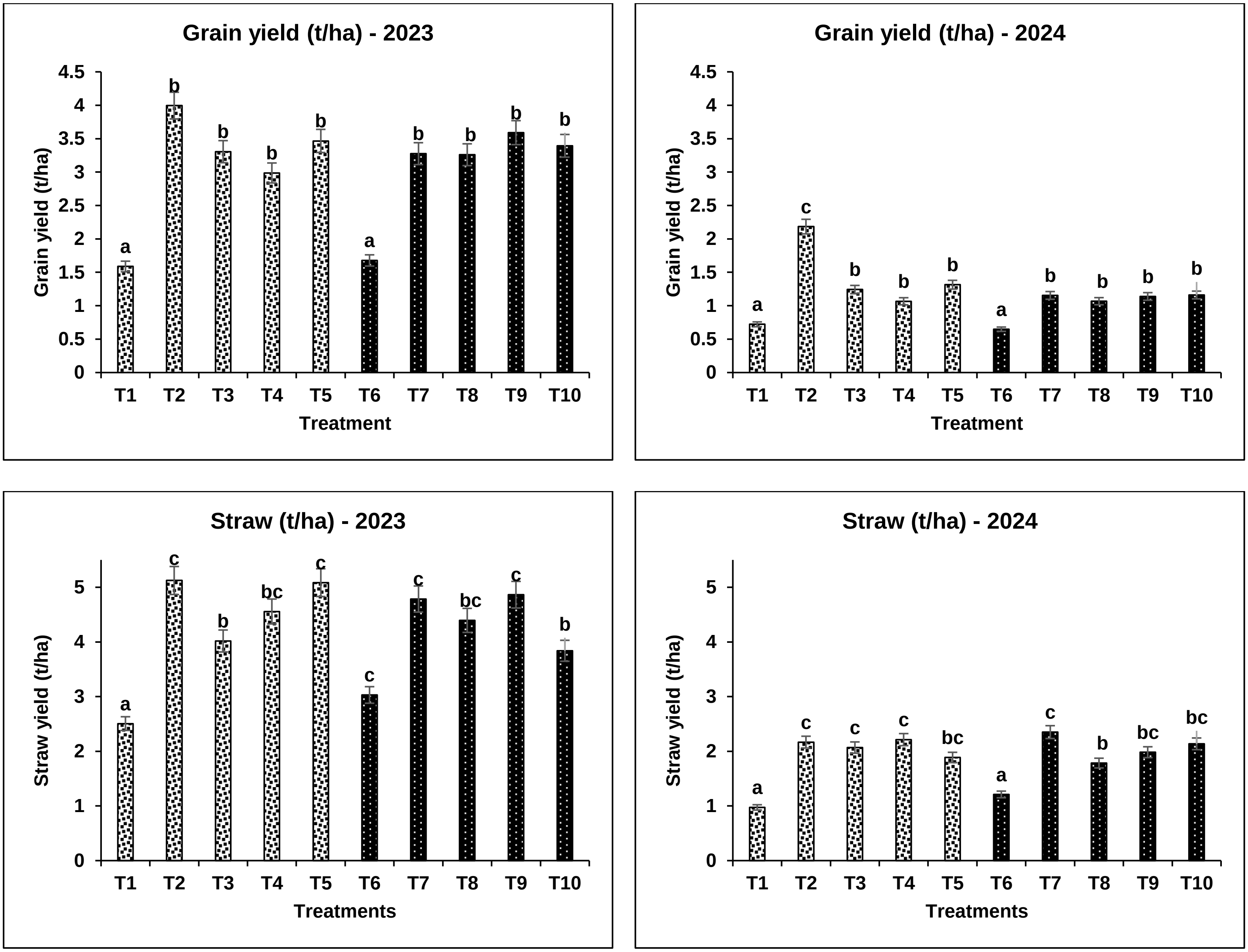


Figure 5.3. Leaf area index (LAI) and aboveground biomass (t/ha) as function of treatments

5.3.3 Effect of cattle corralling-based amendment and water management on maize yield

The cattle corralling-based treatment without water stress achieved the highest grain yield in 2023 and 2024 (Figure 5.4). In 2023, the control treatments (T1 and T6) showed the lowest yields (respectively 1.59 t/ha and 1.68 t/ha), whereas the treatment based solely on corralling with additional irrigation showed a better yield (T2=4t/ha). The same trend was observed in 2024, but with lower yields (T1=0.72 t/ha, T6=0.65 t/ha, and T2=2.18 t/ha). The lower yields obtained in 2024 compared to 2023 indicate the effect of increased water stress observed in 2024.


Grain yield (t/ha) - 2023

Grain yield (t/ha) - 2024

Straw (t/ha) - 2023

Straw (t/ha) - 2024

Figure 5.4. Maize grain yield and straw production as a function of cattle-based amendment and water management

5.3.4 Effect of cattle corralling-based amendment and water management nutrients (NPK) on factor productivity

NFP tended to decrease in 2024 across most treatments, except in T1 and T9, which showed slight increases (Table 5.1). The highest NFP in 2023 was recorded in T8 (100.3), followed by T5 (81.54) and T4 (78.45). The lowest was seen in T1 (31.56) and T6 (40.12). these values generally decreased in 2024 compared to 2023, with T9 (64.26) and T10 (61.22) showing the highest values, while T6 (29.3) and T1 (32.82) had the lowest.

T8 had the highest PFP (501.5), followed by T5 (407.72) and T4 (392.23), while the lowest PFP values were recorded in T1 (157.79) and T6 (200.6). PFP values also showed a decreasing trend in 2024, with T8 (287.05) and T9 (321.3) leading. T1 (164.1) and T6 (146.5) again showed the lowest PFP values. A decline in PFP from 2023 to 2024 was observed for most treatments, maintaining a similar ranking pattern with T8 and T9 showing relatively high values. KFP also demonstrated a general decrease from 2023 to 2024 across treatments, with similar patterns as seen in NFP and PFP. Across both years, T8 consistently displayed the highest fertilizer productivity across NFP, PFP, and KFP in 2023, while productivity generally declined across treatments in 2024. Treatments like T1 and T6 consistently recorded the lowest values, indicating potentially lower efficiency in nutrient utilization for these treatments.

Table 5.2. Nitrogen, Phosphorus, and Potassium factor productivity (NFP, PFP, and KFP)

Treatment	**2023**			**2024**		
	NFP	**PFP**	**KFP**	**NFP**	**PFP**	**KFP**
T1	31.56	157.79	23.09	32.82	164.1	24.01
T2	68.82	344.12	50.36	52.08	260.42	38.11
T3	66.21	331.07	48.45	44.47	222.36	32.54
T4	78.45	392.23	57.4	50.42	252.09	36.89
T5	81.54	407.72	59.67	47.8	239.01	34.98
T6	40.12	200.6	29.36	29.3	146.5	21.44
T7	74.53	372.66	54.54	47.56	237.82	34.8
T8	100.3	501.5	73.39	57.41	287.05	42.01
T9	68.17	340.86	49.88	64.26	321.3	47.02
T10	77.47	387.34	56.68	61.22	306.08	44.79
SED	**1.89**	**9.45**	**1.38**	**1.07**	**5.33**	**0.78**
P-Value	**0.001**	**0.004**	**0.001**	**0.006**	**0.001**	**0.001**

5.3.5 Drivers of cattle corralling adoption as soil fertility management option in northern Benin

The highest WUE values in 2023 were recorded in T8 (4.29 kg ha^{-1} mm^{-1}), followed by T5 (3.49 kg ha^{-1} mm^{-1}), T4 (3.35 kg ha^{-1} mm^{-1}), and T10 (3.31 kg ha^{-1} mm^{-1}), while in 2024, WUE values generally decreased across treatments, with T9 (3.06 kg ha^{-1} mm^{-1}) and T10 (2.91 kg ha^{-1} mm^{-1}) showing the highest values (Figure 5.5). T8 also maintained a relatively high WUE, though it decreased from 4.29 kg ha^{-1} mm^{-1} in 2023 to 2.73 kg ha^{-1} mm^{-1} in 2024.

There was a general decline in WUE from 2023 to 2024 across most treatments, with T8 showing the largest drop in efficiency. However, T9 showed an increase in WUE, indicating an improvement in water use efficiency for that treatment. The ranking pattern of high-efficiency treatments remained similar, with T8, T9, and T10 consistently displaying higher WUE, while T1 and T6 remained lower in both years.

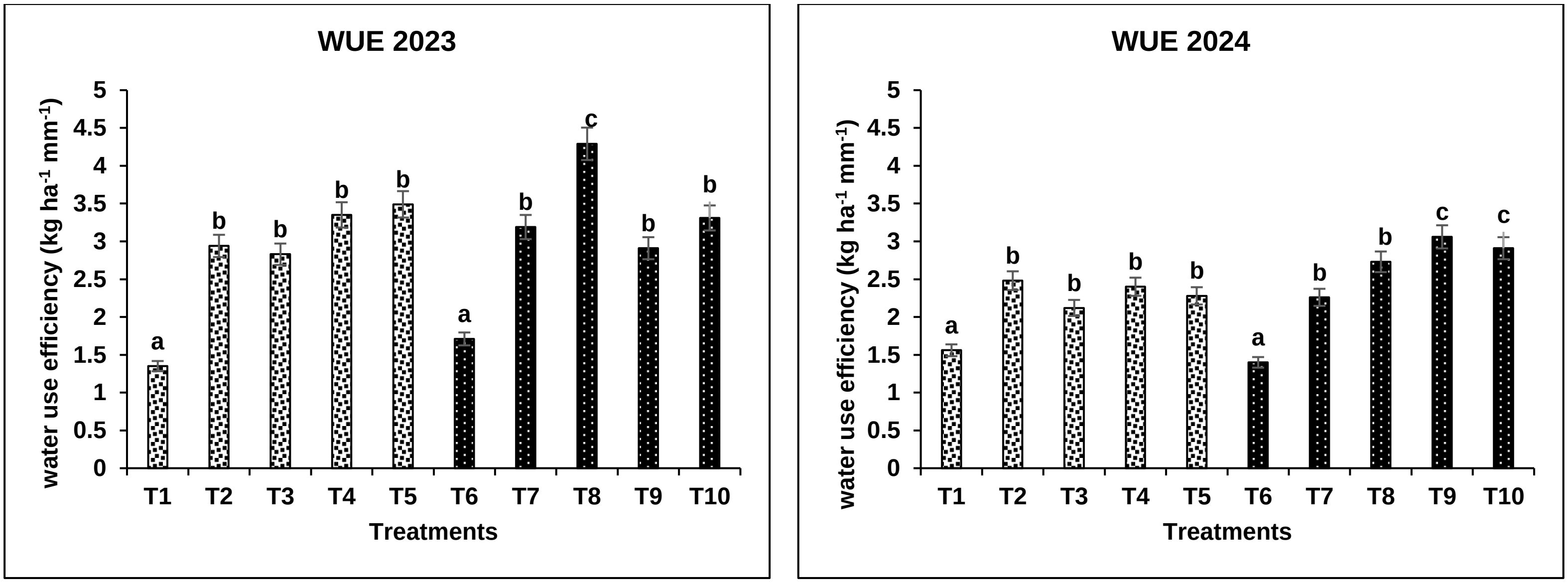


Figure 5.5. Water use efficiency as affected by cattle corralling based amendments and water management

5.3.6 Effect of cattle corralling-based amendment and water management on carbon input in soil

The Aboveground carbon input (in 2023) ranged from 0.02 t C/ha (T1 and T6) to a maximum of 0.05 t C/ha (T8), with most treatments showed values around 0.03 t C/ha to 0.04 t C/ha (Figure 5.6). In 2024, the pattern remained similar to 2023, with most treatments showing 0.03 t C/ha to 0.04 t C/ha. There was a slight decrease in belowground carbon input from 2023 to 2024 across treatments, especially in treatments with previously high values like T8, T4, and T7. Rhizodeposition (in 2023) was highest in T8 (0.12 t C/ha) and generally higher in T5, T4, T7, and T10 (0.09 t C/ha). Lower values were recorded in T1 and T6 (0.04 t C/ha and 0.05 t C/ha, respectively). The same trend was observed in 2024, with T8 maintaining higher values (0.07 t

C/ha - 0.08 t C/ha) along with T9 and T10, while T1 (0.04 t C/ha) and T6 (0.04 t C/ha) stayed lower. Rhizodeposition showed minimal change between the two years, with a slight reduction in high-value treatments like T8 and T5. Across both years, T8 generally exhibited the highest carbon inputs across all three variables, particularly in belowground and rhizodeposition categories. Overall, there was a slight reduction in belowground and rhizodeposition carbon input from 2023 to 2024 across treatments, while aboveground carbon input remained relatively stable.

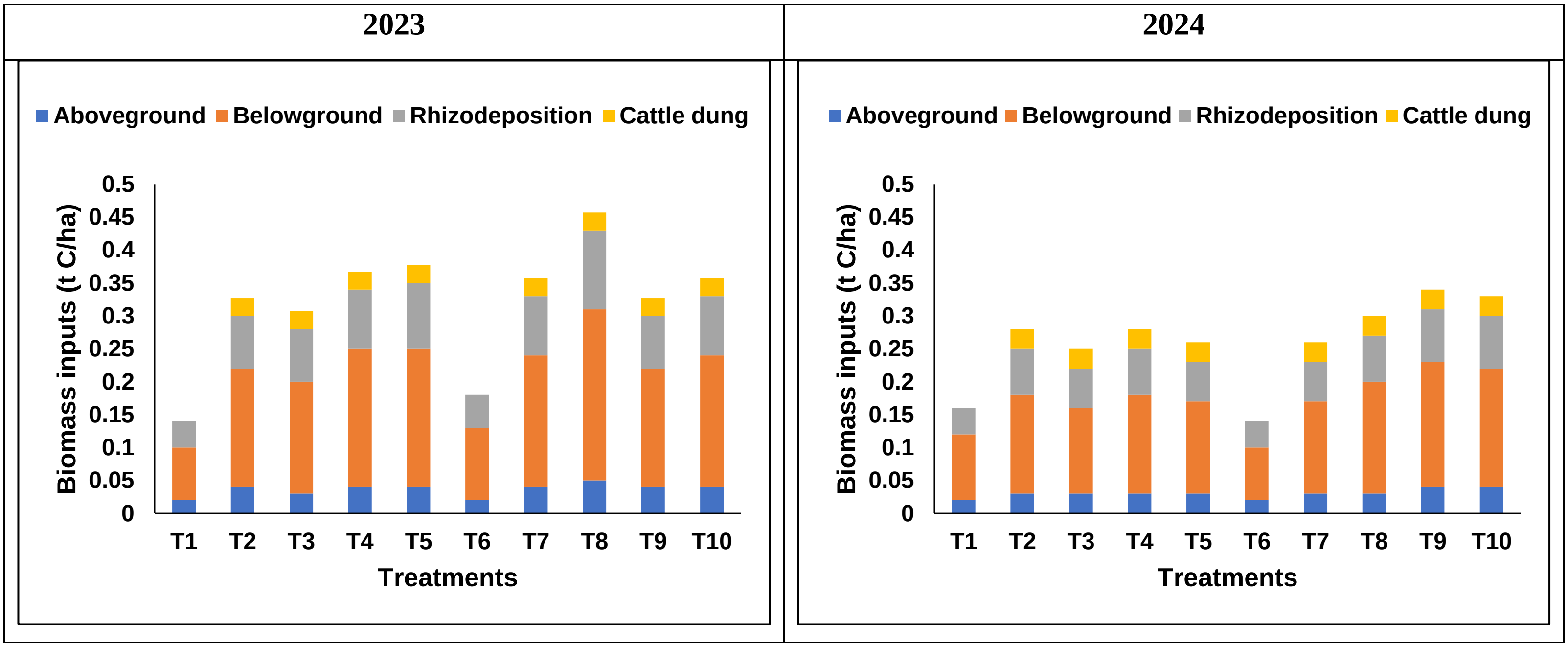


Figure 5.6. Carbon input in soil as affected by cattle corralling-based amendment and water management

5.4. Discussion

5.4.1 Effect of cattle corralling-based amendment and irrigation on maize growth and yield

The use of cattle corralling-based amendments combined with irrigation management (particularly under conditions of full irrigation) showed a positive effect on maize growth metrics, such as Leaf Area Index (LAI) and biomass, as well as yield outcomes. Treatments with cattle-based amendments (cattle corralling, cattle corralling+biochare, cattle corralling+biochare+mulching) especially those combined with additional or full irrigation (e.g., T8: cattle corralling + mulching + full irrigation), yielded the highest biomass (T8 =3.97 t/ha) and grain (T8 =3.26 t/ha) output in both years of the experiment. This trend suggests that the organic matter from cattle dung enhances soil fertility, which is crucial under both deficit and adequate irrigation scenarios (Farhad et al., 2018; Gao et al., 2023; Mucheru-Muna et al., 2014). Ayoola and Makinde, (2008) demonstrated that yields obtained from enriched cattle dung were comparable to those from inorganic fertilization. Their findings indicate that N-enriched cattle dung can serve as an alternative to inorganic fertilizers, as it increased soil N, P, and K contents by 25%, 1%, and 62%, respectively. Organic amendments through cattle corralling likely improved soil structure and water retention, providing a favourable environment for maize growth (Hosseinzadeh et al., 2021). These results corroborate studies highlighting manure's role in boosting soil nutrient levels and water-holding capacity, which are critical for crop resilience in semi-arid settings (Imran, 2024; Tubeileh and Thomas, 2023).

