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Validating methods for estimating carbon sequestration and potential of *Vitellaria paradoxa* c.f. Gaertn. in delivering ecosystem services from parkland systems in southern Mali, West Africa

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DEDICATION

This work is dedicated to my wife, Bintou Dembele and to all those who have supported me in the hardest times. This is for you!

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PREFACE

Mali is one of the least developed countries reported to be more vulnerable to climate variability and change especially for people who are living in rural areas like farmers. Indeed, rural farmers rely for their living on rainfed agriculture complemented by products from the natural resources both of them being among the most affected by climate change. As a consequence, they are no longer able to deliver good yields in crop products and ecosystem services to sustain the livelihoods of rural people. Such under-performance is mainly due to recurrent droughts, one of the most prominent climate change effect in the Sahel region, leading to increase rural poverty, food insecurity, land and ecosystem degradation including the most widespread production systems which are the parklands. In these mixed systems (tree-crop-livestock), even the less vulnerable component which is the tree is also showing some signs of decline. Such signs are more visible on the most dominant tree species, which is shea butter tree (*Vitellaria paradoxa*), jeopardizing its delivery of ecosystem services. In the context of erratic rainfall these ecosystem services play an important buffering role at the production stage through the micro-climate modification (less evaporation and more soil moisture, reduced soil temperature, etc.) as well as through the provision of food products in case of crop failure and during the period of food shortage (June-September).

Despite the severity of the impacts of climate change on the ecosystems and agro-ecosystems, it remains less documented in Mali in general and particularly in southern Mali. Hence, the importance of the present study which was undertaken to provide insight on the impacts of climate change on the delivery of ecosystem services by the most dominant species (*V. paradoxa*) of the most widespread production systems (parklands) in southern Mali. And ultimately, how all this affects human well-being. Thus, our focus was put on validating methods to assess the potential of carbon stocks and the growth relationship of *V. paradoxa* with climate change as well as with the delivery of the ecosystem services. In addition the present study explored more broadly the strategies adopted by farmers to deal with the climate change in southern Mali.

ABSTRACT

Vitellaria paradoxa is an indigenous tree species endemic to the African savannas. This species plays an important role in farmer's mitigation and adaptation to climate change through its ecosystem services. Unfortunately, the species is declining in the Sahel including southern Mali because of its sensitiveness to recurrent drought due to climate change. Understanding the underlining processes of such decline and their consequences on the livelihoods of the rural farmers requires the development of appropriate methods and approaches. Therefore our study aimed at validating methods for estimating carbon sequestration and evaluating the potential of *V. paradoxa* in delivering ecosystem services for the well-being of the population in southern Mali. But before we attempted to elucidate farmers' perception of climate change and their coping measures. Our findings revealed a range of coping measures used by farmers to adapt to climate change effects including the use of improved drought-tolerant crop varieties, diversification of crops, off-farm activities and seasonal migration. The contribution of *V. paradoxa* in annual gross income of rural households ranged from 4% in Koutiala (northern site) to 8% in Yanfolila (southern site). This seems to indicate an increase of the importance of this species in relation to increase rainfall and increase density of *V. paradoxa* going from the north to the south of Mali. Methods testing revealed that agent based could be used for *V. paradoxa* yield dynamics assessment in one hand and in another hand that fractal branch analysis (FBA) could be used for the above and belowground biomass and carbon estimation of this species. The aboveground carbon stock in Koutiala (2.16±0.44 Mg C ha^{-1}) by shea trees was not significantly different from that of Yanfolila (3.21±0.60 Mg C ha^{-1}). Similar trend was observed for the belowground carbon stocks between sites. This study indicated the risk of overestimating the biomass using generic model as all values of b were below 2.67. Furthermore, it clearly indicated that dendrochronology can be applied to study the impact of climate change on the growth of *V. paradoxa.*

Keywords: Allometric equations, coping strategy, rainfall distribution, tree-rings, vulnerability

RESUME

Vitellaria paradoxa est un arbre endémique des savanes africaines. Cette espèce joue un rôle important dans l'atténuation et dans l'adaptation des agriculteurs au changement climatique à travers ses services écosystémiques. Malheureusement, l'espèce est en déclin dans le Sahel, surtout dans le sud du Mali, en raison de sa sensibilité aux sécheresses récurrentes dues aux changements climatiques. La compréhension des processus qui induisent ce déclin et leurs conséquences sur les moyens de subsistance des agriculteurs ruraux exige l'élaboration d'approches et de méthodes appropriées. C'est pourquoi notre étude vise à valider les méthodes d'estimation de la séquestration du carbone et l'évaluation du potentiel de *V. paradoxa* dans la provision des services écosystémiques pour le bien-être de la population dans le sud du Mali. Mais avant cela, nous avons tenté d'élucider la perception paysanne du changement climatique et leurs mesures d'adaptation. Nos résultats ont révélé une série de mesures utilisées par les agriculteurs pour s'adapter aux effets du changement climatique incluant, l'utilisation de variétés améliorées résistantes à la sécheresse, la diversification des cultures, les activités non agricoles et la migration saisonnière. La contribution de *V. paradoxa* dans le revenu brut annuel des ménages ruraux varie de 4% à Koutiala (site du Nord) à 8% à Yanfolila (site du sud). Cela semble indiquer une augmentation de l'importance de cette espèce proportionnellement à celle des précipitations et à la densité allant du nord au sud du Mali. Le test des méthodes a révélé que le modèle « agent-based » pourrait être utilisé pour l'estimation de la dynamique du rendement de *V. paradoxa* d'une part et, d'autre part que l'analyse fractale de branche (FBA) pourrait être employée pour l'estimation de la biomasse et du carbone aérien et souterrain de cette espèce. Le stock de carbone aérien du karité à Koutiala (2.16±0.44 Mg C ha^{-1}) n'était pas significativement différent de celui de Yanfolila (3.21±0.60 Mg C ha^{-1}). Une tendance similaire a été observée pour les stocks de carbone souterrains entre des deux sites. Cette étude a montré un risque de surestimation de la biomasse en utilisant le modèle générique, vu que toutes les valeurs de b étaient en dessous de 2.67. En plus, elle a permis de démontrer que la dendrochronologie peut être appliquée á l'étude de l'impact des changements climatiques sur la croissance de *V. paradoxa*.

Mots clés: Cernes, distribution des précipitations, équations allométriques, stratégie d'adaptation, vulnérabilité

Table of Contents

ABBREVIATIONS AND ACRONYMS

ABM: Agent- Based Model

AGB: Aboveground Biomass

ANOVA: Analysis of Variance

BGB: Belowground Biomass

C: Carbon

CO_2: Carbon Dioxide

CSA: Cross-Sectional Area

DBH: Diameter at Breast Height

DRSI: Direction Régionale de la Statistique et de l'Informatique

EPS: Expressed Population Signal

FBA: Functional Branching Analysis

FCFA: Franc de la Communauté Financière Africaine

FMNR: Farmer' Managed Natural Regeneration

GIS: Geographic Information System

GLK: Coefficient of parallel variation between tree-ring series

H: Height

ICRAF: World Agroforestry Centre

IIA: Independence of Irrelevant Alternatives

KCA: K-means Cluster Analysis

LSD: Least Significant Difference

LUDAS: Land-Use Dynamic Simulator

MDGs: Millennium Development Goals

MEA: Millennium Ecosystem Assessment

Mg:	Mega gram
MNL:	Multinomial logistic
MS:	Mean Sensitivity
N:	North
NAPAs:	National Adaptation Programmes of Action
P:	Probability
PCA:	Principal Component Analysis
R:	Root
REDD:	Reducing Emissions from Deforestation and Forest Degradation
S:	Shoot
SE:	Standard Error
SEE:	Standard Error of the Estimate
SD:	Standard Deviation
SDG:	Sustainable Development Goals
SPSS:	Statistical Package for the Social Sciences
TISAP:	Times Series Analysis and Presentation
USD:	United States Dollars
W:	West
WASCAL:	West African Science Service Center on Climate Change and Adapted Land Use

LIST OF FIGURES AND ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

Climate change, one of the main environmental concerns caused by the rising levels of carbon dioxide (CO_2) in the atmosphere and other greenhouse gases, threatens the survival of humans and ecosystems in the world (**Kumar *et al.* 2011; Bennett *et al*. 2015**). The consequences are already visible in many areas of the tropics and temperate regions (**Kandji *et al*. 2006; Remoundou *et al*. 2015**). For instance, since the past three decades, West Africa has experienced perpetual drought (**Nicholson *et al.* 2000; Hulme *et al*. 2001; Leighton 2011**) whilst the Caribbean has lost nearly 30% of its coral reefs (**World Bank 2008)**. Recorded projected impact by **Unitar (2012)** has shown that 10-15% of sub-Saharan ecosystem would be at risk of extinction if global mean temperatures increase by 2°C in 2050. In the tropics, forest conversion contributes as much as 25% of net annual CO_2 release globally (**Federici *et al*. 2015**). In spite of the conversions, several forest ecosystems play a crucial role in the global climate maintenance by reducing CO_2 levels in the atmosphere. In addition to the remaining forests, there are places in world where the farming systems are mixed including a combination of trees and crops on the same piece of land called agroforestry. Agroforestry systems are diverse in their arrangement and species composition. The most widespread agroforestry system in West African Sahel is the parkland system in which trees are preserved from the natural vegetation when clearing the bush to make a field (**Boffa 1999**). Thus, agroforestry parkland was defined as a land use system in which trees and shrubs are grown in association with crops or animals in the same land unit **(Nair 2001; Jama *et al*. 2006; Vinceti *et al*. 2013; Bayala *et al*. 2015).** Because of their perennial tree component, agroforestry parkland ecosystems have been reported to have high carbon sequestration potentials than treeless farming systems **(Nair *et al*. 2009; Luedeling and Neufeldt 2012; De Zoysa and Inoue 2014; Tubiello *et al*. 2015)**. Therefore, agro-ecosystems like agroforestry systems because of their multipurpose nature play an important role in meeting four of the seventeen sustainable development goals (SDGs) through provision of a range of ecosystems services to: 1. end poverty, 2. end hunger, 3. insure well-being and 4. stop climate change. The mitigation aspect of the last mentioned SDG (stop climate change) involves carbon sequestration for which there are some methodological limitations in estimating its sequestered quantity by the above-mentioned farming systems. As a consequence, there are very few studies reporting carbon (C) sequestration potential of agroforestry systems in semi-arid and arid regions (**Peltier *et al*. 2007; Takimoto *et al*. 2008; Luedeling and Neufeldt 2012; Saidou *et al*. 2012**). Assessment of the contribution of such systems to carbon sequestration is important to support the efforts being made in order to stop land degradation and reduce rural poverty.

In the Sahel, apart from the economic services, agroforestry parkland systems provide numerous environmental services to rural population (**Boffa 1999; Kalinganire *et al*. 2008; Jose 2009; Faye *et al*. 2010; Bayala *et al*. 2014**). For instance, they are sources of foods, including fruits, fats, oils, leafy vegetables, nuts and condiments that complement the diet. They also increase soil carbon content leading to better soil fertility and higher soil water and nutrient holding capacity (**Bayala *et al*. 2014**). The provision of these services is threatened as farmers in the Sahel are confronted to deteriorating climatic conditions (**Luedeling and Neufeldt 2012; Traore *et al*. 2015**). One of the way such deteriorating conditions manifest themselves is through reduced tree cover in landscapes including the agro-ecosystems because of the decreasing rainfall **(Maranz 2009; Gonzalez *et al*. 2012)**. Yet, the decrease in rainfall is known to affect the carbon storage potential of the agro-ecosystems together with high temperatures (**Batjes 2001; Takimoto *et al.* 2008**). Besides the impacts of climatic conditions, human action through wood collection also contributes to the reduction in carbon stocks.

As for the Sahel, Mali, a landlocked country (located on the southern edge of the Saharan desert), is dominated by the traditional agroforestry parkland systems. The agroforestry parklands (AP) occupy approximately 90% of the agricultural land (**Boffa 2000**). These parklands are managed to fit environmental conditions (mitigate climate change) and also fulfil specific functions such as the diversification production of the croplands. The density of woody species within the parkland is generally low as well as species composition. This implies that there is a decrease in both richness and abundance of trees and shrubs (**FAO 2000; Kalinganire *et al*. 2008**). The most dominant parkland species in the country are: Shea tree (*Vitellaria paradoxa* CF.Gaertn. Sapotaceae*)*, baobab (*Adansonia digitata* L: Bombacaceae), locust bean (*Parkia biglobosa* (Jacq.) Benth: Mimosaceae) and *Faidherbia albida* (Del.) A. Chev (syn. *Acacia albida*: Mimosoideae). They are the most preferred by farmers due to their potential economical values (**Teklehaimanot 2004; Faye *et al*. 2010**). Mali, as other Sahelian countries, is vulnerable to climate change due to its strong dependence on natural resources and subsistence rainfed agriculture. For instance **Butt *et al*. (2003)** reported that by the year 2030, Malian average temperatures may increase from 1 ^{0}C to 2.75 ^{0}C, with precipitations declining slightly. This trend has also an impact on the carbon sequestration potential in agroforestry parklands.

In southern Mali, where land availability is less constrained compared to the rest of the country, cropping phase years are followed by fallows to restore soil fertility (**Kater *et al*. 1992; Kessler 1992**). The crops (cotton, maize, millet, sorghum, etc.) are grown during the rainy season under scattered trees of traditional parklands making the systems resilient under increasing climate variability. These parkland systems are generally dominated by two species known as shea tree (*Vitellaria paradoxa*) and Locust bean (*Parkia biglobosa*) as reported by **Kindt *et al*. (2008)** Similarly to the whole system, these two main species are also under threat (**Gonzalez *et al*. 2012**) despite the fact shea tree is protected by forest code of Mali, which obliges farmers to retain trees of this species when clearing land for cultivation. **Kelly *et al*. (2004)** reported that the mean density of shea tree ranged from 16 ha^{-1} in parklands to 68 ha^{-1} in fallows in the southern Mali. Tree cover has been declining in parklands in the last four decades due to the species density reduction by human actions and drought (**Boffa 2000; Maranz 2009**) in a context of a likely continuous decrease of the precipitations according to **Meehl *et al.* (2007)**.

Southern Mali is also characterized by several land uses such as parklands, fallow and protected area. Besides developing and validating carbon assessment methods, the approaches must consider the different land uses above-mentioned as these will affect the carbon sequestration potential of trees, especially *V. paradoxa*. However, data on carbon sequestration potential in aboveground and belowground compartments of trees is scarce. Furthermore, no study has compared these land-use types (parkland agroforestry, fallow and protected area) to see what extent their carbon sequestration capacity differs. Many studies were carried out in the southern Mali on various aspects on shea tree like the species' impact on associated crops (**Kater *et al.* 1992**), spatial distribution (**Maranz *et al*. 2004a**), impact of human practices on its ecology **(Kelly *et al*. 2004)**, phenotypes (**Sanou *et al*. 2006**) and phenology (**Kelly *et al*. 2007**). However, none of these studies were about exploring shea tree yield dynamics and assessing its carbon stocks. Therefore, it is necessary to understand the shea tree yield dynamics in agroforestry parkland systems. Furthermore, generic allometric equations are still being used leading to an uncertainty in estimation of tree carbon and therefore calling for the development of species-specific equation.

Given the above-evoked climate variability, there is also a need to evaluate how this impact the amount of carbon stocked. This study, therefore, focuses on the potential of shea tree for carbon sequestration in parklands because these systems have been recognized as one of the most significant adaptation strategies to climate change in the Sahel (**Albrecht and Kandji 2003; Montagnini and Nair 2004**). The study also looks beyond carbon per se and investigate how other products and services provided by this species affect the livelihoods of rural people who nurture it in their farming systems.

- **General objective**

The general objective of the research is to validate methods for evaluating carbon potential of *Vitellaria paradoxa* and assess how the services provided by this species affect the livelihoods of rural people in southern Mali.

- **Specific objectives**

The specific objectives are:

1. To analyse farmers' perceptions of climate change impacts on ecosystem services provide by the parklands;
2. To assess the shea tree yield dynamics in agroforestry parklands systems using farmers survey and Agent-based simulation approach;
3. To develop site-specific allometric equations for shea tree for the estimation of above and belowground carbon stocks using the functional branch analysis;
4. To test the potential of dendrochronology in assessing carbon sequestration rates of *Vitellaria paradoxa* under changing climate.

- **Research questions**

To address the issues mentioned for this study, four research questions are raised:

1. What are farmer's perceptions of the impact of climate change on ecosystem services provide by the parklands?
2. Do the distribution and amount of rainfall have an influence on shea tree yield dynamics in agroforestry parkland systems?
3. Is fractal branch analysis appropriate for developing allometric equations that improve the estimation of above and belowground biomass of shea tree?
4. How climate variability affects the carbon sequestration rates of shea under two different environmental conditions?

Hypotheses

The hypotheses of this work are presented as follow:

1. Farmers perceive climate change impacts on ecosystem services provide by the parklands;
2. Agent-based simulation approach can be used to simulate the shea tree yield dynamics in agroforestry parklands systems;
3. Fractal branch analysis is appropriate for developing allometric equations that improve the estimation of above and belowground biomass of shea tree;
4. Dendrochronology is a good tool to study climate-growth relationships and to estimate carbon sequestration.

Outline of the thesis

The thesis consists of four main chapters, besides the general **introduction and conclusion, recommendations and perspectives.** The first chapter is based on **literature review** relevant to the topic. In this section, we described from the literature the agroforestry parklands and their socio-ecological importance, what are their links with climate change are and how farmers perceived climate change impacts on these farming systems. To end this section, we explored four main gaps from the literature which were the focus of our study. The second chapter of the thesis developed the **materials and methods**. It described the studied species, the study areas and how the research was done (implemented) to fill in the gaps. The third chapter presents the **results**. The results consist of four main subsections according to the gaps. The first subsection provided insight on farmers' perceptions of climate change impacts on ecosystem delivery of parklands while the second subsection highlighted the shea tree yield dynamics over agroforestry parklands. The third subsection provided carbon stocks estimation with site-specific allometric equation for shea tree. The fourth and last subsection of the results treated the potential of dendrochronology to assess the impact of climate change on the growth of shea tree. The fourth and final chapter is about the **discussions**. In this section, we discussed the results of each subsection mentioned in the results chapter.

