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Un Peuple – Un But – Une Foi

ECOLE DOCTORALE DES SCIENCES ET TECHNOLOGIES DU MALI (EDSTM)

DOCTORATE THESIS

THEME:

Impacts of agroforestry technology combined with sustainable land management (SLM) techniques on farmer's resilience to climate change: Case of Mafele village in Bougouni region (Mali)

A THESIS

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

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DEDICATION

This thesis is lovingly dedicated to my parents, Idrissa Tama TRAORE and Fatoumata BAGAYOKO, whom I lost in my youth. May they rest in eternal peace.

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LIST OF ACRONYMS AND ABBREVIATIONS

AF: Agroforestry

ANOVA: Analysis Of Variance

APRM: Accelerated Participatory Research Method

BDL: Bio-reclamation of Degradation Land

C: Carbon

CA: Agricultural Cooperatives

CC: Climate Change

°C: Temperature

CMDT: Compagnie Malienne pour le Developpement des Textiles

C/N: Carbon to Nitrogen ratio

CNRM: College of Natural Resource Management

CO2: Carbon dioxide

CSA: Climate-Smart Agriculture

DNA: Deoxyribo-Nucleic Acid

DNSI: Direction Nationale de la Statistique et de l'Informatique

DSSAT: Decision Support System for Agrotechnology Transfer

FAO: Food and Agriculture Organization

FMNR: Farmer Managed Natural Regeneration

G: Gliricidia

GAP: Good Agricultural Practices

GDT: Gestion Durable des Terres

GCM: General Circulation Models

GDP: Gross Domestic Product

GHG: Greenhouse Gas

IBM: International Business Machines Corporation

ICRAF: International Centre for Research in Agroforestry

ICT: Information and Communication Technology

IPCC: Intergovernmental Panel on Climate Change

IPR/IFRA: Institut Polytechnique Rural de Formation et de Recherche Appliquee.

IT: Information and Technology

K: Potassium

KG: Kilogramme

L: Leucaena

LD: Land Degradation

M: Maize

MARP: Accelerated Method of Participatory Research

MS: Matière sèche

N: Nitrogen

NGOs: Non-Governmental Organizations

P: Phosphorus

PG tool: Public Goods Tool

pH: Potential of Hydrogen

R: Ross Ihaka and Robert Gentleman

RISE: Response-Inducing Sustainability Evaluation

S: Sorghum

SAFA: Sustainability Assessment of Food and Agriculture System

SCB: Semi-Circular Bunds

SHL: Swiss College of Agriculture

SLM: Sustainable Land Management

SPI: Standardized Precipitation Index

SPSS: Statistical Package for the Social Sciences

SSA: Sub-Saharan Africa

SWC: Soil and Water Conservation

T: Treatment

UNCCD: United Nations Convention to Combat Desertification

US: United States

USD: United States Dollar

WAM: West African Monsoon

WMO: World Meteorological Organization

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ABSTRACT

Bougouni, situated in southern Mali, is part of the Sudanese ecological zone characterized by semi-arid conditions, which make it particularly vulnerable to environmental pressures such as overexploitation of natural resources, deforestation, and unsustainable agricultural practices. These factors have contributed to a noticeable decline in land quality, productivity, and overall ecosystem resilience, making it a pertinent location for investigating land degradation dynamics. The climate of the Bougouni region is a semi-arid tropical climate with an annual rainfall of over 1100 mm. Since the 1970s, it has been characterized by significant interannual variability in precipitation. Indeed, during the period from 1984 to 2022, drought years were recorded in 1988, 2002, 2009, and 2017, with an average rainfall of 850 mm. This situation is linked to climate change, which poses a major obstacle to development.

In the village of Mafele, three agroforestry systems are practiced, agrisylvicultural, sylvo-pastoral and agri-sylvo-pastoral, dominated by *Butyrospermum parkii*, *Parkia biglobosa*, *Mangifera indica* and *Tamarindus indica*, combined with annual crops such as cotton, maize, rice and sorghum. Several sustainable land management (SLM) measures have been implemented, such as manure spreading, crop rotation, legume cultivation, fallowing, and crop residue management. Farmers' perceptions of agroforestry practices were also assessed. The agroforestry options used to assess the performance under maize and sorghum production shows a high significant effect ($P<0.05$) on growth parameter such as plant height at 30 and 60 days after planting. The assessment of the agroforestry options on maize and sorghum yield for both experimental years (2023 and 2024) shows a significant effect ($P<0.05$). All these agroforestry options increase maize and sorghum yield compared to the control. The dried biomass of maize estimated (T0 4,553.867 kg/ha, whereas T1 and T2 recorded amounts of 5,835.854 kg/ha and 5,847.729 kg/ha, respectively). Additionally, T3 exhibited a dried biomass of 6,141.446 kg/ha. The agroforestry treatments (T1, T2, and T3) produced higher dried biomass compared to the control plot T0. The same case has been observed with sorghum.

In our experimental site, *Leucaena leucocephala* and *Gliricidia sepium*, planted in alley cropping systems, significantly contributed to soil health and productivity by influencing various soil properties. This study examined also the effects of *Leucaena leucocephala* (*Lam.*) and *Gliricidia sepium* on soil pH, organic matter content, total carbon, total nitrogen, total phosphorus, and total potassium under tropical climatic conditions in Mafele. Four composite soil samples were collected to assess site fertility. At the end of each cropping campaign, a soil sample was taken from the center of each elementary plot. These samples were collected

diagonally and from the center of the plot using a soil auger in the 0-20 cm horizon. They were sent to the Soil-Water-Plant Laboratory of IPR/IFRA for chemical property analysis.
Results showed that total carbon, total nitrogen, total phosphorus, and total potassium in plots with *Gliricidia sepium* and *Leucaena leucocephala* were higher than those in the control plots of each experimental site. The fresh biomass of *Gliricidia sepium* and *Leucaena leucocephala* incorporated into the soil improved its fertility.
Keywords: Climate change, Agroforestry, soil fertility.

RÉSUMÉ

Bougouni, située dans le sud du Mali, fait partie de la zone écologique soudano-sahélienne caractérisée par des conditions semi-arides, qui la rendent particulièrement vulnérable aux pressions environnementales telles que la surexploitation des ressources naturelles, la déforestation et les pratiques agricoles insoutenables. Ces facteurs ont contribué à une diminution notable de la qualité des sols, de la productivité et de la résilience globale des écosystèmes, ce qui en fait un endroit pertinent pour étudier les dynamiques de la dégradation des terres. Le climat de la région de Bougouni est un climat tropical semi-aride avec des précipitations annuelles supérieures à 1100 mm. Depuis les années 1970, il est caractérisé par une variabilité interannuelle significative des précipitations. En effet, pendant la période 1984-2022, des années de sécheresse ont été enregistrées en 1988, 2002, 2009 et 2017, avec une moyenne des précipitations de 850 mm. Cette situation est liée au changement climatique, qui constitue un obstacle majeur au développement. Dans le village de Mafele, trois systèmes agroforestiers sont pratiqués: agrosylviculture, sylvo-pastoral et agri-sylvo-pastoral, dominés par *Butyrospermum parkii*, *Parkia biglobosa*, *Mangifera indica* et *Tamarindus indica*, associés à des cultures annuelles telles que le coton, le maïs, le riz et le sorgho. Plusieurs mesures de gestion durable des terres (GDT) ont été mises en œuvre, telles que l'épandage d'engrais organique, la rotation des cultures, la culture de légumineuses, les jachères et la gestion des résidus de cultures. Les perceptions des agriculteurs sur les pratiques agroforestières ont également été évaluées. Les options agroforestières utilisées pour évaluer la performance sous la production de maïs et de sorgho montrent un effet hautement significatif ($P<0,05$) sur les paramètres de croissance tels que la hauteur des plants à 30 et 60 jours après la plantation. L'évaluation des options agroforestières sur le rendement du maïs et du sorgho pour les deux années expérimentales (2023 et 2024) montre un effet significatif ($P<0,05$). Toutes ces options agroforestières augmentent le rendement du maïs et du sorgho par rapport au témoin. La biomasse sèche du maïs estimée (T0 4 553,867 kg/ha), tandis que T1 et T2 ont enregistré des montants de 5 835,854 kg/ha et 5 847,729 kg/ha, respectivement. De plus, T3 a présenté une biomasse sèche de 6 141,446 kg/ha. Les traitements agroforestiers (T1, T2 et T3) ont produit une biomasse sèche plus élevée que la parcelle témoin T0. Le même constat a été observé avec le sorgho.

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Dans notre site expérimental, *Leucaena leucocephala* et *Gliricidia sepium* plantés en cultures en couloirs ou établis dans des fermes en jachère par des moyens naturels contribuent de manière significative à la santé et à la productivité des sols en influençant diverses propriétés du sol. Dans cette étude, les effets de *Leuceana leucocephala* (Lam.) et de *Gliricidia sepium* sur le pH du sol, la teneur en matière organique, le carbone total, l'azote total, le phosphore total et le potassium total ont été étudiés dans des conditions climatiques tropicales à Mafele. Quatre échantillons composites de sol ont été prélevés pour évaluer la fertilité du site. A la fin de chaque campagne agricole, un échantillon de sol a été prélevé au centre de chaque parcelle élémentaire. Ces échantillons ont été prélevés en diagonal et au centre de la parcelle à la tarière dans l'horizon 0-20 cm du sol. Ils ont été envoyés au laboratoire Sol-Eau-Plante de l'IPR/IFRA pour la détermination des propriétés chimiques du sol. Les résultats ont montré que le carbone total, l'azote total, le phosphore total et le potassium total dans la parcelle de traitement avec *Gliricidia sepium* et *Leuceana leucocephala* sont supérieurs à ceux de la parcelle témoin de chaque site expérimental. La biomasse fraîche de *Gliricidia sepium* et *Leuceana leucocephala* enfouie dans le sol a amélioré sa fertilité.
Mots clés: Changement climatique, Agroforesterie, fertilité des sols.

CHAPTER I: INTRODUCTION

1.1 Problem and justification

Climate change is a significant challenge to agriculture in Mali, a country heavily reliant on farming for both livelihoods and food security (Diallo et al., 2020). Increasing temperatures, irregular rainfall patterns, and frequent droughts are impacting crop yields and livestock (Bogale & Erena, 2022). The Sahel region's already fragile ecosystem is further stressed by climate change, leading to soil degradation and reduced water availability. These impacts exacerbate food insecurity, affect rural communities' wellbeing, and undermine Mali's economic stability (Nchare et al., 2024). To adapt, Mali needs integrated strategies that promote resilient farming practices, water management, and sustainable land use, ensuring agriculture can adapt the pressures of a changing climate.

Agroforestry plays a vital role in strengthening the resilience farmers in Mali, a country facing major challenges such as land degradation, climate variability, and natural resource depletion. By integrating trees and crops on the same plot, this practice promotes soil conservation, improves fertility, and provides protection against erosion (Fahad et al., 2022a). In addition, agroforestry helps diversify income sources, thereby strengthening the ability of rural communities to cope with climatic and economic hazards (Lasco et al., 2014). It is a sustainable approach to increase food security, preserve the environment, and support socio-economic development in the Mali (Misselhorn et al., 2012)

Agroforestry can range from extremely simple and sparse systems to extremely sophisticated and dense systems (Viswanath & Lubina, 2018). It embraces a wide range of practices: crops in corridors, agriculture with trees in contours, or fenced perimeters with trees, multi-stage crops, relay intercropping, polycultures, fallow shrubs and trees, park systems, market gardens etc. (Coelli, 1995). Many of them are traditional land use systems. In order to attain multifunctionality, AF (agroforestry) encompasses a broad idea of trees in crops and livestock systems rather than being a single technology (Coell, 1995).

Agroforestry systems have great potential to diversify food resources and sources of income. Through their capacity to create a microclimate that supports permanent coverage, enhance soil structure and organic carbon content, boost water infiltration into the soil, and enhance soil fertility and biological activity, these can increase land productivity and stop or even reverse land degradation (Tyano et al., 2022). Agroforestry is vital to provide the tropical world's populations with some of the products and services that forests used to offer, even while it is not a magic bullet that can stop forest destruction (Razzaque et al., 2019).

Mali is a country with an agro-sylvo-pastoral vocation. Land suitable for agriculture represents only 14% of the total area, it is the main activity, both in terms of employment and contribution to the economy (Coulibaly, B., & Li, 2020). Indeed, about 75% of the Malian population live in rural areas and agriculture represents about 50% of the Gross National Product (Coulibaly, B., & Li, 2020). The Malian economy is therefore highly dependent on the performance of the agricultural sector, which is particularly sensitive to climatic variations.

The agro-pastoral production in Mali is mostly concentrated in the regions starting south of the Sahara Desert, characterized by distinct climatic zones, the Sahelian, Sudanian and Guinean zones. Situated in the western part of the Sahel Zone, Mali is seriously affected by LD which is causing an agricultural Gross Domestic Product (GDP) loss estimated at 2 - 4% per year, with reduced crop yields (Mirzabaev et al., 2021a) . LD also drives an average annual deforestation of 500,000 ha per year (Touré et al., 2020). Furthermore, erosion affects soil fertility and crop production; it directly impacts the livelihood of local communities. Land degradation (LD) exacerbates food insecurity by pressuring farmers to reduce fallow periods, expand into marginal lands, and adopt practices that are not sustainable (Gomiero et al., 2016). Furthermore, rainfall variability, erosion, and human activities—such as agricultural expansion, overgrazing, excessive fuelwood harvesting, and charcoal production—are regarded as the main factors contributing to land degradation in Mali (Hummel, 2016). The degree of pressure exerted by agricultural activities on soil resources has been gradually increasing.

On the other hand, most farmer in Mali reside on marginal lands in rural areas, relying on rain-fed farming (Touré et al., 2020). Traditional views suggest that these marginal regions have minimal agricultural potential and that development initiatives in these areas are less effective, leading to biased policy decisions. However, many researchers have shown that marginality is not fixed or permanent; land use, agricultural technologies, and socio-economic conditions can all change over time, altering the nature of these areas (Lambin & Meyfroidt, 2010).

Despite growing awareness of the importance of sustainable land management and climate adaptation strategies, several critical gaps hinder effective implementation and policy formulation. First, there is a notable lack of local evidence and comprehensive data on the specific impacts of climate change in the study region. This limits the ability to tailor adaptation strategies effectively to local vulnerabilities and climate trends. Second, there is insufficient understanding of farmers' perceptions, knowledge, and practices related to agroforestry as a climate adaptation option. Strengthening this knowledge base is essential to promote adoption and optimize the benefits of agroforestry systems in the context of climate resilience. Third, limited scientific evidence exists regarding the impact of *Leucaena leucocephala* and *Gliricidia* *sepium* on soil physico-chemical properties under local conditions. Without this information, it is challenging to assess their long-term impact on soil fertility and ecosystem health. Lastly, there is a lack of quantified, empirical data demonstrating the extent to which agroforestry practices contribute to crop yield increases, which is crucial for convincing farmers, policymakers, and development partners of the tangible benefits of adopting such systems. Addressing these gaps will be vital to advancing sustainable land management and climate adaptation efforts in the region.

1.2 State of the knowledge

Farmers have long relied on their rich traditional ecological knowledge and time-tested practices, such as fallowing fields to restore soil fertility, constructing stone bunds to prevent erosion, and planting pits also known as zai or towalen as effective methods to combat land degradation at the local level. These indigenous techniques aim to restore degraded land (LD) and simultaneously increase crop productivity, ensuring food security and sustainability for their communities (Slade et al., 20005). Their underlying goal is to reverse the harmful effects of land degradation and improve agricultural outputs, which are crucial in regions where farming is highly vulnerable to environmental stressors.

On a broader scale, since the 1960s, the Malian government has prioritized sustainable land management and soil fertility enhancement programs as key strategies for national development. These initiatives target soil conservation, improved land productivity, and combating the spread of desertification, recognizing the vital role these efforts play in ensuring long-term agricultural sustainability (O. N. Coulibaly, 2021). Over the decades, various regions across Mali have been identified as critical agricultural zones, including the cotton-producing areas, the Office du Niger, the Office Riz Ségou, the Office Riz Mopti, the Niger Delta, and the Seno. These regions are situated within the country's Sudanese, Sudano-Guinean, and Sahelian ecological zones, each presenting different challenges and opportunities for land management. Data from the Direction Nationale de la Statistique et de l'Informatique (DNSI) indicates that Mali has experienced significant expansion of cultivated land over recent decades (Nkonya et al., 2016). Between 1970/71 and 1994/95, the total area cultivated increased from approximately 1,967,000 hectares (ha) to 3,472,000 ha a growth of about 15% in land clearing. While this expansion reflects efforts to increase agricultural productivity, it has not translated into proportional gains in crop yield, which has remained relatively low averaging around 750 kg/ha across all crops during that period. This disparity underscores the challenge of balancing land use expansion with sustainable productivity improvements. Moreover, increased agricultural pressure particularly in regions with high population density has led to progressive cultivation of marginal and forest lands, reducing fallow periods and soil fertility. Such practices exacerbate land degradation through erosion and loss of soil nutrients, undermining long-term agricultural sustainability.

Land is fundamentally critical to human livelihoods, providing essential ecosystem services that sustain life and support economic activities (Shukla et al., 2021). According to the United Nations Convention to Combat Desertification, land degradation (LD) is defined as the deterioration of the land's productive capacity or functions, which directly threatens rural economies and food security (Briassoulis, 2019). LD results not only from natural biophysical processes but is also significantly driven or intensified by human activities, such as overgrazing, deforestation, and unsustainable farming practices, which disrupt ecosystem balances (Touré et al., 2020). Compounding this issue, climate change (CC) further accelerates land degradation processes, creating a vicious cycle that intensifies the adverse impacts of desertification and soil erosion.

Recognized by scientists and global policymakers, land degradation, alongside climate change, ranks among the most critical challenges facing humanity today. In the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Climate Change and Land, experts emphasized with high confidence that LD and CC are among the world's most urgent threats, requiring immediate and sustained action (Touré et al., 2020). Globally, it is estimated that approximately 3.2 billion people are affected by land degradation, which incurs enormous economic costs accounting for nearly 10% of the planet's gross domestic product annually. The effects are particularly intense in arid areas like the Sahel, where vulnerable communities are at greater risk of food insecurity, poverty, and environmental challenges, highlighting the urgent need for intervention and sustainable land management approaches (Mirzabaev et al., 2021).

1.3 Research hypothesis

Research hypotheses: The hypotheses formulated are as follows:

- The diversity of perceptions and agroforestry systems adopted in southern Mali is more related to the problem of fertility;
- *Gliricidia sepium* and *Leucaena leucocephala* in an alley cropping system, promote nitrogen fixation in the soil, and atmospheric carbon sequestration which is an important element in global warming.
- Burying of fresh *Gliricidia sepium* and *Leucaena leucocephala* leaves improves soil fertility, sorghum and maize grain yields while reducing costly inorganic fertilizer inputs.

1.4 Objectives

1.4.1 Overall objective

The general objective of our study is to raise awareness on agroforestry systems as climate change adaptation strategy in the study area

1.4.2 Specific objectives

Specifically, the objectives were:

- Characterize the climate variability and change in Bougouni region;
- Evaluate farmers perception on agroforestry systems practice as climate adaptation option in the study area;
- Evaluate the effects of fresh leaves biomass of *Gliricidia sepium* and *Leuceana leucocephala* in an alley cropping system on growth of maize and sorghum ;and grain yields;
- Assess the effects of leaves biomass fresh in an alley cropping system with *Gliricidia sepium* and *Leuceana leucoceaphala* on the physico-chemical properties of soils.

CHAPTER II: LITERATURE REVIEW.

2.1 Climate change and variability in West Africa

Climate variability and climate change have impacts on many sectors, such as agriculture, water availability and health (Ahmed et al., 2016). Depending on the adaptive capacity of a society, these impacts might result in strong vulnerability. One of the main features responsible for climatic conditions over West Africa is the West African monsoon system (WAM). The underlying atmospheric processes and interactions with the land surface and ocean are complex and not yet fully understood. Several recent research activities have addressed the knowledge gap and did advance our understanding of the WAM system.

West Africa is often labelled as a climate change hotspot (Pardoe et al., 2016). This label is based on an understanding that West African communities are often comprised of small, rural communities that especially rely on natural resources via agriculture for their subsistence. The close connection with the environment and climatic regime is combined with climate change projections that suggest changes to the rainfall totals for West Africa. Although, projections remain unclear as to the direction of change in total rainfall, with some predicting an increase and others a decrease, it is generally agreed that rainfall patterns will become less consistent, resulting in greater seasonal variability (Nicholson, 2017). Seasonal variability is already apparent and manifest in rural communities in the West Sudanian Savannah climate zone, which is the target agro-ecological zone.

The traditional bi-modal seasonal pattern comprises a rainy season from May to October/early November and a dry season for the remaining months. The single rainy season provides the sole opportunity for rural communities to produce the crops that they depend upon for their subsistence. Yet, growing evidence from scientific and local observations suggests that the rainy season no longer covers the same period as it did traditionally (Padgham et al., 2015). Farmers reported shifts in the onset of the rainy season, which used to start in April, towards May (Sanfo et al., 2014). This causes farmers to delay their planting activities by 10-20 days compared to the previous generation (Marbun, 2024). Furthermore, the rainfall during the wet season is disrupted with prolonged dry spells and heavy bouts of rainfall that exceed the tolerance of traditional cultivation (Masum, 2019). Climate change is expected to exacerbate the patterns of seasonal variability that are already emerging (Nakalembe et al., 2025). In order to manage these current and future projected changes, adaptation strategies are critical. Given that seasonal variability is already manifest in the West Sudanian Savannah, the impetus to develop and implement adaptation strategies has already resulted in the implementation of new strategies and adjustments.