The higher yields observed under full irrigation reflect the importance of adequate water supply, particularly for maize, which has a high water requirement (Panda et al., 2004). The reduced yield in 2024 compared to 2023, attributed to increased water stress, further underscores the sensitivity of maize to water availability, especially in semi-arid regions like Northern Benin (Meng et al., 2016). This variability underscores the importance of supplementing cattle manure with sufficient irrigation, especially in dry seasons when water scarcity intensifies.

Maintaining a high irrigation frequency keeps moisture levels elevated in the crop root zone, thereby preserving hydraulic conductivity and water availability for longer durations. Consequently, fine-tuning both irrigation frequency and water application rates can maximize yield and crop water use efficiency (CWUE), while minimizing nutrient leaching below the root zone and protecting soil and groundwater from contamination. According to Abd El-Wahed and Ali, (2013), semi-arid regions (like northern Benin) require high water holding manures under water shortage for maize planting since water use efficiency is positively affected by irrigation systems and farmyard manure. Moreover, the results indicate that while cattle corralling-based amendments generally improved growth, the highest performance was consistently achieved when organic amendments were paired with full irrigation. This suggests that maximizing maize growth and yield may require integrated management of organic amendments and water resources, ensuring that soil fertility improvements are fully utilized.

5.4.2 Effect of cattle corralling-based amendment and irrigation on nutrients factor productivity, water use efficiency and C input in soil

Nutrient Factor Productivity (NFP) for nitrogen, phosphorus, and potassium, along with Water Use Efficiency (WUE) and carbon (C) input, demonstrated a positive response to cattle corralling-based amendments, though this response varied between the years (Buerkert and Hiernaux, 1998; Sangaré et al., 2002). In 2023, NFP values for treatments such as T8 (with additional irrigation) were highest, indicating efficient nutrient use where adequate water was provided. This supports the idea that cattle-based organic amendments can enhance nutrient cycling and availability in the soil (Fanjaniaina et al., 2022; Rowntree et al., 2020), promoting greater nutrient uptake efficiency when water is not limiting (Sileshi et al., 2019). However, nutrient productivity showed a decline in 2024, likely due to increased water stress, which underscores the need for reliable water management to maximize nutrient efficiency.

Water use efficiency (WUE) was highest in treatments with organic amendments, particularly those with biochar and maize straw, which aligns with previous research showing that biochar enhances soil water retention (Gao et al., 2020; Qin et al., 2021; Wu et al., 2022; Yang et al., 2024;

Zhang et al., 2017). Ali et al., (2018) demonstrated that applying farmyard manure (5 t ha^{-1}) and wheat crop residue (5 t ha^{-1}) alongside 350 mm of irrigation improved soil water availability in the 0–100 cm layer during critical growth stages, resulting in a 62% increase in grain yield. Moreover, water use efficiency (WUE) and rainfall use efficiency (RUE) were boosted by 35% and 50%, respectively, compared with traditional planting without irrigation. The marked reduction in WUE in 2024 highlights the impact of water scarcity, reinforcing the need for effective water management to enhance resource use efficiency. This decline further underlines the importance of integrating soil amendments and irrigation for sustainable maize production in semi-arid regions.

For soil carbon inputs, cattle corralling-based treatments consistently contributed to higher C levels across both years, with T8 leading in aboveground, belowground, and rhizodeposition inputs. This result points to the potential of cattle-based amendments in promoting soil carbon sequestration, which is crucial for improving soil health and mitigating climate change effects. Treatments that included biochar amendments maximized carbon inputs to the soil, both from aboveground and belowground sources, reinforcing the evidence that biochar plays a crucial role in soil carbon sequestration (Gupta et al., 2020). Biochar is a highly stable form of carbon produced through the pyrolysis of biomass at relatively low temperatures (Sarfraz et al., 2019). Its application to soil has been shown to offer multiple benefits, including increased crop yields, improved nutrient and water use efficiency, and various environmental advantages (Faloye et al., 2019; Fischer et al., 2019; Gao et al., 2020). Han et al., (2023) showed that the addition of biochar increased crop yield by 14.45%, water use efficiency (WUE) by 14.28% and nitrogen use efficiency (NUE) by 13.97%. The recalcitrant nature, relatively high carbon content, and readily available feedstock make biochar a sustainable and efficient option for carbon sequestration in soil (Layek et al., 2022; Luo et al., 2023; Mona et al., 2021). Beyond sequestering carbon, biochar application also provides an effective method for managing agricultural residues (Dai et al., 2016; Khawkomol et al., 2021), and reduce methane and nitrous oxide emissions from agricultural fields due to its priming effect on soil (Zhang et al., 2010). These findings suggest that combining cattle corralling with full irrigation not only boosts maize yields but also improves soil nutrient levels and water efficiency, paving the way for sustainable agricultural practices in areas with limited water resources.

The decline in belowground carbon input under deficit irrigation suggests a reduction in root biomass allocation, which may impact long-term soil carbon storage (Singh et al., 2023; Trost et al., 2013). Zhou et al., (2016) found that drought conditions, characterized by an increased root-to-shoot ratio, reduced heterotrophic respiration, and lower soil carbon turnover, resulted in only a modest rise in the soil carbon pool (SCP). Under irrigation, however, the addition of newly fixed carbon to the soil played a more significant role in increasing SCP.

5.5. Conclusion

This study demonstrates the potential of integrating cattle corralling-based fertilization with strategic irrigation to sustainably enhance maize production in semi-arid regions like Northern Benin. Cattle corralling-based fertilization significantly improved soil fertility, crop growth, and yield performance, especially under full irrigation conditions. Among the treatments, the combination of cattle corralling, mulching, and biochar (T8) consistently yielded the highest grain output, nutrient factor productivity, water use efficiency, and soil carbon input across the experimental years. These results emphasize the synergistic benefits of combining organic matter amendments with adequate irrigation to optimize water and nutrient use efficiency. Moreover, the integration of biochar further enhanced soil water retention and carbon sequestration, highlighting its value in building resilience against climate variability. Water management emerged as a critical determinant of the system's effectiveness. While full irrigation maximized crop yields and nutrient use, deficit irrigation revealed limitations in nutrient uptake and water use efficiency, underlining the importance of reliable water availability to harness the full potential of organic amendments.

This research underscores the importance of adopting integrated soil fertility and water management strategies tailored to the agroecological context of semi-arid regions. The findings provide a scientific basis for scaling up cattle corralling-based practices, particularly when complemented with innovative amendments like biochar, to achieve sustainable agricultural intensification. Future research should focus on long-term field trials and cost-benefit analyses to validate the economic feasibility and broader applicability of these practices across different farming systems. Ultimately, this study contributes to the global agenda of sustainable agriculture by presenting a scalable, resource-efficient model that enhances productivity, improves soil health, and mitigates the impacts of climate variability on food security.

CHAPTER 6: MODELLING CATTLE CORRALLING-BASED AMENDMENT EFFECTS ON MAIZE GROWTH AND DEVELOPMENT UNDER FUTURE CLIMATE CONDITIONS

Manuscript: Modelling cattle corralling-based amendment effects on maize growth and development under future climate conditions; A. M. Atakoun, M. dos Santos Vianna, P. G. Tovihoudji, R. V. C. Diogo, W. Amponsah, T. Gaiser, N. Kyei-Bafour, B. Kyereh

ABSTRACT

Climate change poses significant threats to agricultural productivity, particularly in staple crops like maize, which are highly sensitive to temperature and water stress. This study evaluates the impacts of cattle corralling-based amendments on maize growth, biomass accumulation, and yield under historical and future climate scenarios, employing the Decision Support System for Agrotechnology Transfer (DSSAT). Field experiments were conducted during the 2023 and 2024 growing seasons, utilizing a strip-plot design with four treatment combinations of irrigation and cattle corralling. Simulations run under two Shared Socioeconomic Pathways (SSP126 and SSP585) to project maize performance across diverse environmental conditions. Results indicate that integrating cattle corralling and additional irrigation (T2) significantly enhanced maize productivity. Under historical scenarios, T2 achieved grain yields of 3,250.09 kg ha^{-1}, which declined to 2,688.66 kg ha^{-1} under SSP585. Cattle corralling improved soil organic carbon (TOC), with values peaking at 103,901.85 kg ha^{-1} under historical conditions. Water productivity (yield-ET) reached 13.89 kg ha^{-1} mm^{-1} in historical scenarios but decreased to 11.5 kg ha^{-1} mm^{-1} under SSP585. Nitrogen uptake productivity also peaked under T2, with values of 26.41 kg kg^{-1} and 23.79 kg kg^{-1} for historical and SSP585 scenarios, respectively. This study demonstrates the potential of cattle corralling to mitigate climate-induced stresses on maize production by enhancing soil health, water retention, and nutrient use efficiency. While future climate scenarios diminish productivity gains, cattle corralling remains a viable adaptation strategy. Integrating this practice with complementary approaches, such as biochar application and precision irrigation, can further optimize resource use efficiency and sustain agricultural productivity in the face of climate change. These findings provide actionable insights for advancing climate-resilient agriculture and ensuring food security under evolving environmental conditions.

Keywords: Soil fertility management, Climate scenarios, Water productivity, Nitrogen use efficiency, Crop simulation

6.1 Introduction

Climate change is one of the most pressing challenges of the 21st century, with significant implications for agricultural productivity and food security (Anand and Khetarpal, 2015; Bouteska et al., 2024). Recent projections indicate that global surface air temperatures may increase by 1.4 to 5.8°C due to the doubling of atmospheric carbon dioxide concentrations, posing a severe threat to the sustainability of agroecosystems (Altieri et al., 2015; El-Sharkawy, 2014; Laza et al., 2023). While some regions may experience potential benefits, such as expanded cultivation areas or improved water use efficiency, the overarching impacts of global warming on crop growth and yield remain predominantly negative, particularly in temperature-sensitive crops like maize (Saddique et al., 2020; Wu et al., 2018).

Maize, a staple crop worldwide, is highly vulnerable to extreme climatic conditions (Heisse and Morimoto, 2024). Rising temperatures are known to alter crop phenology, accelerate maturity, and reduce the duration of key growth stages, ultimately impacting biomass accumulation and grain yield (García et al., 2015; Lesjak and Calderini, 2017; Wang et al., 2018). Elevated temperatures have been associated with increased evapotranspiration, potentially exacerbating water stress in areas with limited water resources (Emmerichs et al., 2024, 2023; Swelam et al., 2010). Furthermore, high temperatures disrupt physiological processes, such as photosynthesis and hormone synthesis, leading to stunted growth and reduced productivity (Li et al., 2024; X. Yang et al., 2022). These challenges underscore the need for innovative and adaptive agricultural strategies to mitigate the effects of climate change on maize production.

Cattle corralling-based amendments have emerged as a promising practice for enhancing soil fertility, improving water retention, and sustaining crop productivity in climate-stressed environments (Nurudeen Abdul Rahman et al., 2019; Ayantunde et al., 2018b; Shinjo, 2017). This traditional yet underutilized practice involves the application of organic materials derived from livestock corralling, which can enhance soil organic matter, nutrient availability, and water-holding capacity (Tovihoudji et al., 2024). By improving the resilience of agroecosystems, cattle corralling-based amendments could offer a viable solution to mitigate the adverse effects of high temperatures and water scarcity on maize production.

In the context of climate change, the Decision Support System for Agrotechnology Transfer (DSSAT) provides a robust framework for assessing the impacts of various agricultural practices and environmental scenarios on crop growth and yield (Yang et al., 2022). The DSSAT model integrates biophysical processes with environmental data, enabling researchers to predict changes in crop phenology, biomass growth, water use, and yield under diverse temperature and management conditions (Wang et al., 2018).

By incorporating daily weather inputs, soil characteristics, crop management practices, and genetic information, DSSAT effectively models key aspects such as phenological development, biomass accumulation, water utilization, and yield outcomes (Attia et al., 2021; Malik and Dechmi, 2019; Tovihoudji et al., 2019). For instance, the DSSAT-CERES-Maize model has been employed to simulate maize yield and nitrogen cycling in long-term continuous maize production systems, demonstrating its capability to assess the impacts of different management practices on crop performance (Kumar et al., 2024; Liu et al., 2011; Yang et al., 2013). Similarly, DSSAT has been utilized to simulate upland maize yield under diverse temperature scenarios, providing insights into how changing climatic conditions affect crop productivity (Kipkulei et al., 2022; Saddique et al., 2020; Wang et al., 2018). These applications underscore DSSAT's robustness in integrating complex environmental and management variables to predict crop responses, thereby serving as a valuable decision-support tool for researchers and practitioners aiming to optimize agricultural practices in the face of environmental variability.

This study leverages the DSSAT model to evaluate the effects of cattle corralling-based amendments on maize phenology, biomass growth, and yield under contrasting future temperatures and rainfall conditions. By addressing these objectives, this study aims to contribute to the development of sustainable agricultural practices and adaptive strategies that enhance crop resilience in the face of climate change.