CHAPTER I: LITERATURE REVIEW

1.1. Agroforestry parklands of *Vitellaria paradoxa* (shea tree)

Agroforestry parklands appear as the most common land-use systems widespread in semi-arid zones of West African Sahel where the majority of a predominantly rural population are subsistence farmers. Parklands are traditional practices and rural dwellers inherited these practices from their ancestors. In West Africa, the dominant tree species of agroforestry parkland systems are *Vitellaria paradoxa* C. F Gaertn (commonly known as shea tree) and *Parkia biglobosa* (Jacq.) R. Br. ex G. Don. Among these key tree species, *Vitellaria paradoxa* or shea butter tree is the most dominant species (**Boffa 1999**) in agroforestry parklands (Figure 1). Its population is about 500 million (shea trees) with a potential of production of shea nuts worth about 150 million USD yearly for the whole Africa (**Bup *et al*. 2014**). Within the continent, its high production areas (Benin, Burkina Faso, Côte D'Ivoire, Ghana, Mali, Nigeria, Sudan and Uganda) could potentially produce about 70.000-300.000 tons of shea nuts per year (**Bup *et al*. 2014**). Conserving *V. paradoxa* in the parklands of the Sahel is not fortuitous because this species provides a range of socio-economic services to rural farmers (**Faye *et al.* 2010**). It therefore plays an important role in farmer's strategies to mitigate and adapt to climate change through its ecosystem services like fruits, shea butter, firewood, charcoal, medicine, microclimate through its shade, and fertilizer through its biomass. etc. (**Alander 2004; Bayala *et al*. 2014**). Among its products, shea butter is the most valuable because it is locally consumed but also has export potential for both chocolate and cosmetics. For instance, this butter is naturally rich in vitamins A, E and F for which rural dwellers manifest severe deficiencies (**Okullo *et al*. 2010**). In light of all these ecosystem services, shea parklands contribute to alleviating rural poverty and improve their livelihoods, especially during the food shortage period which remains a challenge in the Sahel due to erratic rainfall. For the income generation, **Pouliot (2012)** found that 7% of total gross income of richer household farmers against 12% of total income of poorest households is derived from shea tree in Burkina Faso. In Benin, the contribution of shea in rural household gross income varied from 36 to 46% (**Gnanglé *et al*. 2009; Dah-Dovonon and Gnangle 2006**). The contribution of shea tree in gross income for household up to 12% in savanna areas in Ghana (**Pouliot 2012**) and 35% in Nigeria (**Jimoh and Asinwa 2012**). The contribution of the native species of agroforestry parklands in annual gross income of rural household varied from 26 to 73% in Mali (**Faye *et al*. 2010**). Indeed, in this country, the parkland systems cover 90% of agricultural land and their tree component is mostly composed of native fruit species (**Kalinganire *et al*. 2008**). The preserved native species, (*V. paradoxa* is the most dominant), covers more than 20 million hectares in Mali because of its utility and also because being protected by the forest code (**Nouvellet *et al*. (2006**)

1.2. Ecosystem services provided by shea parklands to sustain farmers' livelihood

The concept of ecosystem services has been introduced by the Millennium Ecosystem Assessment (**MEA 2005**) and has been defined as the collection of benefits a society enjoys from a range of resources and processes supplied by the nature. These ecosystem services were categorized into four groups namely: provisioning services (food, fodder, fuel wood, fiber, biochemical, and genetic resources); regulating services (climate regulation, carbon storages, diseases, water regulation and purification), supporting services (soil formation and renewal of their fertility, nutrient cycling, primary production and provision of habitat to biodiversity) and cultural services (recreational and ecotourism, aesthetic, inspirational, educational, and cultural heritage) according to **Mainka and McNeely 2008**. Shea parklands provide a range of the above-listed ecosystem services that contribute to improve rural farmers' livelihood.

Figure 1: Typical agroforestry parklands in southern Mali dominated by shea trees

1.2.1. Provisioning services

The products derived from ecosystems are called provisioning services which directly benefit to people. The delivery of these ecosystem services is highly dependent on the environment. In agroforestry system, annual crops are grown under preferred scattered trees (edible tree species like *V. paradoxa*). These associations may increase farmer's resilience to climate vagaries by complementing their food needs. Shea tree in parklands, provides an important part of family income and even country income. At individual level, shea tree supports rural people during the sowing period (June to August) of crops, especially when fruits are ripened. According to **Wiesman *et al*. (2003)** the nutritional values of the shea fruit pulp are: protein (2.5% to over 10%); phosphorus (0.17 to 2.26 mg g^{-1}) and potassium (4.55 to 37.46 mg g^{-1}). Therefore, the fruits are used to compliment food needs while its butter derived from shea nuts (Figure 2) is the main source of cooking oil and also has medicinal properties for rural communities. The shea butter and the nuts used in chocolate industry explain why both are exported (**Bup *et al*. 2014**). Chemical analysis of shea nuts indicates that their fat content ranges from 20% to 50% with the following components: oleic, stearic, linoleic, and palmitic acids (**Maranz *et al*. 2004b)**.

In addition to the fruit and the butter, the wood of *V. paradoxa* is highly appreciated for building house (house cover) due to its capability to resist termite attacks (**Maranz 2009**). Moreover, agroforestry parklands are also the source of firewoods for cooking. Finally, its leaves are used as fodder to complement the oxen at the beginning of rainy season in order to gain more energy for ploughing (**Bayala *et al*. 2014**).

1.2.2. Regulating services

The regulating services include carbon storage and influence microclimate at local scale (**Jasaw *et al*. 2015**). Agroforestry systems modify the local microclimate through tree shade and consequently, moderate the effects on heat sensitive crops under trees as opposed to those in the open area (**Bayala *et al*. 2014**). Shea tree in parklands also contributes to reduce the wind speed and physical damage to crops. The shade of tree reduces soil surface temperature by up to 4 ^{0}C while increasing relative air humidity at 2 m aboveground by about 12% (**Steffan-Dewenter *et al*. 2007**). Other benefits (regulating services) from trees in parklands are erosion control and reduction of the evapotranspiration. Trees are also able under certain conditions to redistribute ground water in soil profile along the gradient created by the root systems through the hydraulic lift process (**Bayala *et al*. 2014**). For example, water redistributed from deeper to shallower soil layers was found to be equivalent to18-20% of the quantity of water transpired by *P. biglobosa* and *V. paradoxa* in Saponé in Burkina Faso **(Bayala *et al*. 2008).** Trees have also been reported to increase ground water recharge in parkland systems (**Bargués *et al*. 2014; Ilstedt *et al*. 2016**). Trees contribute to the reduction of the carbon dioxide (CO_2) in the atmosphere by capturing and storing it in its biomass. The carbon stock estimate over agroforestry parklands showed a range of 22.4 to 54.0 Mg C ha^{-1} (**Takimoto *et al*. 2008)** and 22.2 to 70.8 Mg C ha^{-1} (**Luedeling and Neufeldt 2012)**.

1.2.3. Supporting services

Such services are not of direct benefit to people but are necessary in the production of the other services (provisioning, regulating and cultural ecosystem services). Agroforestry parklands maintain soil fertility through nutrient cycling and create favourable microclimate for associated crops and livestock **(Bayala *et al*. 2006; Teklehaimano 2004)**. **Bayala *et al*. (2006)** reported higher soil carbon contents under *P. biglobosa* and *V. paradoxa* than in the open area. Indeed, the soil carbon under *V. paradoxa* (6.43±0.45 g kg^{-1}) and *P. biglobosa* (5.65±0.27 g kg^{-1}) were significantly higher than in open area (4.09±0.26 g kg^{-1}) asserted **Bayala *et al*. (2006)**. Moreover, tree species belonging to the Mimosaceae family like *Faidherbia albida* which are able to fix atmospheric nitrogen contribute to improve soil fertility.

1.2.4. Cultural services

The cultural ecosystem services are the non-material benefits people derived from the ecosystems. Agroforestry parklands are part of the cultural heritage of local communities of the Sahel. However, in agroforestry parklands some tree species including *Vitellaria paradoxa* play spiritual roles. According to **De Leew *et al*. (2014)** trees are used to mark the boundaries of land, which improves social cohesion and mutual respect.

Figure 2: Examples of shea tree (*Vitellaria paradoxa*) provisioning ecosystem services

A = shea fruits on shea tree
B = shea kernels
C = shea nuts
D = shea butter

1.3. Climate change impacts on parkland production systems

1.3.1. Climate change impacts on parklands

The Sahel region remains a vulnerable zone due to its unpredictable rainfall and its high variability is likely to worsen in the future (**Kandji *et al*. 2006; Mortimore *et al*. 2009**). Such rainfall pattern may partly explain the decrease of the tree density of a certain number of species (**Kelly *et al*. 2004; Tappan *et al*. 2004; Teklehaimanot 2004; Maranz 2009; Idinoba *et al*. 2010; Gonzalez *et al*. 2012)**. Of course the effect of human pressure on land and the vegetation (overgrazing and shortened periods of fallow, severe lopping of trees for feed requirements and firewood supply) should not be overlooked (**Maranz 2009**). As the vegetation coverage is crucial for maintaining the key ecosystem services, the current degrading trend regardless of the causes is posing a serious threat to the sustainability of the production systems and ecosystems. A reduction of shea tree population between 6-10% due the climate hazard (low rainfall and drought) has been reported by **Idinoba *et al*. (2010).** Hence, this indigenous species (shea tree) contributes to mitigate the climate change impacts on rural livelihoods.

1.3.2. How did farmers' perceive climate change?

African's agriculture is the backbone of the economies and employs about 70% of the active population **(FAO 2003)** but this sector is more and more under-performing. Such trend is perceived by rural dwellers as the direct consequence of climate variability. Indeed, this sector is more vulnerable to climate change than others **(Kurukulasuriya *et al*. 2006)**. Climate variability induces a decline in the production potential (low crop yields) because of the rainfed nature of the agriculture **(Mortimore *et al*. 2009)**. Studies of farmers' perceptions of climate change revealed that they have observed high increase in temperature associated with frequent droughts and a decrease in rainfall, as well as an increase in pest and diseases **(Ayanwuyi *et al*. 2010; Sofoluwe *et al*. 2011; Odewumi *et al*. 2013)**. Some of these perceptions are not always substantiated by existing data, for example the decreasing rainfall. In turn, the high variability with changes in the start and end times of the rainy season is commonly accepted and supported by data (**Nicholson *et al.* 2000**). Consequently, farmers responded by adopting various coping strategies to climate change **(Mertz *et al*. 2009)**. These strategies include: soil conservation, agroforestry practices, diversification of crops, early and late sowing **(Ayanwuyi *et al*. 2010; Sofoluwe *et al*. 2011; Olayemi 2012)**. Besides, these strategies, off-farm activities are increasing in order to cope with the changing climate. There are however some barriers to adopting some of the strategies like the lack of capital, poor access to relevant information about the weather, etc. These barriers require the assistance of other categories of actors including governmental or non-governmental organizations **(Jamala *et al*. 2013)**.

1.3.3. Knowledge gaps and contribution of the present work to fill in these gaps

As prerequisite to support actions concerning climate change impacts in the agricultural sector, some studies have been conducted about the perception of this phenomenon (**Ayanwuyi *et al*. 2010; Sofoluwe *et al*. 2011; Olayemi 2012; Traore *et al*. 2015).** The scope of such studies has been rather broad (agriculture in general, livelihood, etc.) and the scale was local (village). Of course local studies are appropriate as they better capture the socio-economic variability but climate change issues are of rather large scale nature. Therefore there is a need of repeating in large numbers local investigations to be able to have meaningful information when aggregated at lager scale to address climate change issues. The scale of our investigation will remain the village but the main focus will be the parkland systems and more specifically *V. paradoxa*-based ones as they are the most widespread in the study area. We have done that in southern Mali by trying to provide answers to the following research questions: (1) What are the changes in climate as perceived by farmers and the factors explaining such perception? (2) What are the impacts of these changes on the dynamics of the parklands according to farmers? (3) How do these affect the delivery of the ecosystem services (provisioning services; regulating services; supporting services and cultural services? and (4) what are the strategies to cope with climate change effects and bottlenecks for their implementation?

Beyond the perception, there is a need for evaluating the ecosystem services that can be delivered by the parkland systems. We have tested and validated three approaches to estimate *V. paradoxa* fruit yield, biomass and finally potential of using dendrochronology to assess the impact of climate on its growth and carbon sequestration. Being mixed systems, there are rigorous methods to evaluate crop yield and analyse it in link with climate **(Traore *et al*. 2013).** Such method doesn't exist yet for fruit yield of indigenous species. We've therefore developed an agent-based model (ABM) to explore *V. paradoxa* yield dynamics in agroforestry parkland systems in response to the rainfall amount and variability. The key question to answer was therefore: Do the rainfall distribution and amount have an influence on shea tree yield dynamics in agroforestry parkland systems?

In the domain of biomass accumulation and carbon stocks of parklands, there is a dearth of information (**Takimoto *et al*. 2008; Luedeling and Neufeldt 2012**). For the little existing data, there is a problem of accuracy as most of the equations used to calculate the biomass are generic **(Henry *et al*. 2011)**. However, generic equations applied to local data tend to overestimate the biomass and carbon storage of trees **(Ketterings *et al*. 2000, Van Noordwijk *et al*. 2002).** There is therefore a need for species and site-specific allometric equations for most of the dominant tree species of parklands including *V. paradoxa*. To contribute to generating more specific equation, we have tested the use of functional branch analysis (FBA) to estimate the above and belowground carbon stocks of *V. paradoxa*. The choice for this tool is related to the fact it is a non-destructive method (**Van Noordwijk and Mulia 2002)** and therefore relevant for such valuable and protected species, *V. paradoxa***.**

In the absence of long term experiments to generate data that can reveal the impact of climate change or variability on the growth and carbon accumulation, dendrochronology offers an alternative **(Couralet *et al*. 2010; Gebrekirstos *et al*. 2011)**. The use of this technique in Africa remains limited to few cases like the semi-arid savannas **(Fichtler *et al*. 2004; Gebrekirstos *et al*. 2008; Worbes and Raschke 2012)**, the miombo woodlands in Southern Africa **(Trouet *et al*. 2006, 2010)**, and the Central Highlands of Ethiopia **(Wils *et al*. 2011)**. Mali, like other Sahelian countries, is characterized by recurrent drought events **(Butt *et al*. 2005)** and clear distinct rainy and dry seasons which all may affect the growth pattern of species as well as their carbon accumulation. And of course, climate change may modify such patterns if they exist. Therefore, empirical data on these aspects are required for effective conservation and management of tree species under changing climate conditions. As a case study, the dendrochronology method was applied to *V. paradoxa* with the aims to: 1) investigate the formation of rings in *V. paradoxa* for dendrochronological studies, 2) assess growth dynamics and climate-growth relationships, and 3) determine total carbon stock and the sequestration potential of *V. paradoxa* under different land-use types and climatic conditions.

For clarity of our message we have provided some definitions of key concepts of our study. Thus, parklands constitute a land-use type which is formed of scattered trees and shrubs from the natural woodland after clearing the bush for agricultural cropping (**Boffa 1999**). These are dominated by *V. paradoxa* in southern Mali. In turn, a fallow is a cultivated land which has been left uncropped for few years as a way of restoring its soil fertility. The protected areas are delimited areas of forest reserves consisting of mixed species (plants and animals) mainly for biodiversity conservation.

CHAPTER II: MATERIALS AND METHODS

2.1. PRESENTATION OF STUDIED SPECIES AND SITES

2.1.1. Studied species

Vitellaria paradoxa C.F Gaertn. (formerly *Butyrospermum parkia* G. Don), is commonly known as shea butter tree, belonging to the Sapotaceae family. It is the only species in the genus *Vitellaria* with two sub-species: (1) *Vitellaria paradoxa* subsp. *paradoxa* occurs in West Africa whereas (2) *Vitellaria paradoxa subsp. nilotica* is found in Northern Uganda and Southern Sudan **(Hatskevich *et al*. 2011)**. *V. paradoxa* is endemic to the African Savannas, north of the equator **(Maranz *et al*. 2004a)** and extends from Senegal to Sudan and to western Ethiopia and Uganda, in a belt of 500-700 km wide **(Hall *et al.* 1996; Bouvet *et al*. 2004)**. This species is found in a total of twenty countries as follows (Figure 3): Benin, Burkina Faso, Cameroon, Central African Republic, Chad, Côte d'Ivoire, Democratic Republic of Congo, Ethiopia, Ghana, Guinea Conakry, Guinea Bissau, Gambia, Mali, Niger, Nigeria, Senegal, Sierra Leone, Sudan, Togo and Uganda **(Salle *et al*. 1991; Hatskevich *et al*. 2011)**. However the most important producing countries of shea nuts are found in West Africa **(Bup *et al*. 2014).**

V. paradoxa is a characteristic species of the savanna woodlands **(Byakagaba *et al*. 2011).** According to **Nouvellet *et al*. (2006)**, *V. paradoxa* is the most dominant deciduous tree species in the parklands (Figure 4) reaching up to 15 m height with leaves as large as 12-25 cm **(Hall *et al*. 1996)** and girths of about 175 cm. It covers more than 20 million hectares in Mali (**Bouvet *et al*. 2004**).

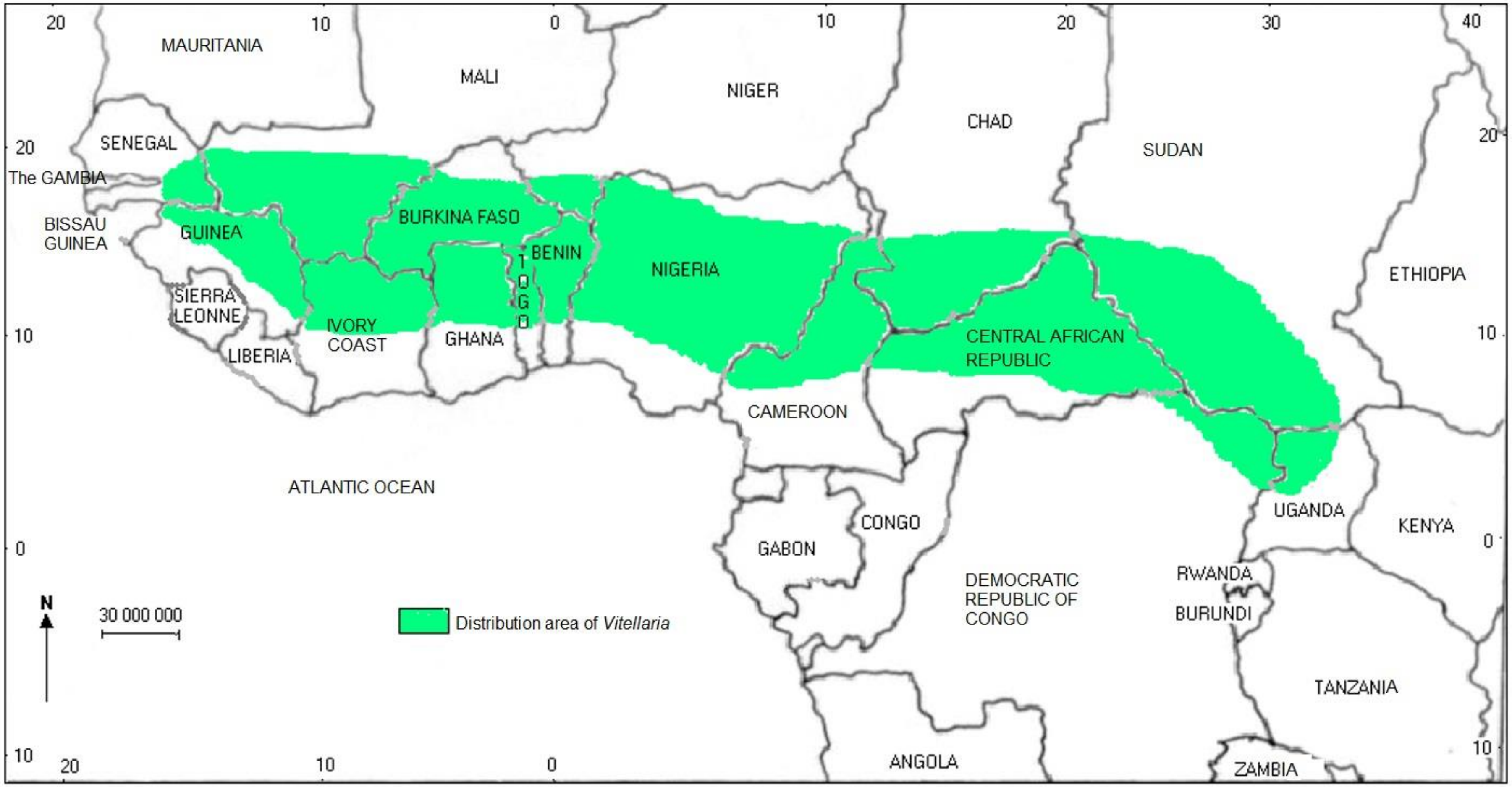


Figure 3: Spatial distribution of *Vitellaria paradoxa* in Africa (Salle *et al*. 1991)

Figure 4: Study species (*Vitellaria paradoxa*) in farmer field in southern Mali

2.1.2. Description of study sites

The study was carried out in two districts (Koutiala, and Yanfolila) in southern Mali (Figure 5). Koutiala is located at 12°38'N and 5°66'W in the Sudano Sahelian zone and Yanfolila is located at 11°10'N and 8°09'W in the Sudano Guinea zone. These areas are characterized by poor soil fertility and low agricultural crop productivity **(Voortman *et al*. 2004)**. The distance between the two study sites is about 445 km and they were selected to represent two different climatic zones of *V. paradoxa* distribution area. Other selection criteria included their accessibility, shea tree (*V. paradoxa)* density with 16 trees ha^{-1} in the parklands in Koutiala **(Kelly *et al*. 2004)** against 27 trees ha^{-1} in Yanfolila **(Sanogo *et al*. 2016)** and the socio-economic importance of *V. paradoxa* particularly for women who are normally the most active in processing and selling tree products. Generally, women are less engaged in farmland activities but more in collecting and processing non-timber forest products such as shea nuts which contribute significantly to improve family livelihoods in the study sites.