2.1.1 Climate change impacts, adaptation strategies and policy developments for crop production sector

West Africa continues to be susceptible to sporadic climate shocks, chiefly drought. The region is still experiencing food crises, especially in the arid regions, which lead to the loss of lives and livelihoods and a cycle of disaster assistance that impedes long-term progress (Haile, 2005). Increasing agricultural systems' resilience to climate change is a key developmental agenda item in the fight to eradicate hunger and poverty while simultaneously reducing greenhouse gas emissions, as the region generates at least 30% of the food needed by the African continent (Haile, 2005).This development strategy is central to the idea of climate-smart agriculture (CSA), which seeks to promote the creation and application of agricultural innovations that adapts and builds resilience to climate change from the farm to the national level; creates opportunities to reduce greenhouse gas emissions from agriculture in comparison to previous trends; and sustainably increases agricultural productivity to support equitable increases in incomes, food security, and development (Verge et al, 2007). Notwithstanding the potential advantages that CSA may provide to West Africa, it faces numerous obstacles. Among these, it is noteworthy that farmers, policymakers, and possible investors all have a thorough understanding of the CSA concept; the technologies supporting CSA activities are packaged appropriately for broader farmer acceptance;

The marginalization of agro-ecological regions in West Africa necessitates research on the biophysical adaptation of CSA practices throughout the region; institutional arrangements to upscale CSA from the farm scale to the landscape and country levels; limited technological capabilities and human resources competence; integrating CSA into the existing policy frameworks; dealing with trade-offs from the viewpoints of farmers and policymakers; and the creation and execution of efficient risk-sharing schemes (Garrison Jr et al., 2013) Given the aforementioned difficulties, a crucial query emerges: How can West African agriculture adjust to the effects of climate change and variability both now and in the future? Answering this question, among other things, necessitates first understanding the different agricultural subsectors and their current adaptation strategies; institutional settings and policy developments may encourage the adoption of sustainable agricultural systems that successfully mainstream climate change in the region.

2.1.2 Socioeconomic consequences of climate change and the economic implications for climate adaptation in West Africa

Climate change will have significant socioeconomic effects on both national economies and individuals, as about 70% of West Africans are employed in agriculture. At different scales, the effects of climate change on output are anticipated to have an impact on the economy. At the farm level, households will have less money due to climate change, which will restrict their ability to purchase tangible assets and pay for their children's health and education (Zougmoré et al, 2016).

For example, estimations from the Ricardian regression models in Northern Ghana indicated that temperature and precipitation had a considerable effect on net revenue per hectare of sorghum and maize. Indeed, a 1 mm rise in precipitation and a 1°C decrease in temperature would influence net revenue, although the magnitude of these effects would differ depending on the season and the specific crop (B. Traore et al., 2013). Besides generating new vulnerabilities and opportunities for opportunistic individuals and groups who might exploit shocks and crises because of their adaptable assets and power dynamics, this will also exacerbate existing poverty and inequality (C. Singh & Basu, 2020).

This demonstrates the significance of the relationship between crop income and climate change and the necessity of acting to strengthen current adaption strategies and possibly create new ones. For nations whose economy rely heavily on agriculture, climate change may have macroeconomic repercussions at the national level. Climate change can impede agricultural progress by deterring investments, especially when paired with other non-climatic pressures such as environmental degradation, market instability, and decreasing soil fertility (Reddy & Reddy, 2015); the impact of climate change on production at the regional level will have quantity and price effects, increasing market tension; and impacts on bilateral contracts and/or import/export behavior, disrupting trade patterns.

It will not be cheap to advance climate-smart agriculture in West Africa. To promptly and effectively address present and anticipated gaps for adaptation and mitigation, this calls for large-scale investments at the regional level that call for creativity, teamwork, and political will (Oberlack & Eisenack, 2014). Overall, there is limited information on the investment needs for climate finance and agriculture, and it may not encompass all the essential investments. (Glemarec, 2022).

Previous estimates suggest that Africa will require approximately USD 48.5 billion each year to support its agriculture sector and around USD 3 billion annually for climate change adaptation from 2005 to 2050. (Williams et al., 2015). West Africa, which is heavily dependent on agriculture and allied sectors, will need at least 25% of these investment demands. Additionally, there will be additional expenses for planning, capacity building, and research related to climate change adaptation.

National budgets (which are in line with national priorities and goals that are pertinent to CSA), private sector funds and bonds, concessionary mechanisms, bilateral and multilateral finance, development banks, global adaptation funds (such the Green Climate Funds), etc. will have to provide these investments.

2.2 Characteristics of agroforestry adoption in developing countries

Since it is the primary source of income for most people, especially those who reside in rural regions, agriculture is vital in developing nations (Herrero et al., 2013). Rural populations have long used traditional agroforestry to raise their standard of living. For example, communities that reside close to forest areas frequently use forest goods, such as selling timber or eating fruits or edible plants that grow there naturally (Vinceti et al, 2012).Furthermore, in order to earn a livelihood, subsistence farmers in rural areas frequently maintain animals or plant crops in addition to some perennial trees (Achmad et al, 2022).

Generally speaking, there are a number of agroforestry techniques used worldwide, including multipurpose trees, riparian buffers, improved fallow, silvoarable systems (combining trees and shrubs with crops), silvopastoral (combining trees and livestock), and agro-silvopastoral (combining shrubs and trees with both crops and livestock) (Table 1).

Although with some adjustments to the components, some of these practices exist in several developing countries. For example, in Sub-Saharan Africa, agroforestry variation can be found in a variety of locations, such as rational woodlots in Kenya, silvoarable (cacao system) in Côte d'Ivoire, and multi-story home gardens on Mt. Kilimanjaro in Tanzania (Mukhlis et al, 2022). Similarly, farming practices vary considerably across Latin America, such as the use of silvopastoral systems in Chilean and Argentine rangelands, which integrate eucalyptus, pine, and native grass species for cattle production (Bussoni et al., 2019) silvoarable with intercropping coffee and native tree species in Brazilizan Cerrado (de Abreu et al., 2020) and agro-silvopastoral combining livestock production (cattle, goat/sheep) with crops and/or native tree plantation in the Andean region of Venezuela, Colombia, Peru and Ecuador (Bare & Ashton, 2016). Meanwhile, in South East Asia, agroforestry system can range from home gardens, the agro-silvopastoral (cattle, oil palm and timbers), silvoarable (coffee or cacao with timbers) and silvopastoral (combination between livestock and timber) (LUFUNG, 2016).

Table 1: Several practices of agroforestry that are commonly adopted in several developing countries and their brief description according to (Mosquera-Losada et al., 2018).

Type of practice	**Description**
Silvoarable	Trees are inter-cropped with annual or perennial crops. It comprises alley cropping, scattered trees and line belts.
Silvopastoral	Combining trees with forage and animal production. It comprises forest or woodland grazing and open forest trees.
Agro-silvopastoral	Combining trees with annual crops and animal production, but the arable and livestock components are usually temporally and spatially distinct.
Multipurpose trees	Fruit and other trees are planted in cropland or pasture for the purpose of providing fruit, fuelwood, fodder and timber, among other services.
Riparian buffer	Strips of perennial vegetation (tree/shrub/grass) natural or planted between croplands/pastures and water sources such as streams, lakes, wetlands and ponds to protect water quality.
Improve fallow	Fast growing, preferably leguminous woody species planted during the fallow phase of shifting cultivation. This species can also improve soil fertility and may yield economic products.

However, a number of criteria, such as resource availability, economic viability, topography, sociocultural influences, and environmental conditions, determine whether an agroforestry system is present in a given location. For example, (Konan et al., 2025) Analyzed socioeconomic factors affecting farmers' willingness to adopt agroforestry in Brazil's Atlantic rainforest through logistic regression analysis and multiple regression techniques.. They discovered that perceptions of behavioral control, labor availability, and conservation views all had an impact on farmers' adoption. Another study (Clément et al., 2023) demonstrated that plot location, ecological compatibility, and market accessibility all had an impact on the existence of coffee agroforestry systems in Northwest Vietnam.

There are various methods for identifying a particular aspect of community-appropriate agroforestry practices. To choose practices that are appropriate for adoption, it is necessary to show all significant distinguishing traits, which requires the inclusion of several criteria (Tornatzky & Klein, 1982).

Factors such as the availability of natural resources and geographical position can influence a farmer's decision to implement a specific practice or system (Liu et al., 2018). For example, residents of the nearby forests who own livestock may favor silvopastoral or agro-silvopastoral practices because the resources (cattle, goats, etc.) are readily available and they may be able to obtain feed from naturally occurring shrubs or grasses in the forests while earning additional revenue from the production of crops or timber.

Moreover, some forms of agroforestry require low input and less maintenance yet still generate a higher recycling rate, making them more profitable and therefore preferable by low income farmers. However, despite some component diversity, a number of agroforestry systems can be used in various agro-ecological zones and serve the same purposes, especially in terms of livelihoods and landscapes.

Therefore, no universal standard can be applied to define the best agroforestry system for the adoption.

Agroforestry includes a wide range of methods and approaches based on the state of the environment and the availability of resources. To identify the variables driving the acceptance and establishment of agroforestry, a more thorough evaluation of their independent performance in relation to various environmental, sociocultural, and political contexts is crucial. To ascertain the reasoning behind the selection process, it could be worthwhile to look into the trade-offs associated with a farmer's decision about various land management techniques, including non-agroforestry ones. These previously mentioned variables may differ in different time and space, creating a need for more study, especially in the area of agroforestry intervention tool creation.

2.2.1 Agroforestry and Climate Resilience

Climate change increasingly threatens smallholder farmers, particularly in semi-arid regions like Mali, where agriculture is highly vulnerable to climate variability (Dembélé, 2015). Agroforestry, integrated with sustainable land management (SLM) practices, has emerged as a promising approach to enhance resilience, improve livelihoods, and mitigate climate impacts (Hakimi et al., 2024)

- **Definitions and Concepts**

Agroforestry combines trees with crops or livestock systems, providing ecological and socioeconomic benefits (Mbow et al., 2014). It enhances biodiversity, soil fertility, and water retention, crucial for resilience against climate stressors (Banga & Kang, 2014).

- **Evidence of Resilience Enhancement**

Agroforestry systems help mitigate climate impacts by enhancing soil moisture retention, minimizing erosion, and creating multiple income opportunities (Kassam et al., 2020). For example, in Mali, farmers practicing agroforestry reported increased resilience due to better water conservation and crop diversification (Traore et al., 2019). Similarly, agroforestry's role in carbon sequestration has potential benefits in climate mitigation (Mbow et al., 2014).

- **Challenges and Opportunities**

While benefits are evident, challenges such as land tenure insecurity and limited access to inputs hinder adoption (Mucheru-Muna et al., 2021). Nonetheless, policy support and community engagement enhance the success of agroforestry systems (Krebs & Bach, 2018).

2.2.2 Sustainable Land Management (SLM) Techniques and Climate Adaptation

SLM Principles and Practices

SLM encompasses practices aimed at conserving and renewable land resources, including terracing, crop rotation, cover cropping, and erosion control ((Sanz et al., 2017). These practices help avoid land degradation, sustain productivity, and boost resilience (Hossain et al., 2020).

- **Impact on Climate Resilience**

SLM techniques reduce vulnerability by improving soil health, water availability, and crop yields under changing climatic conditions (Okolie et al., 2022). For instance, in Mali, SLM has reduced the risks of desertification and helped sustain agricultural productivity (Traore et al., 2018).

- **Integration with Agroforestry**

Integrating agroforestry with sustainable land management enhances resilience, since trees aid in preventing erosion, regulating microclimates, and conserving resources (Sauer et al., 2021). Such integrated practices align with climate-smart agriculture objectives, promoting adaptation and mitigation simultaneously (Matteoli et al., 2020).

2.2.3 Case Studies and Empirical Evidence in Mali and West Africa

- **Mali-Specific Findings**

In Mali's Bougouni region, previous research indicates that agroforestry combined with SLM enhances farmers' adaptive capacity by diversifying income, improving soil fertility, and conserving water (Traore et al., 2019). Farmers adopting these practices report better coping mechanisms during drought periods (Mwadzingeni et al., 2023).

- **Mafele Village Context**

Although specific studies on Mafele are limited, similar villages in Bougouni showcase that participatory approaches to agroforestry and SLM foster community resilience (Abberton et al., 2021). These practices promote sustainable livelihoods amidst climate variability.

- **Gaps and Future Directions**

Although the benefits are well documented, there is still a need for research tailored to specific contexts, particularly long-term studies that evaluate the sustained impacts of combining agroforestry with sustainable land management (Bishaw et al., 2013). Furthermore, understanding social, institutional, and policy factors influencing adoption is essential to scaling interventions.

2.2.4 Socio-Economic Impacts of Agroforestry

The incorporation of woody plants into the system is what sets agroforestry apart from other land use strategies. From an economic standpoint, diversifying products through the use of tree-based farming can increase economic resilience (Keprate et al., 2024). In example, the use of multipurpose trees may increase the profitability of agroforestry since they may be used for a variety of purposes, including providing alternative sources of revenue, food (such as wild edible fruits), or fodder during times of scarcity in rural communities (Guyassa et al., 2014).

Furthermore, in addition to the money earned from annual crops, some woods with higher economic worth can give the community additional revenue. For example, studies on teak-agroforestry (*Tectona grandis*) systems in Indonesia show that, despite their slower recycling time (caused by their sluggish growing season), they can contribute up to 12% of total household income. Additionally, a study conducted in Pesisir, West Sumatra, on damar (*Agathis dammara*) agroforestry revealed that the damage output generated as much as 50% of the household income. Furthermore, compared to just 12% from the conventional agriculture system (non-agroforestry system), Establishing coffee agroforestry in the Wey-Besay

Watershed, Lampung, contributed to more than 50% of household income. (Shekmohammed et al., 2021) However, care must be given when evaluating the economic benefits of various approaches because the results may vary depending on a number of factors, including the type of trees used, the weather, pest availability, and commodity price volatility. Agroforestry can also result in a higher benefit-to-cost ratio.

Some practices include cultivation of woody plants requiring low inputs (chemical fertilizers, pesticides, etc.), thus it can minimize the production costs and improve income gained by the farmers (Shanka, 2020). However, the farmers' understanding of the technique, especially how to choose the best plants and trees for their system, may have a significant impact on this result. Some trees can grow better when they were cultivated along with their complementary crops. On the contrary, the wrong selection of tree or crop components can cause nutrient competition which consequently reduce yield and therefore the profit gained by the farmers.

In rural areas, the use of agroforestry can also lead to the creation of new jobs in off-farm industries including furniture manufacture, wood cutting, and grain drying (Kodithuwakku et al., 2025).

Increased job opportunities might also benefit women as they can be directly involved in the production activities, which can improve gender equality in rural areas (Bieri & Sancar, 2009). Furthermore, job absorption in the rural areas might prevent rural exodus (Lipton, 1980) and therefore, can contribute to improved rural economy. However, care must be taken when developing industrial sites next to primary forests or conservation areas because there is a chance that people will infringe on these protected areas, which could harm the ecology (Okello & Kirige, 2004). In addition to producing revenue, agroforestry can contribute to increased food security in the neighborhood surrounding the trees.

In this case, (Caraka et al., 2024) employed spatial data to analyze micronutrient absorption among children aged one to five years in Indonesia.. They found a correlation between agroforestry and increased consumption of legumes at the national level. At the regional level, however, their results showed a link between agroforestry and higher intake of fruits and leafy vegetables high in vitamin A. Furthermore, individuals practicing silvopastoral methods were more inclined to include meat in their diets within agroforestry systems. (Jara-Rojas et al., 2020). Low-income farmers who had received agroforestry training also shown increased food yield and diversity, suggesting that food availability increased after agroforestry was implemented (Pratiwi & Suzuki, 2019). Other studies, including those conducted in numerous Sub-Saharan African, South Asian, and Latin American nations, have also shown evidence of a beneficial relationship between the adoption of agroforestry and food security among communities (Liu et al., 2021).

Agroforestry may also encourage adopters to engage in sociocultural activities. For example, farming groups can get together to talk about fertilizer management, crop or tree species selection, cultivation techniques, and other topics. According to Mungmachon's study, for small forest tribes in Thailand, gathering was an important cultural activity (Phukamchanoad, 2025). They frequently talked about the issues they were having and worked together to find answers. They started by researching their issues as a group, re-discovering old knowledge and wisdom, and then incorporating fresh information. Peer-to-peer dialogue and community involvement result in the community becoming more informed and involved.

2.2.5 Overview on alley Cropping system

The practice of cultivating rows of trees and/or shrubs to create alleys for the cultivation of horticultural or agricultural crops is referred to as "alley cropping." The trees in question could be desirable softwood species for the production of wood fiber, nuts, or other specialty crop trees or shrubs, or valuable hardwood veneer or timber species. An agroforestry technique known as alley cropping involves the planting of trees within agricultural field systems. The practice of intercropping is a particular method that has been employed in tropical regions. Producers seeking to enhance whole-farm productivity by cultivating multiple crops within the same acreage find this approach particularly compelling. Producers stand to benefit significantly from cultivating a diverse array of crops in close proximity, thereby mitigating risk. Alley cropping systems are known to undergo evolution over time. The light, water, and nutrient regimes present within the field are impacted by the growth of trees and shrubs. Alley cropping differs from more prevalent mono-cropping techniques due to the unique nature of these interactions. Alley cropping systems are designed by certain farmers to serve supplementary purposes that complement and improve other facets of their business. A livestock producer, for instance, might cultivate crops that provide their animals with bedding, feed, or mast crops. The generation of biomass for on-farm consumption by other producers is a distinct possibility. Tree species capable of fixing nitrogen may be selected by organic producers. Alley cropping systems should be regarded as a component of the farm operation in its entirety, akin to any other agroforestry system. Alley cropping is a strategy that aims to enhance crop diversification and bolster economic and environmental resilience. This agricultural method utilizes the symbiotic relationships between trees and shrubs, as well as the cultivation of crops within the alleys. However, multi-cropping systems also engender complexities when it comes to some management activities. Alley cropping can also be used to transition to other forms of perennial agriculture. Alley cropping has emerged as a promising strategy for enhancing the overall productivity of agricultural systems, particularly in temperate regions. This approach has witnessed a notable surge in adoption among farmers in these areas.

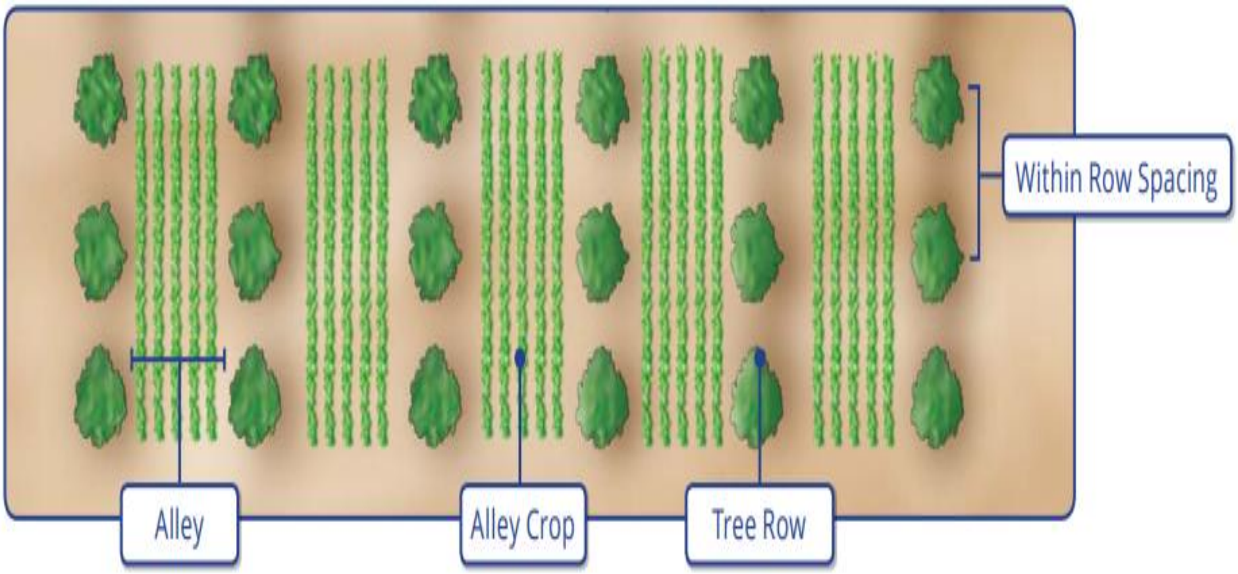

Figure 1: Alley cropping (Garret, H et al., 2021)

2.3 Land use in Mali

Soil organic and macronutrients that are beneficial for plant growth are greatly impacted by land use and land cover, which also negatively affect runoff and the physical and chemical characteristics of the soil (Shete et al., 2016). The pace of soil erosion is also influenced by land cover and land use (Tsegaye, 2019). According to studies (Garcia-Ruiz et al., 2015), places where natural vegetation has been gradually replaced by farms, settlements, and grasslands have shown an increase in soil erosion rates (Veen et al., 2014).

Significant soil nutrients including nitrogen (N), phosphorus (P), and potassium (K) are lost as a result of excessive and unchecked erosion, which lowers the potential crop production at the plot and farm levels (Weight & Kelly, 1999). According to a World Bank Group report, Mali's population grew at a high rate in 2021 (2.9%), compared to 2.6% in sub-Saharan Africa. The country's most populous region, the southern part of Mali, is putting a lot of strain on the land because of the physical growth of both urban and agricultural areas. As a result of this growth, there has been an increase in soil erosion over time (Jiao et al., 2009).

Extreme climatic unpredictability, soil degradation, and intensive farming practices are characteristics of Southern Mali's semiarid region. Most agroecological farm fields and landscapes use monocultures, intercropping, tillage, and agroforestry, which are traditional and less mechanized farming approaches. The primary crops grown with a mix of manure and inorganic fertilizers are millet (*Pennisetum glaucum*), groundnut (*Arachis hypogaea*), cotton (*Gossypium spp.*), maize (*Zea mays*), and sorghum (*Sorghum bicolor*).