6.2 Materials and methods

6.2.1. Study site

The study was conducted in research station conditions during the rainy season (June-September 2023) and dry seasons (February-May 2024) at the Agronomic Research Station, University of Parakou, Benin. It is located on the northeast side of the university at coordinates (9°33’77’N; 2°64’87’99 E) with an altitude of 369 meters. The region's climate is classified as Aw (Tropical Savannah) based on Köppen-Geiger classification (Beck et al., 2023), characterized by two seasons: a rainy season from May to October and a dry season from November to April. The site receives an annual rainfall average of 1000-1200mm. The soil of the experimental site is classified as tropical ferruginous type and loamy sand in texture. The selection of this site for the trial was based on the availability of water, site security, and easy access to tools and equipment essential for the trial's proper execution.

6.2.2 Experimental design and treatments

A strip plot design was used for the trial due to a superimpose cattle corralling application on the site, and each treatment was repeated thrice. The experiment included two water application modalities: full crop water needs or additional irrigation (I0) and only normal rainfall (I1). The full crop water needs here (I0) means that the crops were irrigated in addition to the normal rain to reach the standard maize crop water requirement. Two levels of soil amendment (F0 = control, and F1 = cattle corralling) were applied on each plot. Therefore, we had four treatments (**T1**=I0F0, **T2**=I0F1, **T3**=I1F0, **T4**=I1F1). Knowing that a LU (Livestock Unit) with an average weight of 317 kg produces an average of 1.44 kg of dry matter per night and 3.40 litters of urine per night (Ayantunde et al., 2018b; Kasse, 2019), the computation was done to determine the number of cattle that was confined on the single plot to have 8.2t of dry manure per hectare (Tovihoudji, 2018). Corralling was performed on a given plot from 6-7 pm to 8-9 am. The net plot size was 3 × 3 m, and a buffer plot was kept to avoid the effect of soil moisture from neighboring plots (Farhad et al., 2018; Khalili et al., 2013). Five overnight corralling with two cattle confined per plot was enough to reach 8.2 t ha^{-1} from these conditions. After the corralling treatment application, the real quantity of cattle dung deposited was determined using three quadrats (0,5m x 0,5m) for each plot before sowing. The dung was weighted from each quadrat for total estimation (13.2 t/ha of fresh dung in 2023, and 14,6 t/ha of fresh dung in 2024). Cattle dung nutrient content was assumed to be 3.0 g/kg of N, 0.6 g/kg of P, and 4.1 g/kg of K (Gbenou et al., 2017).

6.2.3 Crop management and data collection

The maize variety DMR-ESR-W (Downy Mildew Resistant, Early-Streak Resistant – White) was used (for the 2023 and 2024 experiments), known for its sensitivity to drought and a 90-day growth cycle. Certified seeds were procured from the Agricultural Research Center of INA. Maize was sown (07 June 2023 and 17 February 2024) with three seeds per hole and then thinned at two plants per hole two weeks after sowing, leading to a density of 62,500 plants per hectare (0.8 m×0.4 m spacing). During the dry season, the full crop water needs were supplied through full irrigation, while for the water stress application, irrigation was reduced to 50% during two weeks at two growth periods: vegetative (20 to 60 days after sowing) and flowering (60 to 80 days after sowing) stages. At the vegetative stage, stress was imposed 21 days after planting for 2 weeks, and at the flowering stage after the emergence of flower buds (65 DAS) for 2 weeks (Ge et al., 2012). These irrigation treatments were randomly distributed across the plots. In all treatments, plants were sufficiently irrigated twice daily (morning and evening) to avoid water stress until 21 days after planting to ensure uniform germination and good seedling establishment. The FAO Penman-Montheith methodology through the CROPWAT 8.0 Windows program and CLIMWAT 2.0 Windows program was used for water-supplying scheduling at 2 mm depletion.

The data collection included 15 Days After Sowing (DAS), 30 DAS, 45 DAS, 60 DAS, 75 DAS, and 90 DAS. Biomass was measured by destructively sampling whole plants from two planting holes at each date. Leaf area was recorded in each experimental plot by randomly tagging three plants from three different planting holes in the three middle rows reserved for final biomass measurement. The green leaf length and width were measured every fortnight with a ruler and the leaf area (LA) was calculated as Leaf area (LA) = Leaf length * maximum width * k, where k is a shape factor with the value of 0.75. The leaf area index (LAI) was calculated as the ratio of LA to the soil surface area of the hill. The final harvest was done by hand, and aboveground biomass and grain yields were recorded as described by Tovihoudji et al. (2017).

6.2.4 Crop simulation model

6.2.4.1 Model Description

The CERES-Maize model, integrated into DSSAT version 4.8 (Decision Support System for Agro-technology Transfer), was employed in this study as a dynamic, mechanistic framework to simulate the phenological development and growth of maize on a daily time scale. This model incorporates environmental and management factors, including soil and climatic conditions, crop varieties, fertilization regimes, planting practices, and irrigation. DSSAT is a modular system comprising independent components such as crop, weather, soil, and water modules, which are interconnected through the Cropping System Model (CSM) as the central core, allowing for the simulation of crop rotations (Jones et al., 2003). The CSM-CERES-Maize model operates by simulating maize growth and development based on physiological processes that describe the crop's responses to both soil and atmospheric conditions. The interception of solar radiation governs potential growth, whereas factors such as suboptimal temperatures, soil water deficits, and nitrogen limitations constrain actual biomass accumulation. Running the DSSAT models requires input data, including daily weather records, soil characteristics, cultivar-specific coefficients, and detailed crop management information. The CSM-CERES-Maize model has been rigorously evaluated across diverse soil types, climatic scenarios, and maize hybrids (Abdrabbo et al., 2013; Amiri et al., 2024; Chisanga et al., 2021). In this study, the model was calibrated and evaluated using data from field experiments conducted in 2023 and 2024. These experiments provided observations on plant phenological stages, above-ground biomass, crop yields, and leaf area indices, ensuring the model's reliability and applicability under the studied conditions.

6.2.4.2 Model input data

Simulations were carried out using the CERES-Maize, along with the CENTURY-based soil module within the DSSAT framework (version 4.8) (Attia et al., 2021). Soil data WI_LVBJ003 was adopted from WISE database for its geographical proximity to our experimental site (Batjes, 2009). Crop management practices included planting date and density, row spacing, tillage method and timing, fertilization schedules (both inorganic and manure application), and harvest dates. Field management data were sourced from observations conducted during the 2023 and 2024 growing seasons (previously described). Weather data required for the simulations were obtained from the NASA POWER (Prediction of Worldwide Energy Resource) database, ensuring comprehensive daily weather coverage for all years and locations (https://power.larc.nasa.gov/). For the future climate simulations, we employed two climate scenarios from the CMIP6 database, extending to the end of the century: SSP1 (RCP2.6, low CO_2) and SSP5 (RCP8.5, high CO_2) (Vianna et al., 2022). We selected five GCM projections based on data availability from the Inter-Sectoral Impact Model Intercomparison Project: GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL. Meteorological variables were bias-corrected to the 1980-2010 weather station baseline using the quantile mapping bias adjustment method outlined by Lange, (2019). Since the CMIP6 scenarios do not provide data on a sub-daily time scale, we assumed that the diurnal pattern of events remains consistent in our projections. The model simulations were run at two levels: historical (1981-2010), and future projection (2041-2070).

6.2.4.3 Model calibration and evaluation

The CSM-CERES-Maize model operates based on phenologically defined growth stages, which are regulated by energy input quantified as growing degree-days (GDD) (Hoogenboom et al., 2019). In DSSAT, growth stages are defined in terms of cultivar coefficients, which are specific to both the crop cultivar and the local climate, and must therefore be individually calibrated under optimum conditions (i.e., minimum stress in weather and nutrients) for the region. These include three phenology coefficients (P1, P2, P5), two for grain-filling processes (G2, G3), and one for the phylochron interval (PHINT), which governs the rate of leaf tip appearance. Their values were calibrated using the Generalized Likelihood Uncertainty Estimator (GLUE) alongside a trial-and-error approach within DSSAT version 4.8 (Mereu et al., 2019). Phenology coefficients were first calibrated, then followed by growth coefficients after ten thousands of runs for each step. The cultivar EVDT (Gh0012) was used as a template for the initial condition. This process allowed for the refinement of key genetic and ecotype coefficients, ensuring the model's reliability. The results of this calibration, including the critical parameters, are summarized in Table 6.1. These genetic and ecotype coefficients were used for the model calibration using data collected from the 2023 field experiment under minimal environmental and nutrient stress to ensure the precision of simulated crop growth and development. Leaf area index, total biomass, and grain yield were considered for the model calibration and evaluation. Data from the 2024 field experiment were used for the model evaluation.

Table 6.1. Genotype coefficients for Maize calibrated for DSSAT model

Parameteter	Acronym	Value
The period from emergence to the end of the juvenile phase, expressed in degree-days above a base temperature of 8°C, represents the interval during which the plant's development is independent of photoperiodic influences.	P1 (˚C day)	177.498
The coefficient of photoperiod sensitivity quantifies the extent to which the plant's development is delayed, expressed in days, for each hour of increase in photoperiod beyond the critical threshold where maximum development occurs (typically 12.5 hours).	P2 (days)	1.039
The degree-days above a base temperature of 8°C from silking to physiological maturity represent the thermal time required for the grain-filling phase	P5 (˚C day)	638.096
The maximum possible number of kernels per plant	G2 (number)	762.112
The rate of potential kernel growth	G3 (mg day^{-1})	8.231
The degree-days required for a leaf tip to emerge, also known as the phyllochron interval	PHINT (˚C day)	40

6.2.4.4 Model evaluation

The model's performance was evaluated using the coefficient of determination (R2), d-index value, and normalized root mean square error (nRMSE) between the simulated and observed data (Wallach et al., 2018). The d-index value was calculated using the following equation:

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P'_i| + |O'_i|)^2}\right], \ 0 \leq d \leq 1, \qquad (1)$$

where n = number of observations, Pi = predicted value for the ith measurement, Oi = observed value for the ith measurement, O = the overall mean of observed values, Pi′ = Pi − O, and Oi′= Oi

− O. The root mean square error (RMSE) was used to calculate the fitness between the estimated and measured results. The RMSE summarizes the average difference between observed and predicted values (Willmott, 1985).

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Pi - Oi)^2} \qquad (2)$$

The normalized RMSE is expressed as RMSE as a percentage over the mean observed value.

$$nRMSE = (RMSE/\bar{\mathrm{O}}) \times 100 \qquad (3)$$

where, Pi is the predicted value, Oi is the observed value, Ō is the observed mean and n is the number of samples. The nRMSE (%) shows the relative difference between the predicted and observed data. The prediction is considered excellent, good, fair, and poor for the nRMSE< 10%, 10–20%, 20–30% and > 30%, respectively.

6.2.5 Scenarios Simulation

The model was run to simulate daily crop growth processes, including growth stages, leaf area index, biomass accumulation, and grain yield. In addition, the model provides summary outputs, such as evaluations of crop performance, an overview of simulation results, and a detailed soil water balance. These summaries offer insights into overall system dynamics and resource utilization. Moreover, DSSAT includes graphical display tools, such as GBUILD, to visually represent the results, enabling easier interpretation and analysis of simulated crop growth and environmental interactions. The growth and yield of maize under current weather conditions and different changing scenarios with the rise in temperature and precipitation were simulated using CERES-maize model. The analysis begins by defining two time periods of 30 years each: a historical period starting in 1981 and a future period starting in 2041. Unique combinations of

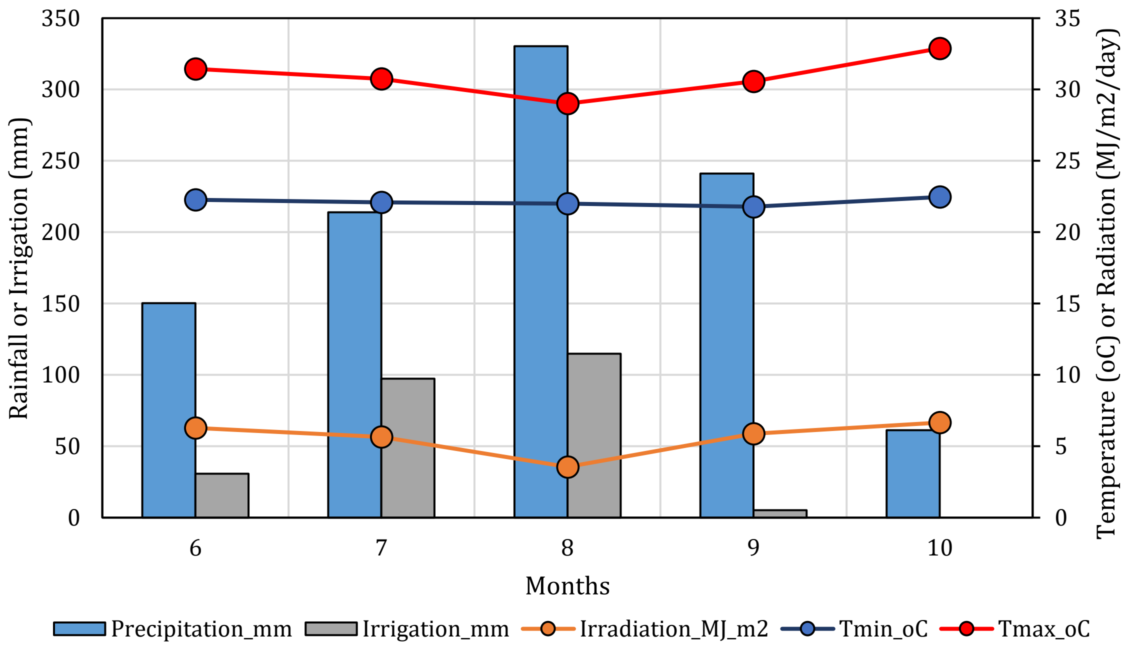
GCMs, scenarios, and treatments are generated using the `make_SQX_combinations` function, which combines data from two input files: `List_SQX_templates.csv` (sequence templates) and `List_WTH.csv` (climate projections). For each combination (row in the `df_runs` dataframe), DSSAT's summary output is processed iteratively, storing results in a list named osu. This structure allows the systematic evaluation of DSSAT model simulations across multiple climate scenarios, treatments, and time periods, ensuring thorough and organized data analysis. All the simulations were run in R.4.3.3 interface using senquence (.SQX) files from DSSAT (Alderman, 2020). ANOVA test followed by Tukey's Honest Significant Difference (HSD) was performed to compare the effect of different climate scenarios on the treatments considering the following variables: grain yield, total organic carbon, water productivity, and Nitrogen uptake productivity.