The rainfall pattern at both sites is uni-modal, but rainy season length and annual rainfall amount are quite different. In Koutiala district, the length of the rainy season is 3 to 4 months (Figure 5) with a mean annual rainfall of 889±173.16 mm and temperature of 27.98±0.42°C. In Yanfolila district, the rainy season lasts for 4 to 5 months (Figure 6) with a mean annual rainfall of 1126±173.96 mm and temperature of 27.79±0.48°C (Figure 6).

In both sites the livelihood systems of farmers are based on mixed tree-staple cereals (maize, sorghum, and millet) production in rotation with cash crops (cotton and groundnut). Thus, people in both study sites are mainly farmers and herders and they earn their living through rainfed agriculture, herding (cattle, sheep and goats) and the exploitation of ecosystem services (fruits, shea butter, and firewood) from the trees of the parklands and forests.

The population of Koutiala is estimated to be 622,999 people with a density of 71 inhabitants km^{-2} while that of Yanfolila is about 228,308 people with a density of 26 inhabitants km^{-2} (**DRSI 2013**). The main tribes in the study sites are Minianka, Bambara, Malinke, Sarakole, Sonrail, Mossi, Dogon and Fulani. Fulani and Minianka dominate in Yanfolila and Koutiala, respectively.

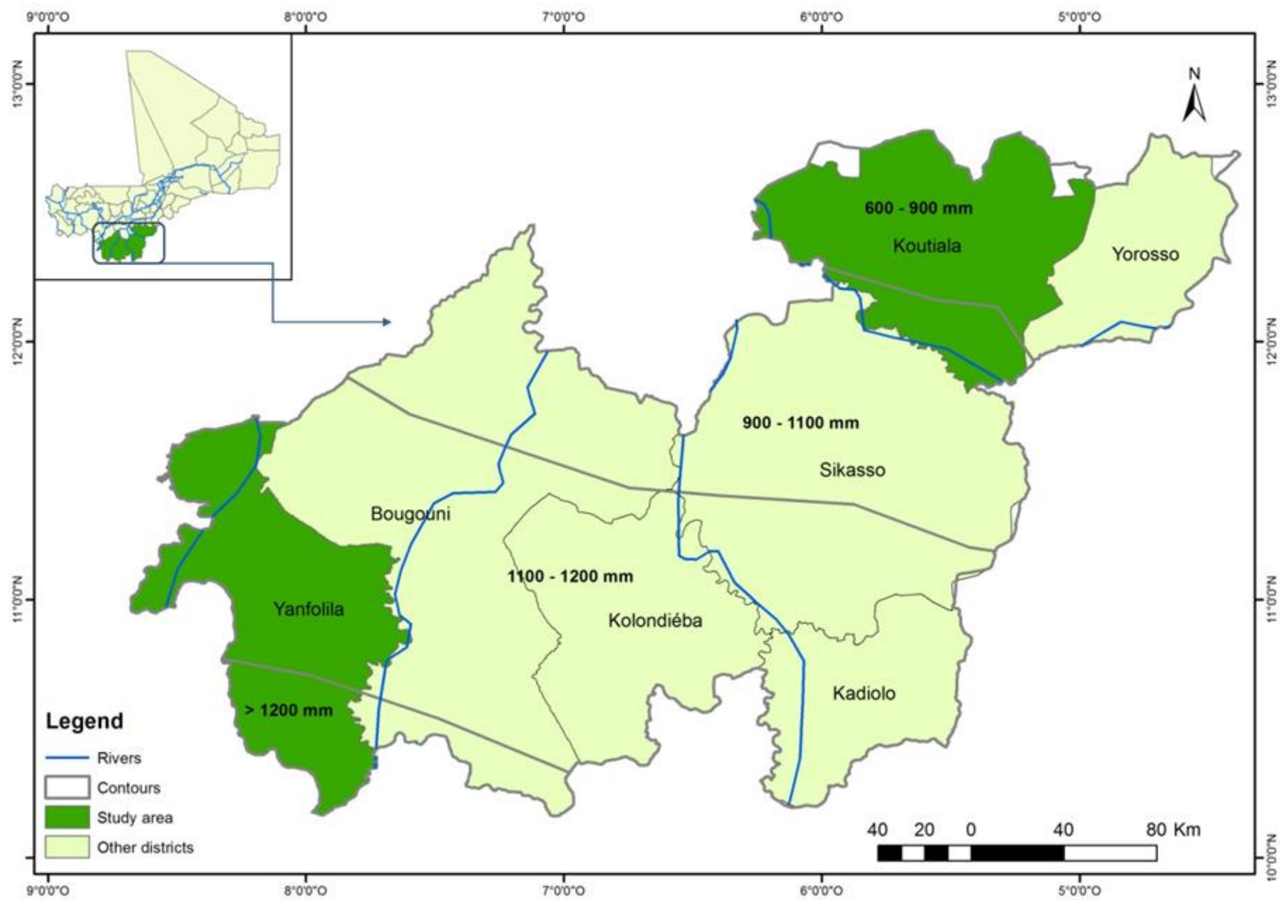


Figure 5: Location of the study sites in southern Mali, West Africa

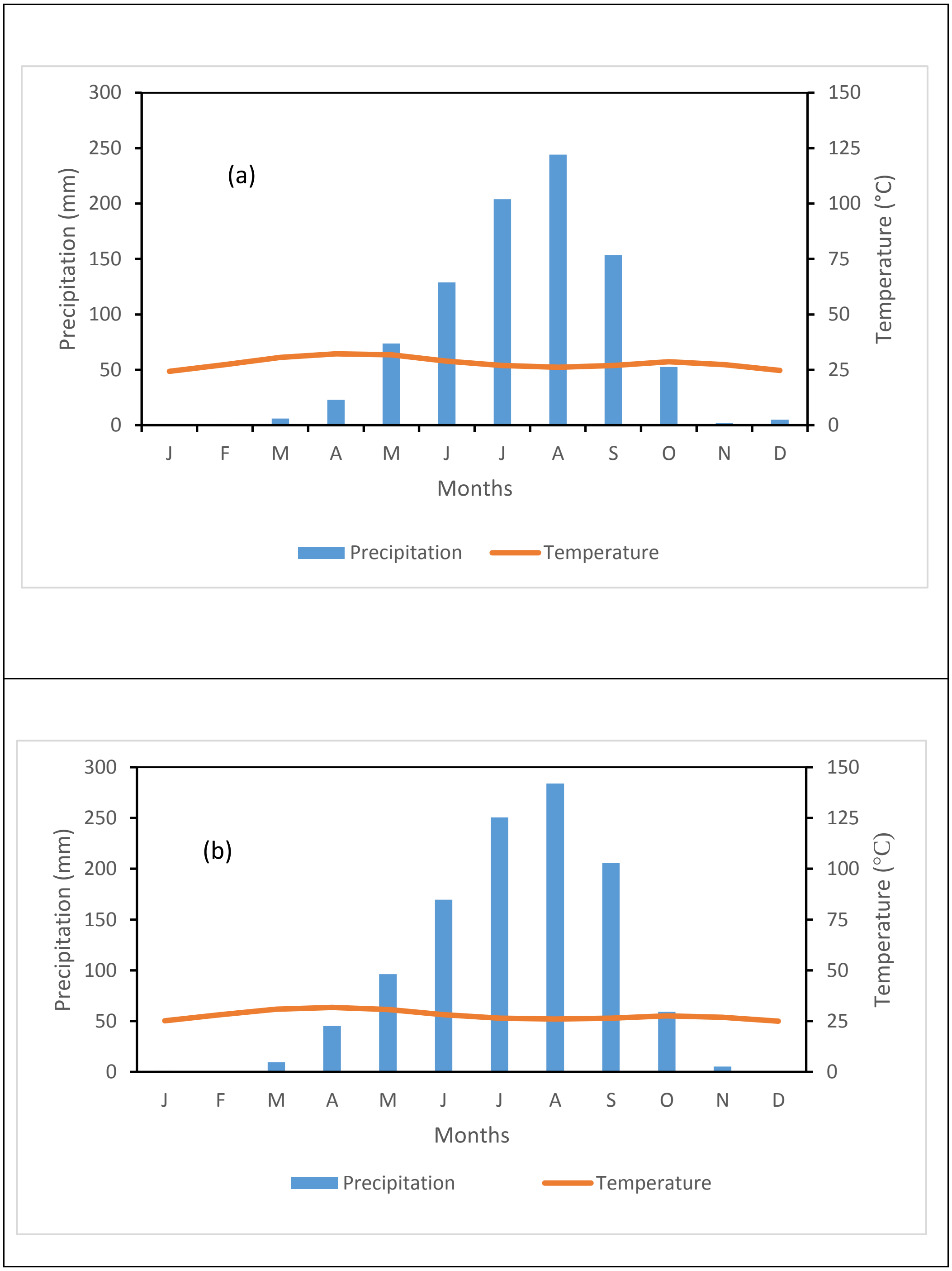


Figure 6: Ombrothermic curves for Koutiala (a) and Yanfolila (b) in southern Mali, West Africa

2.2. METHODS

2.2.1. Farmers' perceptions of climate change impacts on ecosystem services provided by the parklands

2.2.1.1. Farmers' sampling

A sample size of 60 individuals from two agro-ecological zones (study sites) was used in a preliminary investigation to determine the proportion of respondents who have observed both changes in temperature and rainfall. Temperature and rainfall have been selected for the current study because their variation can easily be detected by the farmers. Fifty percent of the respondents who have observed both changes in temperature and rainfall were used to calculate the sample size (N) following **Dagnelie (1998)** formula:

$$N = \frac{U_{1-\alpha/2}^{2} p(1-p)}{d^{2}} \qquad (1)$$

Where, N is the total number of households surveyed, i.e., the sample size; $U_1^2 - \alpha/2$ is the value of the normal random variable for a probability value of α = 0.05; $U_1 - \alpha/2$ = 1, 96; p is the estimated proportion of people in the villages who have both observed a change in temperature and rainfall (p=0.50); and d is the expected error margin of any parameter to be computed from the survey, which was fixed at 0.05.

Then, from this formula the sample size (N) was estimated at 384 farmers for the two sites. However, this was adjusted to 400 farmers to cater for gender balance given the heavy involvement of women in the economy activities of shea. Hence, 400 farmers were used in this study and the sample size for each site was prorated to its total number of households giving 240 farmers in Koutiala and 160 farmers in Yanfolila. The sample for each site included 50% of either sex randomly selected for the interviews. Even though, women are not decision-makers at any step of the farmland management they have more decision power for provisioning ecosystem services derived from the non-timber forest products **(Brockhaus *et al*. 2013).** These ecosystem services are the mainstay of women income and are used by them to support the livelihoods of their families.

2.2.1.2. Data collection

A structured interview was carried out in order to collect information on households' characteristics and their perception of climate change. More precisely, questions were asked to ascertain whether farmers had observed changes in some selected indicators like temperature, rainfall, drought, floods, winds and dust, number of hot days and length of rainy season. The consequences of these changes on shea tree [*Vitellaria paradoxa* C.F. Gaertn. (Sapotaceae)], parkland dynamics were recorded as well as the type of ecosystem services provided (provisioning, supporting, regulating and cultural services) by shea parklands and used by farmers to mitigate climate change effects. Farmer's perceptions of drivers of climate change, the strategies used to adapt and the barriers for adaptation to it were also recorded.

2.2.1.3. Statistical analyses

Descriptive statistics were used to analyse farmers' perception of climate change whereas Chi-squared test was used to determine whether there is a significant difference in the perception between the two sites (Koutiala and Yanfolila). A multinomial logit (MNL) regression was used to identify the main determinants of farmers' perception of climate change**.** The advantage of the multinomial logit is that it permits the analysis of decisions across more than two categories allowing the determination of choice probabilities for different categories of climate attributes. Apart from the well-known drawbacks of the Independence of Irrelevant Alternatives (IIA), this approach is more appropriate than the probit or logit models that have been conventionally used. Instead of having two dichotomous alternatives (0, 1) as in the multivariate logit or probit models, the multinomial logit has ***J*** possible states or categories (**Tse 1987; Cramer 2003**).

To describe the MNL model, let **y** denote a random variable taking on the values {1,2….**J**} for choices **J**, a positive integer, and let **x** denote a set of conditioning variables. In this case, **y** representing the category chosen by any farmers in the study sites. Therefore y represents a number of climate attributes (temperature, floods, droughts, rainfall, wind and dust and number of hot days) and **x** the vector of farmers' characteristics (gender, age, education level, household size, farm size, marital status and farming experience).

The question is how cetirus paribus (a positive integer) changes in the elements of **x** affect the reponse probalilities:

P(y=j/x), **j** = 1, 2, ..., **J**. Since the probabilities must sum to unity, P(y = j/x) is determined once we know the probabilities for **j** = 2, ..., J (**Deressa *et al*. 2009**).

Let **x** be a 1**x K** vector with first element unity, the MNL model response probabilities are given by:

$$P(y = j/x) = \frac{\exp(x\beta_j)}{[1+\sum_{h=1}^{J}\exp(x\beta_h), j=1,\ldots,J]} \quad (2)$$

Where β_j is **K**x1, **j** = 1, …, **J.**

Unbiased and consistent parameter estimates of the MNL model in equation (2), require the assumption of independence of irrelevant alternatives (IIA) to hold. Specially, the IIA assumption requires that the probability of using a certain perception by a given farmer needs to be independent from the probability of choosing another perception (that is, P_j/P_k is independent of the remaining probabilities).

The premise of the IIA assumption is the independent and homoscedastic disturbance terms of the basic model in Equation (2). The parameter of the MNL model provides only the direction of the effect of the independent variables on the dependent (response) variable, but estimates do not represent either the actual magnitude of the change nor probabilities (**Greene 2003**). Differentiating equation (2) with respect to the explanatory variables (gender, age, education level, household size, farm size, marital status and farming experience) provides marginal effects of the explanatory variables given as:

$$\frac{\partial P_j}{\partial x_k} = P_j(\beta_{jk} - \sum_{J=1}^{J-1} P_j\beta_{jk}) \quad (3)$$

Thus, the marginal effects or marginal probabilities are functions of the probability itself and measure the expected change in probability of a particular choice being made with respect to a unit change in an independent variable from the mean (**Greene 2003**). Data were analysed with the STATA (Version 13.1).

2.2.2. *Vitellaria paradoxa* yield dynamics in agroforestry parkland systems

2.2.2.1. Farmers' sampling and data collection

The sample mentioned above (see section 2.2.1.1) has been used for the data collection of this sub-section. Therefore, the same of 400 farmers (men and women) from 200 households were involved in this study. All farmers were available for interviews on which this study is based.

There are two sets of data (i.e., socio-economic and biophysical) that are collected for this study.

- **Socio-economic data**

For the socio-economic data, the farmers were interviewed using a structured questionnaire. The interviews focused on household characteristics such as: farmland size, household size, including sex and age distribution. The labour availability as well as man-day per year for each crop, the yield of each crop per year, natural resources (land holdings and land structures), physical capital (distance from house to the field) were recorded. Shea tree nuts and woman-day per year of shea nuts collection were considered especially for the women because they have the full responsibility of the management of these ecosystem services, although the main decision making on farm activities are men. Thus, in the same household both (man and woman) investigations were complementary.

- **Biophysical data**

For the biophysical data, field measurements were conducted. Rectangular quadrats of 2500 m^2 (50 m x 50m) were set out in the 200 farms and fallows by using measuring tape whereas 1000 m^2 (50 m x 20 m) was set out at five replicates in the protected area due to its smaller size (about 15 ha). For all standing trees of *V. paradoxa* within these quadrats the diameter at breast height (DBH), the height and the crown diameter were recorded. The coordinates of each plot were recorded with GPS (Global Position System). Biophysical properties like monthly precipitation were provided by the meteorological station of Koutiala; and the Yanfolila precipitation data were obtained from the Bougouni meteorological station located at a distance of 80 km. The recorded data of rainfall covered a period of 45 years (1968- 2012) for Koutiala and 30 years (1982-2012) for Yanfolila. However, to harmonize the rainfall use in our model we considered in this subsection the covered period of 30 years (1982-2012) for both sites.

2.2.2.2. Data analysis

Data collected were subjected to descriptive statistics, such as mean, standard deviation (SD), confidence interval, frequency counts, tables and percentages. The principal component analysis (PCA) was used for household categorization. The PCA was done following the Varimax rotation methods which keep all components with eigenvalues > =1.0. From the results of PCA we derived K-means cluster analysis (KCA) to generate the typical household agent groups. The value of K varied from 2 to 10. Then the explanatory variables of shea tree yield were estimated using the Cobb-Douglas formula (see section 2.2.2.3.6). The software STATA (version 13.1) was used for the data analysis.