However, because it impacts the entire landscape, soil erosion has been a significant issue affecting agricultural output, and efforts to reduce it at the farm level rarely make an impact. Prior to recently, the majority of Mali's sustainable land management techniques concentrated on using soil and water conservation (SWC) techniques, like contour bunding, to lower runoff and soil erosion at the plot or farm level (Sanogo et al., 2023). The effectiveness of contour bundling in addressing landscape deterioration and crop production loss is modest, despite its significance in its application at the plot or farm level.

The main source of excessive soil erosion is accumulated runoff from bushlands, grazing areas, and farms. The majority of studies frequently lack landscape-level information regarding soil erosion, Water infiltration and the subsequent loss of vital nutrients are impacted by limited data or estimation methods (Akhtar et al., 2021).

2.3.1 Land degradation in sub-Saharan Africa

Land degradation is a significant threat to agriculture and food security in many parts of sub-Saharan Africa (SSA). Diminishing suitable agricultural land, soil erosion, and the continuous extraction of farm nutrients result in declining productivity and severe livelihood challenges to the agriculture-based communities of developing countries (Akhtar et al., 2021). By reducing soil fertility and agricultural yields, land degradation undermines livelihood security. As a result, communities already struggling to cope with the impacts of climate variability and change are trapped in a vicious cycle of conflicts, low farm incomes, poverty, and food insecurity (Akhtar et al., 2021), making it difficult for SSA states to achieve sustainable development. In SSA, land degradation is a complex challenge driven by many dynamic factors, including population growth and urbanization (Tefera et al., 2024), unsustainable agricultural practices, the conversion of pasture and forest lands to croplands, deforestation (Birhanu et al., 2024), and climate variability and change (IPCC, 2014, 2019). A history of food insecurity and poverty means that many governments have always focused on agriculture as a solution to both challenges. However, these well-intentioned efforts, through the expansion and intensification of agriculture, have inadvertently led to soil degradation and decreased agricultural productivity (Zulu et al., 2020). Diminishing grazing and pasture lands restricts the traditional practice of livestock mobility and further drives the conversion of pastoral and livelihoods to sedentary farming, leading to severe land degradation and competition for scarce land and water resources; this has often led to conflict for pastoral communities and diseases moving more easily across livestock and people (Reid et al., 2014). Deforestation for agriculture and fuelwood further exacerbates the problem, disrupting ecosystems and altering land cover (Roy et al., 2022). The prevailing land degradation problems are more complex when they happen across different land uses in fragile and ecologically sensitive landscapes that typify much of SSA; technological solutions alone do not provide lasting and sustainable solutions. This underscores the urgent need for sustainable and integrated land management practices that consider positive outcomes for people and the environment. The problems need to be tackled through an integrated landscape solution that considers the balance of supply and demand, integration of production system and natural resource conservation, and sociotechnical and socio-economic, local, and national objectives. Solutions must be driven from the description and analysis of the current context at farm and landscape scales and the co-design of strategic pathways for resilient, adaptive, and transformative interventions and action areas (Tilahun et al., 2023). To ensure adaptation and sustainability of the solutions, planning and implementation of interventions have to be derived by community-led processes and partnerships with all interest groups (Coger et al., 2022). Despite being fragmented, sustainable landscape management practices are available in a few SSA landscapes with varying complexity, implementation status, and commitments by different actors at different levels. With support from the government and NGOs, smallholder farmers have improved traditional natural resources management practices (Bizikova et al., 2020). Landscape management and soil health recovery could successfully be achieved using existing, often traditional techniques and through affordable strategic management innovations at scale from individual fields to a more integrated system that combines technologies of soil, water, crops, livestock, and tree systems (Shah & Wu, 2019). For example, to restore degraded landscapes, implementing various soil and water conservation options in northern Ethiopia resulted in a significant decline in runoff and soil loss with a significant sediment yield reduction of 77% at the watershed level (Admas et al., 2023). Intending to manage torrential rains and flood water management, the once degraded landscape in the Afar region of Ethiopia (Cherinet et al., 2022) turned out to be a productive land for growing dryland crops (Wang et al., 2022) and forages for livestock feed (Moorby & Fraser, 2021). The Ethiopian government restored several degraded areas through its watershed management program since the 1980s. (Kibret et al., 2022) reported that restoration practices such as exclosure-based management are effective interventions to restore degraded lands and the associated ecosystem services. In Mali, landscape restoration practices focused on improvements in plant-available soil water, bridging dry spells, and shallow aquifer recharge by implementing soil and water conservation works (Traore and Birhanu, 2019). In other parts of West Africa, for example, Burkina Faso, the government planned to set up 120,000ha of degraded lands treated using earthen benches (Faltermeier, 2009). In Niger, landscape restoration techniques combine one or more agricultural technologies with land and water management practices. Half-moons, stone bunds, and benches were standard techniques at the farm level, while Farmer Managed Natural Regeneration (FMNR) has been widely considered a successful landscape restoration technique. Since the 1980s, 500,000ha of degraded land has been covered by the FMNR technique in the Maradi region of Niger (Rinaudo, 2023). Other restoration techniques that are common in West Africa include the Zaï technology (Bado et al., 2016), contour bunding combined with fast-growing tree species (Dembele et al., 2021), and semi-circular bunds (Rostampour et al., 2023). Zaï became popular in the early 1980s in the West African Sahel (Zida et al., 2019). Contour bunding technology was introduced in southern Mali in 1980 as a Soil and Water Conservation (SWC) practice to control erosion and improve soil fertility in many farm fields ((Wolka et al., 2018). It provided multiple benefits of increasing crop yield (Isbell et al., 2017) and reducing soil water erosion by over 40% (Xiong et al., 2018). Semi-circular bunds (SCB) are earthen embankments practiced in semi-arid areas for rangeland improvement (Heshmati et al., 2018). They can increase crop yields by 112% (Gregory & George, 2011). The bio-reclamation of degraded land (BDL) system is an integrated system aimed at increasing the food production and income of poor farmers (mainly women) by utilizing degraded lands to produce rainfed fruit trees and vegetables. The BDL is very popular in Niger (Karimou, 2022).

Against this background, managing degraded landscapes in many SSA countries faces several barriers. Often, there are limited efforts to integrate natural resource management practices with agricultural intensification and livelihood options, and only some of the proven technologies and practices at the farm level can be implemented at scale successfully. In Ethiopia, for example, despite significant progress by the government to restore degraded landscapes, rural growth and poverty reduction have been critically hampered by land degradation in the past decade. In Mali, the aggravated land degradation is exacerbated by climatic changes and inaction due to several factors that complicate efforts to increase food production and security. The absence of timely data monitoring, documentation of successful practices, and identification of appropriate scaling options still needs to be addressed. Decision-makers require tangible evidence to believe in the success of technologies and practices for broader scaling. For this, it is imperative to record successful stories where integrated solutions have been co-validated with relevant stakeholders. The limited available documentation highlighted the challenges related to degraded landscapes in SSA and the efforts made by government and development programs.

2.3.2 Soil erosion in Mali

Mali's economy is essentially based on the primary sector where agriculture accounts for more than 35 percent of gross domestic product (GDP) and 80 percent of livelihoods (Bank, 2018). The predominantly rain fed nature of its agriculture remains problematic because of rainfall unreliability which threatens dangerously crop production and development strategy (K. Traore & Zemadim, 2019). Water is one of the main constraints to crop production (B. Singh et al., 2015) as it influences directly plants growth, therefore it's very important to minimize rain water runoff in rain fed agriculture (Rockstrom et al., 2007). Runoff negatively affects agricultural productivity by decreasing water supply for crops and parkland trees, while also causing soil deterioration through erosion of the topsoil layer (Diop et al., 2022). Water erosion, which removes nutrients, thins the soil layer, reduces rooting depth and infiltration, damages soil structure is the most common form of land degradation worldwide. Erosion usually increases with agricultural activity, particularly with annual cropping systems where the soil surface is seasonally exposed to rain with high intensities. This situation results in negative nutrient balances and lower crop yields in most farming systems in West Africa (Bationo et al., 1998). In Sub-Saharan Africa (SSA), rain comes as downpours under high anthropogenic (deforestation and population) pressure leading to over 50 tons·ha−1 soil losses in many situations (Ofori et al., 2021). Soil chemical properties that were most adversely influenced by erosion or topsoil removal in SSA include pH, organic matter content, total N, available P, exchangeable bases, and cation exchange capacity (Weight & Kelly, 1999). Losses were estimated in cultivated soils of southern Mali (Sanogo et al., 2023) to 25 kg of N .ha^{-1}·year^{-1} and 20 kg of K·ha^{-1}·year^{-1}. (Sanogo et al., 2023) concluded that 44% of farmer's agricultural incomes losses are due to soil depletion which is a major factor influencing food security in the area and finally the economy of the country since it affects the main rain fed staple crop. According to (K. Traore & Zemadim, 2019), the major staple crops grown in southern Mali are millet (*Pennisetum glaucum* (L.) R. Br.), sorghum (*Sorghum bicolor* (L) Moench), and maize (*Zea mays*) and these crops are becoming dominant southwards. In southern Mali, erosion was emphasized by inadequate soil and crop management which could even jeopardize national food security goals, since impacting negatively directly on crop productivity (K. Traore & Zemadim, 2019). So, because of unpredictable rainfall and decreased agricultural productivity, many soils and water conservation technologies such as stone lines, half-moons, contour hedgerows, rock bunds, filter walls, zai, agroforestry, mulching, soil amendments, water harvesting, contour ridges, terraces, check dams, benches and no-tillage have been developed and are now widespread to improve soil quality, decrease runoff, erosion and nutrient losses, and increase infiltration and crop productivity (Winterbottom et al., 2013).

2.4 Overview of crop production in West Africa

West African crop production relies heavily on rainfall and is still susceptible to the effects of climate change, which include erratic rainfall patterns and high temperatures. In West Africa, millet (16.0), sorghum (14.3), cowpea (10.3), maize (7.8), and rice (5.7) are the top five crops by harvested area (measured in millions of hectares) (Peano et al., 2020). Declining soil fertility and the anticipated effects of climate change have made it difficult to sustain the yields of these important crops (Kang et al., 2009). Typically, farms are modest and use basic farm equipment like cutlasses and hoes.

The majority of farmers use little fertilizer and pesticides and engage in low-input agriculture. In farming systems in West Africa, diversity is the norm. Farmers usually grow ten or more crops in a variety of mixes that differ in soil type, topography, and distance from the home complex, even at the level of the individual farm unit.

2.3.1 Crop production in Mali: Case of Bougouni region

Cotton is the main industrial and cash crop in the region of Bougouni. The main food crops are: Sorghum, Millet and Maize. Secondary activities such as logging (non-timber forest products and wood), market gardening, trade, gold panning and crafts are practiced there. According to the data in Tables 2 and 3, there is a trend towards increasing yields of sorghum and millet production over the years, attesting to the positive impacts of management and ecological conditions that are still relatively undisturbed. The tables on cereal production show a marked increase in average production over three marketing years. This increase is mainly driven by maize production, which accounts for more than half of cereal production.

Table 2: Evolution of sorghum production in the Bougouni region.

Designations	**Sorghum**				
	2013/2014	**2014/2015**	**2015/2016**	**2016/2017**	**2017/2018**
Supervised holdings	28800	29000	29500	30000	31000
Herbicide area (ha)	71000	74000	76000	77500	80000
Production (tons)	65000	70000	74000	77000	94000
Yield (kg/ha)	915	946	974	994	1175

Source: Coordination CMDT/Bougouni (2019)

Table 3: Evolution of maize production in the region.

Designations	Maize				
	2013/2014	2014/2015	2015/2016	2016/2017	2017/2018
Supervised holdings	34059	35000	36000	36600	37200
Area. sown (ha)	93500	101000	103000	105000	107000
Area with Organic Manure (ha)	32200	33000	35000	38000	40000
Area with cereal complex	93500	101000	103000	105000	107000
Area with urea (ha)	93500	101000	103000	105000	107000
Herbicide area (ha)	45000	50000	60000	75000	76000
Production (tons)	210300	244000	252000	262000	350000
Yield (kg/ha)	2249	2416	2447	2495	3271

Source*: Coordination CMDT/Bougouni (2019)*

2.5 Agroforestry for Soil Conservation and Improvement

Although soil erosion has always been an issue for all forms of livelihood, soil conservation initiatives gained more attention after (Do Nascimento, 2023) formulated the World Soil Charter and the world's focus shifted to environmental issues and the fight against desertification. These days, maintaining soil fertility and preventing soil erosion are both included in soil conservation. Alley cropping has unquestionably proven to be an effective method for preserving soil fertility, promoting sustainable production, and conserving soil in highland environments.

Windbreaks are used by farmers in plains and slightly rolling farmlands throughout Africa to safeguard crops, water sources, soil, and towns. In the arid savannas of Tanzania and Kenya, *Euphorbia tirucalli* hedgerows are frequently planted to safeguard villages and corn fields. Multispecies shelterbelts are cultivated in Chad and Niger to prevent the expansion of deserts on croplands, while tall rows of casuarina can be observed along Egypt's canals and irrigated fields. For tiny areas like nurseries and residential gardens, small living fences and hedgerows can also serve as windbreaks.

The most successful windbreaks offer a semipermeable wind barrier that extends from the ground to the tallest trees' crowns. A double-row planting of fast-growing, tall plants like eucalyptus, casuarina, or neem (*Azadirachta indica*) in the center of the windbreak should be ideal. On either side of the core should be two rows of shorter spreading plants like *Cassia,* *Prosopis, Gliricidia,* or *Leucaena.* Away from agriculture areas, agave and euphorbia species are also utilized, particularly on the outer rows.

A greater range of beneficial items for local consumers can also result from diversifying the species in the windbreaks. Compatibility, environmental risks (such mosquitoes and pests), palatable to both human and wild animals, soil conditions, water management, micro catchments, etc. should all be taken into consideration when choosing a species. On a gross area basis, the protected region's millet yields were 23% higher than the unprotected area's when the wind breaks were 10 years old (Bielders et al., 2001).

Comprehensive descriptions of the function of agroforestry in soil conservation across different ecoregions have been provided by (Schroth et al., 2013). Improvement of soil fertilizing trees dealt in earlier sections is equally relevant here.

2.5.1 Environmental Impacts of Agroforestry

Agroforestry provides numerous ecological-based techniques that can potentially increase the ecosystem service for the rural community. These activities include crop diversification (crop-tree integration), crop rotation, soil conservation (cover crop integration), better fallows and boundary planting.

For instance, increased soil fertility and physical structure (soil conservation) can be achieved by utilizing pruning materials (from the trees or crop residues) as soil amendments (Libutti et al., 2021). However, the quality of the pruning materials in the system can affect the results of this operation.

Plant residues have different C/N ratio which can affect their decomposability in soils. Consequently, the amount of nutrients released in the soil might vary between type of residues resulting in distinct soil chemical content (Mandal et al., 2004) and therefore its impacts on crop growth. Different decomposition rate due to variation in C/N ratio can also influence soil carbon content (either increase or decrease), which may compromise the carbon sequestration capability of a particular agroforestry system as a whole (Lorenz & Lal, 2014)

The cultivation of different tree species in agroforestry system also improves biodiversity providing a habitat for the wildlife (Udawatta et al., 2021). In addition, trees can also prevent soil erosion and landslides (in the higher slopes) due to the strong rooting system around the soil matrix (Vergani et al., 2017). The presence of trees in agroforestry systems can also change microclimatic conditions through shading which might reduce the sun radiation buffering the temperature around the farm (Menezes et al., 2024). Highly intensified solar radiation can hamper crop physiology and growth, hence incorporating trees through agroforestry can improve crop growth and subsequently, its yield (Lebrazi & Fikri-Benbrahim, 2022). Caution needs to be taken however, when selecting tree coverage, as oversharing can significantly reduce the light penetration which can potentially reduce the growth of co-cultivated crops and increase disease emergence (Mukhlis et al., 2022)

Improved water conservation is another ecological advantage of agroforestry for the local population. The combined tree-crop system's optimal water uptake may produce such an ecological service. Only around 25% of the rainwater during the dry season was transpired from plant biomass, according to a study conducted on an agroforestry system (maize-tree) in Kenya. This suggests that the system is effective at using off-season rainfall, which makes up 15-20% of the total annual rainfall.

Meanwhile, the rest of the water remains in the soil layers even after the harvest period (Zheng et al., 2000). Improved organic carbon in agroforestry soils (as a result of organic amendment addition) can increase water retention and therefore prevent excessive evaporation or water runoff (Fahad et al., 2022). However, again, the choice of the tree species matters as water uptake might vary between plant species. Water uptake by plant roots is generated by the water potential difference between the soil and the atmosphere when leaf stomata are open and this depends on the root exploration capacity of a particular plant species (Lambers & Oliveira, 2019)

Furthermore, a research revealed that while less vegetation lowers rainfall, more vegetation density (because of the increased biomass from trees and shrubs) positively correlates with precipitation rates.

Such decline in precipitation might be attributed to the reduced evapotranspiration and increased light reflection to the atmosphere under less vegetation density (Dai et al., 2018). Furthermore, analysis of the water cycle highlights the importance of managing tree cover to improve the quantity of rainfall (Zafirah et al., 2017). Therefore, one tactic to reduce dryness in some desert regions and boost community resilience in the face of climate change is agroforestry. Although promising, these studies were only performed at farm level and rely on data correlation or modeling. Hence, more studies need to be done to validate such findings covering different geographical locations. A brief summary of environmental impacts of agroforestry on rural communities and their respective studies.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Study areas

Mafele village is located at a specific geographical point between 11° 19′ 00″ N and 7° 46′ 00″ W, where the isohyets range from 900 mm to 1000 mm (Figure 2). The presence of heavy rainfall has been demonstrated to result in a degradation of soils in areas where vegetation cover is absent. The temperature of the environment is subject to variation, ranging from 20°C to 35°C. The annual evapotranspiration rate is 2100 mm. The topography is characterized by the prevalence of gravelly and lateritic soils, with sandy and clayey limonite prevalent on glacial formations. The constraints present at the soil level are manifold, including the risk of erosion and suboptimal drainage conditions. This area is characterized by its agricultural significance, and it is notable for its pastoral characteristics. The region's climate is categorized as Sudano-Sahelian, characterized by hot, arid conditions. The climate is characterized by a marked alternation between a dry season, dominated by dry winds (Harmattan) and a rainy season of three to six months (between May and October), with humid winds originating from the Gulf of Guinea (Monsoon). The dry season is divided into two distinct periods: a warm season, which extends from March to May, and a cold season, which persists from December to February.

The vegetation of the Mafele village is characterized by a diverse array of structures, ranging from open forests to shrubby savannahs, with a varied herbaceous mat. The forage potential is high. The village was once home to a rich and varied fauna, but today it is inhabited by only a few warthogs, antelopes, rabbits, and a variety of birds, including guinea fowls, partridges, and ducks, some of which are nocturnal and some diurnal. The biodiversity of the aquatic ecosystem is limited. The area is characterized by a high diversity of pollinating and melliferous insects. As asserted by (Coulibaly et al. in 2024).

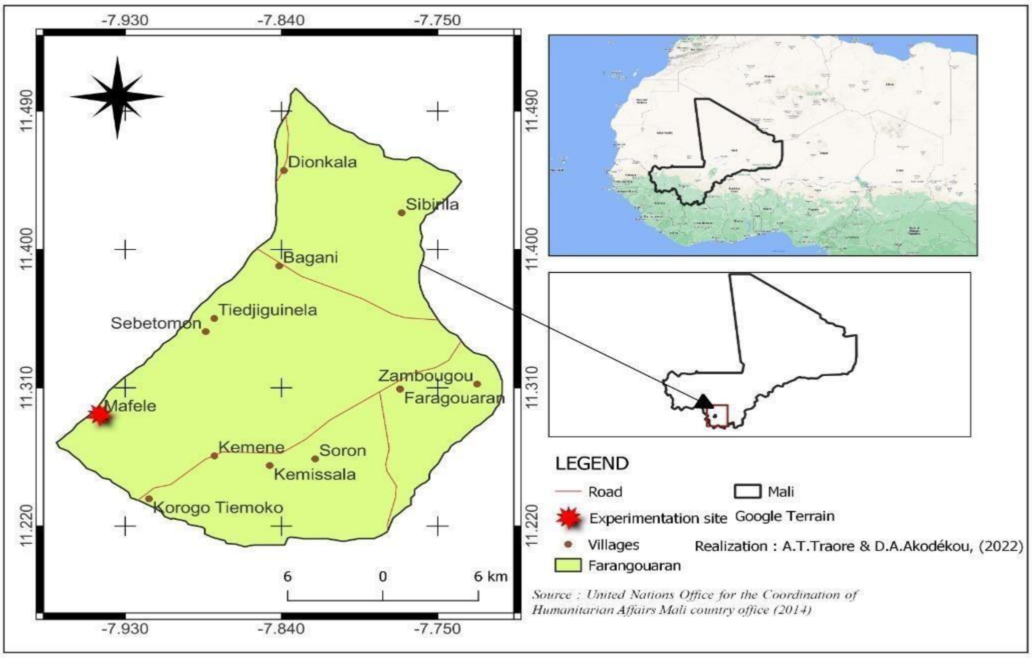

Figure 2: Farangouaran commune with Mafele village as study area in Bougouni region.

3.1.1 Choice of study area.

The selection of Mafelé village within the Bougouni region as the study area is strategic and highly justified given the context of land degradation in the region. Bougouni, situated in southern Mali, is part of the Sudanese ecological zone characterized by semi-arid conditions, which make it particularly vulnerable to environmental pressures such as overexploitation of natural resources, deforestation, and unsustainable agricultural practices. These factors have contributed to a noticeable decline in land quality, productivity, and overall ecosystem resilience, making it a pertinent location for investigating land degradation dynamics.