6.3 Results

6.3.1. Weather conditions and irrigation during the experiments

For the 2023 experiment, the rainfall increased significantly in mid-year, peaking in August (330.3 mm), then gradually declining in September (241.2 mm) and further in October (61.2 mm). Irrigation significantly decreased as natural precipitation increased, with the highest irrigation in July (97.3 mm) and August (114.9 mm), and minimal irrigation in September (5.3 mm) (Figure 1a). During the 2024 field experiment, the total rainfall gradually increased from very low levels in the early months (0.1 mm in February) to moderate levels in May (27.4 mm). The precipitation for these five months was relatively low. However, irrigation was substantial in the same period, particularly in April (460.00 mm) and March (252.7 mm), compensating for the lack of rainfall during this period (Figure 1b).

a) Weather conditions during 2023 experiment



b) Weather conditions during 2024 experiment

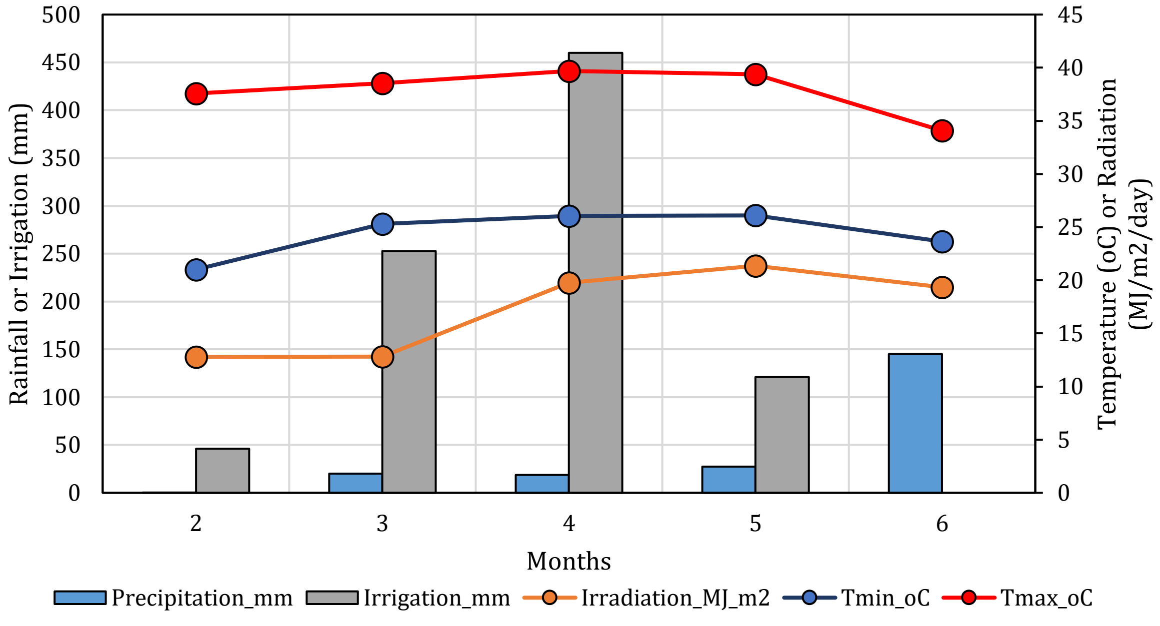


Figure 6.1. Weather conditions during the experimentation

6.3.2 Model calibration and evaluation

The model predicted accurately and precisely with a coefficient of determination (R^2) and d-index values ranging respectively from 0.40 to 0.96, and from 0.78 to 0.93 for LAI (Figure 6.2), and respectively from 0.83 to 0.94, and from 0.67 to 0.97 for aboveground biomass (Figure 6.2). The model predicted the LAI time-series with a RMSE ranging from 0.91 to 0.98 for cattle corralling treatments (T2 and T4), and from 0.41 to 0.91 for additional irrigation treatments (T1 and T2) (Figure 6.2). The aboveground biomass was predicted with RMSE values ranging from 950.86 kg/ha to 1233.91 for treatments under cattle corralling, and from 950.86 kg/ha to 950.97 kg/ha for the treatments under additional irrigation (Figure 2). The model showed a satisfactory fit between predicted and observed values of LAI and aboveground biomass with respective nRMSE of 18.81%, and 15.46% (Table 6.2).

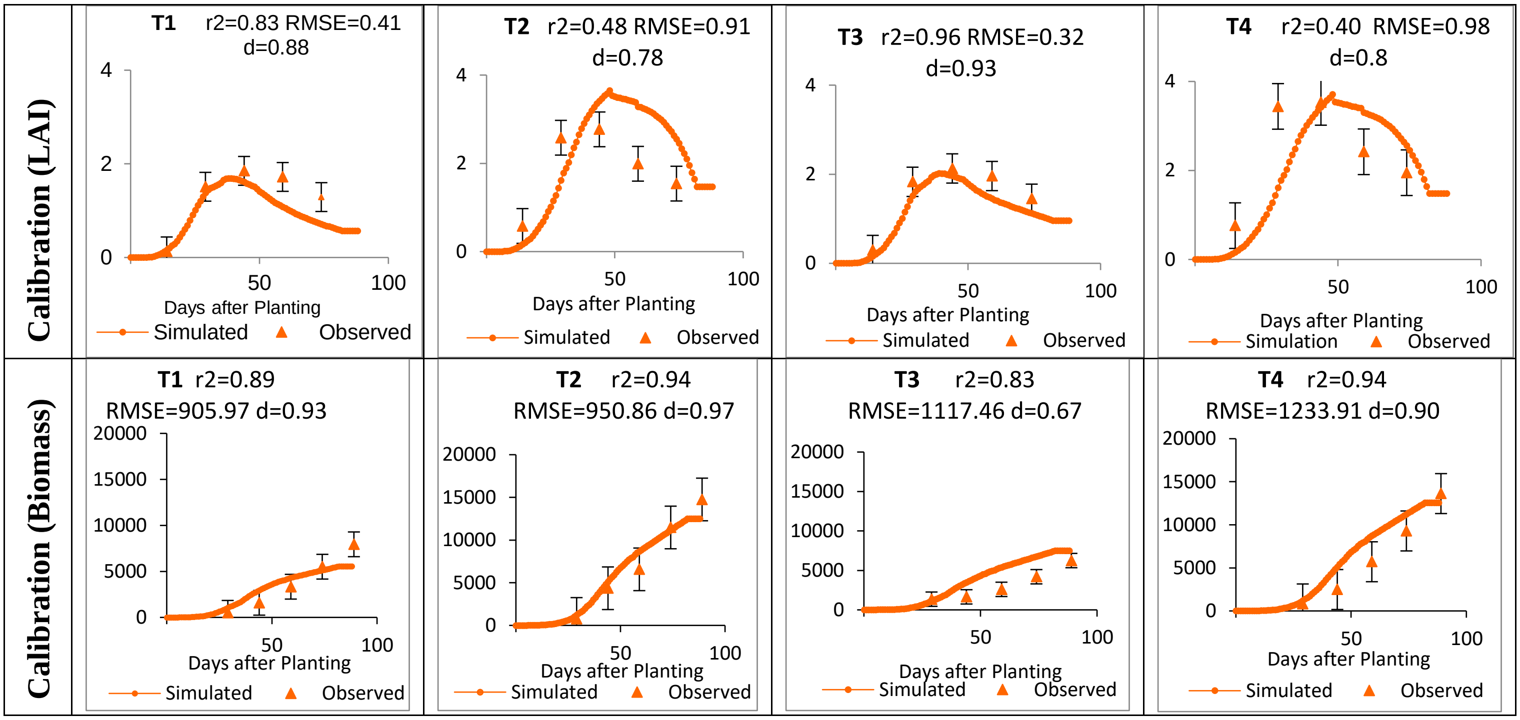


Figure 6.2. Observed and simulated time-series leaf area index and total abovegroud biomass for maize during model calibration

The predicted values showed the same trend in evaluation as in calibration for both LAI and biomass. For the evaluation, the coefficient of determination (R2) and d-index values ranged respectively from 0.23 to 93, and from 0.70 to 0.80 for LAI (Figure 6.3), and respectively from 0.82 to 0.97, and from 0.85 to 0.98 for aboveground biomass (Figure 6.3). The LAI time series were evaluated with RMSE values of 0.80 to 1.10 for treatments under cattle corralling, and for 0.64 to 1.1 for the treatments under additional irrigation (Figure 6.3). The biomass was evaluated with RMSE values of 976.40 kg/ha to 1059.39 kg/ha for treatments under cattle corralling, and of 807.67 kg/ha to 976.40 kg/ha for the treatments under additional irrigation (Figure 6.3).

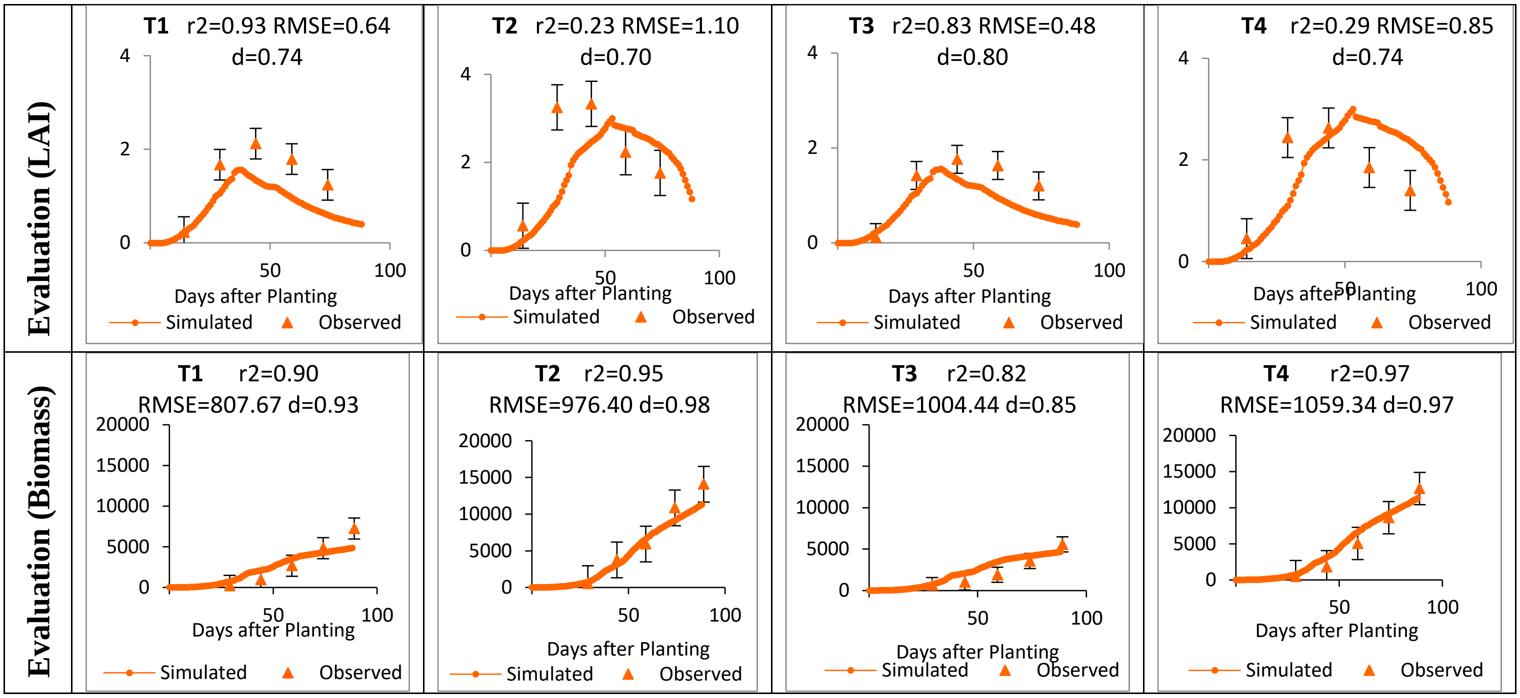


Figure 6.3. Observed and simulated time-series leaf area index and total aboveground biomass for maize during model evaluation

Table 6.2. Normalized root means square error (nRMSE) for LAI, biomass, and grain yield during the calibration and evaluation

Treatments	LAI		Biomass		Grain yield	
	nRMSE % (Calibration)	nRMSE % (Evaluation)	nRMSE % (Calibration)	nRMSE % (Evaluation)	nRMSE % (Calibration)	nRMSE % (Evaluation)
T1	15.76	21.56	10.46	21.10	27.21	16.28
T2	27.40	21.74	19.87	12.84	17.66	37.36
T3	7.84	23.36	11.11	25.14	27.50	13.56
T4	24.25	26	20.40	21.55	0.025	38.64
Overall	18.81	23.16	15.46	20.15	18.10	26.46

6.3.3 Long-term effect of cattle corralling, and additional irrigation on maize productivity under climate scenarios

6.3.3.1 Grain yield

Grain yield varied significantly ($p<0.001$) across climate scenarios and treatments (Table 3). The lowest values were observed under T3 (no cattle corralling, no additional irrigation), with 321.57 kg ha^{-1}, 263.34 kg ha^{-1}, and 217.63 kg ha^{-1} for historical, SSP126, and SSP585 scenarios respectively (Figure 4). Conversely, the highest grain yield was recorded under T2 (cattle corralling and additional irrigation), with values of 3,250.09 kg ha^{-1}, 3,061.07 kg ha^{-1}, and 2,688.66 kg ha^{-1} for historical, SSP126, and SSP585 scenarios respectively. Historical scenarios consistently exhibited higher grain yield compared to SSP126 and SSP585.

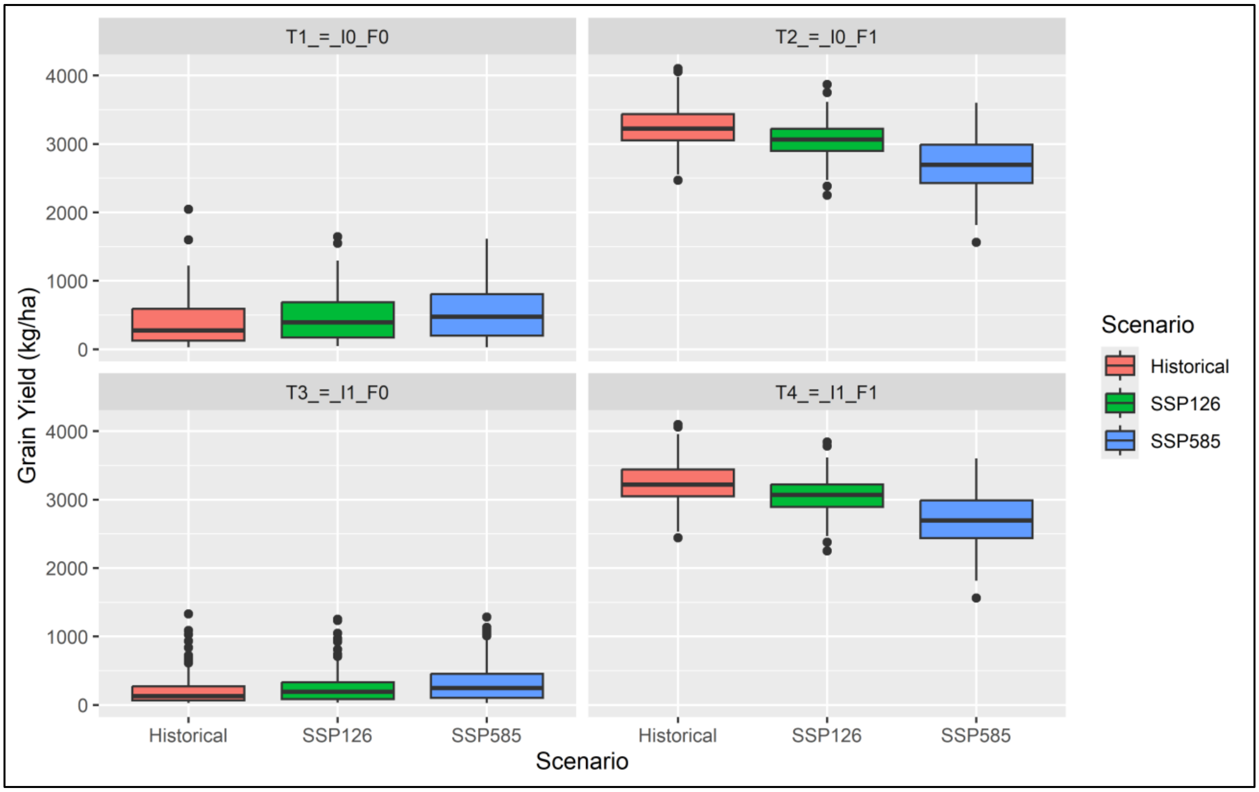


Figure 6.4. Grain yield (kg/ha) projection under historical and future climate condition

6.3.3.2 Water productivity

Yield-ET productivity varied significantly ($p<0.001$) across scenarios and treatments (Table 3). T3 (no cattle corralling, no additional irrigation) consistently produced the lowest values: 1.13, 0.88, and 0.73 kg ha^{-1} mm^{-1} for historical, SSP126, and SSP585 scenarios respectively (Figure 5). On the other hand, T2 (cattle corralling and additional irrigation) achieved the highest productivity, with values of 13.89, 12.62, and 11.5 kg ha^{-1} mm^{-1} for historical, SSP126, and SSP585 scenarios. Historical scenarios provided the best results compared to SSP126 and SSP585.