2.2.2.3. Agent-based model (ABM)

ABM is a simulation model composed of autonomous interacting entities known as agents within an environment **(Kelly *et al*. 2013)**. These agents are programmed to react to the computational environment. The method encodes the behaviour of individual agents in simple rules so that the agent's interactions are observed **(Wilensky and Rand 2015)**. In addition it has the capability to simulate the dynamics and interactions between the social and natural (socio-ecological) systems **(Kelly *et al*. 2013; Villamor *et al*. 2014).** ABM has also been extensively applied to simulate socio-spatial processes for land-use change (**Bousquet and Le Page 2004**).

2.2.2.3.1. Purpose

The agent-based model (ABM) is intended to explore the shea tree yield dynamics in agroforestry parkland systems according to the rainfall response.

2.2.2.3.2. Entities and state variables

Two kinds of data were used as inputs in the Land Use Dynamics Simulator (LUDAS) model: household data and landscape data. First regarding to household data, each household represents an agent. The household data are used to characterize the livelihood status of the agents (household). The agents are related to five capitals which include social identity (identification number, age and household type), human resources (household size and labour availability), natural resources (land holding land area per crop) and financial resources (gross income). Secondly, other agent (landscape) is composed of a satellite image raster of land cover with a grid pixel of 250 m x 250 m in the model. The geographical coordinates of each household agent are part of the landscape agents.

2.2.2.3.3. Design concepts

The model was mainly designed with two types of state variables like household agents and landscape agents. The first are dynamic variables (can change over time) while the second are static variables (can't change over time). The landscape agent are referred to GIS-raster with their attributes whereas the household agent are related to their own attributes. Moreover, each household is represented on the landscape by a grid cell or patch. The household agent characteristics included explanatory variables related to the shea tree yield. The livelihood group dynamics of each household was defined in the model.

2.2.2.3.4. Initialization

Two steps are required for the initialization of the model. The first step was to import the data of a sample household (N = 120; N = 80) in Koutiala and Yanfolila respectively. As for the last step, the 2006 land-use map was imported as GIS (Geographic Information System) raster files which is the initial landscape of the model that are secondary data. The initial state starts at t = 0 for each simulation run in the model **(Villamor *et al*. 2014).** The simulations of the shea tree yield have been run separately for each individual site.

2.2.2.3.5. Data inputs

The 30-year (1982-2012) rainfall data generated from descriptive statistics were included in the model for simulations. The household data and landscape data (GIS raster files) were also included in the LUDAS model in forms of text files. These two types of data (household and landscape data) were linked to each other in the LUDAS model and were translated into NetLogo (version 5.2.0). Both types of data are linked to each other as a preliminary in LUDAS before the initialization **(Le *et al*. 2008).** In this study, we parameterized farmland as one class and the sub-model generated the shea tree yield. The sub-model of agronomic-yield of shea was calibrated with the coefficients of elasticities (β) derived from log-linear regression analysis. The coefficients of elasticities (β) were derived from the parameters like labour input, parkland size, mean DBH (diameter at breast height) of shea, basal area of shea, shea density per hectare and the distance from house to the field.

2.2.2.3.6. Sub-model of agronomic yield

The agronomic yields were estimated using the following functions **(Cobb and Douglas 1928; Villamor 2012):**

$$P(L, K) = bL^{\alpha}K^{\beta} \tag{4}$$

Where:

P is total annual production,

L is labour input (total number of man-days employed per year),

K is capital input (fertilizer, seedling, etc.),

b is total factor productivity,

α and β are outputs elasticities constant, value of labour and capital, respectively; derived from log-linear regression analysis.

The table 1 describes the variables used for this sub-model of shea tree yield dynamics.

2.2.2.3.7. Scenarios and validation of the model

The amount of rainfall during the rainy season from May to September has been used as a scenario for the simulations. The models were first tested and adjusted to produce a reliable simulation. Thereby, a total of five scenarios based on rainfall (Table 2) were simulated to compute the average and the standard error values of each simulation. The time of running varied between sites and was related to the sample size. However there is no universal method for ABM model validation. Thus, we applied the empirical technique of validation by comparing the present model outcomes (simulated results) to the survey data collected on the field **(Schreinemachers and Berger 2011; Villamor *et al*. 2012).**

Table 1: Major variables used for the agronomic-yield dynamics sub-model of *Vitellaria paradoxa* in agroforestry parklands in southern Mali, West Africa

Variables	Definition	Data source
Yield (dependent variable)		
P_y-shea	Yield from shea in agroforestry parkland (kg ha^{-1} $year^{-1}$)	Field survey
Natural predictor (independent variables)		
$P_{areashea}$	Parkland size (m^2)	Field survey
I_{shea}	Woman-days employed for shea nut collection (woman-day ha^{-1} $year^{-1}$)	Field survey
$I\_{sheadbh}$	Diameter at breast height (DBH) cm ha^{-1}	Field measurement
$P\_{sheabasalarea}$	Tree basal area (m^2 ha^{-1})	Field measurement
$I\_{sheadensity}$	Tree density ha^{-1}	Field measurement
$I\_{distance}$	Distance (km) from house to field	Field survey

Table 2: Rainfall scenarios for *Vitellaria paradoxa* yield simulation in agroforestry parklands in southern Mali, West Africa

Simulations	Rainfall scenarios	Monthly rainfall				
		May	Jun	Jul	Aug	Sep
S1	Minimum monthly rainfall	x	x	x	x	x
S2	Mean monthly rainfall	x	x	x	x	x
S3	Maximum monthly rainfall	x	x	x	x	x
S4	Lower rainfall of 95% confidence interval	x	x	x	x	x
S5	Upper rainfall of 95% confidence interval	x	x	x	x	x

2.2.3. Fractal scaling of *Vitellaria paradoxa* carbon stocks estimation

Functional branch analysis (FBA) or fractal branching model is a model-based method on the measurements of tree branches. It provides tree architectural (tree form) and derive allometric scaling coefficients of equations that relate diameter at breast height (DBH) to biomass **(van Noordwijk and Mulia 2002)**. FBA can also be applied to estimate root length and root biomass in standing trees **(Smith 2001; Salas *et al*. 2004)** and predicts biomass in tree components **(Martin *et al*. 2010)**. In addition, the FBA model is a non-destructive method.

2.2.3.1. Field sampling and data collection

A total of 70 trees of *V. paradoxa* were selected in three land-use types (parklands, fallows and protected area) in southern Mali with 30 trees in Koutiala and 40 trees from Yanfolila. As no protected area was found in Koutiala, only parklands and fallows were considered while in Yanfolila samples were collected from three land-use types (parklands, fallows and a protected forest). The 70 sample trees were grouped into six classes based on their diameter at breast height (DBH) as following: 3 to 7; 7 to 10; 10 to 14; 14 to 24; 24 to 32 and > 32 cm. We were not able to record fifty measurements of diameter on tree with diameter less than 3 cm. Thus we considered only tree with diameter ≥ 3 cm. The different classes of DBH were built at each 5 cm of diameter but some classes presented less individual trees species and we extended such classes to 10 cm of diameter. These six classes of DBH have been identified by setting 200 plots of 2,500 m^2 (50 m x 50 m) in parklands and fallow (plots set in the farms and fallows of all men investigated in this study) and 5 plots of 1,000 m^2 (50 m x 20 m) in protected area in the study sites. Within each plot we recorded the DBH using diameter tape and height using hypsometer only for *V. paradoxa* tree species which allowed us to record the total number of standind individual of each class. Then the sample size for each class of diameter was determined by prorating the total sample size of each site to the total number of each class of diameter.

The data on branching points required for the FBA model calibration were collected in two steps for each sample tree. The first step was about the aboveground biomass measurement (Figure 7) whereas the belowground (root) biomass was measured during the second step. For the aboveground part we started with the first link and the diameter was recorded at three levels (lower diameter ($D_{proximal}$), the diameter in the middle of the link (D_{middle}) and the diameter at the distal end of the link (D_{distal}). The length of each link was recorded with a tape in addition to its link number as well as the parent number of each link. The number zero was attributed to the main parent with the link number 1, whereas its offsprings were 2 and 3 and so on. From the first branch point, the largest branch was selected and followed to a terminal branching point. The number of leaves of each link was counted. The measurements were repeated on each successive link in the path. This process was repeated, moving up the sample tree, following and measuring connected links to different terminal links. The DBH, height of each sample tree and land-use types were recorded. For the belowground part we excavated (in a circle) and exposed the root system (Figure 7) for the sample trees and thereafter we measured the diameters, link lengths and link number of the roots as for the aboveground part. Data for at least 100 branching points were recorded for each sample tree in above as well as in belowground parts as recommended by **van Noordwijk and Mulia (2002).** However, it was not possible to record 100 measures on some sample trees with small diameter, as a result we recorded at least 50 branching points.

2.2.3.2. Functional branching analysis model calibration

The independent relationship between p and q values and parent diameters/root diameters are the prerequisite for the applicability of FBA model. To test this, FBA help file was used for above as well as for belowground compartments. That means before applying the FBA model it is necessary to check first the relation between these two parameters (p and q) with the parent diameter. The Equations (Eq). (5) and (6) were used to check these relationships, respectively. The transfer coefficient p is defined as the ratio of the square of diameters before bifurcation to the sum of squares of the diameters after bifurcation **(van Noordwijk and Mulia 2002):**

$$p = D_{before}^2 / \sum D_{after}^2 \qquad (5)$$

Whereas the allocation coefficient for the split of cross-sectional area, q, over the branches/roots is estimated:

$$q = maxD_{after}^2 / \sum D_{after}^2 \qquad (6)$$

Where D_{before} is diameter before bifurcation and D_{after} is diameter after bifurcation.

The p values should be centered around 1 and explain a wide range of values of cross-sectional area . A q value of 0.5 indicates a perfect fork and higher values that one branch was larger than the others. The value of q is at least 1/n where there are more links after a branching point. If a null-hypothesis of statistical independence is not rejected, FBA can be used to reconstruct a large number of trees of various diameters that follow the same branching rules and derive their allometric scaling coefficients (**van Noordwijk and Mulia 2002**).The equations 5 and 6 mentioned above were applied for aboveground as well as for belowground data. As no statistically significant difference was found between the mean values of p and q for land-use types within sites, we combined them into a single group in each site to increase sample size. The woody part of the tree was stratified into three diameter categories: twig (link with diameter of less than 2 cm), branch (link between 2 and 10 cm) and stem (link above 10 cm diameter) according to **David *et al*. (2014); Panwar *et al*. (2014)**. Thus, the FBA model was parametrized for above and belowground parts of a tree with the following inputs:

- Average number of branches at each branching point;
- Link length-diameter relationships;
- The scaling factor (p);
- The allocation parameter (q);
- Tapering coefficient $(D^2_{distal} / D^2_{prox})/L$; where L is the length of link diameter
- Twigs length (cm);
- Branch length (cm);
- Wood length (cm);
- Wood density (g cm^{-3}).

The wood density used to parametrize this model was derived from twenty trees of *V. paradoxa* in our previous study at the same sites (**Sanogo *et al*. 2016**).

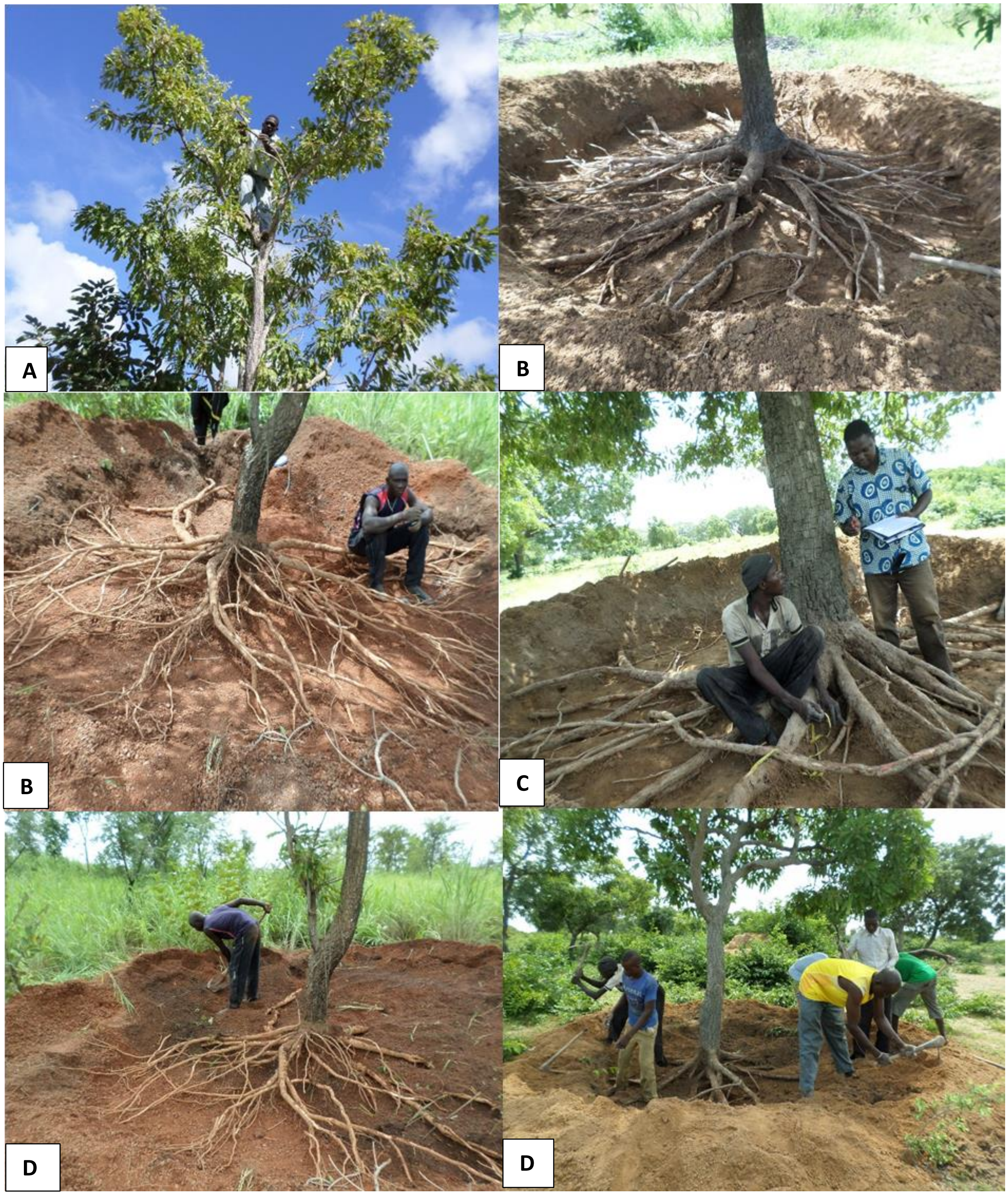


Figure 7: Measurements for above and belowground biomass of *Vitellaria paradoxa* in southern Mali, West Africa

A = Aboveground biomass measurements of *V. paradoxa*, B = Exposed roots of *V. paradoxa* , C = Belowground biomass measurements of *V. paradoxa*, D = Covering of exposed roots

2.2.3.3. Generation of biomass equation coefficients and carbon stocks estimation

The allometric power equation based on diameter has been used to calculate biomass and carbon stocks of the trees is:

$$B = aD^b \qquad (7)$$

Where B is biomass (kg $tree^{-1}$) of the stem or root and D is diameter (cm) at breast height for above and proximal root diameter for belowground. The parameter “a” indicates tree biomass when the diameter is 1 cm, whereas the parameter “b” is the allometric scaling power.

Both parameters “a” and “b” were generated with input data through FBA **(van Noordwijk and Mulia 2002)** rules using some stochastic variation within measured parameter ranges. Thus the biomass of individual tree was estimated through the Eq. (7) for above as well as for below-ground. A mean carbon concentration of dry woody biomass of 0.50 was used to work out for above and belowground biomass (**Basuki *et al*. 2009**).

Mean biomass per diameter class was multiplied by the density of trees in this class to obtain the biomass for this diameter class. Biomass per diameter classes was sum up to obtain total biomass per hectare. The rate of 50% was applied to this biomass for the C stocks.

2.2.3.4. Statistical analyses

A pair-wise test was used to compare the carbon stocks between sites. The statistical software STATA (version 13.1.0) was used for data analysis. The site-specific allometric equations were evaluated based on the coefficient of determination (R^2); standard error of the estimate (SEE) and the F-values generated from linear regression analysis.

2.2.4. Potential of dendrochronology in assessing carbon sequestration rates of *vitellaria paradoxa* under changing climate

Dendrochronology or tree-ring analysis, studying the annual wood ring growth, has been used to analyse the ecological and environmental factors that influence tree growth. In addition, tree- ring analysis can improve our understanding of tree ecology and forest dynamics and therefore could help implement mitigation strategies.

2.2.4.1. Field sampling and tree-ring analysis

Stem disks of *V. paradoxa* were collected at breast height (1.3 m) from trees of different diameter classes, ranging from 9.03 to 38.23 cm at both sites. In total, 20 stem disks, four from each land-use type, were collected using a chain-saw. The following information was recorded: tree morphological characteristics (diameter and height) and land-use types (parklands, fallow, protected area) .

The stem disks were dried in an open area under shade before being transported to the Dendrochronology Laboratory at ICRAF (World Agroforestry Centre) in Nairobi, Kenya. Standard dendrochronological methods were used to prepare the samples for measurement (**Cook *et al*. 1990**). To improve the visibility of the growth ring boundaries, the samples were polished gradually using sand paper of grit size 400-1200 and then the dust was removed with compressed air. To study the features that characterise the growth ring boundaries, transversal micro-thin sections (20-30 µm) were prepared from disks of different sites using a microtome. Tree-ring boundaries were marked under a microscope (Figure 8) connected with a LINTAB 6.0 measuring systems (Rinntech Inc., Germany). Tree-ring widths were measured from two to four radii (from pith to bark) to the nearest 0.01 mm using a LINTAB 6.0 supported by the software TSAP-Win (Times Series Analysis and Presentation, version 4.6x for Microsoft windows; **Rinn *et al*. 1996**). Individual tree chronology were obtained by combining ring-width curves of 2 to 4 radii after cross-dating. Cross-dating was done both visually and statistically. The visual cross-dating was conducted using pointer years (extreme wide or narrow rings). The pointer years allowed to detect and correct errors due to possible missing or false rings (**Gebrekirstos *et al*. 2008**). Cross-dating was further verified statistically by using the TSAP which allowed to measure the '*Gleichläufigkeitkoeffizient'* (coefficient of parallel variation between tree-ring series) or GLK and T-value that verifies the degree of similarity of two curves (**Baillie and Pilcher 1973**). The

COFECHA program was also used to check the accuracy of cross-dating (**Cook and Holmes 1999**). Those series with GLK higher than 65% (**Eckstein and Bauch 1969**) and T-value greater than 2 were selected for further analysis. Using the same procedure, successfully cross-dated mean ring width series of different sample trees were averaged to build land-use specific mean chronologies. A master sites chronology, with a length of 78 years and 68 years, was further constructed by building the mean of the different land-use types in Koutiala and Yanfolila, respectively.