Mafelé village, in particular, presents a representative case of rural communities that are directly impacted by land degradation. The community relies mainly on subsistence farming, with agriculture being the primary livelihood, thereby making them highly sensitive to changes in land productivity. The village is experiencing ongoing challenges such as soil erosion, fertility decline, and reduced crop yields all symptoms of progressive land degradation. Studying Mafelé offers insights into the local drivers, impacts, and coping mechanisms related to land degradation within small rural settings.

Furthermore, selecting Mafelé allows for the integration of local indigenous knowledge, traditional land management practices, and community perceptions, which are crucial for designing context-specific interventions. The community's active engagement and firsthand experience with land issues make it an ideal site for assessing the effectiveness of conservation strategies and exploring the potential for sustainable land management.

From a broader perspective, Mafelé's conditions reflect the wider challenges faced by similar villages across Bougouni and the broader Sudanese zone. Findings from this area can be scaled or adapted to inform regional policies and programs aimed at reversing land degradation, enhancing land productivity, and building resilience against climate variability.

In sum, Mafelé village within the Bougouni region was chosen for its high vulnerability to land degradation, its representativeness of typical rural land use systems, and its potential to generate locally relevant, actionable insights. This focus aims to support sustainable development initiatives that specifically address land degradation and promote resilient land management practices in vulnerable ecosystems.

3.2.1 Characterisation of the climate variability and change in Bougouni region

3.2.1.1 Data

To achieve this objective, data were collected from the Bougouni meteorological station, which serves as a key source of climate information for the region. The primary parameters examined included temperature covering maximum, minimum, and average values as well as rainfall, both on a monthly and annual basis. These datasets span a period of 39 years, from 1984 to 2022, providing a comprehensive longitudinal record of climate variability and trends in the area. By analyzing this extensive period, we were able to characterize the climate patterns and distinguish deviations from the long-term norm. The reference framework for this analysis was established using the standard climate normal set by the World Meteorological Organization (WMO), as outlined by (Herrero et al., 2019), which serve as baseline benchmarks for comparing current and future climate data. This historical and statistical approach enables us to understand climate fluctuations and set a foundation for identifying anomalies, trends, and potential impacts related to climate change in the region.

3.2.1.2 Method

We analyzed climate parameter using Instat+.3.36 software (rain fall and temperature). The types of analysis included anomalies and the Standardized Precipitation Index (SPI), and statistical homogeneity test.

a) Ran fall and temperature anomalies analysis

To analyze rainfall and temperature anomalies, we compared observed data against a long-term average to identify deviations that indicate periods of unusual moisture or temperature conditions following these steps:

- Collecting 39 years monthly temperature data;
- Calculating the long-term mean (average) as a reference point for normal conditions;

- Determine anomalies by subtracting the long-term mean from the observed data for each year

$$\text{Anomaly} = \text{Observed value} - \text{Long} - \text{term mean}$$

Positive anomalies suggest above-average rainfall or temperature; and negative anomalies indicate below-average conditions.

b) Standardized Precipitation Index (SPI)

The SPI is calculated using the arithmetic mean and standard deviation of the precipitation series. It is used to illustrate and categorize drought periods. In the model, negative values obtained from this equation indicate precipitation deficits (drought events) while positive values illustrate precipitation excesses (wet events) (Table 4). (Moreira et al., 2015), define four different categories of drought. It is calculated from the following equation:

$$\text{Si} = \frac{\text{Xi} - \bar{\text{x}}}{\text{Sx}}$$

Where Xi is the cumulative rainfall for year i; $\bar{x}$ is the cumulative average rainfall; Sx is the standard deviation of precipitation in the series.

Table 4: Drought categorization

N`	**SPI values**	**Drought category**
1	SPI ≥ 0 0	Non-drought
2	-1 < SPI <0	Near normal
3	-1.5 < SPI ≤ -1	Moderate drought
4	-2 < SPI ≤ -1.5	Severe drought
5	SPI ≤ -2	Extreme drouth

Source: (Moreira et al., 2015)

c) Statistical tests used

We applied the Pettitt test (Pettitt, 1980) to examine variations in climate parameters. This test detects the point at which a sudden shift or discontinuity occurs within a data series. It helps identify the specific year when a significant change in precipitation or temperature happened for the station being studied. The Pettitt test is non-parametric and based on the Mann-Whitney test. The null hypothesis assumes that there is no break in the data series.

3.2.2 Evaluation of the diversity of perceptions and agroforestry systems as climate adaptation measure in Bougouni region.

3.2.1.1 Data collection

Before starting the study, a survey and consultation mission was carried out with local authorities and residents of the selected area. This effort was supported by the presidents of the agricultural cooperatives in the intervention village. As a result, the agroforestry systems and sustainable land management practices, which were central to the study, were identified. The goal of the survey was to locate agroforestry systems that would encompass a large portion of the study area, ensuring that the findings would be representative.

The study was structured so that each cultivated speculation was linked to a farmer from the sample group. This approach ensured that every speculation grown in the village had a corresponding study participant. The questionnaires had been prepared beforehand in French, but due to the village's low literacy rates, interviewers were instructed to ask questions in Bambara during conversations. Interviews took place in the farmers' fields, as the farmers were typically present in their agricultural environments. When farmers weren't in their fields, interviews were conducted at their homes. The participants were cooperative and provided accurate responses, which reinforced the credibility of the survey results in Mafele. The climatic data used for the study was sourced from the meteorological station in the Bougouni region.

3.2.1.2 Methodology

a) Sampling Methodology

The simple random sampling technique was employed in order to maintain equilibrium with regard to the number of informants in the village, irrespective of gender, ethnicity, or religion (Rafiq et al., 2019). Consequently, the sample size was determined by the number of informants collected within the village. An open-ended, semi-structured questionnaire was utilized to collect pertinent information (Saglam, 2024). A questionnaire was meticulously designed and disseminated to all participants. The survey encompassed one hundred farmers residing in Mafele village, including twenty-five women and seventy-five men. The questionnaire was designed to assess the farmers' utilization of sustainable land management techniques within their agricultural fields.

b) Data Collection (Survey)

The survey inquired about farmers' experiences with and information regarding the agroforestry system. It also solicited their perceptions of the agroforestry system in their fields, the quality of their soils, the SLM measures they use in Mafele, and the fluctuation of rainfall from 1984 to 2022. Additionally, it sought to ascertain the main crops cultivated in Bougouni from 2013 to 2018. The data regarding the fluctuation of rainfall were obtained from the meteorological readings made by the meteorological station of the region of Bougouni. The period for which the fluctuation of rainfall was measured is from 1951 to 2022. The data on crops were obtained through a survey conducted in the village of Mafele and at the CMDT of Bougouni. The interviews were conducted during the months of August and September of the year 2022. The interviews were conducted in Bambara, the national language, for the village of Mafele and in French for the CMDT of Bougouni.

c) Data analysis

The data was analyzed using IBM SPSS STATISTICS version 25, Excel, Access, Python, and R. The collected data underwent a meticulous review to address any missing information on the questionnaires and ensure the accuracy of the results. This process entailed a thorough examination of the completed cards in the office following the data collection phase. The collection, coding, and processing of the data was conducted using Excel and Access software. A database has been created to compile the information collected during the survey. For quantitative secondary data, the analysis was conducted on flattening. Conversely, for qualitative data, a synthesis matrix was developed and utilized to enhance the structure of the information. Subsequently, the data were coded using SPSS v25 and Access. The coding of the data facilitated the categorization of the respondents' views and subsequent analysis. The collected data underwent statistical analysis, including means and frequencies, to ascertain the underlying patterns and relationships. A comprehensive array of descriptive statistics was employed, encompassing frequency distribution, percentage, mean, and standard deviation, to ascertain the prevalence and proportion of sustainable land management techniques, along with the proportion of farmers' perceptions of agroforestry practices. The Pearson correlation coefficient was employed to ascertain the income levels of the agroforestry systems utilized in Mafele. In light of the findings, it was possible to formulate conclusions and propose suitable policy recommendations.

3.2.3 Assess the effects of leaves biomass fresh in an alley cropping system with *Gliricidia sepium* and *Leuceana leucoceaphala* on the physico-chemical properties of soils, growth of maize and sorghum and yield.

3.2.3.1 Source of data

For these objective, we collected data through field experiment in year 2023 and 2024 in Mafele village.

3.2.3.2 Equipment

The equipment used is:

- Plough,
- hoe,
- rope,
- pickaxe,

- scale,
- cameras

3.2.3.3 Field experiment

a) Sowing material

Table 5: maize planting material characteristics

Maize variety	**BRICO**
Baptismal name	BRICO
Origin:	CIMMYT/IITA
Variety Type	Improved
Type of technology	confirmed
Date obtained	1994
Grain characteristics	Horn yellow
Agronomic characteristics	Cycle 65-70 days, grain yield 3-4t/ha.

Table 6: Sorghum sowing material characteristics

Sorghum variety	**Djakumbe**
Name	Djakumbe
Origin:	Mali
Rainfall	400-600 mm
Cycle	100 days
Color	Red plant
Yield	2 t/ha
Sow	5-6 seeds / poquet, then unmarry to 2 plants / poquet

b) Experimental design

The experimental setup employed complete random blocks, also known as Fischer blocks, each consisting of four randomized units that correspond to four repetitions (Figure 3). Each repetition contained four small plots, representing four different treatments with various amendments. The study focused on a single factor at three different levels, including a control. The small plots, each measuring 16 m² and arranged in a square layout of 4 meters per side, were separated by 1-meter alleys and a 2-meter rehearsal space. The entire testing area covered 544 m², with 16 plots for each crop occupying 256 m² (4 m by 4 m each), and additional walkways taking up 303 m². Tree spacing was set at 1 meter between individual trees, with 2-meter intervals between the lines of *Gliricidia* and *Leucaena*. For maize and sorghum, planting dimensions were 0.80 meters by 0.40 meters.

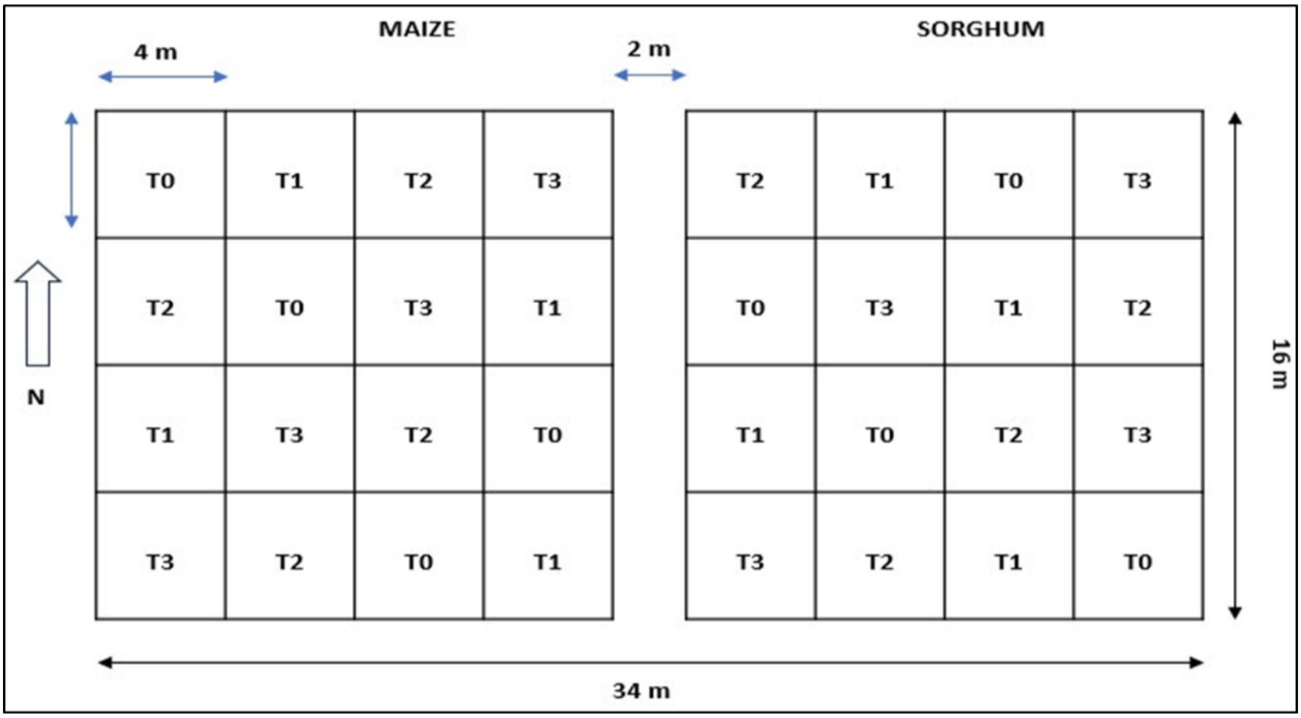

Figure 3: experimental design.

Table 7: Various treatments approaches for the test.

Treatments	Composition
T0	control
T1	G
T2	L
T3	G+L

G = Gliricidia, L = Leuceana,

c) Experiment field Management

- **Sowing operation**

The sowing was done after a useful rain in June. The spacing used was 0.80 cm between rows and 0.40 cm between planting holes for maize. The spacing for sorghum was 0.75 cm between rows and 0.35 cm between planting holes. Seeds were sown at 2 seeds per planting hole for maize and 4 to 5 seeds for sorghum.

- **Application of foliar biomass**

The soil was tilled with the help of animal traction. Following this, the planting phase began, which involved physically establishing the basic plots. Fresh leaf biomass was applied at a rate of 2.5 tons per hectare. The soil surface was then covered with a thin layer of about 2 centimeters of soil using a hand harrow. The study used leaf biomass from two woody species, *Gliricidia sepium* and *Leuceana leucocephala*, which were collected from our experimental field and immediately buried in the soil before planting maize and sorghum. The experimental plots were set up in August 2022. Starting in June 2023, when we aimed to collect leaves of Gliricidia and Leuceana for soil burial, the available quantities of these leaves were insufficient. Each basic plot required 4 kilograms of leaves from each species, and each experiment consisted of 32 plots. Overall, there were 4 experimental sites. To make up for the shortfall, the remaining leaves of Gliricidia and Leuceana were sourced from ICRAF in Samanko.

Figure 4: Soil plowing operation.

- **Harvesting operation**

For the grain yield, two rows of observations were collected, taking the border effect into account. The harvested ears and panicles were dried and threshed before being weighed. The yield is reported per hectare.

In terms of biomass yield, each plot is systematically harvested and died separately before weighing. The quantity is also reported per hectare.

3.2.3.4 Soil sample collection

A total of four composite soil samples were collected to assess the initial fertility of the site. At the conclusion of each crop year, a soil sample was obtained from the center of each elementary plot. These samples were obtained from the auger at the soil surface level, specifically between 0- 20 centimeters above the soil surface. These samples were subsequently sent to the Soil-Water-Plant Laboratory for the purpose of determining the chemical properties of the soil.

3.2.3.5 Data Analysis

The collected data were then entered and organized using the Microsoft Excel spreadsheet. Subsequently, an ANOVA was conducted utilizing R, Studio software.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Results

4.1.1 Characterisation of climate variability and change in Bougouni region.

4.1.1.1 Rainfall and drought parameters

The figure 5 (**a**) analysis shows rainfall irregularities in the Bougouni region from 1984 to 2022, with a drought observed in 1984 and 1985 (-300 and -185 mm), followed by increased rainfall in 1986. Drought conditions were recorded in 1987 and 1988, with rainfall amounts falling below -245 mm and -240 mm, respectively. Between 1989 and 1992, rainfall heights ranged from 95 to 200 mm, between 1989 and 1992, rainfall ranged from 95 to 200 mm. In 1993, rainfall was lower at -180 mm, while in 1994, it increased to 200 mm. From 1995 to 1998, rainfall was below average, between -95 and -120 mm. Conversely, in 1999 and 2000, rainfall was higher, reaching 305 mm and 295 mm respectively. Lastly, decreased rainfall was observed in 2001 and 2002, with values of -103 mm and -298 mm. Rainfall was above average in 2003, 2005, 2007, and 2008, with amounts of 100, 96, 108, and 309 mm, respectively. In contrast, it was below average in 2004, 2006, and 2009, recording -102, -136, and -218 mm. In 2010, 2012, 2015, 2020, 2021, and 2022, rainfall was above average, registering 203, 104, 100, 80, 30, and 345 mm, respectively. However, rainfall was below average in 2011, 2013, 2014, 2016, 2017, 2018, and 2019, with values of -102, -102, -20, -186, -300, -65, and -102 mm, respectively.

The data indicates years of non-drought, near-normal, moderate, and severe drought. Severe drought conditions were specifically observed in 1994, 2002, 2009, and 2017, with values of -300, -293, -297, and -300 mm, respectively.

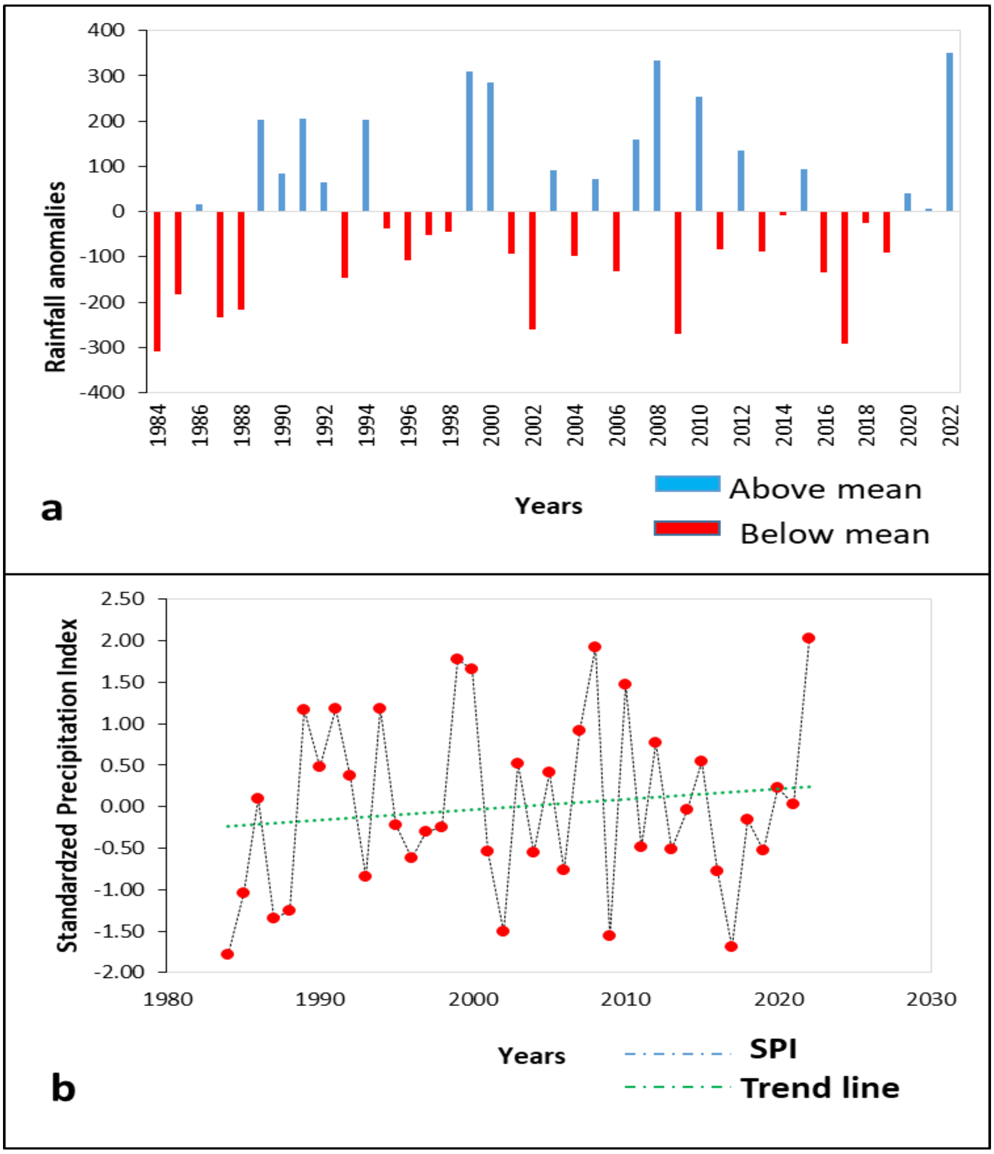

Figure 5: Evolution of precipitation from 1984 to 2022.

4.1.1.2 Temperature parameters

An analysis of Figure 6 shows that the temperature was below the mean from 1984 to 2001, with notable exceptions in 1993 and 1997, when temperatures ranged from -0.2°C to -1.4°C. Between 2002 and 2008, temperatures rose, reaching up to 1.6°C above the mean. From 2009 to 2012, as well as in 2014, 2016, and 2020, temperatures remained below -0.6°C. In 2017, the temperature exceeded the mean by 0.5°C.