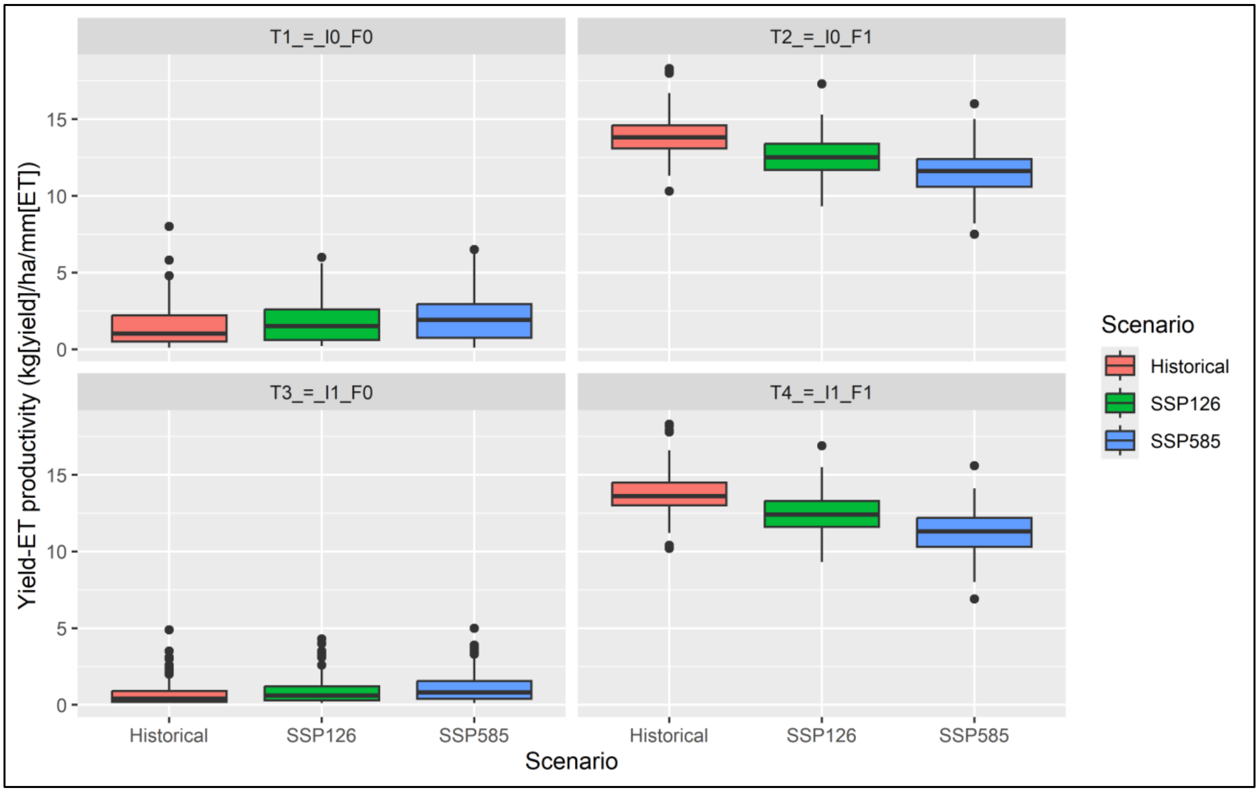


Figure 6.5. Yield-ET productivity (kg/ha/mm) projection under historical and future climate condition

6.3.3.3 Nitrogen uptake productivity

Yield per nitrogen uptake unit also varied significantly ($p<0.001$, Table 3). Historical scenarios showed the highest values in T2 (26.41 kg kg^{-1}) compared to SSP126 (24.92) and SSP585 (23.79). T3 showed the lowest values: 21.75, 21.29, and 21.08 kg kg^{-1} for historical, SSP126, and SSP585 scenarios respectively.

Table 6.3. Effect of different climate scenarios, cattle corralling, and additional irrigation on maize productivity

Scenario	**Treatment**	**Total organic carbon at maturity (kg ha^{-1})**	**Grain yield (kg ha^{-1})**	**Yield-ET productivity (kg/ha/mm)**	**Yield-N uptake productivity (kg/kg)**	**Average atmospheric CO2 (ppm),**
		Mean	**Mean**	**Mean**	**Mean**	**Mean**
Historical	**T1_=_I0_F0**	91406.96a	537.44a	2.1a	22.84a	616.35a
SSP126	**T1_=_I0_F0**	91069.48a	464.21ab	1.72b	22.39a	470.39b
SSP585	**T1_=_I0_F0**	90774.05a	401.03b	1.49b	21.7a	363.34c
Historical	**T2_=_I0_F1**	103901.85a	3250.09a	13.89a	26.41a	616.35a
SSP126	**T2_=_I0_F1**	102521.08b	3061.07b	12.62b	24.92b	470.39b
SSP585	**T2_=_I0_F1**	101281.27c	2688.66c	11.5c	23.79c	363.34c
Historical	**T3_=_I1_F0**	91295.88a	321.57a	1.13a	21.75a	616.35a
SSP126	**T3_=_I1_F0**	90945.65a	263.34ab	0.88b	21.29a	470.39b
SSP585	**T3_=_I1_F0**	90664.97a	217.63b	0.73b	21.08a	363.34c
Historical	**T4_=_I1_F1**	103789.09a	3245.97a	13.78a	26.65a	616.35a
SSP126	**T4_=_I1_F1**	102397.73b	3058.65b	12.5b	25.06b	470.39b
SSP585	**T4_=_I1_F1**	101124.13c	2690.97c	11.28c	23.85c	363.34c
F value		**44.84**	**120.7**	**131.5**	**55.94**	**1291**
P value		***0.001***	***0.001***	***0.001***	***0.001***	***0.001***

6.3.3.4 Total organic carbon at maturity

Total organic carbon at maturity varied significantly ($p<0.001$) under the different climate scenarios and treatments (Table 3). The highest values were observed under T2 (cattle corralling and additional irrigation) with 103,901.85 kg ha^{-1}, 102,521.08 kg ha^{-1}, and 101,281.27 kg ha^{-1} for the historical, SSP126, and SSP585 scenarios respectively (Figure 6). The lowest values were seen under T3 (no cattle corralling, no additional irrigation), with values of 91,295.88 kg ha^{-1}, 90,945.65 kg ha^{-1}, and 90,664.97 kg ha^{-1} for the historical, SSP126, and SSP585 scenarios respectively.

Historical scenarios consistently exhibited the highest total organic carbon compared to SSP126 and SSP585.

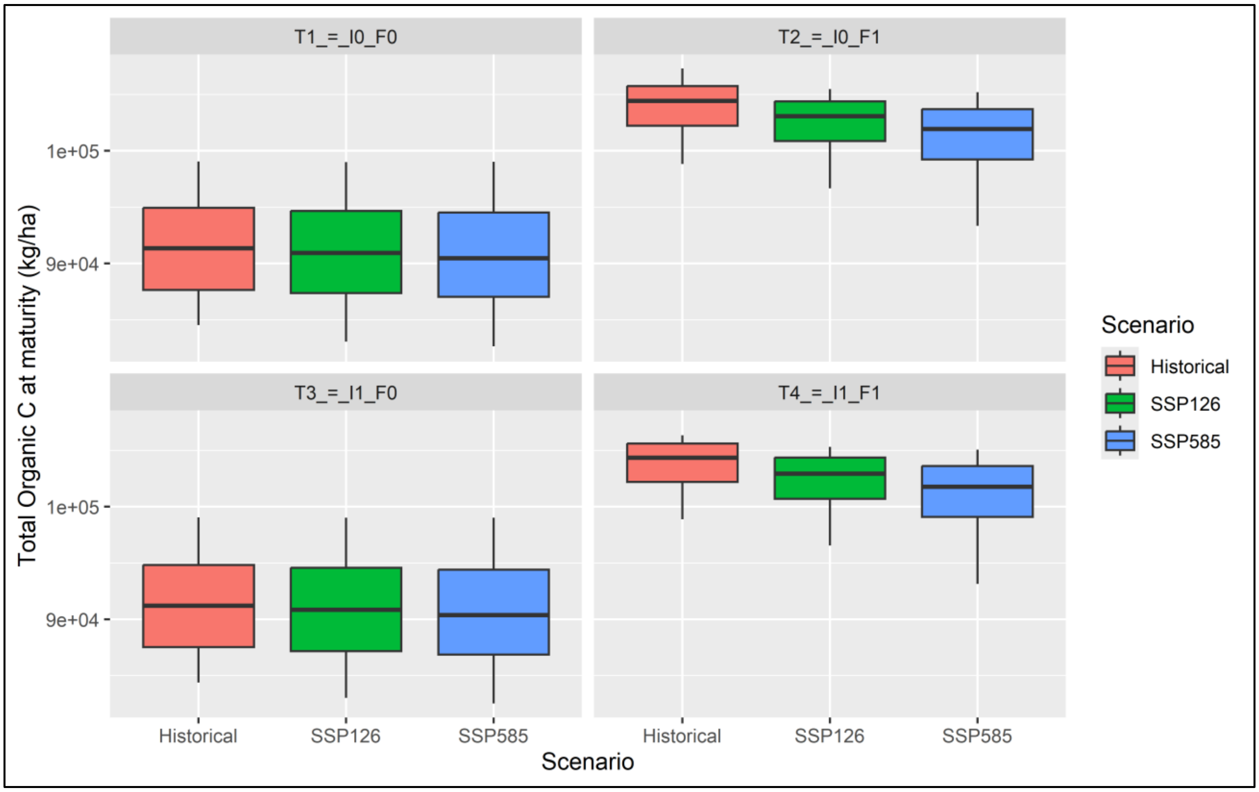


Figure 6.6. Total organic carbon at maturity (kg/ha) projection under historical and future climate condition

6.3.3.5 Climatic conditions from planting to harvest

The average atmospheric CO_2 concentration during planting to harvest varied significantly ($p<0.001$) across climate scenarios but remained constant within treatments (Table 3, Table 4). Historical scenarios recorded the highest values (616.35 ppm) across all treatments, while SSP126 and SSP585 consistently showed lower concentrations, at 470.39 ppm and 363.34 ppm, respectively.

Table 6.4. Historical and projected climate characteristics (temperature and precipitation)

GCM	**Historical (1981-2010)**		**SSP126 (2041-2070)**			**SSP585 (2041-2070)**		
	Mean (mm)	**CV (%)**	**Mean (mm)**	**CV (%)**	**Diff (%)**	**Mean (mm)**	**CV (%)**	**Diff (%)**
				Temperature				
GFDL-ESM4	1097.28	16.156	1088.64	15.416	-0.78	1016.64	13.29	-7.34
IPSL-CM6A-LR	1080	16.099	1221.12	14.237	13.06	1278.72	15.048	18.4
MPI-ESM1-2-HR	1149.12	17.38	1097.28	15.767	-4.51	1166.4	20.036	1.50
MRI-ESM2-0	1126.08	17.992	1215.36	18.712	7.92	1146.24	18.353	1.79
UKESM1-0-LL	1160.64	10.112	1255.68	9.012	8.18	1232.64	10.227	6.20
Ensemble	1126.08	7.539	1175.61	5.863	4.39	1168.12	7.639	3.73
				Precipitation				
GFDL-ESM4	27.96	1.129	29.11	0.567	4.11	29.89	1.814	6.90
IPSL-CM6A-LR	27.99	1.684	29.39	1.095	5.00	30.71	2.297	9.71
MPI-ESM1-2-HR	27.98	0.941	28.85	1.154	3.10	28.53	1.012	1.96
MRI-ESM2-0	28.01	0.797	29.33	0.954	4.71	30.26	1.94	8.03
UKESM1-0-LL	27.95	1.458	29.91	1.034	7.01	31.09	2.854	11.23
Ensemble	27.98	0.767	29.32	1.199	4.78	30.09	2.929	7.54

6.4. Discussion

6.4.1 Cattle corralling effect on grain yield and total organic carbon at maturity under future climate conditions

Cattle corralling substantially enhanced grain yield and total organic carbon (TOC) across historical and future climate scenarios (SSP126 and SSP585). Treatments integrating cattle corralling and additional irrigation (T2) recorded the highest grain yield (3250.09 kg ha^{-1} under historical scenarios), emphasizing its capacity to offset the negative impacts of climate stress. In contrast, untreated plots (T3) showed dramatic reductions in yield under all scenarios, with the lowest values under SSP585 (217.63 kg ha^{-1}). The TOC also showed a significant response to cattle corralling. The T2 treatment resulted in TOC levels of 103,901.85 kg ha^{-1} under historical scenarios, decreasing to 101,281.27 kg ha^{-1} under SSP585. These findings indicate that while future climate scenarios degrade soil organic carbon, cattle corralling mitigates these losses. This resilience is likely attributed to the organic inputs enhancing soil structure, microbial activity, and carbon sequestration potential, particularly under irrigation (Ayantunde et al., 2018b).

Future climate scenarios, characterized by rising temperatures and altered precipitation patterns, are projected to accelerate the decomposition of soil organic matter, leading to significant losses in soil organic carbon (SOC). This process diminishes soil fertility and exacerbates atmospheric CO_2 levels, contributing to climate change (Figure 8, Table 3). Stanley et al., (2024) discussed how improved grazing management practices can enhance soil carbon sequestration, offering a scalable solution for atmospheric CO_2 removal. Implementing livestock corralling practices, such as adaptive multi-paddock grazing, has been shown to mitigate SOC losses (Ikpe and Powell, 2002). Strategic corralling enhances soil health by improving soil structure, increasing nutrient cycling, and promoting carbon sequestration (Rufino et al., 2006). For instance, studies have demonstrated that sheep and goat corralling significantly increases soil organic carbon and microbial biomass carbon, thereby enhancing soil fertility (Abdul Rahman et al., 2019). Additionally, such practices can lead to increased herbaceous biomass yield in degraded rangelands, further contributing to SOC accumulation. The results underscore the potential of cattle corralling in sustaining soil health and crop productivity, especially in climate-stressed regions, by enhancing organic carbon reserves that drive critical soil functions.

6.4.2 Water productivity projection under future climate scenarios

Water productivity metrics, including yield-ET productivity, were significantly influenced by cattle corralling and irrigation. Under historical conditions, T2 achieved the highest yield-ET productivity (13.89 kg ha^{-1} mm^{-1}), compared to minimal values under T3. Future climate scenarios reduced water productivity across all treatments; for example, T2's yield-ET productivity declined to 11.5 kg ha^{-1} mm^{-1} under SSP585.