The average series were detrended by fitting a cubic spline with a 50% frequency response cut-off at 32 years to minimize non-climatic signals (age-related growth trends and competition effects, etc.) using the ARSTAN software (**Holmes 1994**). Finally, standard and residual chronology were obtained for each site. The standard chronology was processed as above without autoregressive modeling. The residual chronology was additionally processed using autoregressive modeling to remove autocorrelation, making it more suitable for regression analysis. The chronology quality was evaluated in each site by using the value of EPS (expressed population signal) with a threshold of 0.85, which determines at which degree the chronology is reliable (**Wigley *et al*. 1984**).

The following equation of EPS was used:

$$EPS = n.r_{mean}.[1 + (n-1).r_{mean}]^{-1} \qquad (8)$$

Where: EPS = expressed population signal; r_{mean} = mean correlation coefficient between high-frequency standardized series, n = number of series.

Figure 8: Different steps of *Vitellaria paradoxa* tree-ring width analysis

"1= disk, 2 = disk polishing, 3 = ring width marking, 4 = ring width measurement with LINTAB**"**

2.2.4.2. Wood density measurement

Accurate estimates of aboveground biomass and carbon requires measurements of wood density. Because of the variability of wood density between and within tree species, wood specific density for individual sample trees was determined. To do so, a sub-sample was taken from each stem disk and saturated with water for 30 minutes. The wood specific density (ρ) of each individual sample tree was calculated as dry weight to fresh volume ratio after drying the samples for 72 hours at 105°C (**Nogueira *et al*. 2005**).

2.2.4.3. Estimation of carbon stocks in aboveground biomass

The aboveground biomass (AGB) estimation requires the use of many predictors in order to reduce error. However, **Chave *et al*. (2014)** argued that two parameters namely, diameter at breast height (DBH) and wood density (ρ), are enough as the main predictors of AGB. Species-specific allometric equations for *V. paradoxa* have been developed in this study. We used also the improved pantropical allometric model developed by **Chave *et al*. (2014)** to compare with our carbon estimates. The improved pantropical allometric model has been selected because of the similarity of the conditions in which it was developed (dry tropical forests) with our study sites: distinct dry season and rainfall below 1500 mm per year, more than 5 months of dry season (**Chave *et al*. 2014**). Moreover, this equation was developed from 4004 tree species originating from 58 sites, and 1429 (36%) from Africa **(Chave *et al*. 2014)**.

$$AGB = exp[-1.803 - 0.976E + 0.976\ln(\rho) + 2.673\ln(D) - 0.0299[\ln(D)]^2] \qquad (9)$$

Where:

For the units of the parameters used in equation (9): AGB is in kilograms, ρ is in grams per cubic centimeter and D is in centimeters.

E is a measure of environmental stress and is defined as:

$$E = (0.178xTS - 0.938xCWD - 6.61xPS)10^{-3} \qquad (10)$$

Where:

The parameters used in equation (10) were defined as following: TS is the standard deviation (SD) of the mean temperature over a year, expressed in degrees Celsius multiplied by 100; CWD (maximum climatological water deficit) is computed by summing the difference between monthly rainfall and monthly evapotranspiration, only when the difference is negative and PS (precipitation seasonalty) is the coefficient of variation in monthly rainfall values, or the SD expressed in percent of the mean value.

2.2.4.4. Estimation of C- sequestration from tree ring analysis

The age and diameter increment rates of each sample were determined from tree-ring analysis. Hence, the relationship between age and diameter, age and height of *V. paradoxa* was established using a non-linear regression.

The AGB of each individual tree was estimated by replacing D in equation (9) by its corresponding diameter derived from the tree-rings. Then the AGB of each individual tree over its life span was divided by the corresponding age derived from tree-ring analysis to obtain the annual biomass production (**Worbes and Raschke 2012**). Carbon stock and carbon sequestration were derived as representing 50% of the AGB (**Basuki *et al*. 2009**).

The estimates of both biomass and carbon stock for the stand were obtained by multiplying the average values by a given land-use of the sample trees by the densities recorded in that same land-use type.

2.2.4.5. Climate data

Mean monthly precipitation and temperature were provided by the meteorological station of Koutiala; and the Yanfolila climate data was obtained from the Bougouni meteorological station located at 80 km. The recorded meteorological data of rainfall covered a period of 45 years (1968-2012) for Koutiala (Figure 9a), 31 years (1982- 2012) for Yanfolila (Figure 9b). Temperature data for both sites was recorded for the last 31 years (1982-2012), see figure 10. Evapotranspiration data covering a 12-year period (2000-2012) were collected from the above mentioned meteorological stations for the two sites, respectively.

2.2.4.6. Statistical analyses

The climate-growth relationships were investigated through Pearson's correlation coefficient analysis between tree-ring index and climatic factors (rainfall and temperature). Pearson's correlation analysis was also applied to investigate the existence of similarities in *V. paradoxa* growth patterns of the two climatic zones. Annual and major seasonal precipitation (defined as the amount of rain recorded between June to September) and mean annual temperature of each site were considered. The ring-widths of the two sites were compared with a t-test. Data of carbon accumulated per year and over the life span of trees were subjected to a one-way ANOVA for both land-use types within the sites and between the sites using the statistical software SPSS (version 20.0). When the analysis proved to be significant at 5% level, mean separation was done using the least significant difference (LSD) test.

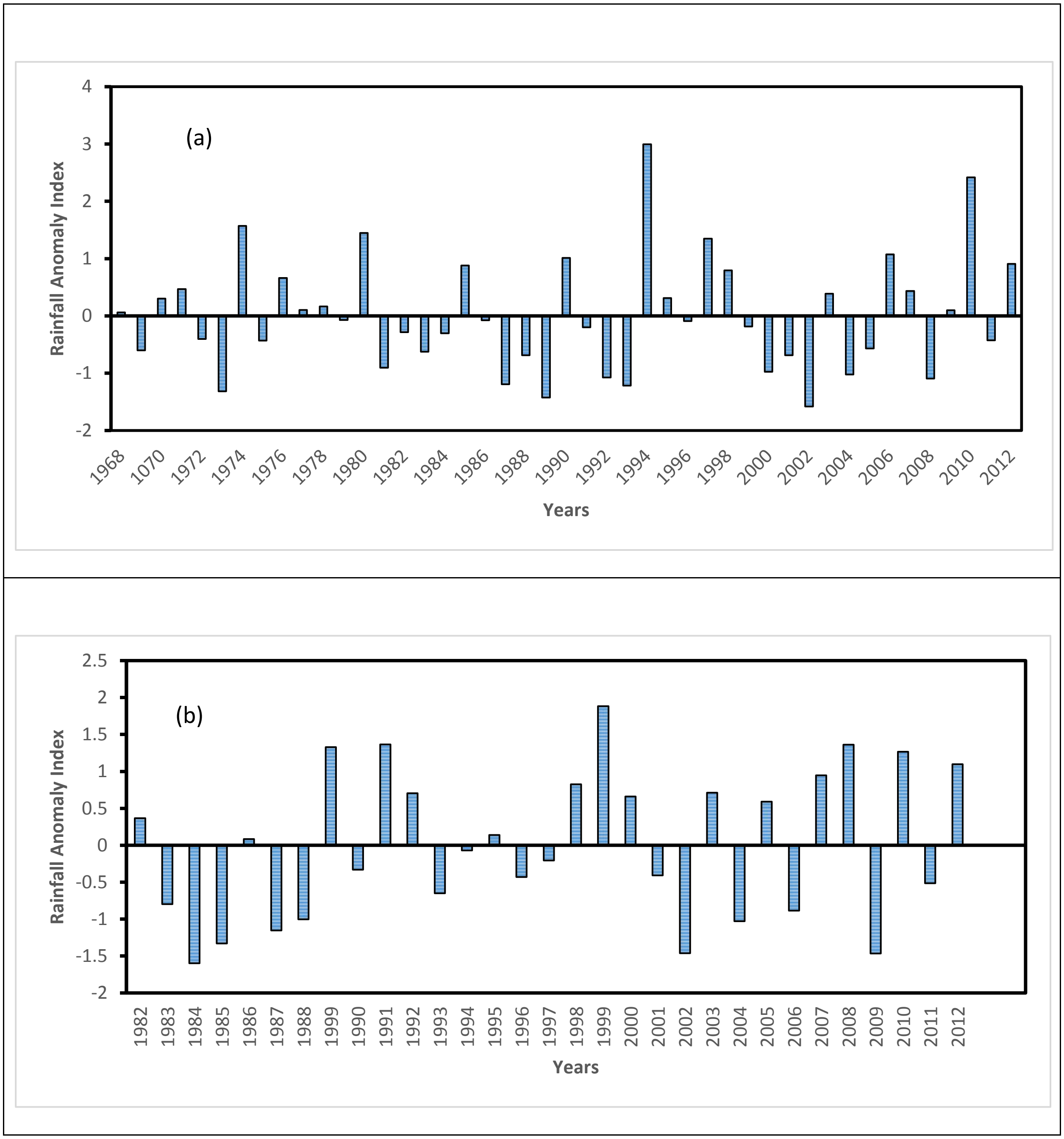


Figure 9: Annual rainfall anomalies in Koutiala (a) and Yanfolila (b) in southern Mali, West Africa

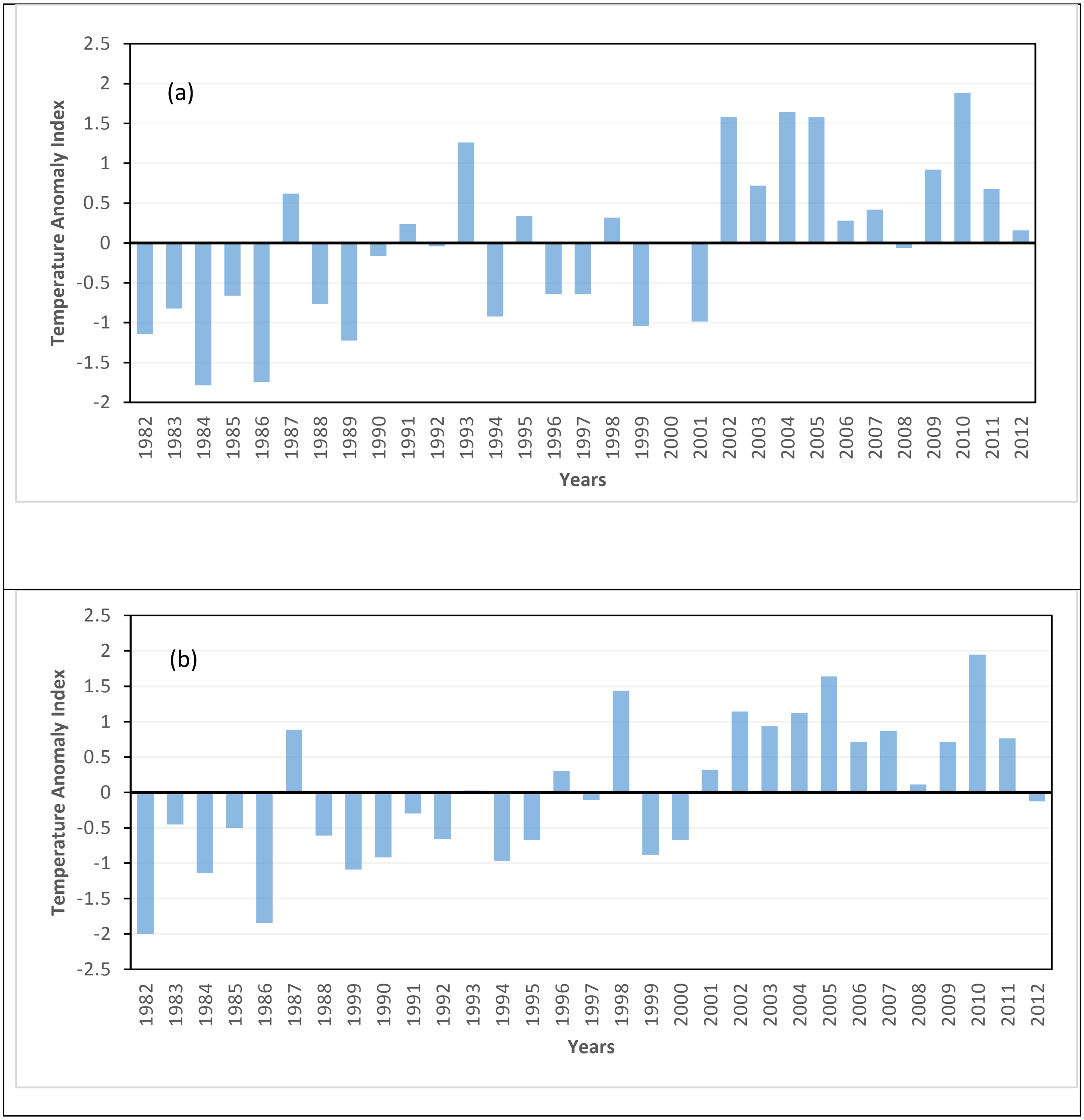


Figure 10: Annual temperature anomalies in Koutiala (a) and Yanfolila (b) in southern Mali, West Africa

CHAPTER III: RESULTS

3.1. Farmers' perceptions of climate change impacts on ecosystem services provided by the parklands

3.1.1 Socio-demographic characteristics of the respondents

The results show that farmers in the study areas were largely illiterate with the highest illiteracy rate observed in Yanfolila (Table 3). The average age of the farmers interviewed was 45 (±13) in Koutiala and 42 (±12) in Yanfolila. The average household size (number of person per household) was higher in Koutiala compared to Yanfolila and similar trend was observed for farm size. In contrast, the number of years of experience in farming as a head of household was higher in Yanfolila (Table 3).

All interviewed men were married at both sites whereas 87% and 96% of women were married in Koutiala and Yanfolila, respectively. Widows were 13% in Koutiala and 4% in Yanfolila. Farmers' main activity is rainfed agriculture in both sites, which increases their vulnerability to climate change.

3.1.2. Farmers' perceptions of climate change

More than 80% of the respondents in both sites have observed an increase in drought frequency making them more vulnerable as a result of crop failure (Table 4). However, the majority of the respondents indicated that the occurrence of floods has decreased but 30% of them thought otherwise. Even though, floods can partially damage crops, farmers generally preferred floods to drought because the latter tends to be more detrimental to crop production. A greater proportion of farmers was of the opinion that temperatures and number of hot days have increased across southern Mali (Table 4). About 11% of the respondents in Koutiala and 26% in Yanfolila indicated that there was no change in the number of hot days. In addition, a greater proportion of farmers perceived an increase in strong wind and dust at both sites. Thus, 36% of the respondents observed no change in strong wind and dust in Yanfolila, and they argued that formerly strong wind and dust were prevented by a high density of vegetation, which is now sparse. About 90% of the farmers said annual total rainfall used to be higher when they were young but the total amount had declined over the years. More than 51% of the respondents at both sites reported that the rains are now unpredictable and the onset tends to delay as the years progress. Most of the respondents observed that the rainy season starts late and rather ends earlier in southern Mali. According to the majority of the respondents, the duration of the rainfall has reduced from 6 months occurring between May and October) to 4 months at both sites. A decrease in rainfall amount was mentioned by 89% and 67% of the respondents in Koutiala and Yanfolila, respectively (Table 4). A few number of farmers from both sites did not perceived any change in rainfall pattern but they argued that the spatial distribution of rainfall is more variable over the last two decades.

The Chi-square results indicated that farmers' perceptions of climate change do not differ between the two sites (Table 5).

Table 6 shows the multinomial logit results of how farmers perceive variation in the selected variables as a result of changes in climate in both sites. It appears that four out of seven explanatory variables are significantly associated with farmer's perception of climate change in southern Mali (Table 6). Indeed, the multinomial logit analysis revealed that variables such as age, education level, farm size and gender are the main factors significantly influencing farmers' perception of climate change. In contrast, other variables like household size (number of person per household), experience in farming and marital status had no statistical effect on farmer's perception of climate change in southern Mali.

Aged farmers observed an increase in drought severity, temperature, strong wind and dust, and decrease in rainfall pattern as a result of climate change. Furthermore, when considering the ages of the farmers, the results show that the older farmers were able to perceive the changes in climatic variables compared to the young farmers. The probability of observing changes in climatic events increased with educational level of the farmer. Thus farmer with higher education perceived an increase in the following climatic variables: drought, floods, temperature, hot days, wind and dust in Koutiala whereas a change in rainfall pattern was observed in Yanfolila by this category of farmers (Table 6). Our results revealed that farm size was significantly associated with a perceived change in rainfall pattern in Koutiala at 10% level of probability.

Gender perception of changes in climatic variables (drought, floods, temperature, number of hot days, wind and dust and rainfall) was significantly different between the two sites. Male farmers were more able to perceive the changes in climatic variables compared to female farmers at both sites.

Table 3: Socio-demographic characteristics of the respondents of farmers' perceptions of climate change study in southern Mali, West Africa

Variables	**Sites**			
	Koutiala		**Yanfolila**	
Gender	**Frequency**	**Percentage**	**Frequency**	**Percentage**
Female	120	50	80	50
Male	120	50	80	50
Education level				
Illiterate	142	59.25	103	64.38
Primary school	77	32.17	32	20.4
Secondary school	21	9.2	25	16
Age group				
25-40	110	46	86	54
41-60	103	43	59	37
>60	27	11	15	9
Marital status				
Married	227	95	156	97
Widowed	13	5	4	3
	Mean	SD[1]	Mean	SD
Family size	11	±7.38	7	±4
Farm size (ha)	10	±5.1	7	±5
Experience in farming (year)	14	±10.45	15	±11

[1] SD=Standard Deviation

Table 4: Descriptive statistics of farmer's perceptions of climate variables in southern Mali, West Africa

Parameters		Sites			
		Koutiala		Yanfolila	
		Frequency	Percentage	Frequency	Percentage
Drought	Increase	200	83.33	115	72
	Decrease	24	10	18	11.25
	No change	16	7	27	17
Precipitation	Increase	10	4.17	18	11.25
	Decrease	213	89	107	67
	No change	17	7	35	22
Flood	Increase	88	37	39	24.37
	Decrease	139	58	91	56
	No change	13	5.40	30	19
Temperature	Increase	173	72	114	71.25
	Decrease	44	18.33	17	11
	No change	23	10	29	18.13
Number of hot days	Increase	166	69.17	105	66
	Decrease	48	20	14	20
	No change	26	11	41	26
Frequency of wind and dust	Increase	169	70.42	77	48.12
	Decrease	49	20.42	26	16.25
	No change	22	9.17	57	36
Onset of rainy season	later	122	51	111	69
	No change	60	25	8	7
	Not stable	58	24	41	25
End of rainy season	End early	197	82	108	68
	no change	20	8.33	11	7
	Not stable	23	10	41	26

Table 5: Chi-square test (χ²) between farmer's perceptions on both sites (Koutiala and Yanfolila) in southern Mali, West Africa

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	288.000[a]	272	.24
Likelihood Ratio	101.281	272	1.000
Linear-by-Linear Association	14.250	1	.000
N of Valid Cases	18		

a. 306 cells (100%) have expected count less than 5. The minimum expected count is 0.06.