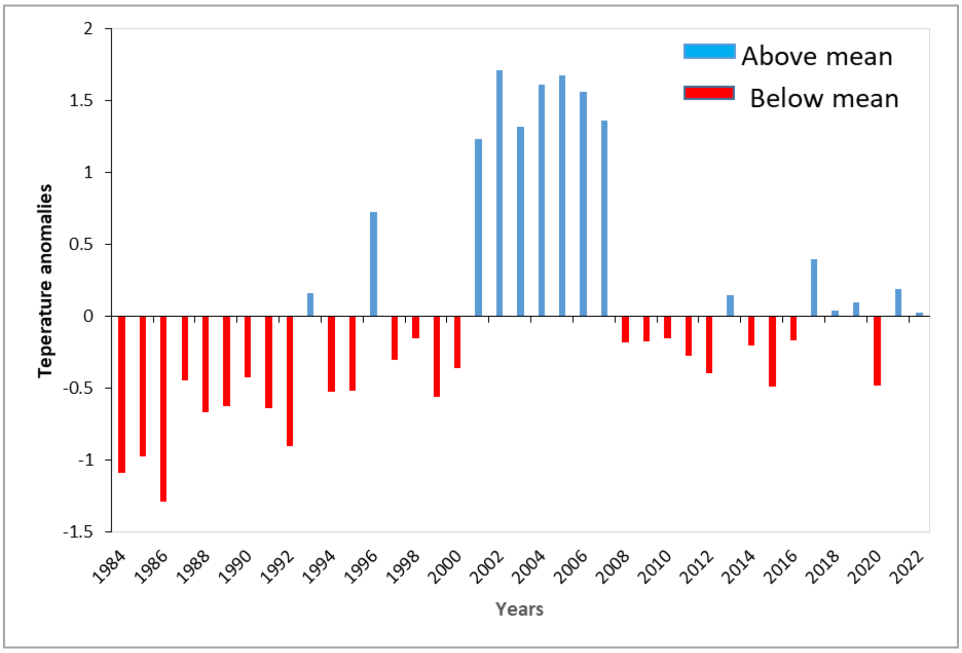

Figure 6: Temperature anomalies in Bougouni region from 1984 to 2022

Analysis of the figure 7 (**a**) shows temperature records in Bougouni from 1984 to 2022. From 1984 to 1999, the maximum temperature was around 33°C, with a mean of 26°C and a minimum of 21°C. Between 1999 and 2009, the maximum temperature rise to 36°C, while the mean and minimum were 28°C and 23°C. From 2009 to 2022, the maximum temperature declined back to 33°C, with the mean and minimum at 26°C and 22°C.

Analysis of figure 6 (**b**) reveals two mean trends: Trend 1 and Trend 2. Trend 1 had an average of 26.685 from 1984 to 1999, while Trend 2 averaged 27.592 from 2000 to 2022. The difference between the two trends is approximately 0.9ºC indicating a subtle yet significant warming trend that aligns with global climate change signals.

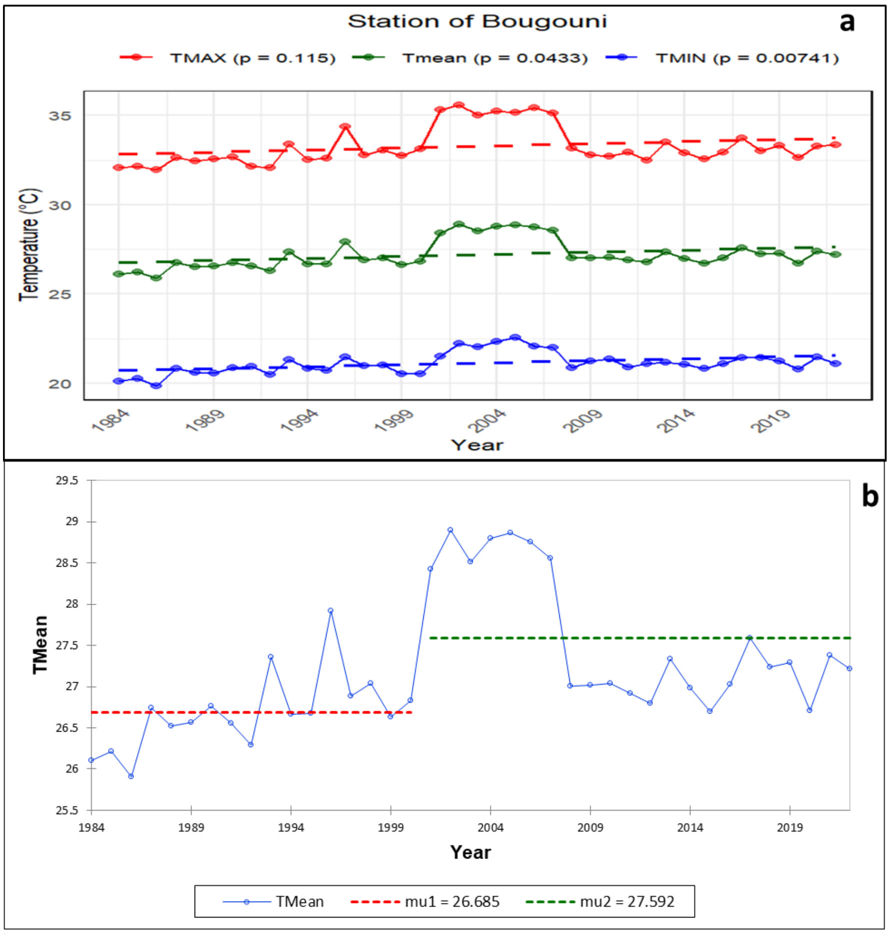

Figure 7: Maximum, minimum, mean temperature and increase in temperature in Bougouni station from 1984 to 2022. Mu1= mean of the first trend; mu2= mean of the second trend

4.1.2 Farmers perception on agroforestry systems practice as climate adaptation option in the study area.

4.1.2.1 Farmers perception of agroforestry practice advantages in Mafele.

An analysis of Figure 8, which presents the results of a survey on farmers' perceptions of agroforestry practices, indicates that 90-100% of respondents concur with the assertion that agroforestry practices reduce wind speed, mitigate soil loss through erosion, and enhance soil moisture. Indeed, a substantial proportion of the global population, ranging from 78% to 85%, subscribe to the notion that the implementation of agroforestry practices is instrumental in augmenting crop yields, enhancing farmers' economic well-being, escalating the production of timber and forestry products, and curtailing the contribution of manure to agricultural fields.

However, a significant proportion of respondents, ranging from 69% to 83%, expressed the conviction that the implementation of agroforestry practices is associated with a reduction in sedimentation, downstream flooding, and deforestation. Moreover, 70% of respondents posit that agroforestry confers a multitude of additional benefits. However, 15% of respondents disagreed with the statement that agroforestry practice reduces the amount of fertilizer applied to the field, while 2% and 6% respectively disagreed with its impact on farmers' income and soil loss. The extant literature on the subject of agroforestry's capacity to engender increased wood production and forest products, increased crop yield, reduced deforestation, mitigated downstream sedimentation, or other potential benefits is not readily explicable. A survey of respondents revealed a lack of knowledge regarding the aforementioned questions, with 20-30% reporting uncertainty.

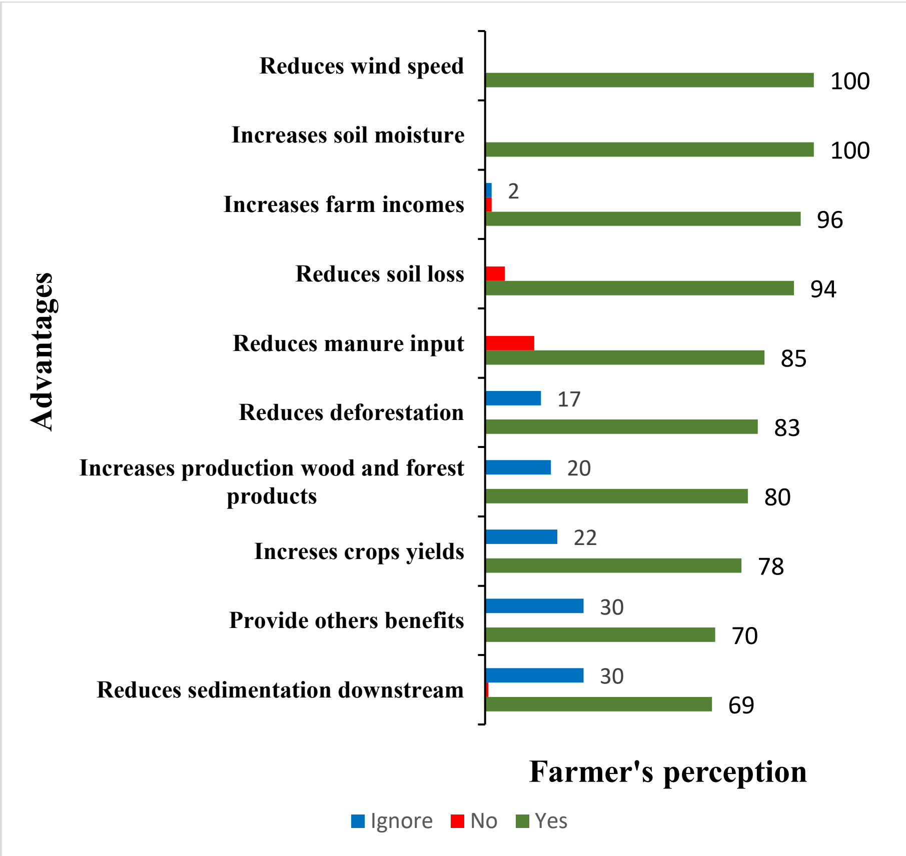

Figure 8: Farmers perception of agroforestry practice in Mafele.

4.1.2.2 The most dominant trees species used by farmer in agroforestry system for climate adaptation in Mafele

In Mafele, three agroforestry systems are practiced (agrisilvicultural, silvo-pastoral, and agrisylvo-pastoral) though the agrisilvicultural system remains the most predominant. As shown in Figure 6. *Vitelaria paradoxa* is the most common specie in the fields, with an average presence of 59%. Following that, *Mangifera indica* and *Anacardium occidentale* are observed, at 15% and 14%, respectively. The average proportions of the other species include 5% for *Moringa oleifera, Andasonia digitata*, and 2% for *Parkia biglobosa*.

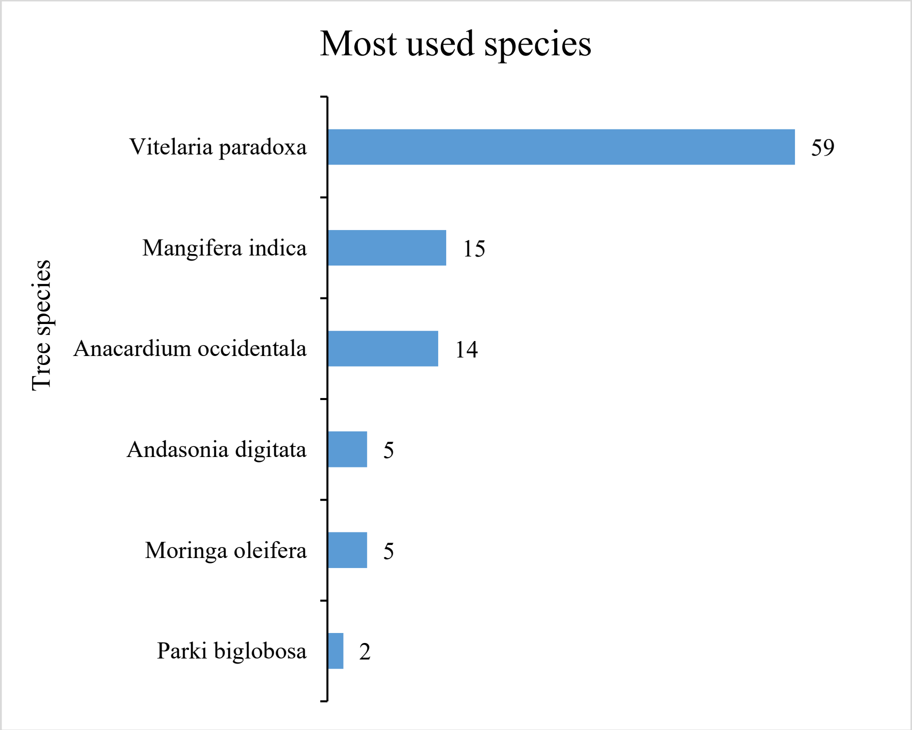

Figure 9: Trees species most used by farmers in Mafele.

4.1.2.3 Sustainable Land Management (SLM) techniques in Mafele.

Analysis of Figure 10, which presents the results of a survey on sustainable land management practices, shows that crop rotation and manure application are used by 95% of farmers, while crop residue management, fallow and legume cultivation are used by 55%, 72% and 83% of farmers respectively. However, sustainable land management technique such as zai is not practiced in the village of Mafele.

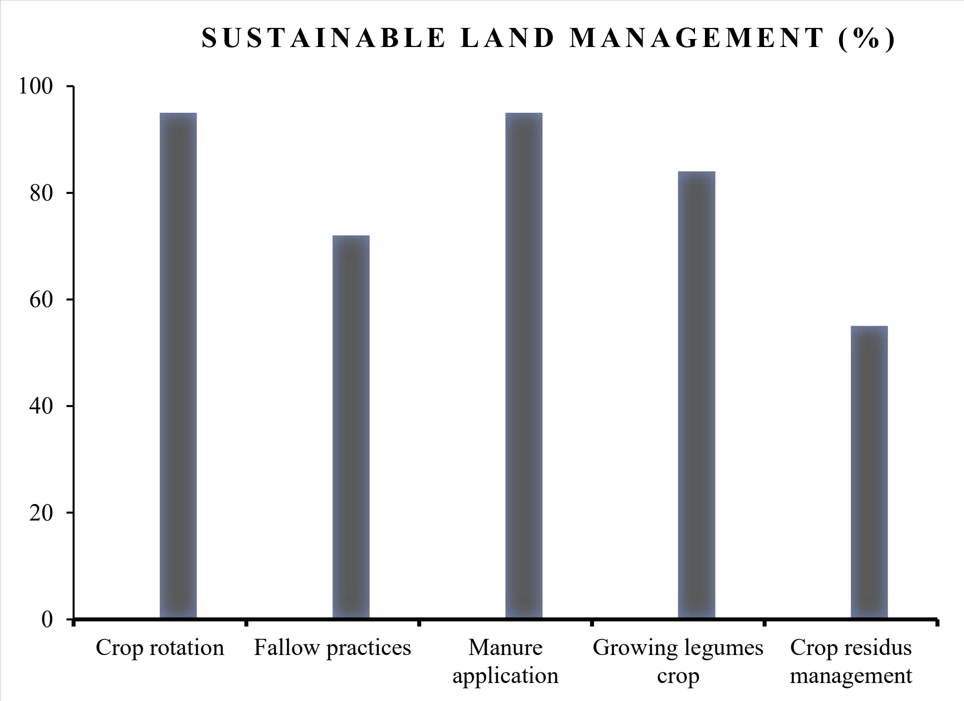

Figure 10: Sustainable land management technics practiced by farmers in Mafele.

4.1.3 The effects of leaves biomass fresh in an alley cropping system with *Gliricidia sepium* and *Leuceana leucoceaphala* on the physico-chemical properties of soils

As shown in Figure 11, the analysis reveals that the proportions of nitrogen, organic carbon, organic matter, and potassium are higher in the treatments (S+L, S+G, S+G+L) compared to the control plot. Conversely, the phosphorus content in the control plot slightly exceeds that of the S+G and S+G+L treatments, while remaining similar to the S+L treatment. The S+L treatment displayed the highest levels of organic carbon and organic matter relative to the other treatments. Notably, the total phosphorus was at its peak, with potassium levels reaching 12 mg/g and nitrogen at 0.03%. The (L+G) treatment showed satisfactory levels of carbon and organic matter, with high total phosphorus and the most abundant potassium content at 17 mg/g; nitrogen remained at 0.03%. Similarly, the (S+G) treatment had satisfactory organic carbon and matter percentages, high total phosphorus, 16 mg/g of potassium, and 0.04% nitrogen. The soil in the control plot (S) had lower percentages of nitrogen, carbon, and organic matter compared to all treatment plots, while potassium was reduced and phosphorus increased. Comparing the soil samples from the experimental treatments with the control, the former contained higher amounts of organic matter, total carbon, nitrogen, phosphorus, and potassium. This suggests that the presence of *G. sepium* and *L. leucocephala* enhances these key nutrients. These findings support the growth results shown in Figure 8, where crops in the control plot were shorter than those in the treated plots. Overall, *G. sepium* and *L. leucocephala* appear to improve soil fertility by affecting various soil chemical properties.

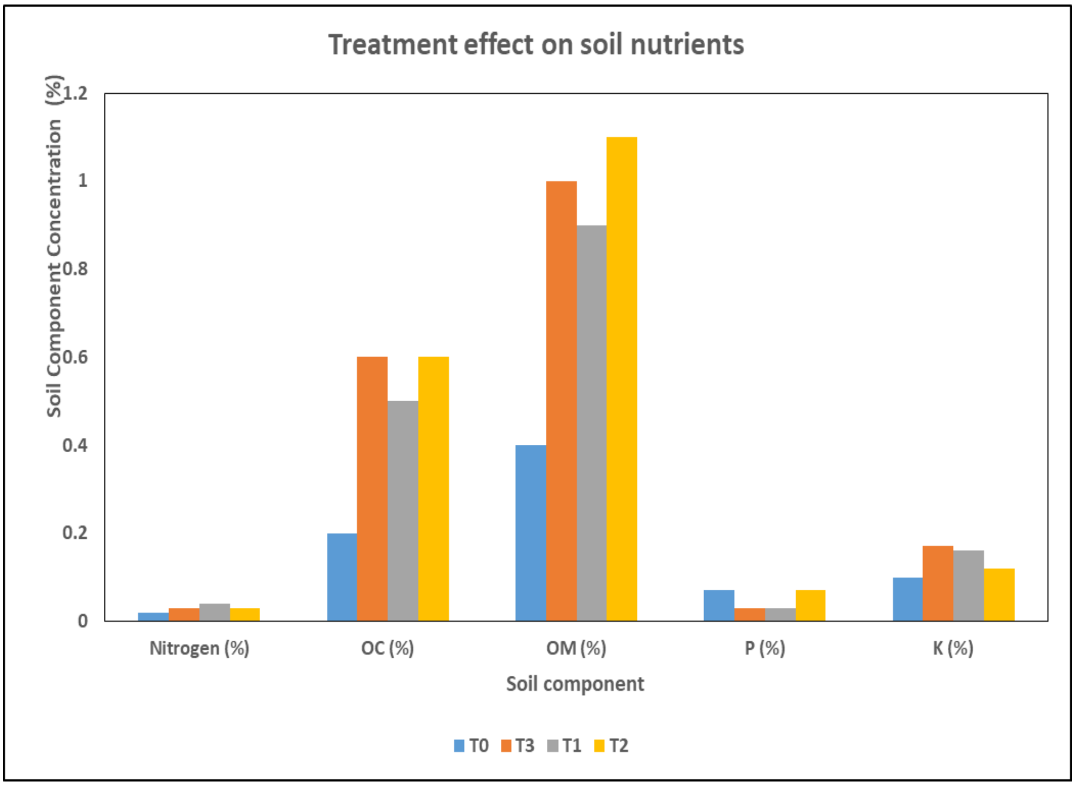

Figure 11: Treatment effect on soil nutrients (2023)

In 2024, as illustrated in Figure 12, the analysis indicates that the levels of nitrogen, organic carbon, organic matter, and potassium in the treatments (L, G, and G+L) are higher than those in the control plot. In contrast, the phosphorus content in the control plot shows a slight increase compared to the G and G+L treatments, with phosphorus levels in the control similar to those in the L treatment.

The S+L treatment recorded higher percentages of carbon and organic matter than the other treatments. Furthermore, the highest total phosphorus levels were observed, with potassium reaching 13.39 mg/g and nitrogen at 0.04%. The (L+G) treatment demonstrated satisfactory levels of carbon and organic matter, with high total phosphorus. Potassium was most abundant at 17.74 mg/g, and nitrogen remained at 0.04%. The (S+G) treatment also showed satisfactory carbon and organic matter percentages, with high total phosphorus, 16 mg/g of potassium, and nitrogen at 0.06%. The soil sample from the control plot (S) showed lower percentages of nitrogen, carbon, and organic matter compared to all treatment plots. Potassium levels were reduced, while phosphorus was elevated. Comparing the soil from the experimental plots to the control revealed higher concentrations of organic matter, total carbon, nitrogen, phosphorus, and potassium in the former. This suggests that the presence of *Gliricidia sepium* and *Leucaena leucocephala* increased these essential nutrients. These findings align with the crop growth results shown in Figure 9, where crop height in the control plot was less than in the treatment plots. Overall, *G. sepium* and *L. leucocephala* appear to enhance soil fertility by positively affecting various chemical properties.