The interaction of irrigation and organic amendments proved critical in optimizing water use efficiency. Studies have demonstrated that integrating organic materials, such as biochar and compost, with irrigation methods like alternate wetting and drying (AWD) can significantly improve WUE. For instance, incorporating rice husk biochar (RHB) under AWD irrigation has increased WUE in rice cultivation (Haque et al., 2021). Similarly, using acidified biochar as a soil amendment in drought-stressed conditions has been found to enhance WUE in faba bean crops (Abd El-Mageed et al., 2021). Additionally, integrating organic amendments with optimized irrigation practices has been reported to improve soil organic carbon content, WUE, and maize productivity (Yang et al., 2024). Cattle corralling enhanced soil water-holding capacity and nutrient retention, sustaining productivity despite reduced rainfall under SSP scenarios (Figure 8, Table 3). By confining livestock to specific areas, cattle corralling can enhance soil health by increasing soil organic matter (SOM) through manure deposition. This increase in SOM improves soil structure, leading to better water infiltration and retention, which is crucial for maintaining productivity, especially under reduced rainfall conditions projected in Shared Socioeconomic Pathway (SSP) scenarios (Rayne and Aula, 2020).

These findings align with earlier studies demonstrating the role of organic matter in reducing evapotranspiration and buffering water deficits (Emmerichs et al., 2024). The higher water productivity in historical scenarios indicates that climate stress, particularly increased temperatures under SSP585 (Table 8), may outweigh the compensatory effects of cattle corralling without additional adaptation measures.

6.4.3 Nitrogen uptake projection under future climate scenarios

Nitrogen uptake productivity displayed a complex response to treatments and climate scenarios. The yield-N uptake productivity peaked with T2 treatments (26.41 kg kg^{-1} under historical scenarios). This suggests that cattle corralling supports efficient nitrogen utilization for grain production, whereas untreated plots exhibit disproportionate nitrogen allocation. This practice has been documented to elevate soil organic matter and nutrient levels, with a particular emphasis on nitrogen, an essential element for plant growth (Bayu et al., 2005; Sangaré et al., 2002; Smith et al., 1997).

Future climate scenarios reduced nitrogen productivity across all treatments. Under SSP585, T2's yield-N uptake productivity fell to 23.79 kg kg^{-1}, reflecting reduced nitrogen availability and crop assimilation efficiency due to elevated temperatures and altered rainfall patterns (Figure 8, Table 3) (Lesjak and Calderini, 2017). The ability of cattle corralling to sustain nitrogen productivity, albeit at lower levels, highlights its role in maintaining soil fertility and crop performance. This analysis suggests that integrating cattle corralling with adaptive nutrient management strategies could further optimize nitrogen use efficiency under climate-stressed conditions. Improving the corralling practice through mulching, biochar, and cover crop integration may increase nitrogen use efficiency (Abd El-Mageed et al., 2021; Abiola et al., 2023; Atakoun et al., 2023).

6.4.4 Average atmospheric CO_2 projection under future climate scenarios

Projected atmospheric CO_2 concentrations varied significantly between historical and future scenarios, affecting crop performance. Historical scenarios recorded the highest levels (616.35 ppm), decreasing to 470.39 ppm (SSP126) and 363.34 ppm (SSP585) (Figure 7). This trend reflects anticipated mitigation efforts under SSP pathways, with SSP126 representing conservative reductions and SSP585 indicating aggressive emission cuts (Bian et al., 2024; Siabi et al., 2024).

Cattle corralling treatments consistently outperformed controls under all CO_2 scenarios. However, the declining CO_2 levels under SSP pathways (Figure 8) may limit the photosynthetic benefits of elevated CO_2, reducing the "fertilization effect" on maize productivity (Liao et al., 2024; Oliver et al., 2009; Sun et al., 2024). This effect is particularly pronounced under SSP585, where yields and productivity metrics were lowest. While cattle corralling cannot directly influence atmospheric CO_2, its role in enhancing crop resilience and resource use efficiency suggests it remains a viable strategy under various CO_2 concentration trajectories. The results emphasize the need to integrate biological and technological innovations to maintain productivity in a low-carbon future.

6.5. Conclusion

This study underscores the efficacy of cattle corralling-based amendments in enhancing maize growth, biomass accumulation, and yield under both historical and future climate scenarios. The findings reveal that treatments combining cattle corralling and additional irrigation (T2) consistently outperformed other strategies, achieving the highest grain yields of 3,250.09 kg ha^{-1} under historical scenarios and 2,688.66 kg ha^{-1} under the SSP585 climate scenario. Moreover, the practice significantly enhanced total organic carbon at maturity (TOC), with the highest recorded levels of 103,901.85 kg ha^{-1} under historical scenarios, compared to the lowest values of 90,664.97 kg ha^{-1} in untreated plots under SSP585. These results highlight the resilience conferred by cattle corralling in mitigating climate-induced stresses on agroecosystems. Water productivity also demonstrated substantial improvement under cattle corralling treatments, with yield-ET productivity peaking at 13.89 kg ha^{-1} mm^{-1} under historical conditions. However, climate scenarios like SSP585 resulted in a decline to 11.5 kg ha^{-1} mm^{-1}, underscoring the necessity of integrating this practice with advanced water management techniques. Similarly, nitrogen uptake productivity showed significant enhancement in T2 treatments, reaching 26.41 kg kg^{-1} under historical scenarios and 23.79 kg kg^{-1} under SSP585. These findings affirm the critical role of cattle corralling in optimizing nitrogen use efficiency and maintaining soil fertility under climate-stressed conditions.

Cattle corralling-based amendments represent a scalable and effective approach to improving maize productivity and resilience against climate variability. Future research should explore integrating this practice with complementary strategies, such as biochar application, mulching, and precision irrigation, to further optimize resource use efficiency and ensure sustainable agricultural productivity in a changing climate. These findings contribute to the growing body of knowledge aimed at mitigating the adverse impacts of climate change on food security, offering actionable insights for policymakers, researchers, and practitioners in climate-resilient agriculture.

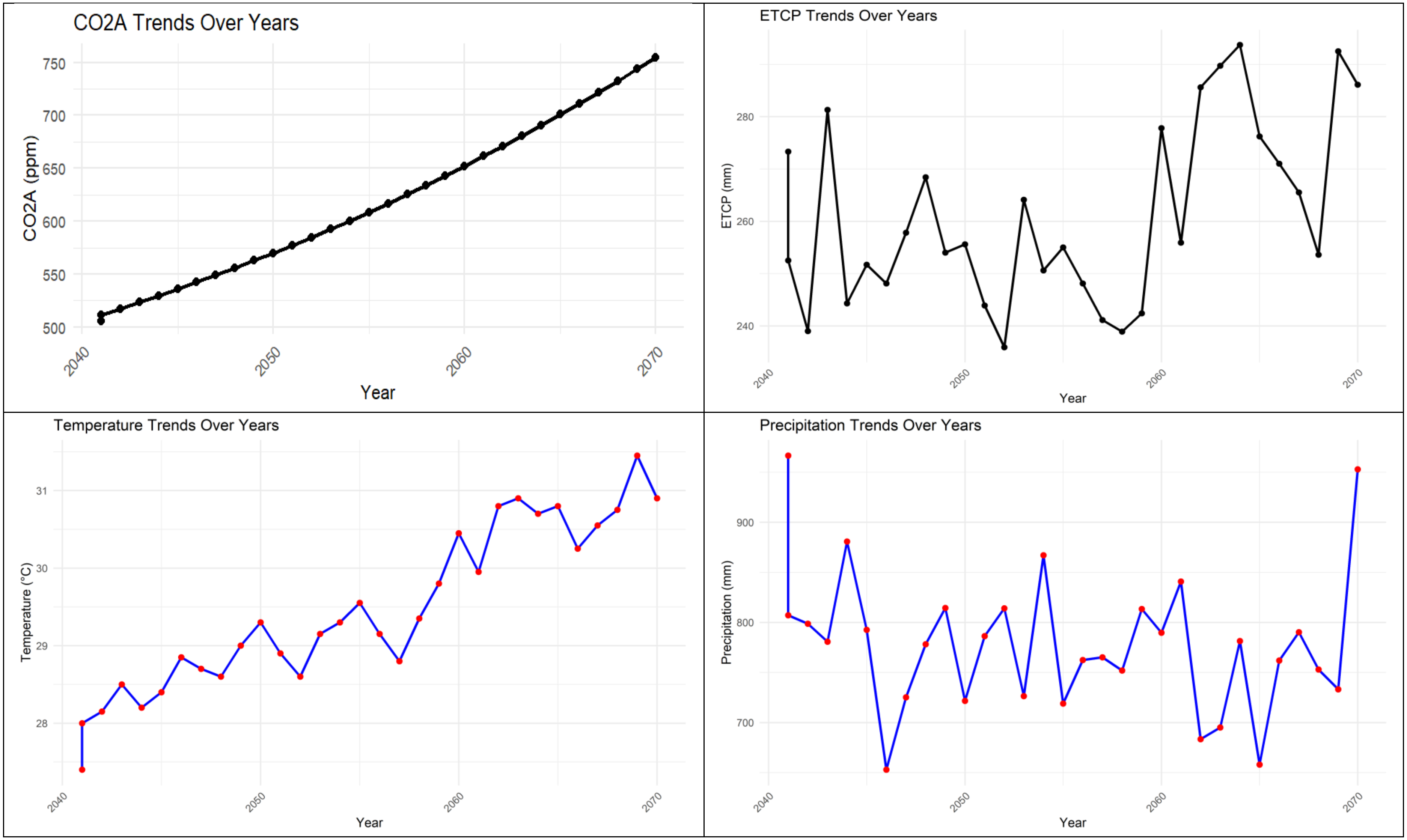


Figure 6.7. Climatic trend projection from 2041 to 2070

CHAPTER 7: GENERAL CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This study found that the potential of cattle corralling-based practices to enhance soil fertility, maize productivity, and climate resilience in the Sudano-Savanna region of Benin is hidh. Against the backdrop of declining agricultural productivity, climate variability, and limited access to synthetic fertilizers, the findings provide critical insights into sustainable agricultural practices that can benefit smallholder farmers. The research objectives were addressed through a combination of field surveys, experimental trials, and modelling approaches, leading to the following key conclusions:

Socio-cultural and economic dimensions of cattle corralling (Chapter 3):

Cattle corralling is widely recognized and adopted as a soil fertility management strategy by smallholder farmers in northern Benin. The practice is influenced by socio-economic factors, agroecological contexts, and access to resources. Key constraints include herd security, water and forage availability, and logistical challenges. Understanding these dynamics is critical for scaling up sustainable livestock-crop integration practices.

Impact on soil health (Chapter 4):

Traditional cattle corralling practices significantly improve soil physical and chemical properties, such as bulk density, hydraulic conductivity, and macronutrient (NPK) levels. These improvements are critical for enhancing soil fertility and resilience to climate variability, underscoring the importance of promoting corralling as an effective soil amendment strategy.

Effect on maize production (Chapter 5):

Cattle corralling-based amendments, combined with water management strategies, enhance maize growth and yields under both deficit and additional irrigation scenarios. These practices also improve water-use efficiency and nutrient factor productivity, demonstrating their potential to address food security challenges in resource-constrained farming systems.

Adaptation to future climate conditions (Chapter 6):

Modelling results indicate that cattle corralling-based practices can sustain maize productivity under projected climate scenarios involving increased temperatures and reduced rainfall. The integration of these practices into farming systems contributes to long-term carbon sequestration and climate resilience, highlighting their relevance for sustainable agricultural intensification.

Cattle corralling is a viable nature-based solution for improving soil health, crop productivity, and climate adaptation in smallholder farming systems. Its successful implementation requires addressing socio-economic constraints, enhancing farmer awareness, and integrating scientific insights into local practices. These findings provide a foundation for informed policy-making and practical interventions to promote sustainable agriculture in the Sudano-Savanna region and beyond.

7.2 Recommendations

7.2.1 Recommendations for farmers

1. Adopt rotational cattle corralling practices: Farmers should implement rotational corralling to evenly distribute manure across fields, maximizing soil fertility improvements while minimizing nutrient concentration and soil compaction.
2. Combine corralling with water management strategies: Incorporating water-saving techniques, such as supplemental irrigation during dry periods, enhances the effectiveness of cattle corralling by improving maize yield and water-use efficiency.
3. Integrate manure spreading and crop management: After corralling, manually spread livestock manure evenly across fields to ensure uniform nutrient distribution. This practice,

combined with optimal planting densities and timely fertilization, enhances crop productivity.

4. Prepare for climate variability with sustainable practices: Farmers should prioritize climate-resilient agricultural methods, including cattle corralling and conservation agriculture, to adapt to projected climate changes. These practices improve soil carbon sequestration, mitigate temperature stress, and sustain crop yields.

7.2.2 Recommendations for policy

1. The ministry of agriculture should establish a support framework to address resource constraints for sustainable cattle corralling, including enhanced access to water and forage resources, herd security measures, and credit facilities.
2. Civil society organizations should promote and support sustainable annual cattle corralling practices as a soil fertility management and carbon sequestration strategy. This policy would address both agricultural productivity and environmental sustainability, supporting soil health and climate resilience in semi-arid regions like Northern Benin.
3. Extension services providers should offer training programs on combining cattle corralling with organic amendments like biochar and mulching, alongside effective water use techniques. This training would empower farmers to maximize productivity and water use efficiency sustainably.

7.2.3 Recommendations for future research

Further in-depth research is necessary on crop-livestock integration at different levels.

1. Explore long-term impacts of cattle corralling on soil microbial properties: Future research should investigate the effects of cattle corralling on soil microbial activity and biodiversity to better understand its implications for long-term soil health and ecosystem sustainability.
2. Evaluate the socio-economic dynamics of adoption: Conduct in-depth studies on the socio-economic factors influencing the adoption of cattle corralling, including labour dynamics, land tenure systems, and gender-specific roles, to design more inclusive and scalable interventions.
3. Assess the role of cattle corralling in climate mitigation: Quantify the carbon sequestration potential and greenhouse gas emission reductions associated with cattle corralling to validate its role in mitigating climate change and enhancing sustainable land management.

7.2.4 Major contributions to knowledge

1. Socio-cultural and economic insights into cattle corralling practices: The study provides a comprehensive characterization of cattle corralling practices in northern Benin, including their socio-cultural and economic determinants. It identifies key factors influencing adoption, such as education, agroecological zones, access to credit, and extension services, offering actionable insights for promoting sustainable livestock-crop integration.
2. Demonstration of soil fertility improvement through corralling: The research highlights the significant impact of cattle corralling on improving soil physical and chemical properties, such as bulk density, macronutrient content (NPK), and organic matter. This evidence supports the practice as a viable soil fertility management strategy, particularly in resource-constrained farming systems.
3. Quantification of benefits for maize productivity: The study demonstrates how cattle corralling-based amendments, in combination with irrigation strategies, significantly

enhance maize yields, water-use efficiency, and nutrient productivity. These findings validate the practice as a cost-effective alternative to synthetic fertilizers for smallholder farmers.

4. Projection of corralling effectiveness under future climate scenarios: Through crop modelling, the thesis projects the long-term benefits of cattle corralling under anticipated climate change conditions, including increased resilience to temperature fluctuations and reduced rainfall. This contribution underscores its potential for sustainable agricultural intensification and climate adaptation.