Table 6: Results of multinomial regression of farmer's perceptions of climate change according to some explanatory variables in southern Mali, West Africa

A: Perception variable = **Drought**

Covariates	Sites			
	Koutiala		Yanfolila	
	Unchanged	Decreased	Unchanged	Decreased
Gender (1 if male)	-0.334 (0.601)	**-1.498 (0.594)****	**-4.046(1.052)*****	**-3.576(1.064)*****
HHsize (household size)	0.492 (0.709)	0.300 (0.556)	-0.4055 (0.544)	-0.142 (0.621)
Fsize (farm size in ha)	-0.895 (0.964)	-0.398 (0.767)	0.277 (0.435)	0.034 (0.496)
Age (age category of the respondent: 1=young active; 2=adult active; 3=older)	0.060 (0.385)	**-0.952(0.413)****	-0.356 (0.478)	-0.802 (0.588)
Field_mgt (number of years of experience in farming)	0.063 (0.324)	0.226 (0.271)	0.355 (0.322)	0.490 (0.389)
Status (marital status=1 if married)	-0.225 (0.871)	0.999 (1.096)	-0.726 (1.247)	-15.033 (1423.48)
Educ (level of education =0 if illiterate; 1 if primary; 2 if formal)	**-1.546 (0.747)****	**-1.018 (0.484)****	-0.168 (0.333)	-0.485 (0.408)
Number of observations	240		158	
Chi2	**38.5*****		**69.66*****	
Pseudo R^2	0.138		0.279	

B: Perception variable = **Flood**

Covariates	Sites			
	Koutiala		Yanfolila	
	Unchanged	Decreased	Unchanged	Decreased
Gender (1 if male)	-0.256 (0.715)	0.398 (0.307)	**-2.605(0.663)*** **	-0.550 (0.435)
HHsize (household size)	0.490 (0.816)	-0.377 (0.348)	-0.065 (0.551)	0.560 (0.422)
Fsize (farm size in ha)	-0.706 (1.109)	0.168 (0.491)	0.498 (0.453)	0.176 (0.338)
Age (age category of the respondent: 1=young active; 2=adult active; 3=older)	0.077 (0.445)	-0.084 (0.210)	0.004 (0.467)	0.230 (0.323)
Field_mgt (number of years of experience in farming)	-0.120 (0.364)	-0.090 (0.167)	0.042 (0.328)	0.002 (0.247)
Status (marital status=1 if married)	-0.908 (0.987)	-0.553 (0.639)	-0.542 (1.500)	-0.277 (1.301)
Educ (level of education =0 if illiterate; 1 if primary; 2 if formal)	**-1.411 (0.752)***	**-0.538(0.220)****	0.067 (0.367)	0.215 (0.291)
Number of observations	240		158	
Chi2	**16.65****		**30.52****	
Pseudo R^2	0.04		0.098	

C**:** Perception variable **= Temperature**

Covariates	Sites			
	Koutiala		Yanfolila	
	Unchanged	Decreased	Unchanged	Decreased
Gender (1 if male)	**-1.771 (0.617)****	**-1.737(0.448)*****	**-3.155 (0.772)*****	**-2.015(0.695)*****
HHsize (household size)	0.282 (0.602)	-0.034 (0.460)	-0.392 (0.519)	-0.691 (0.608)
Fsize (farm size in ha)	-0.848 (0.840)	0.701 (0.647)	0.593 (0.421)	0.427 (0.496)
Age (age category of the respondent: 1=young active; 2=adult active; 3=older)	0.055 (0.361)	**0.534 (0.279)***	-0.649 (0.485)	-0.400 (0.519)
Field_mgt (number of years of experience in farming)	-0.209 (0.273)	-5.055 (0.222)	0.143 (0.303)	0.310 (0.366)
Status (marital status=1 if married)	-0.522 (0.786)	-0.709 (0.625)	-13.933 (933.987)	0.214 (1.263)
Educ (level of education =0 if illiterate; 1 if primary; 2 if formal)	**-0.934 (0.519)***	-0.093 (0.295)	-0.048 (0.314)	-0.029 (0.380)
Number of observations	240		158	
Chi2	**50.01*****		**50.28*****	
Pseudo R^2	0.135		0.205	

D: Perception variable **= Hot days**

Covariates	Sites			
	Koutiala		Yanfolila	
	Unchanged	Decreased	Unchanged	Decreased
Gender (1 if male)	**-0.961 (0.519)***	**-1.366(0.406)*****	**-2.144(0.488)*****	-0.557 (0.686)
HHsize (household size)	-0.0545 (0.550)	0.105 (0.437)	-0.344 (0.452)	-0.999 (0.645)
Fsize (farm size in ha)	-0.176 (0.766)	0.373 (0.261)	0.583 (0.361)	0.098 (0.549)
Age (age category of the respondent: 1=young active; 2=adult active; 3=older)	-0.344 (0.359)	0.357 (0.261)	-0.160 (0.382)	0.356 (0.494)
Field_mgt (number of years of experience in farming)	0.027 (0.263)	-0.021 (0.209)	0.371 (0.268)	0.022 (0.394)
Status (marital status=1 if married)	-0.692 (0.789)	-0.674 (0.619)	-14.433 (920)	0.468 (1.329)
Educ (level of education =0 if illiterate; 1 if primary; 2 if formal)	**-0.821 (0.451)***	-0.241 (0.287)	-0.107 (0.275)	-0.359 (0.472)
Number of observations	240		158	
Chi2	**35.93*****		**38.12*****	
Pseudo R^2	0.092		0.148	

E: Perception variable **= Wind and dust**

Covariates	Sites			
	Koutiala		Yanfolila	
	Unchanged	Decreased	Unchanged	Decreased
Gender (1 if male)	-0.588 (0.505)	**-2.431(0.570)*****	**-1.482(0.406)*****	-0.396 (0.492)
HHsize (household size)	0.538 (0.599)	-0.164 (0.484)	-0.601 (0.405)	-0.490 (0.504)
Fsize (farm size in ha)	0.244 (1.427)	-0.410 (0.674)	0.126 (0.320)	0.515 (0.407)
Age (age category of the respondent: 1=young active; 2=adult active; 3=older)	-0.469 (0.371)	**-0.725 (0.321)****	-0.028 (0.316)	-0.042 (0.393)
Field_mgt (number of years of experience in farming)	0.269 (0.300)	-0.119 (0.227)	0.124 (0.233)	0.027 (0.285)
Status (marital status=1 if married)	0.051 (1.145)	-0.840 (0.605)	-0.480 (1.064)	-13.542 (950.614)
Educ (level of education =0 if illiterate; 1 if primary; 2 if formal)	-0.524 (0.411)	**-0.898 (0.372)****	-0.111 (0.258)	-0.226 (0.333)
Number of observations	240		158	
Chi2	**71.46*****		**21.57***	
Pseudo R^2	0.192		0.067	

F: Perception variable = **Rainfall**

Covariates	Sites			
	Koutiala		Yanfolila	
	Unchanged	Decreased	Unchanged	Decreased
Gender (1 if male)	-0.496 (0.874)	0.163 (0.655)	**-2.278(0.502)*** **	**2.163 (0.693)*** **
HHsize (household size)	-0.097 (1.006)	-0.722 (0.782)	0.418 (0.631)	0.358 (0.599)
Fsize (farm size in ha)	**-1.442 (0.843)***	1.273 (1.128)	-0.472 (0.523)	-0.658 (0.498)
Age (age category of the respondent: 1=young active; 2=adult active; 3=older)	1.094 (0.675)	**0.974 (0.576)***	0.984 (0.660)	**1.335 (0.640)** **
Field_mgt (number of years of experience in farming)	0.377 (0.457)	0.427 (1.182)	-0.336 (0.394)	-0.456 (0.374)
Status (marital status=1 if married)	-0.081 (1.336)	0.768 (1.182)	-0.661 (4068.819)	16.291(3189.002)
Educ (level of education =0 if illiterate; 1 if primary; 2 if formal)	-0.880 (0.683)	-0.267 (0.459)	**-0.770 (0.332)** **	0.300 (0.358)
Number of observations	240		158	
Chi2	14.62*		**52.55*** **[2]	
Pseudo R^2	0.067		0.195	

[2] ***, **, *=Significant at 1, 5 and 10% probability level, respectively. Standard errors in parentheses.

3.1.3. Farmer's perceptions of climate change drivers

Even though 23% and 36% of the respondents in Koutiala and Yanfolila respectively have no idea about the drivers of climate change, some of them listed God's will, deforestation and human behaviour as being the main drivers of climate change in southern Mali. Deforestation was the main driver identified by 63% of the respondents in Koutiala and 49% in Yanfolila. Most of the farmers indicated that total amount of rainfall was higher in the past because the vegetation was denser but due to deforestation, the vegetation has become sparse and the rainfall is therefore decreasing every year. There are also some spiritual considerations in explaining changes in climate. Indeed, 12% of those farmers interviewed in Koutiala and 9% in Yanfolila found human behaviour (i.e., abandoned and disrespectful attitudes of human beings to ancestral spirits) as a cause of climate change.

3.1.4. Perceived impacts of climate change on ecosystem services provided by the parklands

Farmers perceived that drought has been occurring once every two years in the last two decades (variability and not change which requires 30-year period of observations) with different intensity and severity at both sites. The erratic rainfall and its variable distribution negatively impact parklands and their provision of ecosystem services. In general, all the respondents are aware that climate change impacts negatively on the ecosystem services provided. According to most of the farmers, shea tree production is directly related to water availability. The respondents enumerated two major climate hazards (drought and wind) which could reduce the ecosystem services provided by shea trees. According to farmers' perceptions in the study areas, drought has more detrimental impacts on trees whereas wind is responsible for the dropping of flowers thus reducing fruiting. More than 82% of the farmers interviewed asserted that an early cessation of the rainy season and terminal drought results in low fruit set during the next fruiting season which occurs during the following dry season. In addition, more than 50% of the women have observed a decrease in the delivery of the ecosystem services provided by shea tree due to erratic rainfall in southern Mali.

3.1.5. Perceived ecosystem services provided by *Vitellaria* parklands

3.1.5.1. Provisioning services

Our findings showed that 100% of the respondents at both sites reported that parklands contribute to improve their livelihoods. The practice of the leaf pruning as fodder for livestock seems to be only applied in Koutiala because of the lack of pastures. Fruits are used as food and shea butter for cooking and soap production. The different parts (bark, leaves and roots) of shea tree and other species in parklands are used for the treatment of diseases (i.e., dysentery, malaria, relieve rheumatic, whitlow). Thus 100% of women used firewood for cooking, and parklands provide an important amount of that commodity. All the respondents were unanimous about the contribution of the parklands for better livelihood of farmers especially the shea butter tree. For instance, 82% of women in Koutiala and 87% of women in Yanfolila asserted that they sold one-third of the amount of their shea butter to meet family expenditure and the two-thirds are used for family consumption. The rest of the female respondents kept all their shea butter for family consumption. The income generated from shea butter products per production season per women was reported to be about 35,472±21,507 FCFA (USD 74±45) and 28,286±13,376 FCFA (USD 59±28) per person in Koutiala and Yanfolila, respectively.

3.1.5.2. Regulating services

Parklands are also providing regulating services that could potentially reduce farmer's vulnerability to climate change impacts. The most frequently mentioned regulating services of parklands are the protection of the soil against wind and water erosion, reduction of temperature through their shade as well as supporting services through improvement of soil fertility. Nearly 93% of the farmers interviewed in Koutiala and 61% of farmers in Yanfolila argued that parklands are widely used as windbreak that protect farmlands against soil erosion by reducing wind speed and runoff which are responsible for crop damage. The farmers also argued that farmlands without tree are more vulnerable to soil erosion and runoff. About 64% and 41% of the respondents in Koutiala and Yanfolila, respectively, recognized that biomass from parklands improves soil fertility with stable crop yield near the trees compared to the areas away from the trees. About 25% of the respondents at both sites had different opinions, but they recognized that the trees in the farmlands are very important for their livelihood. More than 90% of the farmers interviewed at both sites recognized that parklands provide shade and create good microclimate. The shade provided by parklands is a resting place for farmers and also mostly used by livestock during the dry season when the temperature is very high in southern Mali.

3.1.6. Farmer adaptation strategies to mitigate climate change

A total of six strategies were cited as being used to adapt to climate change (Figure 11). For instance, new varieties and diversification of crops are the main strategies adopted in Yanfolila and Koutiala, respectively to cope with decreasing precipitations. About 11% of the farmers interviewed in Koutiala mentioned parkland system as a strategy to increase and diversify farmer's production, while 8% of the respondents in Koutiala reported that they have adopted afforestation (planting food trees) as a way to reduce their exposure to climate change hazards and improve their livelihoods. Erosion control was adopted by 16% of the farmers in Koutiala against 4% of farmers in Yanfolila (Figure 11). This strategy helps farmer to sustain soil fertility in the farmlands and to conserve soil water. Reduced farm size was mentioned by 10% and 7% of the respondents, respectively in Yanfolila and Koutiala and this strategy is related to the availability of labour and equipment. Drought also often leads to migration of farmers to other sites and this was mentioned by 8% of the respondents in Koutiala against 11% in Yanfolila. Most farmers, 63% at both sites were obliged to carry out off-farm activities (e.g., mason, mechanic, carpenter, trader, and tailor) at the end of the rainy season to cope with food shortages.

Apart from technical responses that were cited as coping strategies, other coping strategies are spiritual (ritual ceremonies and organization of prayers in the mosques). According to most farmers, ritual ceremonies were performed to ask for God's mercy when confronted with drought. Thus, 22% and 25% of respondents in Koutiala and Yanfolila, respectively thought these practices were relevant and continue to apply them. In the past, ritual ceremonies were the only strategies applied by farmers. However, most of the farmers in the study sites have converted to Islam and therefore abandoned the ritual ceremonies in favour of prayers. The study showed that 72% and 74% of the respondents in Koutiala and Yanfolila, respectively thought that organizing prayer in the mosques when farmers are facing drought is an efficient measure.

3.1.7. Barriers to coping strategies adoption

Farmers in southern Mali are facing various barriers that make the adaptation strategies ineffective in their environment. Indeed, a large number of interviewees (more than 75%) reported that it is still difficult to overcome the climate challenges if they don't receive the assistance from the government. The descriptive analysis showed that the barriers to adaptation have not the same prevalence.

The respondents have listed a number of barriers (Table 7) that increase their vulnerability to climate.

- **Lack of financial means**

The lack of financial means was the main barrier that was expressed by more than 70% of the respondents on the study sites. According to the farmers, this lack of financial means included no facility to credit access and lack of government support. This lack of financial means increases their vulnerability to climate change and threatens their livelihoods.

- **Lack of workforce**

The farmers in Yanfolila are suffering more from lack of workforce (16%) as compared 8% to Koutiala. The active populations in Koutiala migrated less than those of Yanfolila for income generation work.

- **Lack of information about climate change**

A total of 16% and 3% of the respondents in Koutiala and Yanfolila have expressed the lack of knowledge about climate change. Moreover at both sites, none of farmers have received any training regarding climate issue.

- **No barriers to adopt strategies**

Only 3% of farmers have perceived no barriers to adapt to climate change in Koutiala. This type of farmers has better livelihood as compared with the others and they gained more from the cash crop like cotton and groundnut.

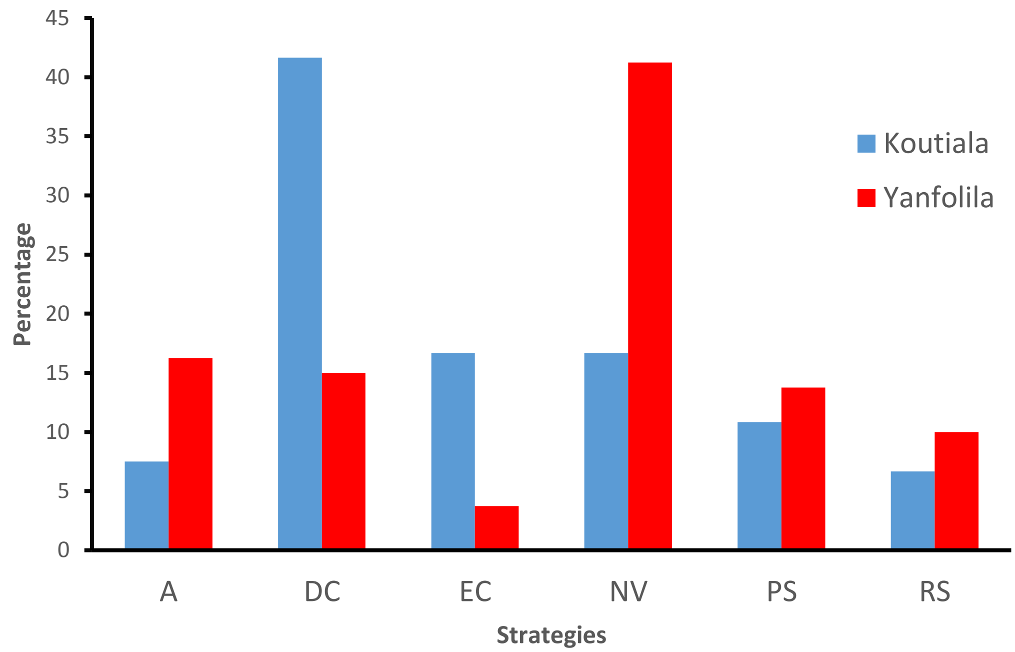


Figure 11: Farmer's adaptation strategies to deal with climate change in Koutiala and Yanfolila in southern Mali, West Africa

A=afforestation; DC= diversification of crops; EC= Erosion control; NV= New varieties adoption; PS=parkland systems; RS= reduce farm size

Table 7: Perceived barriers to adaptation to climate change by farmers (% of respondents) of Koutiala and Yanfolila in southern Mali, West Africa

Sites	barriers for farmers to adopt strategies			
	Lack of information on climate change	Lack of financial means	Lack of workforce	No barriers to adopt strategies
Koutiala	16	73	8	3
Yanfolila	3	81	16	0

3.2. *Vitellaria paradoxa* yield dynamics in agroforestry parkland systems and socio-economic characteristics of the households

3.2.1. Socio-economic sub-system

3.2.1.1. Descriptive statistics of household characteristics

Most of the household characteristics as shown in table 8 constitute the key determinants of farmers' livelihood. Some of these characteristics have values of the same magnitude in both sites and these include dependency ratio, landholding per capita, gross income per capita and % income from shea parklands while others (age of respondent, crop area, gross income, income per capita, shea density and fallow area) displayed different values (Table 8). Even though the family size is higher in Koutiala than Yanfolila, they have a higher gross income per household. In contrast the gross income per capita is higher in Yanfolia compared to Koutiala. A similar trend was observed for shea tree density per hectare, which was almost the double in Yanfolila. Reduced fallow size in Koutiala may be an indication of higher pressure on arable land in this site compared to Yanfolila.