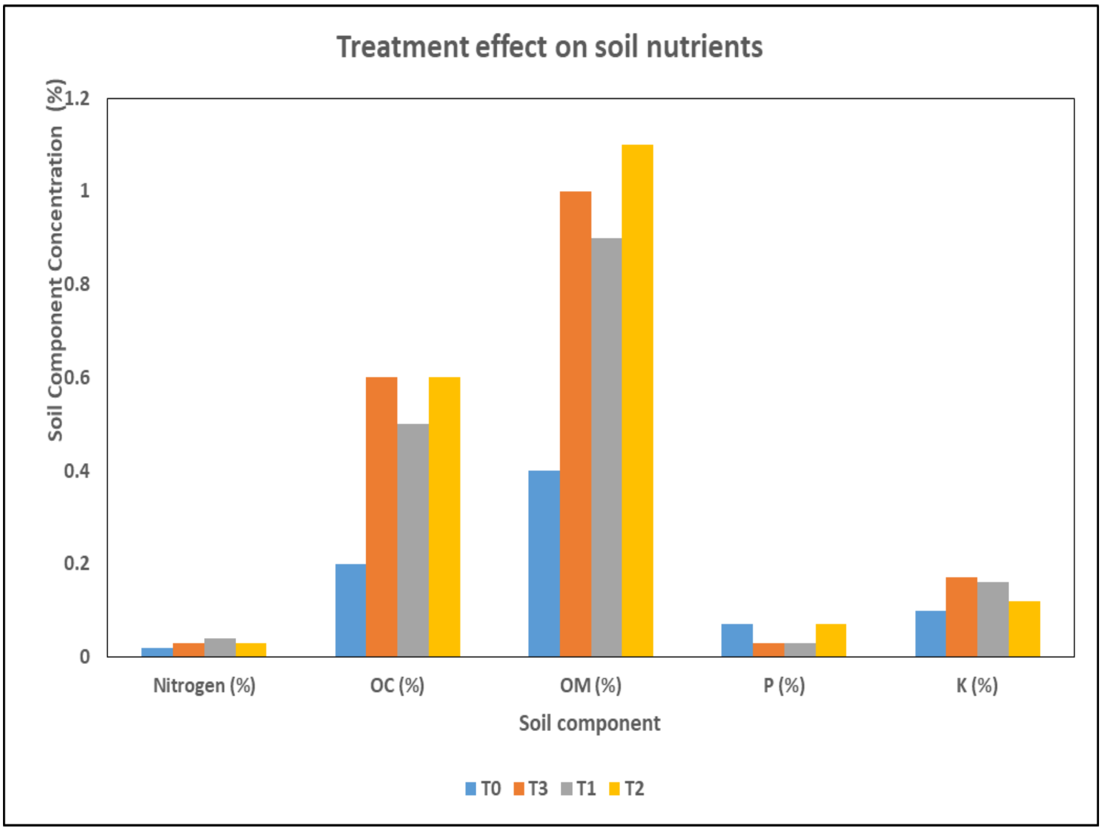

Figure 12: Treatment effect on soil nutrients (2024)

4.1.4 Determine the effects of leaves biomass fresh of *Gliricidia sepium* and *Leucaena leucocephala* on growth of maize and sorghum in an alley cropping system

4.1.4.1. Maize height (30 and 60 days after sowing)

The agroforestry options used to assess the performance under maize production shows a high significant effect (p=0.001) on growth parameter such as plant height at 30 and 60 days after planting (Figure 13 (**a**) and (**b**)). The assessment of the mean performance emphasized that the option T3 which is the combination of the two agroforestry tree outperformed the sole use of each of them. The three options performed better compared to the control.

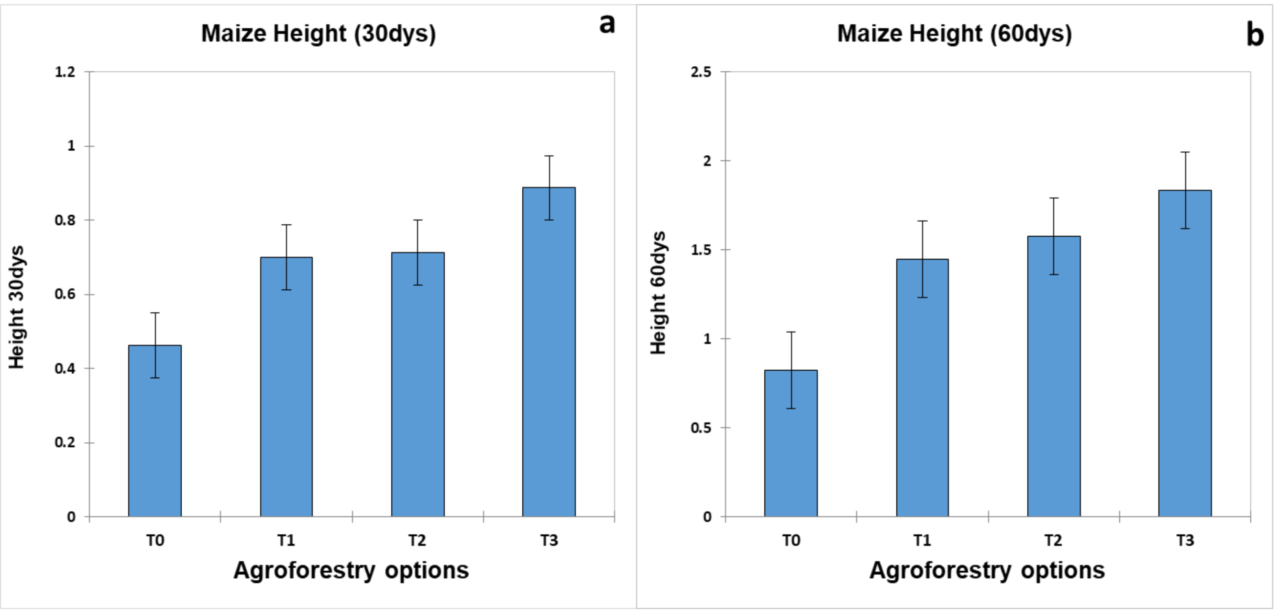

Figure 13: Height crops 30 days and 60 days after sowing in the study area during rainy season 2023 and 2024

4.1.4.2. Maize stem diameter (30 and 60 days after sowing)

The assessment of these agroforestry options on the stem diameter of maize at 30 and 60 days after planting (Figure 14 (**a**) and (**b**)) shows a significant effect (P=0.001) with a good performance of the combination option compared to the sole use of *gliricidia sepium* or *leuceana leucocephala*. All the agroforestry option outperformed the control.

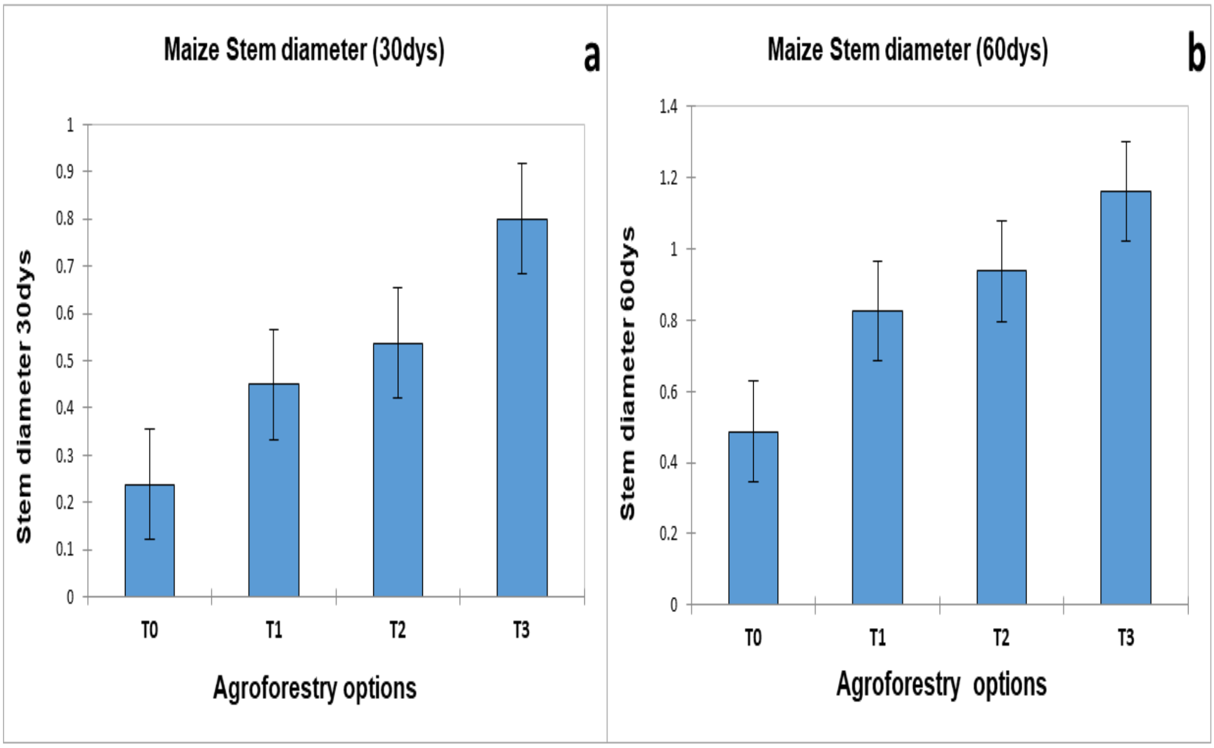

Figure 14: Stem diameter (Maize) 30 days and 60 days after sowing in the study area during rainy season 2023 and 2024

4.1.4.3 Sorghum Height (30 and 60 days after sowing)

Under Sorghum production, the agroforestry options used also highlighted a significant effect ($P<0.05$) on the plant height parameter at 30 and 60 days after planting (Figure 15 (**a**) and (**b**)). The assessment of the mean performance emphasized that the option T3 which is the combination of the two agroforestry tree outperformed the sole use of each of them. The three options performed better compared to the control.

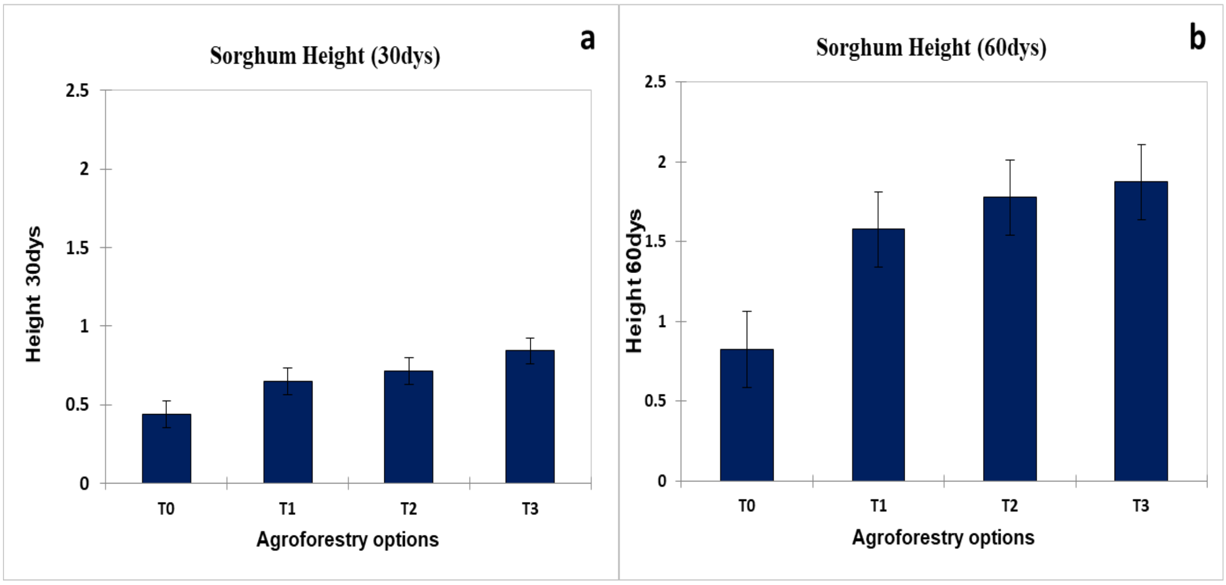

Figure 15: Height crops (Sorghum) 30 days and 60 days after sowing in the study area during rainy season 2023 and 2024

4.1.4.4 Sorghum stem diameter (30 and 60 days after sowing)

These agroforestry options also show a significant effect on the stem diameter of sorghum at 30 and 60 days after planting (Figure 16 (**a**) and (**b**)). The mean performance shows a greater value of the agroforestry options compared to the control.

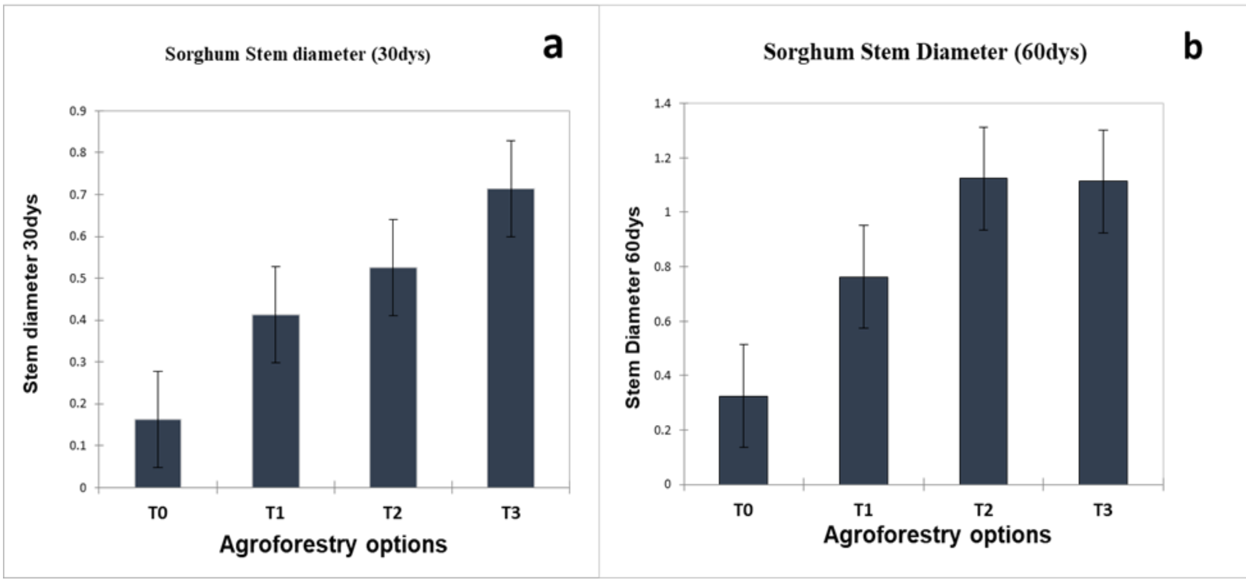

Figure 16: Sorghum stem diameter 30 days and 60 days after sowing in the study area during rainy season 2023 and 2024

4.1.4.5 Evaluate the effects of leaves biomass fresh of *Gliricidia sepium* and *Leucaena leucocephala* on maize and sorghum yields in an alley cropping system.

a) Effects of leaves biomass fresh of *Gliricidia sepium* and *Leucaena leucocephala* on maize yields in an alley cropping system.

The result shows an increase of maize yield with significant effect when using the agroforestry options for both experimental years (2023 and 2024) (Figure 17). All the agroforestry option performed better than the control for yield improvement.

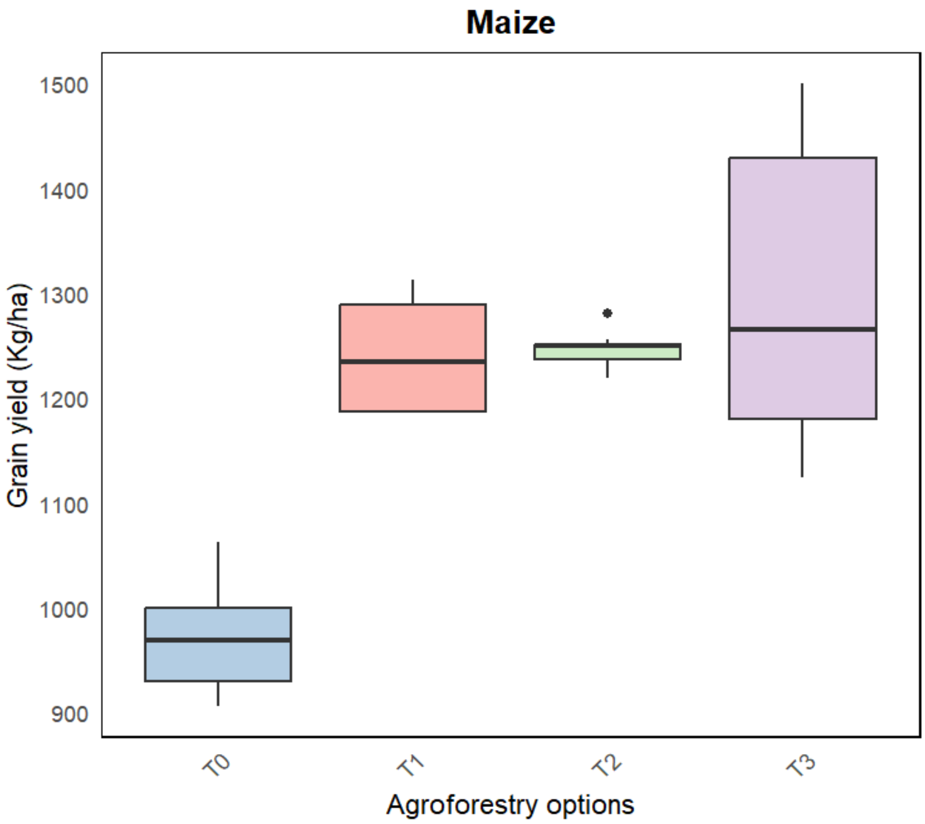

Figure 17: Maize grain yield in the study area during rainy season 2023 and 2024

b) Effects of leaves biomass fresh of *Gliricidia sepium* and *Leucaena leucocephala* on sorghum yields in an alley cropping system

The assessment of these agroforestry options on sorghum yield for both trial years (Figure 18) shows a significant effect (P<0.05). All these agroforestry options increase sorghum yield compared to the control.

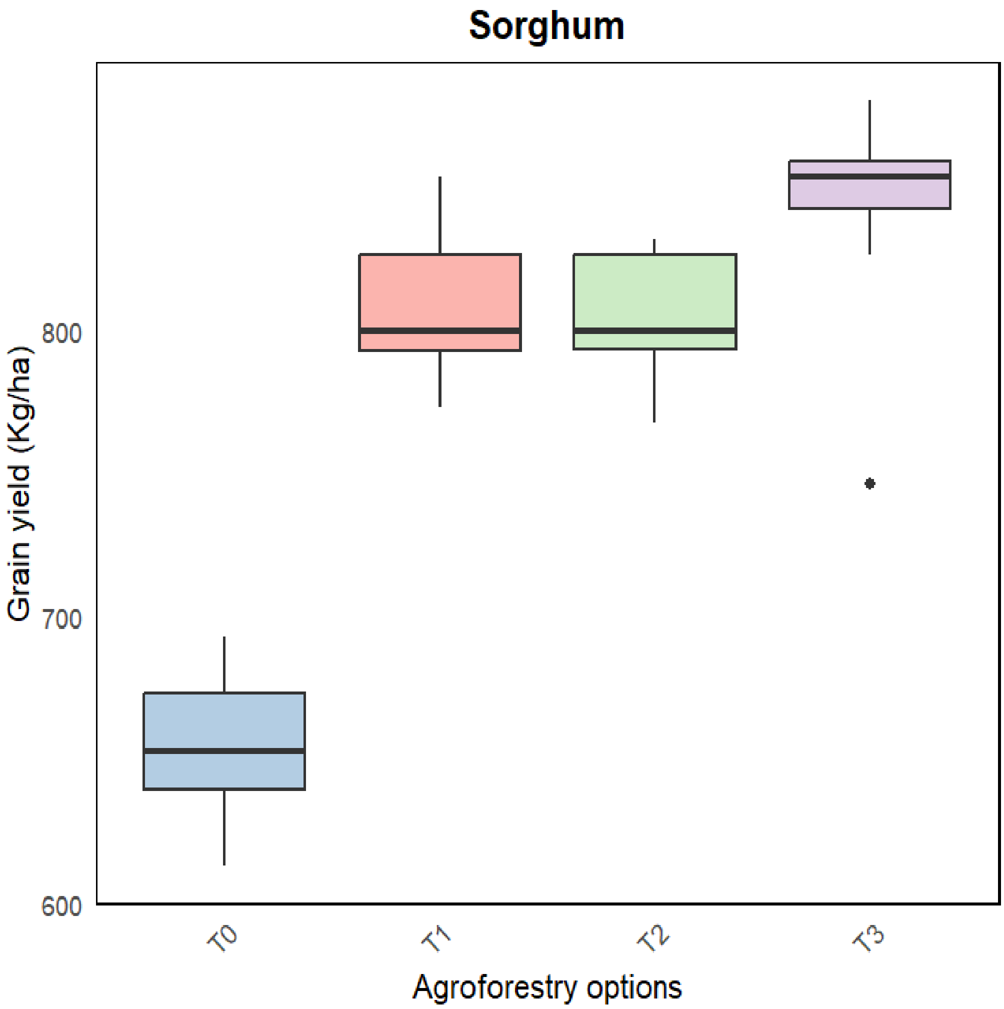

Figure 18: Sorghum grain yield in the study area during rainy season 2023 and 2024

c) Effects of leaves biomass fresh of *Gliricidia sepium* and *Leucaena leucocephala* on maize dried biomass yields in an alley cropping system.

Analysis of Figure 19 indicates that the control plot T0 had an estimated dried biomass of 4,553.867 kg/ha, whereas T1 and T2 recorded amounts of 5,835.854 kg/ha and 5,847.729 kg/ha, respectively. Additionally, T3 exhibited a dried biomass of 6,141.446 kg/ha. The agroforestry treatments (T1, T2, and T3) produced higher dried biomass compared to the control plot T0.