7.2.5 Limitations of the study

1. Short-term assessment of soil biological properties: The study primarily focused on the immediate impacts of cattle corralling on soil physical and chemical properties, with limited exploration of long-term effects on soil microbial activity and biodiversity.
2. Socio-economic generalizations: While the study identified key socio-economic factors influencing the adoption of cattle corralling, the analysis may not fully capture the diversity of cultural, economic, and gender-specific contexts across different farming communities.
3. Modelling assumptions for future climate scenarios: The projections under future climate scenarios relied on assumptions inherent to the crop simulation model (DSSAT) and climate models, which may not fully account for local variability or unforeseen environmental changes.
4. Limited geographic scope: The research was conducted in three municipalities in northern Benin, which may limit the generalizability of findings to other regions with different agroecological, socio-economic, or cultural conditions.

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APPENDIX

Appendix 1. Characteristics of the four selected municipalities for household survey

Municipalities	**Agroecological zone**	**Arrondissement**	**Village**	**Number of respondents**
Malanville	Zone 1 (South Borgou food zone)	GAROU	GAROU I	30
			KAMBOWO TOUNGA	30
		TOMBOUTOU	SAKAWAN-TEGUI	30
			ZENON	30
Bembereke	Zone 2 (South Borgou food zone)	BOUANRI	GANDO-BOROU	30
			GBEROU DABA	30
		GAMIA	BOURI	30
			GANRO	30
Gogounou	Zone 2 (Cotton zone of North Benin)	GOUNAROU	BORO	30
			BORODAROU	30
		SORI	GAMAROU	30
			PIGOUROU	30

Appendix 2. Description of the variables that will be used in the household-level analysis

Codes	Questions	Check or write the correct answer.
HAS	**Household demographic and socio-economic characteristics**	
A1	Agroecological zone	1- Zone 1 ☐ 2- Zone 2 ☐ 3- Zone 3 ☐
A2	Communes	1- Bembereke ☐ 2- Gogounou ☐ 3- Malanville ☐
A3	District (Enter name)	
A4	Village or camp (Insert name)	
A5	GPS Coordinates (Enter values)	
A6	Name and surname (Enter name)	
A7	Phone (Enter number)	
A8	Marital status	1- Bride ☐ 2- Single ☐ 3- Divorced ☐ 4- Widow ☐
A9	Age (Enter age in years)	
A10	Sex	1- Woman ☐ 2- Man ☐
A11	Ethnicity (Enter ethnicity)	
A12	Religion	1- Christian ☐ 2- Muslim ☐ 3- Animism ☐ 4- The others ☐
A13	Education level	1- None ☐ 2- Primary ☐ 3- Secondary ☐ 4- University ☐

A14	What is your main activity?	1- Breeding ☐ 2- Agriculture ☐ 3- Hunting Fishing ☐ 4- Trade ☐ 5- Crafts ☐		
A15	Farming Experience: How long have you been farming (Insert number of years)			
A16	Type of worker?			
A17	Farmed animal species	Species	Presence	Effective
		Bovine	Yes ☐ No ☐	
		Sheep	Yes ☐ No ☐	
		Goats	Yes ☐ No ☐	
		Pork	Yes ☐ No ☐	
		Poultry	Yes ☐ No ☐	
		Others	Yes ☐ No ☐	
A18	Household size	Slice	Total workforce	
		Men (age ≥ 60 years)		
		Men (14<age<60 years)		
		Boy (age≤14 years old)		
		Women (age ≥ 60 years)		
		Women (14<age<60 years)		
		Girl (age≤14 years old)		
A19	Membership in a livestock or agricultural organization	Yes ☐ No ☐		
A20	Are you in contact with extension services?	Yes ☐ No ☐		
A21	Do you have access to agricultural credits?	Yes ☐ No ☐		
A22		What is the slice?		

A23	Estimate the total annual household income (FCFA)	1- R<100,000 ☐ 2- 100,000<R<250,000 ☐ 3- 250,000<R<500,000 ☐ 4- 500,000<R<750,000 ☐ 5- 750,000<R<1,000,000 ☐ R>1,000,000 ☐	
		Estimate in FCFA	
A24	What is the share of livestock in the annual household income?	1- p<25% ☐ 2- 25%<p<50% ☐ 3- 50%<p<75% ☐ 4- 75%<p≤100% ☐	

Farm structure, production method and production objectives

B1	Farm size	1- Area in hectares
B2	1- Corn ☐	
	2- Cotton ☐	
	3- Peanut ☐	
	4- Voandzou ☐	
	5- Cowpea ☐	
	6- Soy ☐	
	7- Other ☐	
B3	Do you own the cultivated land?	Yes ☐No ☐
B5	Distance from the House or campsite to the road (continuous (in kilometers))	
B5	Distance from the house or camp to the field (continuous (in kilometers))	
B6	Access climate information	Yes ☐No ☐
B7	Access market information	Yes ☐No ☐
B8	Access to technical assistance: participation in training	Yes ☐No ☐
B9	Field topography	1- Very flat slope ☐ 2- Average slope ☐ 3- Very steep slope ☐

B10	Number of agricultural workers	Continues (in number of employees)
B11	Land acquisition method	1- Purcha☐ 2- Don ☐ 3- Location ☐ 4- Inheritanc☐ 5- Others ☐
B12	Agriculture mode	1- Sedentary ☐ 2- Semi-sedentary ☐ 3- Roaming on burn ☐
B13	Breeding method	1- Sedentary ☐ 2- Semi-sedentary ☐ 3- Transhumant ☐
B14	Production target (to be specified)	1- Consumption/subsistence ☐ 2- Market ☐ 3- Both ☐
B15	Region of origin (Binary: If the household comes from the study area)	Yes No☐ ☐
B16	Gender of head of household	Man Wom☐n ☐
C	**The practice of Ox Parking**	
C1	Are you aware of the parking practice?	Yes No☐ ☐
C2	Are you used to practicing it?	Yes No☐ ☐
C3	How do you usually practice it?	1- Nocturne 2- Rotary 3- Parking contract
C4	Where do you usually practice it?	1- Fields near the house (distance) 2- Field far from home 3- On poor plot 4- On a rich plot
C5	Frequency of parking the same plot	1-Every year 2-Every two years 3-Every three years 4-Others
C6	Do you think that penning improves soil fertility more than mineral fertilizers?	Yes No☐ ☐
C7	Do you practice parking contracts with farmers?	Yes No☐ ☐
	What are the clauses of these contracts?	

C8	(If it is a breeder) Would you accept to charge for parking in agricultural fields? How much	Yes No☐ ☐	How much ?
C9	Will you agree to include goods in kind in the parking contract? If so, which ones?		
C10	What do you think of the condition of the ground after parking?	1- Very fertile, 2- Fertile 3- Moderately fertile 4- Not fertile	
C11	Have you received any government grants?	Yes No☐ ☐	
C12	How long do you think it takes to park (1-7 months)?		
C13	How many oxen do you use to pen a hectare?		
C13	Do you spread manure after penning in order to homogenize the plots?		
C12	Are there any constraints related to the parking system?	1- very restrictive, 2- moderately restrictive, 3- weakly restrictive and 4- no constraint	
C13	Are there any constraints related to the lack of fodder allowing for penning?	1- very restrictive, 2- moderately restrictive, 3- weakly restrictive and 4- no constraint	
C14	Are there any constraints related to the lack of water for parking?	1- very restrictive, 2- moderately restrictive, 3- weakly restrictive and 4- no constraint	
D	**Perception of the effects of climate change**		
D1	Do you perceive (feel) that the weather (climate) is changing in this region?	Yes N☐ ☐	
D2	If yes, what are the types of CC perceived? Drought: Perceived or not	Yes N☐ ☐	
D3	If yes, what are the types of perceived CC? Rainfall: Perceived or not	Yes N☐ ☐	
D4	If yes, what are the types of perceived CC? Temperature: Perceived or not	Yes N☐ ☐	

D5	What are the different forms of CC perceived? Cyclicity of drought	Increase ☐ Decreased ☐ Don't know ☐
D6	What are the different forms of CC perceived? Drought extension	Increase ☐ Decreased ☐ Don't know ☐
D7	What are the different forms of CC perceived? Duration of dry pockets	Increase ☐ Decreased ☐ Don't know ☐
D8	What are the different forms of CC perceived? Rains delayed	Increase ☐ Decreased ☐ Don't know ☐
D9	What are the different forms of CC perceived? Prolongation of the rains	Increase ☐ Decreased ☐ Don't know ☐
D10	What are the different forms of CC perceived? Floods	Increase ☐ Decreased ☐ Don't know ☐
D11	What are the different forms of CC perceived? Poor spatial distribution of rainfall	Increase ☐ Decreased ☐ Don't know ☐
D12	What are the different forms of CC perceived? Decrease in rainfall	Increase ☐ Decreased ☐ Don't know ☐
D13	What are the different forms of CC perceived? Increased heat	Increase ☐ Decreased ☐ Don't know ☐
D14	What are the different forms of CC perceived? Decrease in rainfall	Increase ☐ Decreased ☐ Don't know ☐
D15	Do you think that the decline in soil fertility is linked to climate change?	Yes N☐ Don't know☐ ☐

Appendix 3. Irrigation schedule during 2023 experimentation

Date	Day	Stage	Rain mm	Ks fract.	Eta mm/day	Etc (mm/day)	Depl %	Net irr mm	Deficit mm	Loss mm	Gr. Irr mm	Irr req mm	Irr req L/15m^2	Nbr Arros nomb
07-Jun	1	Init	0	1	1.4	1.4	2	0	1.4	0	0	0	0	**0**
08-Jun	2	Init	0	1	1.4	1.4	2	0	1.4	0	0	0	0	**0**
09-Jun	3	Init	0	1	1.4	1.4	3	0	2.8	0	0	0	0	**0**
10-Jun	4	Init	0	1	1.4	1.4	4	2.8	4.2	0.14	2.94	2.94	44.1	**4**
11-Jun	5	Init	0	1	1.3	1.3	5	0	0	0	0	0	0	**0**

12-Jun	6	Init	29.2	1	1.3	1.3	1	2.8	1.3	0.14	2.94	2.94	44.1	**4**
13-Jun	7	Init	0	1	1.3	1.3	2	0	2.6	0	0	0	0	**0**
14-Jun	8	Init	0	1	1.3	1.3	1	2.6	1.3	0.13	2.73	2.73	40.95	**4**
15-Jun	9	Init	0	1	1.3	1.3	2	0	2.6	0	0	0	0	**0**
16-Jun	10	Init	29.2	1	1.3	1.3	3	2.6	4	0.13	2.73	2.73	40.95	**4**
17-Jun	11	Init	0	1	1.3	1.3	4	0	0	0	0	0	0	**0**
18-Jun	12	Init	0	1	1.3	1.3	1	2.6	1.3	0.13	2.73	2.73	40.95	**4**
19-Jun	13	Init	0	1	1.3	1.3	2	0	2.6	0	0	0	0	**0**
20-Jun	14	Init	0	1	1.3	1.3	3	2.6	4	0.13	2.73	2.73	40.95	**4**
21-Jun	15	Init	0	1	1.4	1.4	4	0	0	0	0	0	0	**0**
22-Jun	16	Init	30	1	1.4	1.4	1	2.6	1.4	0.13	2.73	2.73	40.95	**4**
23-Jun	17	Init	0	1	1.4	1.4	2	0	2.7	0	0	0	0	**0**
24-Jun	18	Init	0	1	1.4	1.4	1	2.7	1.4	0.135	2.835	2.835	42.525	**4**
25-Jun	19	Init	0	1	1.4	1.4	2	0	2.7	0	0	0	0	**0**
26-Jun	20	Init	30	1	1.4	1.4	3	2.7	4.1	0.135	2.835	2.835	42.525	**4**
27-Jun	21	Dev	0	1	1.4	1.4	3	0	0	0	0	0	0	**0**
28-Jun	22	Dev	0	1	1.4	1.4	1	2.7	1.4	0.135	2.835	2.835	42.525	**4**
29-Jun	23	Dev	0	1	1.4	1.4	2	0	2.7	0	0	0	0	**0**
30-Jun	24	Dev	0	1	1.4	1.4	2	2.7	4.1	0.135	2.835	2.835	42.525	**4**
01-Jul	25	Dev	0	1	2.2	2.2	3	0	0	0	0	0	0	**0**
02-Jul	26	Dev	30.7	1	2.2	2.2	1	2.7	2.2	0.135	2.835	2.835	42.525	**4**
03-Jul	27	Dev	0	1	2.2	2.2	2	2.2	4.5	0.11	2.31	2.31	34.65	**3**
04-Jul	28	Dev	0	1	2.2	2.2	1	2.2	2.2	0.11	2.31	2.31	34.65	**3**
05-Jul	29	Dev	0	1	2.2	2.2	2	2.2	4.5	0.11	2.31	2.31	34.65	**3**
06-Jul	30	Dev	30.7	1	2.2	2.2	3	2.2	0	0.11	2.31	2.31	34.65	**3**
07-Jul	31	Dev	0	1	2.2	2.2	1	2.2	2.2	0.11	2.31	2.31	34.65	**3**
08-Jul	32	Dev	0	1	2.2	2.2	1	2.2	2.2	0.11	2.31	2.31	34.65	**3**
09-Jul	33	Dev	0	1	2.2	2.2	2	2.2	4.5	0.11	2.31	2.31	34.65	**3**
10-Jul	34	Dev	0	1	2.2	2.2	3	2.2	0	0.11	2.31	2.31	34.65	**3**
11-Jul	35	Dev	0	1	3.2	3.2	1	2.2	2.2	0.11	2.31	2.31	34.65	**3**
12-Jul	36	Dev	31.7	1	3.2	3.2	2	2.2	0	0.11	2.31	2.31	34.65	**3**
13-Jul	37	Dev	0	1	3.2	3.2	1	3.2	3.2	0.16	3.36	3.36	50.4	**5**
14-Jul	38	Dev	0	1	3.2	3.2	1	3.2	3.2	0.16	3.36	3.36	50.4	**5**
15-Jul	39	Dev	0	1	3.2	3.2	3	3.2	0	0.16	3.36	3.36	50.4	**5**
16-Jul	40	Dev	31.7	1	3.2	3.2	1	3.2	3.2	0.16	3.36	3.36	50.4	**5**
17-Jul	41	Dev	0	1	3.2	3.2	3	3.2	0	0.16	3.36	3.36	50.4	**5**
18-Jul	42	Dev	0	1	3.2	3.2	1	3.2	3.2	0.16	3.36	3.36	50.4	**5**
19-Jul	43	Dev	0	1	3.2	3.2	2	3.2	0	0.16	3.36	3.36	50.4	**5**
20-Jul	44	Dev	0	1	3.2	3.2	1	3.2	3.2	0.16	3.36	3.36	50.4	**5**
21-Jul	45	Dev	0	1	4	4	2	3.2	0	0.16	3.36	3.36	50.4	**5**
22-Jul	46	Dev	32.7	1	4	4	1	3.2	4	0.16	3.36	3.36	50.4	**5**
23-Jul	47	Dev	0	1	4	4	3	4	0	0.2	4.2	4.2	63	**6**