3.2.1.2. Livelihoods typologies and household types

From the collected data, two household types were identified, i.e., type 1 as poor household, and type 2 as rich household (Figure 12a and 12b; Table 9). The type 1 household is composed of 83% (n = 97) households of Yanfolila against 81% (n = 64) households in Koutiala. The spider diagrams (Figure 12) clearly show the difference between the two types of households based on livelihood indicators and land production factor. The type 2 households are more based on cash crops like cotton and are considered as cotton based farmers. This type possesses large farmland size, larger household size and greater annual gross income. In contrast with the type 1 households, the contribution of shea tree (including sale of kernels, sale of butter and consumption of butter) to their annual gross income is higher than those of the type 2. Shea tree ecosystem services are one of the most important factors against poverty for type 1. A similar trend was observed concerning the distance between house and field and between both types of household for the same site.

Table 8: General description of household characteristics on the study sites in southern Mali, West Africa

Variables	Koutiala		Yanfolila	
	Average	SD	Average	SD
Age of the respondents	45	13	42	12
Labour availability (nb)	7.31	5.25	5.25	2.65
Dependency ratio	0.54	0.32	0.36	0.34
Household size (nb)	11	7.38	7.05	3.74
Landholding per capita (ha)	1.1	0.29	1.1	0.75
Farmland size (ha)	10.58	5.44	6.74	5
Maize area (ha)	2	0.98	2.44	1.76
Sorghum area (ha)	2.88	1.87	0.57	0.88
Millet area (ha)	2.16	1.59	0.12	0.48
Cotton area (ha)	3	2.76	1.43	2.21
Groundnut area (ha)	0.4	0.56	1.42	1.72
Cowpea area (ha)	0.45	0.66	0.38	0.5
Other area (ha)	0.14	0.28	0.4	0.45
Gross income (US dollars)	3735.29	2178.44	3015.18	2183.06
Gross income per capita (US dollars)	427.83	274.98	467.59	314.46
% income from cotton	35.74	24	22	13.22
% income from shea tree	6.21	3.07	7	4.1
Distance house to field (km)	2.57	1.61	3.4	1.4
Shea density in parklands ha^{-1}	16	10	27	15.30
Shea density in fallows ha^{-1}	13	8.30	23	11.7
Shea density protected areas ha^{-1}			18	6.50
Fallows area (ha)	1.02	2	6.35	8.52

SD= Standard deviation

Table 9: Descriptive statistics for key variables for each classified agent group derived from K-CA analysis for southern Mali

Variables	Sites	Agent group	N	Mean	Standard deviation
Labour availability (nb)	Koutiala	1	97	6	0.70
		2	23	11	10.43
		Total	120		
	Yanfolila	1	66	5	1.41
		2	14	7	2.82
		Total	80		
Land holding (ha)	Koutiala	1	97	9.37	2.56
		2	23	15.64	12.98
		Total	120		
	Yanfolila	1	66	5.57	2.17
		2	14	12.29	0.21
		Total	80		
Household size (nb)	Koutiala	1	97	9	2.12
		2	23	17	16.26
		Total	120		
	Yanfolila	1	66	6	2.12
		2	14	11	1.41
		Total	80		
Cotton area (ha)	Koutiala	1	97	2.43	0.40
		2	23	4.15	5.55
		Total	120		
	Yanfolila	1	66	1	0.37
		2	14	3.72	2.34
		Total	80		
Sorghum (ha)	Koutiala	1	97	2.59	1.12
		2	23	4.06	3.61
		Total	120		
Groundnut (ha)	Yanfolila	1	66	1.06	0.75
		2	14	3.11	0.25
		Total	80		
Gross income (US dollars)	Koutiala	1	97	2921.54	1632.55
		2	23	7167.19	6045.40
		Total	120		
	Yanfolila	1	66	2183.70	1348.37
		2	14	6935.03	1887.37
		Total	80		
Gross income per capita (US dollars)	Koutiala	1	97	397.95	209.17
		2	23	553.82	113.77
		Total	120		
	Yanfolila	1	66	413.57	227.19
		2	14	722.26	243.85
		Total	80		
% income from shea	Koutiala	1	97	7	2.41
		2	23	5	0.67
		Total	120		
	Yanfolila	1	66	8	2.73
		2	14	4	2.33
		Total	80		

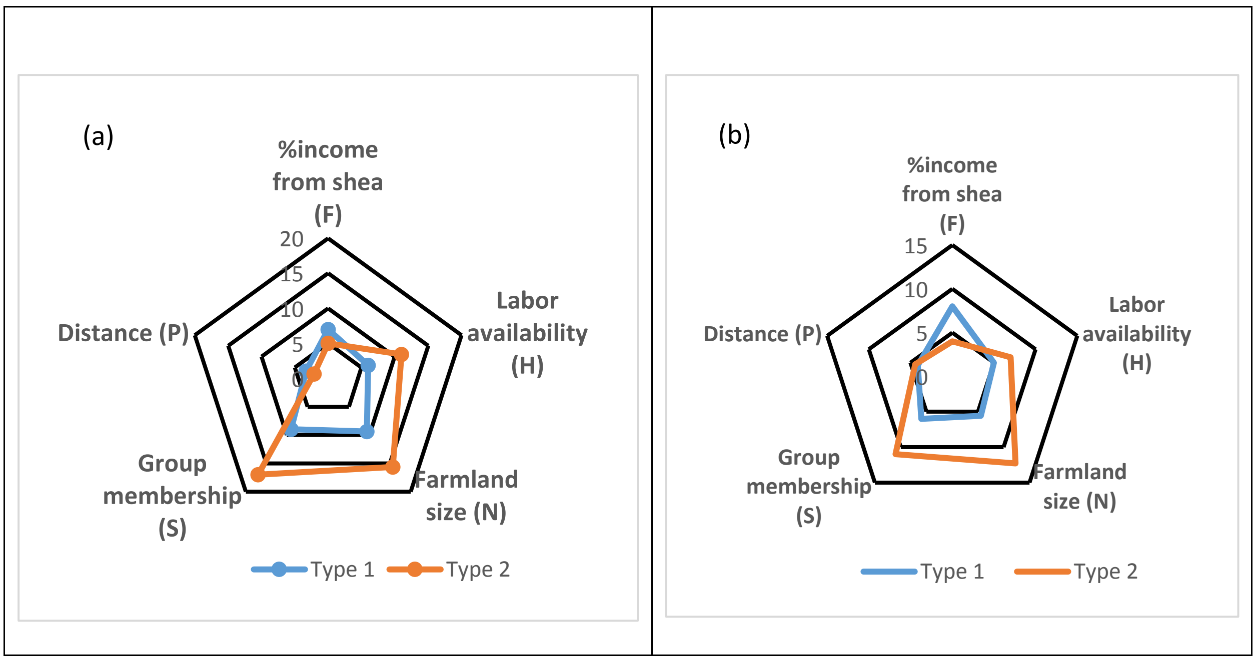


Figure 12: Household types based on livelihood indicators and land possession in Koutiala (a) and Yanfolila (b) in southern Mali, West Africa

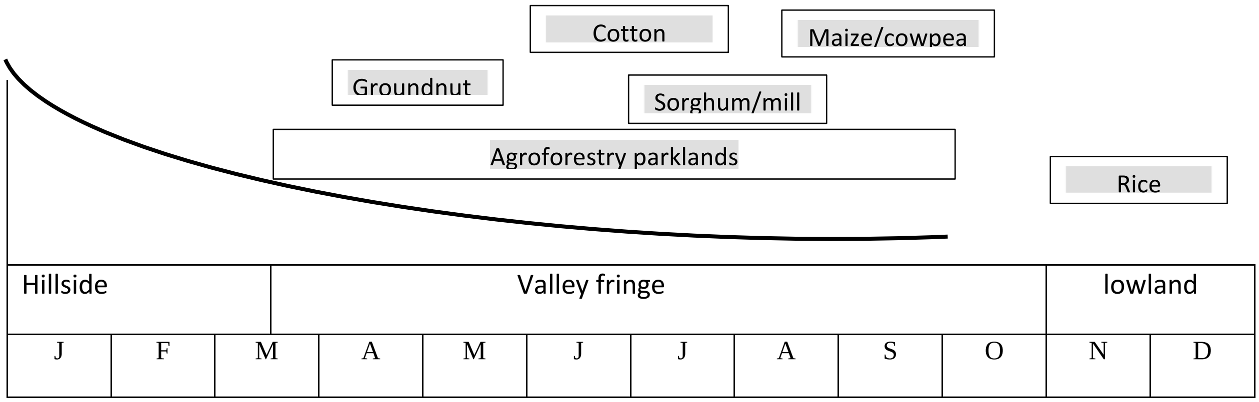
"H=human capital; N=natural capital; F=financial capital; S=social capital and P=physical capital"

3.2.2. Land tenure

The land access policy is traditional on the study sites, managed by the chief of the village. However, all the native farmers in the village have their own arable lands because they gain access to land by patrilineal inheritance systems. That means after the father the land is directly bequeathed to his son. In this context, women are not concerned about the inheritance of land. But their husbands provide them land for cultivation (vegetables) if they request. In most cases, those who borrowed arable land are migrants. Our results revealed that 98% of the farmers in Koutiala have inherited their land against 72% in Yanfolila. The rest borrows land. In Koutiala, land degradation and climate variability have led some farmers to migrate to the south in search for better arable land to reduce their vulnerability to climate change.

3.2.3. Agroforestry parklands management practices in the study sites

There were some similarities in management practices between the sites (Figure 13). In general, the fallow period is becoming shorter as a result of demographic pressure, which induced a lack of arable land. Two main cash crops namely cotton and groundnut, which are grown at both sites, are used to secure household food throughout the year. Lands are cleared before the onset of rainfall by men. About 100% of the farmers fertilized cotton and maize plots with mineral fertilizer (external inputs) at both sites. Organic manure is also applied on the plots of cotton and to less extend on maize plots. The plots of the two crops (cotton and maize) benefit from tillage before sowing whereas other crops (sorghum, millet) plots are sowed directly without tillage. In Koutiala farmland activities involve both men and women whereas in Yanfolila women are less engaged in farming (Figure 13). However, on both sites almost each woman has her own piece of land for groundnut or rice production. Moreover, women have the full responsibility for shea tree (shea nuts collected from the parklands) that contributes to support family food security (especially during food shortage). By doing so, the shea tree remains the mainstay as the income source of women.



a) Management of agroforestry parklands and *Vitellaria paradoxa* (Koutiala)

Gender	Activities or roles according to key stages					
Males	Transport organic manure	Clearing	Planting/sowing	Fertilizer/weeding (NPK, Urea)	Weeding	Harvesting	Transport harvest
Females		Clearing	Planting/sowing (vegetables)	Collect of shea Kernel/weeding	Weeding	Harvesting	

b) Management of agroforestry parklands and *Vitellaria paradoxa* (Yanfolila)

Gender	Activities or roles according to key stages					
Males	Transport organic manure	Clearing	Planting/sowing	Fertizer/weeding (NPK, Urea)	Harvesting		Transport Harvest
Females			Planting/sowing (vegetables)	Collect of shea kernel	Sale/kernel Weeding	Harvesting	

Figure 13: Cropping calendar and activities in agroforestry parklands in southern Mali, West Africa

3.2.4. Agronomic yield of crops

The yield of crop varied between sites and between crops. For instance, the main cash crop (cotton) yield was higher in Yanfolila compared to Koutiala (Table 10). In contrast, the maize yield is highly higher in Koutiala than that of Yanfolila. Similar trend was observed for the sorghum yield whereas the yield of second cash crop (groundnut) was higher in Yanfolila than Koutiala. However, mean annual millet yield recorded in Koutiala was 745.09±407.24 kg ha^{-1} $year^{-1}$ with a confidence interval of 827.26 kg ha^{-1} $year^{-1}$. The yield of crops is characterized by a high value of the standard deviations (Table 10).

3.2.5. Dry nut yield dynamics of shea tree in agroforestry parklands

The dry nut yield of shea tree varied according to the climatic gradient (Table 11). For instance, the dry nut yield of shea tree was 298.57± 272.73 kg ha^{-1} $year^{-1}$ (dry nut) in Yanfolila against 219.11± 146.5 kg ha^{-1} $year^{-1}$ (dry nut) in Koutiala (Table 11). A similar trend was observed for labor inputs (woman-day ha^{-1} $year^{-1}$) and shea density between both sites. In contrast, the mean diameter at breast height (DBH) of shea tree and its basal area in Koutiala are greater than those of Yanfolila as well as the parkland size (Table 11). In turn, the distance (km) from parklands to farmers' houses is far in Yanfolila compared to Koutiala.

In Koutiala, two out of six explanatory variables are significantly related to shea tree yield using log-linear regression analyses (Table 12). These two factors are labour inputs (woman-day ha^{-1} $year^{-1}$) and shea tree density. In Yanfolila, three out of six explanatory variables are significantly associated to the shea tree yield. These are labor inputs (woman-day ha^{-1} $year^{-1}$), parkland size and shea tree density. The yield elasticity or responsiveness to these variables indicates that an increase of 1% in labor (in case of Koutiala) and shea tree density would increase the yield (Table 12).

Table 10: Descriptive statistics of agronomic yield of crops in southern Mali, West Africa

Crops	Sites	Number of plot (n)	Mean (kg ha^{-1} $year^{-1}$)	SD	Values of confidence interval
Cotton	Koutiala	118	822.5	337.4	883.5
	Yanfolila	41	1165.8	2019	1836
Maize	Koutiala	120	1503.81	924.7	1668
	Yanfolila	78	1239.8	985.5	1417.03
Sorghum	Koutiala	120	745.50	489.6	829.5
	Yanfolila	31	634.62	280.2	922.12
Groundnut	Koutiala	70	298.29	266.71	362.85
	Yanfolila	65	1746	1524	2138
Millet	Koutiala	116	745.09	407.24	827.26

Table 11: Descriptive statistics of variables for sub-model agronomic yield dynamics of *Vitellaria paradoxa* in southern Mali, West Africa

Sites	Model	Number of plots (n)	Mean	SD	Values of confidence interval
Koutiala	Shea yield $P_{\_y\text{-}shea}$ (kg ha^{-1} $year^{-1}$)	120	219.11	146.5	245.35
	Labor input (I_{shea})	120	70	17	73
	Parkland size (m^2) ($P_{areashea}$)	120	105,762.5	54,375.9	11,741.35
	DBH (cm) shea ha^{-1} ($I_{sheadbh}$)	120	118.92	32.07	125.04
	Shea basal area (m^2 ha^{-1}) ($P_{sheabasalarea}$)	120	2.27	11.86	4.54
	Shea density ha^{-1} ($I_{sheadensity}$)	120	16.39	6.31	17.57
	Distance (km) village to field ($I_{distance}$)	120	2.57	1.61	2.96
Yanfolila	Shea yield $P_{\_y\text{-}shea}$ (kg ha^{-1} $year^{-1}$)	80	298.57	272.73	367
	Labor input (I_{shea})	80	82	20	85.31
	Parkland size (m^2) ($P_{areashea}$)	80	67,437.5	49,249.1	78,836.6
	DBH (cm) shea ha^{-1} ($I_{sheadbh}$)	80	95.28	20.35	100
	Shea basal area (m^2 ha^{-1}) ($P_{sheabasalarea}$)	80	0.75	0.31	0.82
	Shea density ha^{-1} ($I_{sheadensity}$)	80	26.5	7.11	29.8
	Distance (km) village to field ($I_{distance}$)	80	3.4	1.4	3.73

Table 12: Log-linear regressions for *Vitellaria paradoxa* dry nut yield in agroforestry parklands in southern Mali, West Africa

Sites	Agroforest yield model	Unstandardized coefficient: yield elasticity (β)	Standard error of β (σ_β)	Confidence interval of β at 95% level
Koutiala	Ln of shea yield ln($P_{\_y\text{-}shea}$) n=120; R^2 =0.27; mse = 0.63; p= 0.0000 (constant)	-2.61	2.46	2.27
	Ln of labor input ln(I_{shea})	**0.90****	0.23	1.3
	Ln of parkland size ln($P_{areashea}$)	0.02	0.13	0.27
	Ln of mean DBH shea per ha ln($I_{sheadbh}$)	0.40	0.34	1.09
	Ln of shea basal area ln($P_{sheabasalarea}$)	-0.05	0.13	0.21
	Ln of shea density ln($I_{sheadensity}$)	**0.68****	0.17	1.02
	Ln of distance ln($I_{distance}$)	-0.10	0.09	0.09
Yanfolila	Ln of shea yield ln($P_{\_y\text{-}shea}$) n=80; R^2 =0.49; mse = 0.63; p= 0.0000 (constant)	4.32	56.79	117.52
	Ln of labor input ln(I_{shea})	**1.80****	0.37	2.54
	Ln of parkland size ln($P_{areashea}$)	**-0.37****	0.10	-0.16
	Ln of mean DBH shea per ha ln($I_{sheadbh}$)	-1.20	11.95	22.61
	Ln of shea basal area ln($P_{sheabasalarea}$)	0.63	5.97	12.53
	Ln of shea density ln($I_{sheadensity}$)	**0.84****	0.26	1.36
	Ln of distance ln($I_{distance}$)	0.19	0.15	0.50

3.2.6. Simulated shea tree dry nut yields and validation of the model

Five simulations were ran based on the scenarios described on the table 2 and were averaged for each site. In Koutiala the simulations average was 186.60±97.50 kg ha^{-1} year^{-1} against 227.57±149.24 kg ha^{-1} year^{-1} in Yanfolila. Based on our simulations these findings (shea tree dry nut yield) were related to the amount of rainfall of the previous year. The simulations results have similar trend with those of derived from the surveys (219.11±146 kg ha^{-1} year^{-1} in Koutiala against 298.57±272.73 kg ha^{-1} year^{-1} in Yanfolila). Moreover, the results derived from our simulations are consistent with those of the survey as well as those of the literature. On the other hand, the logic of the current model is correct, which validates the model (ABM) for shea tree yield simulation at both sites. The interface of the model and some examples of simulations are presented in the figure 14, 15.