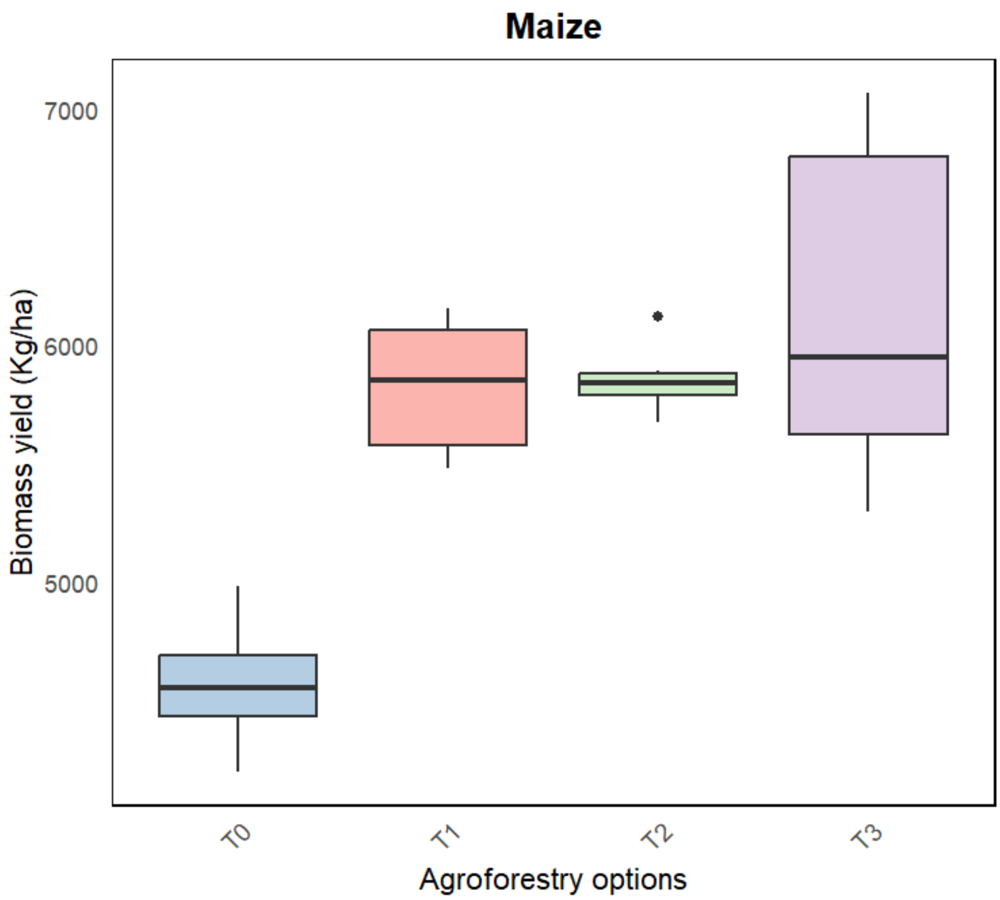

Figure 19: Maize biomass yield in the study area during rainy season 2023 and 2024

d) Effects of leaves biomass fresh of *Gliricidia sepium* and *Leucaena leucocephala* on sorghum dried biomass yields in an alley cropping system

Based on the analysis of Figure 20, the control plot T0 had an estimated dried biomass of 2,621.336 kg/ha. In contrast, T1 and T2 yielded 3,313.460 kg/ha and 3,222.336 kg/ha, respectively. T3 showed the highest dried biomass at 3,613.514 kg/ha. Overall, the agroforestry treatments (T1, T2, T3) resulted in greater dried biomass than the control plot T0.

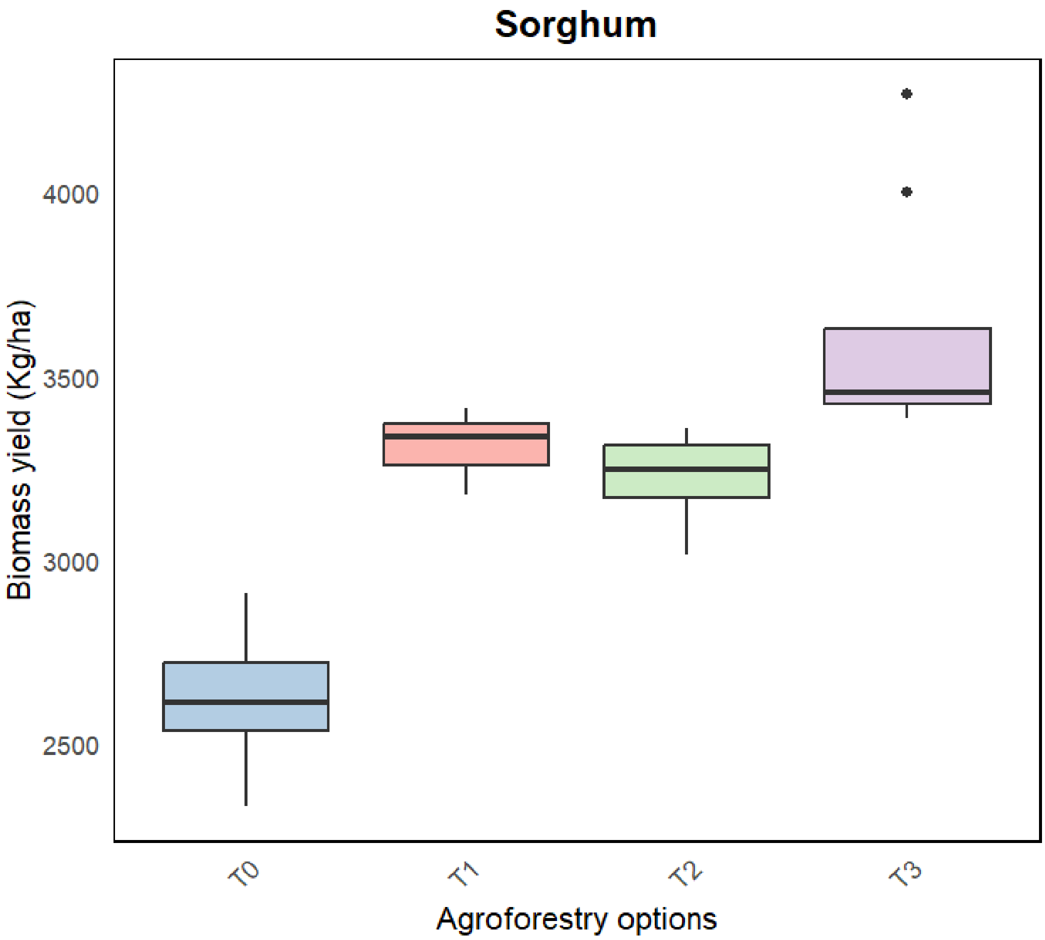

Figure 20: Sorghum biomass yield in the study area during rainy season 2023 and 2024

4.2 Discussion

4.2.1 Climate variability and change, and farmer's perception on agroforestry systems practice as climate adaptation option.

4.2.1.1 Climate variability and climate change in the study area.

Between 1984 and 2022, Bougouni experienced significant climate variability characterized by fluctuations in rainfall and temperature patterns. The analysis of the Standardized Precipitation Index (SPI) reveals distinct periods of both excess and deficit rainfall, reflecting the region's susceptibility to drought and wetter conditions.

The period saw episodes of above-average rainfall, notably in years like 2008 and 2022, indicating potential periods of abundance, while other years, such as 2004 and 2006, recorded below-average rainfall, highlighting drought risk. The SPI categorizes these years into non-drought, moderate drought, and severe drought periods. Severe drought years, notably in 1994, 2002, 2009, and 2017, experienced deficits of up to -300 mm, severely impacting agriculture and water resources.

Temperature analyses from 1984 to 2022 show a general increase, with maximum temperatures rising from around 33°C (1984-1999) to a peak of 36°C (1999-2009), before decreasing back to approximately 33°C (2009-2022). The mean and minimum temperatures followed similar patterns, increasing during the earlier period and stabilizing later. The difference trend between maximum and minimum temperatures is approximately 0.90°C, indicating a subtle yet significant warming trend that aligns with global climate change signals.

The observed variability underscores the impacts of climate change in Bougouni, with more frequent and intense droughts coupled with rising temperatures. Such trends threaten regional water security, agriculture, and livelihoods, emphasizing the need for adaptive strategies to mitigate climate-related risks. Continued monitoring and comprehensive climate resilience planning are essential for sustainable development in the face of ongoing climate change.

4.2.1.2 Farmers' perception on agroforestry as climate adaptation option.

The study reveals that several species are used in agroforestry systems, including *Vitelaria paradoxa*, *Mangifera indica*, *Anacardium occidentale*, *Moringa oleifera*, *Parkia biglobosa*, and *Adansonia digitata*. Their order of use reflects their ecological, economic, and cultural benefits in the study area (Dagar & Tewari, 2017).

Vitelaria paradoxa stands out as the most widely used specie. This is explained by its ability to provide quality wood, its beneficial agricultural properties (improvement of soil fertility), as well as its traditional medicinal uses. Its presence at the top of the list indicates its importance in diversifying agricultural systems and the sustainability of farms. This result confirms the study by (Yoshida et al., 2019) on the role of *Vitelaria* in an agroforestry system.

Mangifera indica is widely appreciated for its fruit, and this species plays a dual role: fruit production and providing shade or windbreak. Its presence at the top of the list indicates its importance in diversifying agricultural systems and the sustainability of farms (Lichtenberg et al., 2017)

Anacardium occidentale occupies a significant place due to its cashew nut, which constitutes an important source of income (Nair & Nair, 2021). In addition, its leaves and branches are used for fodder and organic amendment, illustrating the multifunctionality of this species in the agroforestry system (Dhyani et al., 2009)

Andasonia digitata is often present for its soil enrichment through nitrogen fixation, in addition to its nutritious fruits. Its importance also lies in its medicinal properties and artisanal uses, reinforcing the ethnobotanical dimension of this system (Leonti, 2011)

Moringa oleifera appears as a species with high nutritional and medicinal potential. Its rapid growth and numerous uses in food, phytotherapy, and soil improvement justify its frequent presence in these systems. These results confirm the study by (Mahaveerchand & Abdul Salam, 2024).

Finally, *Parkia biglobosa* is valued for its edible pods, protein-rich seeds, as well as its uses in local pharmacopoeia (Rao et al., 2004). Its ecological and economic roles make it a key species in agroforestry dynamics (Schroth et al., 2004; Depommier, 2003; Asase & Tetteh, 2010)

The order of use of these species reflects an integration of diverse uses: food production, soil improvement, income generation, and respect for traditional practices. The diversification of these species contributes to the resilience of agricultural systems in the face of climate change and socio-economic challenges.

a) Agroforestry advantages

Agroforestry practices offer a multitude of benefits that enhance the sustainability and productivity of farming systems. One of the primary advantages is the reduction of wind speed around fields, which helps minimize wind erosion and crop damage, thus protecting soil health (Nordstrom & Hotta, 2004). Additionally, the presence of trees helps increase soil moisture retention by reducing evaporation and promoting infiltration, which is particularly beneficial in semi-arid regions (Liao et al., 2021). Economically, agroforestry can increase farm income through diversified outputs such as timber, fruit, medicinal plants, and other forest products (Kassie, 2018). This diversification not only provides alternative revenue streams but also stabilizes income against market or climate fluctuations. Moreover, trees in agroforestry systems contribute to reduced soil erosion and runoff, decreasing sedimentation downstream, which is vital for maintaining water quality and stream integrity (Birla et al., 2024)

From an environmental perspective, agroforestry reduces the need for synthetic manure inputs by improving natural nutrient cycling, thanks to the organic matter added through leaf litter and roots. It also mitigates deforestation pressures by providing timber and fuelwood locally, decreasing the need to clear additional forest land (Kumar et al., 2022). The increased production of wood and other forest products supports rural livelihoods while conserving biodiversity.

Crop yields are often enhanced in agroforestry systems due to improved microclimates, better soil fertility, and pest regulation, thereby supporting food security (Fahad et al., 2022). Furthermore, agroforestry practices provide other benefits such as carbon sequestration, habitat creation, and climate regulation (Patel et al., 2023).

In summary, agroforestry systems contribute significantly to sustainable agriculture by improving ecological functions, increasing productivity, and reducing environmental degradation, making them a vital component of resilient farming landscapes.

b) Sustainable land management (SLM) technics

The result highlight the role of Sustainable land management (SLM) practices are in maintaining land productivity while conserving natural resources. Techniques such as crop rotation play a pivotal role in breaking pest and disease cycles, improving soil structure, and enhancing nutrient cycling, thus promoting long-term soil health (Duan et al., 2024). Incorporating fallow practices further aids in restoring soil fertility and organic matter, reducing land degradation and supporting regenerative ecosystems (Baruah, 2024).

Manure application, a cornerstone of organic farming, enriches the soil with essential nutrients, increases microbial activity, and improves soil physical properties, leading to higher crop yields and better resilience against erosion (Imran & Ortas, 2025). Growing leguminous crops as part of land management strategies adds the benefit of biological nitrogen fixation, reducing dependence on synthetic fertilizers and improving soil fertility naturally (Kebede, 2021)

Crop residue management also significantly contributes to sustainable land use by conserving soil moisture, suppressing weeds, and adding organic matter back into the soil, which enhances structural stability and nutrient content (Ranaivoson et al., 2017). Properly managing residues prevents soil erosion and promotes carbon sequestration, contributing to climate change mitigation efforts.

In general, these practices support environmental conservation, enhance agricultural productivity, and foster resilient farming systems, aligning with the principles of sustainable land management. Their integration ensures the sustainable use of land resources for current and future generations (Metternicht, 2018)

4.2.3 Effects of fresh leaves biomass in an alley cropping system with *Gliricidia sepium* and *Leuceana leucoceaphala* on soils physico-chemical properties

The findings indicates that the incorporation of fresh leaves biomass from alley cropping systems involving *Gliricidia sepium* and *Luecaena leucocephala* has been shown to enhance soil physico-chemical properties. These legumes are rich sources of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K), which are critical for crop growth and soil fertility (Giller et al., 2015).

Specifically, the addition of fresh leaf biomass increases soil nitrogen content through biological nitrogen fixation, thereby reducing the need for synthetic fertilizers (Sileshi et al., 2011). This process also contributes to elevated levels of organic carbon and organic matter, which improve soil structure, enhance water retention, and promote microbial activity (Lal, 2009). Studies have shown that soils under alley cropping with *Gliricidia* and *Leucaena* exhibit higher organic carbon and organic matter compared to control plots without biomass addition, indicating improved soil health and nutrient retention (Njenga et al., 2021).

Furthermore, the accumulation of organic matter from fresh leaves helps to buffer soil pH and enhance phosphorus availability, which often become limiting factors in degraded soils. The increased organic inputs also stimulate soil microbial populations, further facilitating nutrient cycling and soil enzyme activities (Giller et al., 2011).

Overall, the treatment plots receiving fresh leaves biomass demonstrated the most significant improvements in soil physico-chemical properties compared to control plots, confirming the beneficial role of leguminous shrub biomass in sustainable soil management and productivity enhancement.

4.2.4 Effects of leaves biomass fresh of *Gliricidia sepium* and *Leucaena leucocephala* on maize and sorghum growth, stem diameter and yield in an alley cropping system.

The result revealed that, the application of fresh leaves biomass from *Gliricidia sepium* and *Leucaena leucocephala* in alley cropping systems has shown to significantly enhance the growth parameters, stem diameter, and overall yield of maize and sorghum. The nutrient-rich biomass provides a readily available source of nitrogen and other essential nutrients, which stimulate vigorous plant development (Elka & Laekemariam, 2020).

Studies have demonstrated that maize and sorghum grown in treatments with fresh leguminous leaves display increased plant height and biomass accumulation compared to control plots, a result linked to improved soil fertility and nutrient availability (Nyuma et al., 2025).

Specifically, the fertilizers derived from *Gliricidia* and *Leucaena* enhance stem development, leading to thicker stems which support better anchorage and reduce lodging risk, positively affecting crop stability and harvest ability.

Moreover, the increased stem diameter in treated plots correlates with higher photosynthetic capacity and resource transport efficiency, culminating in greater grain and fodder yields (Kremer, 2021). Harvest data indicate that maize and sorghum in these treatment systems outperform controls in both grain weight and biomass yields, underscoring the productivity benefits of integrating *Gliricidia* and *Leucaena* biomass addition.

Overall, the superior growth, increased stem robustness, and higher yields in treated plots confirm the positive influence of *Gliricidia* and *Leucaena* fresh leaves biomass, supporting their role in sustainable agroforestry and improved crop performance.

CHAPTER FIVE: CONCLUSION AND PERSPECTIVES

5.1. Conclusions

The escalating impacts of climate variability and change have become undeniable in regions like Bougouni, Mali, where agriculture forms the backbone of livelihoods and food security. Climate models project rising temperatures and increasingly erratic rainfall patterns over West Africa, threatening agricultural productivity, ecosystem stability, and the socio-economic fabric of rural communities. Specifically, temperature trends have shown a consistent upward trajectory, intensifying heat stress on crops and livestock, and exacerbating drought frequency and severity. These climatic shifts have underscored the urgent need for adaptive agricultural practices that can buffer communities against climate shocks, maintain productivity, and secure sustainable livelihoods.

Farmers' perceptions of agroforestry practice advantages corroborate scientific findings about its potential to address climate challenges. Many farmers in Mafelé recognize agroforestry as a resilient land use system that promotes soil fertility, conserves water, and enhances crop yields under variable climatic conditions. Such perceptions are crucial, as local knowledge influences adoption rates and the sustainability of these practices. Empirical evidence indicates that agroforestry, especially systems integrating nitrogen-fixing trees like *Gliricidia sepium* and *Leucaena leucocephala*, offers material and ecological benefits reducing vulnerability to droughts, providing timber and fodder, and promoting biodiversity. These benefits align with global priorities outlined by the FAO (2017), emphasizing agroforestry's role in climate adaptation and mitigation.

Sustainable Land Management (SLM) techniques constitute a pivotal component of adaptive strategies for land degradation control. In Bougouni's context, practices such as contour farming, cover cropping, erosion control structures, and conservation tillage contribute significantly to soil protection, water retention, and nutrient cycling. These techniques help counteract the adverse effects of climate variability, improve land productivity, and ensure food security. Farmers' active engagement in SLM is often facilitated by extension services, policy incentives, and community-driven initiatives, emphasizing the importance of participatory approaches in fostering sustainable practices. Implementing these techniques not only conserves the fragile soils but also enhances farmers' resilience to climate risks.

Research conducted within alley cropping systems incorporating fresh biomass of *Gliricidia sepium* and *Leucaena leucocephala* has shown promising impacts on soil physico-chemical properties. These trees, through leaf biomass deposition, significantly increase organic matter, improve soil structure, and elevate the levels of essential nutrients such as nitrogen, phosphorus, and potassium. The organic matter contribution from fresh leaves enhances soil microbial activity, which is vital for nutrient cycling and plant health. These modifications create a more hospitable environment for crop roots, thereby reducing the dependency on chemical fertilizers and bolstering ecological sustainability.

The effects of leaf biomass on the yield, growth, and stem diameter of maize and sorghum in the alley cropping system further demonstrate agroforestry's agronomic benefits. Data indicate that the incorporation of *Gliricidia* and *Leucaena* leaf biomass leads to a marked increase in crop yields compared to monoculture systems. The nitrogen supplied by these trees enhances crop nutrient uptake, resulting in higher plant biomass and increased stem diameter, which correlates with better plant stability and resilience during stressful conditions. Studies show that maize and sorghum grown under such systems exhibit improved vigor, higher productivity, and greater stem robustness, essential traits for withstanding drought and high temperatures In the specific context of Mafelé village, these agroforestry practices provide locally adapted, economically feasible solutions to land degradation and climate-induced stress. They also promote a cyclical benefit: improved soil health leads to higher crop yields, which in turn incentivizes further adoption by farmers. This integrated approach aligns with the broader goals of sustainable development, emphasizing ecological integrity, economic viability, and social inclusiveness. The findings underscore the importance of combining climate-smart agriculture approaches like agroforestry with robust Sustainable Land Management techniques to build resilient agricultural systems. While the scientific evidence points to the benefits of integrating tree biomass into cropping systems, widespread adoption hinges on effective dissemination of knowledge, policy support, and addressing socio-cultural barriers. Governments and development agencies must prioritize capacity-building, provision of quality planting material, and establishing incentives that motivate farmers to transition toward climate-resilient practices.

Furthermore, ongoing research should focus on evaluating the long-term sustainability and scalability of integrated agroforestry systems under varying climatic scenarios. The role of local knowledge and community participation remains vital, ensuring that interventions are culturally acceptable and practically implementable. Additionally, integrating climate forecasting tools and early warning systems can allow farmers to optimize planting times and resource use, minimizing risks and maximizing benefits.

Finally, there is an urgent need for policy integration that supports agroforestry and SLM practices as part of national climate change adaptation strategies. Secure land tenure, access to financial services, and fair markets are critical enablers that can accelerate widespread adoption and ensure that smallholder farmers derive tangible benefits.

In sum, climate variability and change pose profound challenges to agriculture and land management in Bougouni, Mali. Rising temperatures and erratic rainfall threaten local livelihoods, but embracing agroforestry practices especially systems incorporating *Gliricidia sepium* and *Leucaena leucocephala* offers a promising pathway for enhancing resilience. Farmers' perceptions validate the ecological and economic advantages of these systems, reinforcing their potential as sustainable solutions for land restoration, soil fertility improvement, and crop productivity enhancement. When combined with Sustainable Land Management techniques, agroforestry can effectively combat land degradation, promote ecological balance, and increase climate resilience at the local level. Empirical evidence from field studies demonstrates that incorporating fresh biomass of *Gliricidia* and *Leucaena* into alley cropping systems improves soil physico-chemical properties, such as increased organic matter and nutrient content. These improvements translate into higher yields and better growth parameters for maize and sorghum, which are staple crops in the region. Importantly, these practices contribute to ecological sustainability and socio-economic development, offering a multifaceted approach to climate adaptation. The success of these interventions, however, depends on strengthening local capacity, fostering community participation, and developing supportive policies. Future research should continue to explore the long-term impacts, socio-economic viability, and scalability of agroforestry systems under changing climatic conditions. A holistic approach integrating scientific innovations, indigenous knowledge, and policy support is essential to building resilient, sustainable agricultural landscapes in Bougouni and beyond.

5.2. Perspectives

Based on the findings of this study, we recommend to.

Enhance Climate Resilience through Agroforestry

Encourage widespread adoption of agroforestry practices involving *Gliricidia sepium* and *Leucaena leucocephala*, which have proven effective in improving soil health, increasing crop yields, and mitigating the impacts of climate variability. This aligns with farmers' positive perceptions and can strengthen resilience to droughts and temperature fluctuations.

Encourage farmers to integrate drought-tolerant tree species such as *Leucaena* and *Gliricidia*, which can improve soil fertility, conserve water, and provide shade, thereby reducing the vulnerability of crops to climate variability.

Implement targeted training programs to educate farmers about the benefits of agroforestry systems, climate-smart practices, and sustainable land management. Demonstrating successful local examples can motivate wider adoption.