24-Jul	48	Dev	0	1	4	4	1	4	4	0.2	4.2	4.2	63	**6**
25-Jul	49	Dev	0	1	4	4	3	4	0	0.2	4.2	4.2	63	**6**
26-Jul	50	Dev	32.7	1	4	4	1	4	4	0.2	4.2	4.2	63	**6**
27-Jul	51	Mid	0	1	4	4	3	4	0	0.2	4.2	4.2	63	**6**
28-Jul	52	Mid	0	1	4	4	1	4	4	0.2	4.2	4.2	63	**6**
29-Jul	53	Mid	0	1	4	4	3	4	0	0.2	4.2	4.2	63	**6**
30-Jul	54	Mid	0	1	4	4	1	4	4	0.2	4.2	4.2	63	**6**
31-Jul	55	Mid	0	1	4	4	3	4	0	0.2	4.2	4.2	63	**6**
01-Aug	56	Mid	0	1	4.1	4.1	1	4	4	0.2	4.2	4.2	63	**6**
02-Aug	57	Mid	34.1	1	4.1	4.1	3	4	0	0.2	4.2	4.2	63	**6**
03-Aug	58	Mid	0	1	4.1	4.1	1	4.1	4.1	0.205	4.305	4.305	64.575	**6**
04-Aug	59	Mid	0	1	4.1	4.1	1	4.1	4.1	0.205	4.305	4.305	64.575	**6**
05-Aug	60	Mid	0	1	4.1	4.1	3	4.1	0	0.205	4.305	4.305	64.575	**6**
06-Aug	61	Mid	34.1	1	4.1	4.1	1	4.1	4.1	0.205	4.305	4.305	64.575	**6**
07-Aug	62	Mid	0	1	4.1	4.1	3	4.1	0	0.205	4.305	4.305	64.575	**6**
08-Aug	63	Mid	0	1	4.1	4.1	1	4.1	4.1	0.205	4.305	4.305	64.575	**6**
09-Aug	64	Mid	0	1	4.1	4.1	3	4.1	0	0.205	4.305	4.305	64.575	**6**
10-Aug	65	Mid	0	1	4.1	4.1	1	4.1	4.1	0.205	4.305	4.305	64.575	**6**
11-Aug	66	Mid	0	1	3.8	3.8	3	4.1	0	0.205	4.305	4.305	64.575	**6**
12-Aug	67	Mid	35.3	1	3.8	3.8	1	4.1	3.8	0.205	4.305	4.305	64.575	**6**
13-Aug	68	Mid	0	1	3.8	3.8	3	3.8	0	0.19	3.99	3.99	59.85	**5**
14-Aug	69	Mid	0	1	3.8	3.8	1	3.8	3.8	0.19	3.99	3.99	59.85	**5**
15-Aug	70	Mid	0	1	3.8	3.8	3	3.8	0	0.19	3.99	3.99	59.85	**5**
16-Aug	71	End	35.3	1	3.8	3.8	1	3.8	3.8	0.19	3.99	3.99	59.85	**5**
17-Aug	72	End	0	1	3.8	3.8	3	3.8	0	0.19	3.99	3.99	59.85	**5**
18-Aug	73	End	0	1	3.8	3.8	1	3.8	3.8	0.19	3.99	3.99	59.85	**5**

19-Aug	74	End	0	1	3.8	3.8	3	3.8	0	0.19	3.99	3.99	59.85	**5**
20-Aug	75	End	0	1	3.8	3.8	1	3.8	3.8	0.19	3.99	3.99	59.85	**5**
21-Aug	76	End	0	1	2.5	2.5	3	3.8	0	0.19	3.99	3.99	59.85	**5**
22-Aug	77	End	35	1	2.5	2.5	1	3.8	2.5	0.19	3.99	3.99	59.85	**5**
23-Aug	78	End	0	1	2.5	2.5	2	2.5	0	0.125	2.625	2.625	39.375	**4**
24-Aug	79	End	0	1	2.5	2.5	1	2.5	2.5	0.125	2.625	2.625	39.375	**4**
25-Aug	80	End	0	1	2.5	2.5	2	2.5	0	0.125	2.625	2.625	39.375	**4**
26-Aug	81	End	35	1	2.5	2.5	1	2.5	2.5	0.125	2.625	2.625	39.375	**4**
27-Aug	82	End	0	1	2.5	2.5	2	2.5	0	0.125	2.625	2.625	39.375	**4**
28-Aug	83	End	0	1	2.5	2.5	1	2.5	2.5	0.125	2.625	2.625	39.375	**4**
29-Aug	84	End	0	1	2.5	2.5	2	2.5	0	0.125	2.625	2.625	39.375	**4**
30-Aug	85	End	0	1	2.5	2.5	1	2.5	2.5	0.125	2.625	2.625	39.375	**4**
31-Aug	86	End	0	1	2.5	2.5	2	2.5	0	0.125	2.625	2.625	39.375	**4**
01-Sep	87	End	0	1	1.5	1.5	1	2.5	2.5	0.125	2.625	2.625	39.375	**4**
02-Sep	88	End	36.2	1	1.5	1.5	1	2.5	4	0.125	2.625	2.625	39.375	**4**
03-Sep	89	End	0	1	1.5	1.5	2	0	0	0	0	0	0	**0**
04-Sep	End	End	0	1	0	0	1					0	0	**0**

Appendix 4. Irrigation schedule during 2024 experimentation

Date	Day	Stage	Rain mm	Ks fract.	Eta mm/day	Depl %	Net Irr mm	Deficit mm	Loss mm	Gr. Irr mm	Flow l/s/ha	Irr req L/9 m²	Nbr Arros nomb
02/17/2024	1	Init	0	1	1.8	4	1.8	0	0	3.5	0.41	31.5	2.86
02/18/2024	2	Init	0.9	1	1.8	4	1.8	0	0	3.5	0.41	31.5	2.86
02/19/2024	3	Init	0	1	1.8	4	1.8	0	0	3.5	0.41	31.5	2.86

02/20/2024	4	Init	0	1	1.8	4	1.8	0	0	3.5	0.41	31.5	2.86
02/21/2024	5	Init	0	1	1.8	3	1.8	0	0	3.5	0.41	31.5	2.86
02/22/2024	6	Init	0	1	1.8	3	1.8	0	0	3.6	0.42	32.4	2.95
02/23/2024	7	Init	0	1	1.8	3	1.8	0	0	3.6	0.42	32.4	2.95
02/24/2024	8	Init	1	1	1.8	3	1.8	0	0	3.6	0.42	32.4	2.95
02/25/2024	9	Init	0	1	1.8	3	1.8	0	0	3.6	0.42	32.4	2.95
02/26/2024	10	Init	0	1	1.8	3	1.8	0	0	3.6	0.42	32.4	2.95
02/27/2024	11	Init	0	1	1.8	3	1.8	0	0	3.6	0.42	32.4	2.95
02/28/2024	12	Init	1	1	1.8	3	1.8	0	0	3.6	0.42	32.4	2.95
02/29/2024	13	Init	0	1	1.8	3	1.8	0	0	3.6	0.42	32.4	2.95
03/01/2024	14	Init	0	1	1.8	3	1.8	0	0	3.6	0.42	32.4	2.95
03/02/2024	15	Init	0	1	1.8	3	1.8	0	0	3.6	0.42	32.4	2.95
03/03/2024	16	Init	0	1	2	3	2	0	0	4.1	0.47	36.9	3.35
03/04/2024	17	Init	0	1	2	3	2	0	0	4.1	0.47	36.9	3.35
03/05/2024	18	Init	2.8	1	2	3	2	0	0	4.1	0.47	36.9	3.35
03/06/2024	19	Init	0	1	2	3	2	0	0	4.1	0.47	36.9	3.35
03/07/2024	20	Init	0	1	2	3	2	0	0	4.1	0.47	36.9	3.35
03/08/2024	21	Dev	0	1	2	2	2	0	0	4.1	0.47	36.9	3.35
03/09/2024	22	Dev	2.8	1	2	2	2	0	0	4.1	0.47	36.9	3.35
03/10/2024	23	Dev	0	1	2	2	2	0	0	4.1	0.47	36.9	3.35
03/11/2024	24	Dev	0	1	3.7	4	3.7	0	0	7.5	0.87	67.5	6.14
03/12/2024	25	Dev	0	1	3.7	4	3.7	0	0	7.5	0.87	67.5	6.14
03/13/2024	26	Dev	4.7	1	3.7	4	3.7	0	0	7.5	0.87	67.5	6.14
03/14/2024	27	Dev	0	1	3.7	4	3.7	0	0	7.5	0.87	67.5	6.14
03/15/2024	28	Dev	0	1	3.7	4	3.7	0	0	7.5	0.87	67.5	6.14
03/16/2024	29	Dev	0	1	3.7	4	3.7	0	0	7.5	0.87	67.5	6.14
03/17/2024	30	Dev	4.7	1	3.7	4	3.7	0	0	7.5	0.87	67.5	6.14
03/18/2024	31	Dev	0	1	3.7	4	3.7	0	0	7.5	0.87	67.5	6.14
03/19/2024	32	Dev	0	1	3.7	4	3.7	0	0	7.5	0.87	67.5	6.14
03/20/2024	33	Dev	0	1	3.7	4	3.7	0	0	7.5	0.87	67.5	6.14
03/21/2024	34	Dev	0	1	6.1	6	6.1	0	0	12.2	1.41	109.8	9.98
03/22/2024	35	Dev	0	1	6.1	5	6.1	0	0	12.2	1.41	109.8	9.98
03/23/2024	36	Dev	6.2	1	6.1	5	6.1	0	0	12.2	1.41	109.8	9.98
03/24/2024	37	Dev	0	1	6.1	5	6.1	0	0	12.2	1.41	109.8	9.98
03/25/2024	38	Dev	0	1	6.1	5	6.1	0	0	12.2	1.41	109.8	9.98
03/26/2024	39	Dev	0	1	6.1	5	6.1	0	0	12.2	1.41	109.8	9.98
03/27/2024	40	Dev	6.2	1	6.1	5	6.1	0	0	12.2	1.41	109.8	9.98
03/28/2024	41	Dev	0	1	6.1	5	6.1	0	0	12.2	1.41	109.8	9.98
03/29/2024	42	Dev	0	1	6.1	5	6.1	0	0	12.2	1.41	109.8	9.98
03/30/2024	43	Dev	0	1	6.1	5	6.1	0	0	12.2	1.41	109.8	9.98
03/31/2024	44	Dev	0	1	7.8	6	7.8	0	0	15.7	1.81	141.3	12.85
04/01/2024	45	Dev	0	1	7.8	6	7.8	0	0	15.7	1.81	141.3	12.85

04/02/2024	46	Dev	8.9	1	7.8	6	7.8	0	0	15.7	1.81	141.3	12.85
04/03/2024	47	Dev	0	1	7.8	6	7.8	0	0	15.7	1.81	141.3	12.85
04/04/2024	48	Dev	0	1	7.8	6	7.8	0	0	15.7	1.81	141.3	12.85
04/05/2024	49	Dev	0	1	7.8	6	7.8	0	0	15.7	1.81	141.3	12.85
04/06/2024	50	Dev	8.9	1	7.8	6	7.8	0	0	15.7	1.81	141.3	12.85
04/07/2024	51	Mid	0	1	7.8	6	7.8	0	0	15.7	1.81	141.3	12.85
04/08/2024	52	Mid	0	1	7.8	6	7.8	0	0	15.7	1.81	141.3	12.85
04/09/2024	53	Mid	0	1	7.8	6	7.8	0	0	15.7	1.81	141.3	12.85
04/10/2024	54	Mid	0	1	7.8	6	7.8	0	0	15.7	1.81	141.3	12.85
04/11/2024	55	Mid	0	1	7.9	6	7.9	0	0	15.7	1.82	141.3	12.85
04/12/2024	56	Mid	0	1	7.9	6	7.9	0	0	15.7	1.82	141.3	12.85
04/13/2024	57	Mid	11.7	1	7.9	6	7.9	0	0	15.7	1.82	141.3	12.85
04/14/2024	58	Mid	0	1	7.9	6	7.9	0	0	15.7	1.82	141.3	12.85
04/15/2024	59	Mid	0	1	7.9	6	7.9	0	0	15.7	1.82	141.3	12.85
04/16/2024	60	Mid	0	1	7.9	6	7.9	0	0	15.7	1.82	141.3	12.85
04/17/2024	61	Mid	11.7	1	7.9	6	7.9	0	0	15.7	1.82	141.3	12.85
04/18/2024	62	Mid	0	1	7.9	6	7.9	0	0	15.7	1.82	141.3	12.85
04/19/2024	63	Mid	0	1	7.9	6	7.9	0	0	15.7	1.82	141.3	12.85
04/20/2024	64	Mid	0	1	7.9	6	7.9	0	0	15.7	1.82	141.3	12.85
04/21/2024	65	Mid	0	1	7.3	5	7.3	0	0	14.6	1.69	131.4	11.95
04/22/2024	66	Mid	0	1	7.3	5	7.3	0	0	14.6	1.69	131.4	11.95
04/23/2024	67	Mid	14.3	1	7.3	5	7.3	0	0	14.6	1.69	131.4	11.95
04/24/2024	68	Mid	0	1	7.3	5	7.3	0	0	14.6	1.69	131.4	11.95
04/25/2024	69	Mid	0	1	7.3	5	7.3	0	0	14.6	1.69	131.4	11.95
04/26/2024	70	Mid	0	1	7.3	5	7.3	0	0	14.6	1.69	131.4	11.95
04/27/2024	71	End	14.3	1	7.3	5	7.3	0	0	14.6	1.69	131.4	11.95
04/28/2024	72	End	0	1	7.3	5	7.3	0	0	14.6	1.69	131.4	11.95
04/29/2024	73	End	0	1	7.3	5	7.3	0	0	14.6	1.69	131.4	11.95
04/30/2024	74	End	0	1	7.3	5	7.3	0	0	14.6	1.69	131.4	11.95
05/01/2024	75	End	0	1	4.8	3	4.8	0	0	9.5	1.11	85.5	7.77
05/02/2024	76	End	0	1	4.8	3	4.8	0	0	9.5	1.11	85.5	7.77
05/03/2024	77	End	16.8	1	4.8	3	4.8	0	0	9.5	1.11	85.5	7.77
05/04/2024	78	End	0	1	4.8	3	4.8	0	0	9.5	1.11	85.5	7.77
05/05/2024	79	End	0	1	4.8	3	4.8	0	0	9.5	1.11	85.5	7.77
05/06/2024	80	End	0	1	4.8	3	4.8	0	0	9.5	1.11	85.5	7.77
05/07/2024	81	End	16.8	1	4.8	3	4.8	0	0	9.5	1.11	85.5	7.77
05/08/2024	82	End	0	1	4.8	3	4.8	0	0	9.5	1.11	85.5	7.77
05/09/2024	83	End	0	1	4.8	3	4.8	0	0	9.5	1.11	85.5	7.77
05/10/2024	84	End	0	1	4.8	3	4.8	0	0	9.5	1.11	85.5	7.77
05/11/2024	85	End	0	1	2.6	2	2.6	0	0	5.2	0.6	46.8	4.25
05/12/2024	86	End	0	1	2.6	2	2.6	0	0	5.2	0.6	46.8	4.25
05/13/2024	87	End	19.3	1	2.6	2	2.6	0	0	5.2	0.6	46.8	4.25

05/14/2024	88	End	0	1	2.6	2	2.6	0	0	5.2	0.6	46.8	4.25
05/15/2024	89	End	0	1	2.6	2	2.6	0	0	5.2	0.6	46.8	4.25
05/16/2024	End	End	0	1	0	0						0	0.00