Create simple, context-specific agroforestry manuals that outline best practices for planting, maintaining, and managing trees in farming systems, emphasizing resilience against erratic rainfall and temperature fluctuations.

Facilitate access to quality seedlings, tools, and technical support through local cooperatives or government programs, ensuring farmers can effectively establish and maintain agroforestry systems.

Involve local leaders, women, and youth in planning and decision-making processes to foster community ownership. Encourage collective action to manage shared land resources sustainably.

Support farmers in integrating agroforestry into their traditional cropping systems with minimal disruption, demonstrating how trees can complement and improve overall farm productivity.

Advocate for policies that incentivize agroforestry adoption, such as subsidies, tax breaks, or payments for ecosystem services, to motivate farmers to invest in resilient land use practices.

Establish regular monitoring to evaluate the ecological and socio-economic benefits of agroforestry, allowing for adaptive management and highlighting success stories to encourage broader uptake.

By implementing these recommendations, Mafelé can effectively use agroforestry to build resilience against climate change, improve land productivity, and ensure sustainable livelihoods for local communities.

- **Promote Sustainable Land Management (SLM) Techniques.**

Support training and awareness programs for farmers on SLM techniques like alley cropping, contour farming, and organic soil amendments. These methods improve soil physico-chemical properties and support sustainable productivity under changing climatic conditions.

Encourage farmers to practice crop rotation and intercropping systems that enhance soil fertility, reduce pest and disease incidence, and improve overall land productivity. Incorporating legumes can naturally fix nitrogen and improve soil health.

Promote the use of simple physical structures such as contour ridges, stone barriers, and vegetative cover to prevent soil erosion. Planting cover crops during off-season periods can also protect the soil surface.

Integrate trees and shrubs into farming systems to stabilize the land, improve moisture retention, and diversify income sources. This aligns well with climate resilience objectives and reduces land degradation.

Train farmers on minimal tillage or conservation tillage practices to maintain soil structure, reduce erosion, and improve water retention. Use of organic mulches can also slow soil moisture evaporation.

Introduce simple water harvesting techniques such as runoff trenches, stone bunds, and small ponds to optimize water use during dry seasons and reduce the risk of runoff-induced land degradation.

Work with local authorities to clarify and secure land tenure rights, motivating farmers to invest in long-term land stewardship and sustainable management practices.

Establish local land management committees to coordinate sustainable practices, monitor land conditions, and ensure collective responsibility in land conservation efforts.

Provide ongoing training and technical support to farmers on SLM techniques. Use participatory approaches to incorporate local knowledge and improve acceptance and implementation.

Encourage practices and technologies that are affordable and adapted to local conditions, ensuring sustainability and scalability of land management efforts.

Advocate for policies that promote SLM adoption through subsidies, technical support, and recognition programs to motivate farmers and land users to adopt sustainable practices.

- **Integrate Leaf Biomass Utilization**

Encourage the use of fresh leaf biomass from *Gliricidia sepium* and *Leucaena leucocephala* as organic mulch or soil amendment to boost soil fertility and crop growth. Promote simple, cost-effective methods for collecting and applying biomass to enhance maize and sorghum yields, thereby improving farm income and food security. The sustainable management and utilization of leaf biomass in agroforestry systems present significant opportunities for enhancing agricultural productivity, addressing environmental challenges, and promoting socio-economic development. Among the numerous fast-growing and nitrogen-fixing tree species, *Gliricidia sepium* and *Leucaena leucocephala* stand out due to their high leaf biomass yield, adaptability to diverse agroclimatic conditions, and multiple uses in integrated farming systems. Recognizing their potential, it is essential to develop comprehensive strategies that harness leaf biomass from these species, turning it into practical solutions for farmers and land managers.

Gliricidia sepium and *Leucaena leucocephala* are renowned for their rich leaf biomass, which is high in proteins, minerals, and organic nutrients. When appropriately harvested and processed, their leaves can serve as high-quality fodder for livestock, thereby reducing reliance on commercial feeds and lowering feed costs. Moreover, their biomass can be directly incorporated into the soil as organic amendments, improving soil structure, enhancing microbial activity, and increasing nutrient availability. This dual role as fodder and organic fertilizer makes these species highly valuable in integrated crop-livestock systems.

In particular, leaf biomass can be used in mulching, composting, or as green manure. Mulching with leaf litter helps retain soil moisture, suppress weeds, and gradually release nutrients during decomposition, fostering healthier crop growth. Composting leaf biomass produces nutrient-rich organic matter that can significantly boost crop yields, especially in degraded or low-fertility soils often found in smallholder farms. Such practices align with principles of circular agriculture, minimizing external input reliance and promoting self-sufficiency.

Utilizing leaf biomass from *Gliricidia* and *Leucaena* contributes to climate change mitigation efforts. Their rapid growth and biomass accumulation enable carbon sequestration, while their leaf litter enhances soil organic carbon stocks. Incorporating these leaves into farming systems serves as a form of biological carbon capture, reducing net greenhouse gas emissions. Furthermore, the use of locally available biomass minimizes greenhouse gas emissions associated with transporting external inputs and reduces dependence on chemical fertilizers, whose production is often energy-intensive.

In diversified agroforestry landscapes, these species can act as windbreaks, erosion control agents, and shade providers, further enhancing landscape resilience. Harvesting leaf biomass in a sustainable manner promptly after maturity and with proper management ensures continued productivity without degrading the growth potential of the trees.

Implementing leaf biomass utilization from *Gliricidia* and *Leucaena* has social and economic implications. Farmers can generate additional income through the sale of fodder, organic matter, or compost derived from leaf biomass. In regions where access to mineral fertilizers is limited or expensive, this practice provides an affordable, locally sourced alternative to improve soil productivity and crop yields.

Environmentally, maximizing the use of leaf biomass reduces the need for chemical inputs, which are often associated with pollution, soil degradation, and biodiversity loss. It also promotes sustainable resource management by encouraging the harvesting of biomass in a way that maintains plant health and ecosystem balance.

To tap into the benefits offered by *Gliricidia* and *Leucaena*, several practical strategies must be adopted:

Selective Pruning and Harvesting**:** Regular pruning encourages new growth and optimizes leaf biomass production. Harvesting leaves during the optimal season increases nutrient content and decomposition rate.

Processing Techniques**:** Leaves can be chopped, dried, or fermented to improve storability and digestibility for fodder use. Composting leaves with other organic materials accelerates nutrient release and improves soil health.

Integrated Farming Models**:** Combining leaf biomass harvest with other farm activities—such as using leaf litter as mulch, incorporating it into compost, or supplementing livestock feed—creates a holistic system aimed at sustainability.

Knowledge Dissemination**:** Farmer training programs should emphasize the benefits of leaf biomass, proper harvesting techniques, and safe processing methods to maximize gains and minimize negative effects on tree health.

The integration of leaf biomass utilization from *Gliricidia sepium* and *Leucaena leucocephala* offers a promising pathway toward sustainable and resilient agroforestry and farming systems. Their leaves serve as a valuable resource for enhancing soil fertility, supplying livestock feed, and mitigating climate change impacts. Promoting practices that harness these biomass resources aligns with the goals of sustainable agriculture, environmental conservation, and rural livelihoods improvement. By embracing these strategies, farmers and land managers can foster more productive, sustainable, and environmentally friendly farming landscapes, driving positive change at local and global levels.

- **Strengthen Farmer Perceptions and Knowledge**

Engage farmers through participatory approaches to share knowledge on the benefits of agroforestry and biomass utilization. Recognize and incorporate their perceptions to foster higher adoption rates and ensure practices are contextually appropriate.

Empowering farmers with relevant knowledge and positively influencing their perceptions are crucial steps towards achieving sustainable agriculture. Farmers' perceptions directly impact their willingness to adopt new practices, technologies, or innovations especially those aimed at improving productivity, ensuring environmental protection, and adapting to climate change. Therefore, strengthening their understanding and perceptions is essential for the successful implementation of sustainable farming systems.

Farmers often hold deeply rooted perceptions shaped by cultural beliefs, traditional practices, past experiences, and observational learning. For example, some farmers might associate new technologies with risks or believe that traditional methods are more reliable. Recognizing these perceptions allows development practitioners to tailor interventions that address misconceptions, build confidence, and foster a positive outlook towards innovation.

One of the primary ways to strengthen farmer perceptions is through targeted education and training programs. These programs should be designed to improve awareness about sustainable practices such as agroforestry, organic farming, efficient water use, or integrated pest management. Workshops, demonstration plots, farmer field schools, and peer-to-peer learning platforms enable farmers to observe firsthand the benefits of adopting new practices. Visual and practical learning approaches are often more effective, especially when they incorporate local languages and culturally relevant examples.

Participatory approaches that involve farmers in decision-making foster a sense of ownership and trust. When farmers actively participate in designing trials or selecting practices, their perceptions of the interventions become more positive. They appreciate that their knowledge and experiences are valued, which in turn improves their openness to adopting innovations. Building trust is critical to overcoming resistance and promoting sustained behavioral change.

Demonstration trials and success stories are powerful tools to alter perceptions. When farmers see tangible benefits such as increased yields, improved soil health, or higher income they are more likely to perceive new practices as beneficial and worth adopting. Sharing testimonials from peer farmers who have successfully integrated sustainable methods helps reduce uncertainty and skepticism.

Ongoing technical support and feedback mechanisms are vital for reinforcing positive perceptions. Regular follow-ups, troubleshooting, and sharing new knowledge help farmers see continuous benefits, foster confidence, and maintain motivation. Peer groups or farmer clubs can serve as platforms for ongoing learning, experience sharing, and collective problem-solving.

Strengthening farmer perceptions and knowledge is fundamental to fostering sustainable agricultural practices. By combining education, participatory approaches, demonstrations, and ongoing support, stakeholders can positively influence farmers' attitudes, reduce resistance, and encourage widespread adoption of innovative, environmentally friendly farming techniques. This holistic approach ensures that development efforts are culturally sensitive, effective, and sustainable in the long term.

- **Support Policy and Institutional Frameworks**

Advocate for policies that promote agroforestry and sustainable land use, including subsidies, extension services, and access to seedlings of leguminous trees. Strengthening institutional support can facilitate wider implementation of resilient agricultural practices.

To foster widespread adoption of resilient and sustainable agricultural practices, it is essential to advocate for comprehensive policies that support agroforestry and sustainable land management. Effective policy frameworks can create an enabling environment for farmers, land managers, and rural communities to implement practices that enhance productivity, conserve natural resources, and adapt to climate change.

One of the key policy instruments is the provision of subsidies and financial incentives. These subsidies can reduce the initial costs associated with establishing agroforestry systems, such as purchasing leguminous seedlings, planting materials, or necessary tools. Financial support encourages farmers to experiment with and expand agroforestry practices, which often require upfront investments but deliver long-term ecological and economic benefits.

Extension services play a vital role in translating policy support into practice. Strengthening extension services ensures that farmers have access to technical knowledge, training, and advisory support. Effective extension programs can disseminate best practices for planting, maintaining, and managing agroforestry species like *Gliricidia sepium* and *Leucaena leucocephala*, promoting understanding of their benefits for soil fertility, fodder production, and climate resilience. Well-equipped extension systems foster community trust and facilitate knowledge exchange, making sustainable practices more accessible and acceptable.

In addition, access to seedlings of high-yielding, locally adapted leguminous trees is critical for scaling up agroforestry. Policies that support nursery development and seedling distribution networks can make these seedlings readily available to farmers, especially in underserved or remote areas. Facilitating access ensures that farmers can quickly adopt agroforestry systems without delay or prohibitive costs, accelerating widespread adoption.

Strengthening institutional support is fundamental for institutionalizing resilient agricultural practices. This includes creating or empowering agencies dedicated to land use planning, natural resource management, and climate adaptation. Robust institutions can coordinate efforts across different levels of governance, providing standardized guidelines, monitoring frameworks, and capacity-building initiatives. Institutional support also involves embedding agroforestry into national agricultural policies, land tenure systems, environmental regulations, and climate change strategies, ensuring alignment and long-term commitment.

Moreover, fostering multi-stakeholder partnerships among government agencies, research institutions, non-governmental organizations, and local communities enhances policy coherence and resource mobilization. When institutions support participatory approaches involving farmers and land users in policymaking, the resulting policies are more inclusive, practical, and sustainable. Advocating for supportive policies and strengthening institutional frameworks are integral to scaling up agroforestry and sustainable land use practices. Combining financial incentives, improved extension services, easy access to quality seedlings, and institutional backing can create a conducive environment for farmers to adopt practices that build climate resilience, improve livelihoods, and promote environmental conservation. These collective efforts contribute to transforming land management systems towards sustainability and resilience in the face of mounting environmental challenges.

- **Invest in Research and Monitoring**

Continue research on the long-term impacts of biomass applications and climate trends, and establish monitoring systems. This will help adapt practices to evolving climate conditions and optimize agroforestry systems for maximum benefits.

To ensure that agroforestry and biomass application practices remain effective and sustainable under changing environmental conditions, it is essential to invest in ongoing research focused on the long-term impacts of these interventions. As climate variability continues to intensify, understanding how biomass usage affects soil health, carbon sequestration, biodiversity, and overall ecosystem resilience over extended periods becomes critical. Long-term studies can reveal trends, benefits, and potential unintended consequences, providing valuable insights for refining and adapting practices.

In addition to research, establishing comprehensive monitoring systems is vital. Such systems enable the collection of real-time data on key indicators, including soil moisture, fertility levels, biomass productivity, climate variables, and crop yields. Monitoring enables stakeholders to track the performance of agroforestry systems over time, assess their resilience against climate shocks, and identify early signs of system degradation or opportunities for enhancement.

An integrated monitoring framework combines remote sensing technologies, Geographic Information Systems (GIS), and community-based participatory monitoring approaches.

Remote sensing allows for large-scale surveillance of land-use changes, vegetation health, and biomass growth, while local knowledge and participatory monitoring involve farmers and community members in tracking on-ground conditions. This combination ensures data accuracy, enhances local engagement, and fosters a culture of adaptive management.

By systematically analyzing data collected through these systems, policymakers, researchers, and practitioners can adapt management practices to evolving climate conditions. For instance, if monitoring reveals declining soil fertility or increased drought frequency, adjustments such as diversifying tree species, modifying planting densities, or integrating water conservation techniques can be implemented promptly.

Furthermore, ongoing research and monitoring support the optimization of agroforestry systems to maximize environmental, economic, and social benefits. The data collected can inform best practices tailored to specific regions, climate scenarios, and local needs. This adaptive approach ensures that agroforestry remains a resilient land management strategy capable of delivering sustained benefits amidst changing climate dynamics.

Continuous research on long-term impacts combined with the establishment of dynamic monitoring systems forms the backbone of adaptive agroforestry management. These efforts enable stakeholders to make informed decisions, improve resilience, and ensure the overall sustainability of agroforestry systems in the face of climate variability and environmental uncertainties.

- **Climate Data and Early Warning Systems**

Develop and disseminate localized climate and weather forecasts to help farmers make timely decisions regarding planting, biomass application, and risk management.

Access to accurate, timely, and localized climate and weather forecasts is essential for enabling farmers to make informed decisions that maximize productivity and minimize risks associated with climate variability. Developing tailored forecasts that reflect specific local conditions such as microclimates, soil types, and cropping systems can significantly enhance farmers' ability to plan critical activities like planting, biomass application, and risk management strategies.

To achieve this, research institutions, meteorological agencies, and extension services must collaborate to develop region-specific climate models that incorporate local environmental data. These models should generate short-term, seasonal, and long-term weather forecasts with high spatial resolution, capturing variability within small farming communities. For example, knowing the probability of early or late rains, drought periods, or frost events allows farmers to time their planting to optimize growth conditions and avoid losses.

Dissemination of these forecasts should leverage multiple communication channels suited to farmers' contexts such as community radio, mobile phone alerts, SMS services, local meetings, or visual aids. It is crucial that information is delivered in accessible language, culturally appropriate formats, and at times aligned with peak decision-making periods. For instance, providing weekly or bi-weekly forecasts during critical seasons can help farmers plan the application of biomass, irrigation, fertilization, or pest control interventions.

Additionally, extension services need to be strengthened to interpret and contextualize forecast information, translating meteorological data into actionable advice. Extension officers can facilitate training sessions to help farmers understand forecast uncertainties and develop contingency plans for adverse weather events. Such support increases farmers' confidence and promotes adaptive behaviors that enhance resilience.

Integrating climate and weather forecasts into existing farmer networks fosters community-level planning and coordination. Farmers can share experiences, pool resources, and implement collective risk mitigation strategies based on reliable predictions. Moreover, continuous feedback from farmers using these forecasts can improve their accuracy and relevance over time.

Overall, developing and disseminating localized climate and weather forecasts is a strategic investment in climate-smart agriculture. It empowers farmers with timely information, supports proactive decision-making, reduces vulnerability to climate shocks, and ultimately contributes to sustainable land use, improved livelihoods, and resilient agricultural systems.

These recommendations aim to leverage proven agroforestry practices and SLM techniques to bolster resilience against climate change, improve soil health, and increase agricultural productivity in Bougouni. Implementation should involve close collaboration among farmers, researchers, extension agents, and policymakers for sustainable impact.

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ANNEX (S)

Annex I: Publications, conferences and workshop

Conferences.

Climate situation and measure of sustainable land management with agroforestry system, adoption and benefits perceived by farmers: Case of the Mafele village, Bougouni region in Mali at World Climate Research Programme (WCRP), RWANDA, Kigaly) (Poster presented)

Climate situation, soil fertility improves with *Gliricidia sepium* and *Leuceana leucocephala*, measure of sustainable land management with agroforestry system: Case of the Mafele village, Bougouni region in Mali at Malian Society of Applied Sciences (MSAS), Kabala University in Mali. (Presented)

Publications

Climate situation and measure of sustainable land management with agroforestry system, adoption and benefits perceived by farmers: Case of the Mafele village, Bougouni region in Mali.

Authors, Adama Tama TRAORE1, Dr. Kalifa TRAORE1, Dr. Hady DIALLO1 and Pr. Souleymane DIALLO1

(Int J Res Adv Agri Sci, 2(1): 74-93.https://ijraas.com)

Soil fertility restoration and sustainable land management using agroforestry in the Bougouni region: The case of the village of Mafele**.**

Authors, Adama Tama TRAORE1, Dr. Kalifa TRAORE1, Dr. Hady DIALLO1 and Pr. Souleymane DIALLO1. (*Accepted for publication*) on (AJAES). msasmali.org

Workshop

Clean Alternative Solutions to the Inefficient Cooking-Fuel used in Malian Kitchens (C COOK-Mali)

Réduction des risques de sécheresse dans la GIRE (Cap-Net)

Clean Alternative Solutions to the Inefficient Cooking-Fuel used in Malian Kitchens (C COOK-Mali)

Expert-Lab Technologie.

Annex II: Survey conducted

Annex III: Field work

Annex IV: Bag with biomass fresh of gliricidia and leuceana.

Annex V: Weight operation of biomass fresh

Annex VI: Burying operation

Annex VII: Field crop (maize)

Annex VIII: Crop harvested (maize)

Annex IX: Field crop (sorghum)

Annex X: Some plants species encountered in Mafele village.

Gender	Species	Vernacular name (Bambara)
Vitellaria	*paradoxa*	Chii
Parkia	*biglobosa*	Néré
Adasonia	*digitata*	Zira
Moringa	*oleifera*	Bassiyirini
Anacardium	*occidental*	Sômô
Ziziphus	*mauritiana*	N'tômônô
Mangifera	*indica*	Mangoro
Balanites	*aegyptiaka*	Zèkènè
Prosopis	*africana*	Guélé
Pterocarpus	*erinaceus*	Guenou
Afzelia	*africana*	Lingué
Lannea	*acida*	Bembe
Tamarindus	*indica*	N'tomi
Afromosia	*laxiflora*	Kolo kolo
Piliostigma	*reticulatum*	Niamani
Senna	*siamea*	Mali yirini
Lophira	*lanceolata*	Mana
Jatropha	*curcas*	Bagani
Isoberlinia	*doka*	Chô
Entenda	*abysinica*	Jimbi-jamba
Danelia	*oliveri*	Sanan
Cola	*cordifolia*	N'tabanôgô
Cussonia	*arborea(djalonensis)*	Bolokourouni
Bombax	*costatum*	Boumbou
Burkea	*africana*	Siri

Annex XI: Soil sample analysis 2023

Soil sample	Granulometry				PH water	PHKCL	Nitrogen %	Carbon %	Organic matter %	Phosphorus (P) mg/kg	Potassium (K) mg/kg
	%A	%LT	%ST	Texture class							
S					4.92	4.05	0.02	0.2	0.4	7.860171	10.11
S+L+G					6.62	6.66	0.03	0.6	1.0	3.724112	17.64
S+G	9.79	38.76	51.450	Loamy-sandy texture	6.96	6.77	0.04	0.5	0.9	3.074544	16.20
S+L					5.99	5.81	0.03	0.6	1.1	7.953033	12.99

S = Soil (Sample)

S+L+G = Soil+Leuceana+Gliricidia

S+G = Soil+Gliricidia

S+L = Soil+Leuceana

Annex XII: Soil sample analysis 2024

Soil sample	Granulometry				PH water	PHKCL	Nitrogen %	Carbon %	Organic matter %	Phosphorus (P) mg/kg	Potassium (K) mg/kg
	%A	%LT	%ST	Texture class							
S					4.97	4.08	0.03	0.3	0.5	7.860191	10.18
S+L+G					6.78	6.71	0.04	0.7	1.14	3.724152	17.74
S+G	8.79	39.76	52.450	Loamy-sandy texture	6.96	6.82	0.06	0.6	1.0	3.074564	16.37
S+L					6.12	5.87	0.04	0.8	1.2	7.953043	13.39

S = Soil (Sample)

S+L+G = Soil+Leuceana+Gliricidia

S+G = Soil+Gliricidia

S+L = Soil+Leuceana