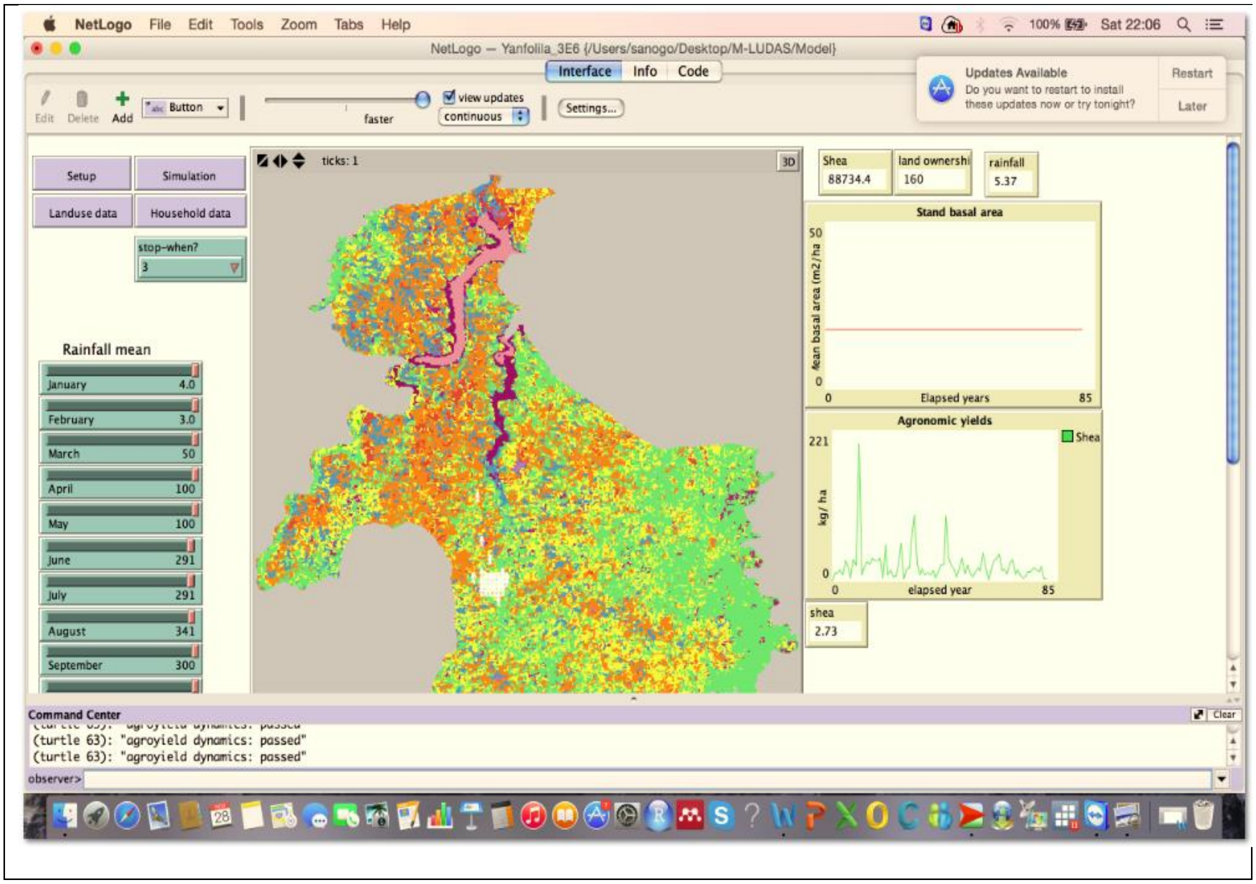


Figure 14: Interface of the agent-based model developed for *Vitellaria paradoxa* yield simulations for southern Mali, West Africa

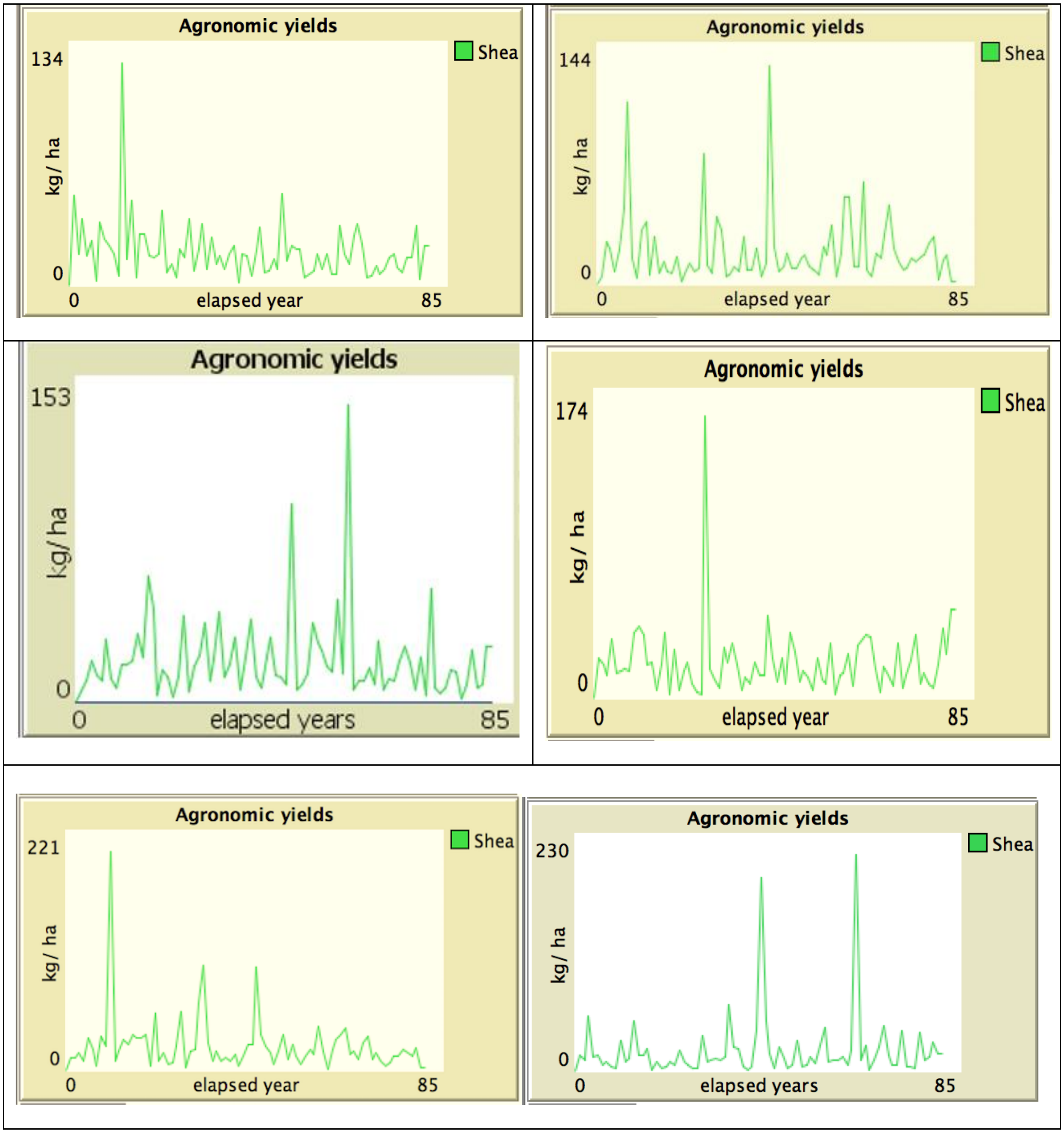


Figure 15: Example of *Vitellaria paradoxa* yield simulations using agent-based modelling for southern Mali, West Africa

3.3. Fractal scaling of *Vitellaria paradoxa* carbon stocks estimation

3.3.1. Applicability of FBA for *Vitellaria paradoxa*

Mean DBH of sample trees ranged from 4.64±1.14 to 36.54±2.04 cm in Koutiala whereas the range for Yanfolila was 5.47±1.43 to 37.95±4.05 cm (Table 13). The relationship between stem diameter and tree height differed between sites for lower diameters but converged for diameters above 32 cm.

In total, 3075 and 2857 branching points were observed on 30 trees in above and belowground in Koutiala, respectively. The values were 3986 and 3761 branching points on 40 trees in above and belowground in Yanfolila, respectively. The p and q were plotted against parent diameters/root diameters (Figures 16, 17). The results revealed very low R^2 (ranged between 0.01 and 0.06 for p and 0.001 to 0.02 for q) values of the relationship between p and q in above and belowground at both sites (Figures 16, 17). The weak relationship for p and q with parent diameter/root diameters indicated that the FBA model is applicable for our studied species (*V. paradoxa*). Moreover, the independence of the parameters p and q with diameters/proximal root diameters suggests self-similarity across multiple scales.

3.3.2. Link length and diameter relationship

The link length and diameter/proximal root diameter relationship for *V. paradoxa* trees components (above and belowground) was not linear separately (Table 14). Therefore, all link length and diameter relationship was significant (R^2 = 0.40 and R^2 = 0.42) for aboveground at both sites (Table 14).

The average link length derived from each tree components (twig, branch and wood) for above and belowground had similar trend. These link lengths increase from the twigs to the wood in above and belowground for *V. paradoxa.* The link length was one of the main inputs in the model for the generation of the scaling coefficient “a” and “b” for above as well as belowground biomass.

Table 13: Characteristics of the samples of *Vitellaria paradoxa* for FBA model application for southern Mali, West Africa

Class of diameter	Koutiala			Yanfolila		
	N	Mean DBH (cm)	Mean height (m)	N	Mean DBH (cm)	Mean height (m)
3 - 7 cm	4	4.64±1.14	1.84±0.18	5	5.47±1.43	2.67±0.77
7 - 10 cm	4	8.03±1.17	2.61±0.48	4	8.57±0.49	3.36±0.51
10 - 14 cm	3	11.70±1.63	3.46±0.34	4	13.00±1.06	3.79±0.45
14 - 24 cm	10	20.57±3.76	4.47±0.64	14	18.83±2.89	4.74±0.45
24 - 32 cm	4	28.84±3.12	6.60±1.75	7	28.78±1.67	6.11±0.71
>32 cm	5	36.54±2.04	9.09±0.81	6	37.95±4.05	10.46±1.32
Total	30			40		

Note: N= sample number per class of diameter

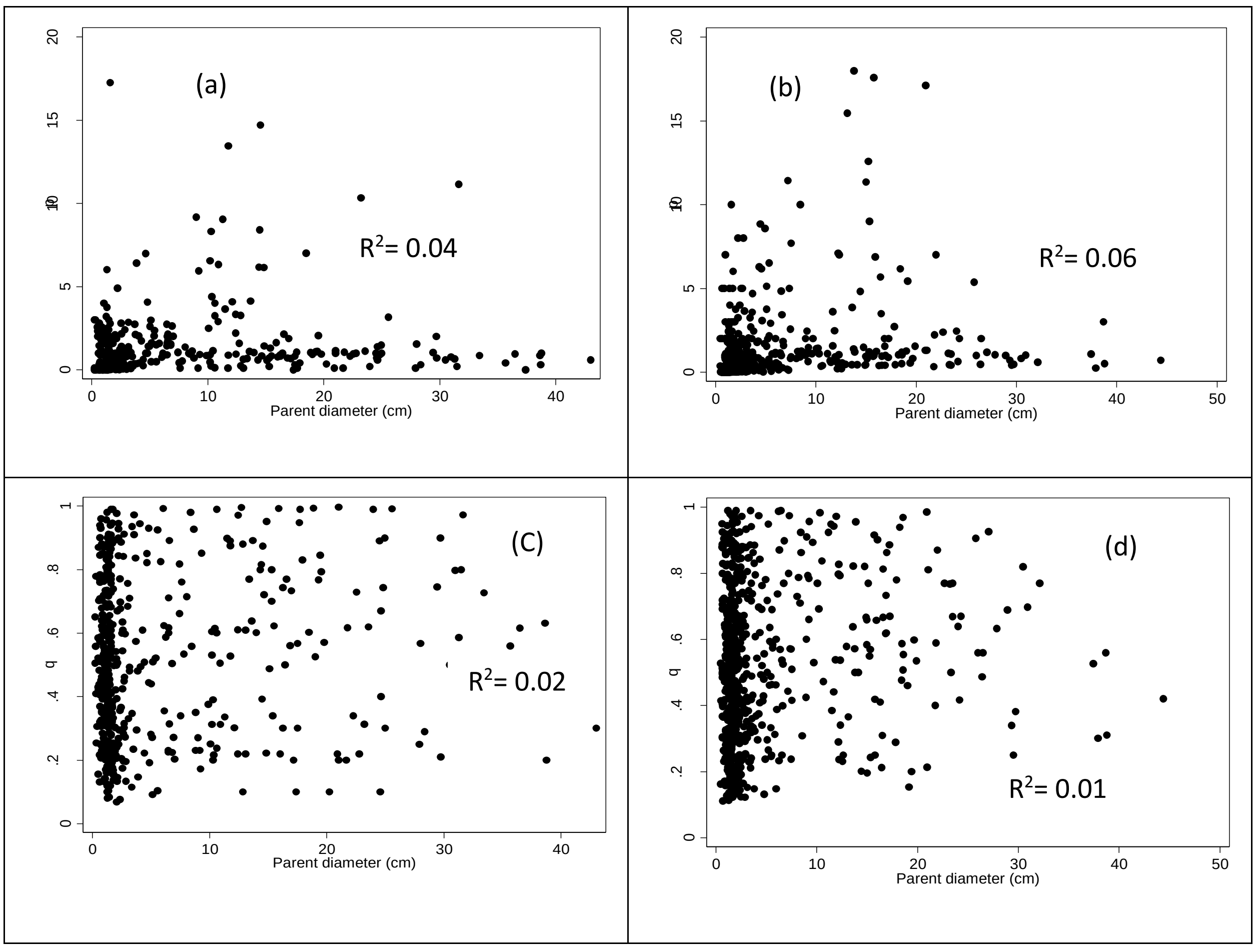


Figure 16: Relationship between parent diameter and p and q values in Koutiala (a, c) and in Yanfolila (b, d) for *Vitellaria paradoxa* in aboveground for southern Mali, West Africa

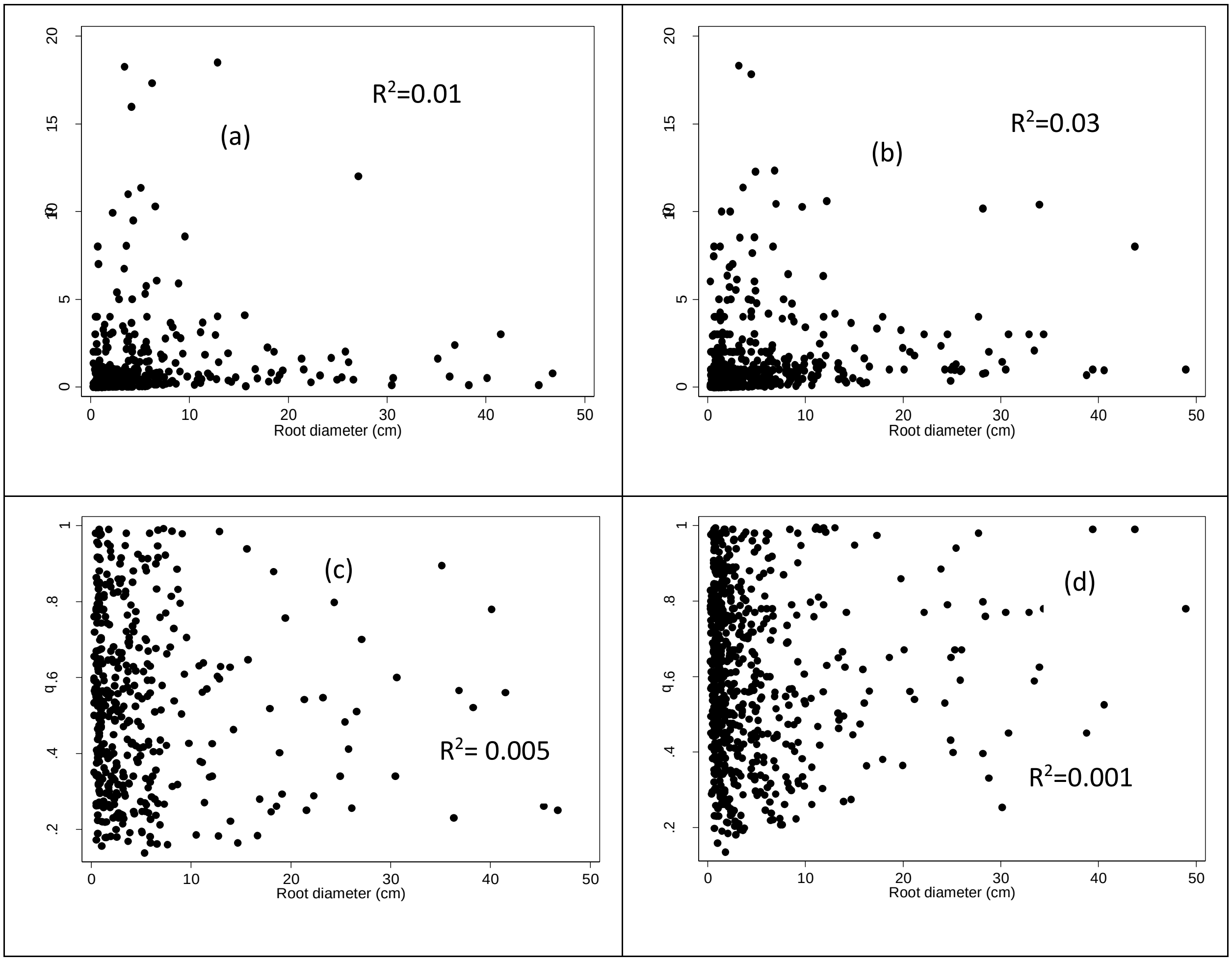


Figure 17: Relationship between root diameter and p and q values in Koutiala (a, c) and in Yanfolila (b, d) for *Vitellaria paradoxa* in belowground for southern Mali, West Africa

Table 14: Linear regression models relating link length (cm) to link diameter for *Vitellaria paradoxa* for southern Mali, West Africa

	Koutiala		Yanfolila	
	Above-ground	Below-ground	Above-ground	Below-ground
Twig (D above and below-ground ≤ 1.99 cm) length (cm)				
Intercept	1.11	0.77	1.33	0.89
Slope	0.01	0.03	0.01	0.14
R^2	0.04	0.20	0.004	0.21
P	0.001	0.0001	0.36	0.0001
Branch (D above and below-ground =2-10 cm) length (cm)				
Intercept	2.86	4.41	2.31	4.36
Slope	0.12	0.07	0.08	0.07
R^2	0.15	0.0002	0.2	0.001
P	0.001	0.57	0.0001	0.18
Wood (D above and below-ground > 10 cm) length (cm)				
Intercept	14.22	16.01	13.39	16.53
Slope	0.97	1.01	0.69	0.61
R^2	0.18	0.005	0.23	0.01
P	0.0001	0.45	0.001	0.96
All links				
Intercept	0.18	2.75	0.54	2.95
Slope	0.07	0.09	0.06	0.09
R^2	0.40	0.002	0.42	0.01
P	0.0001	0.0001	0.0001	0.0001

3.3.3. Branching parameters for FBA model

Table 15 shows the tree parameters for above as well as belowground biomass in the study sites. The current study revealed some similarities in the values between the above and belowground parameters.

In Koutiala, the average number of branches per branching point in aboveground is less than those recorded for the belowground (Table 15). Similar trend of the average number of branches per branching point was observed in Yanfolila. At both sites the root of the species *V.paradoxa* had more branches than the aboveground parts. The results in the table 15 show that 2.6 and 2.5 branches at each node (belowground) as compared to aboveground parts, 2.3 and 2.2 branches at each node in Koutiala and Yanfolila, respectively. The p value is higher for above and belowground which indicated that the link cross-sectional area before branching was greater than the sum of the cross-sectional area of links after branching point.

The weak relationship (or negligible) for p and q with parent diameter/proximal root diameters confirmed the applicability of the FBA model for *V. paradoxa*. The tapering coefficient of *V. paradoxa* was higher in aboveground at each site compared to belowground. Furthermore, it was slightly higher in the Sudano Sahelian zone (Koutiala) as compared to the Sudano Guinea zone (Yanfolila). The average link length derived from each tree component (twig, branch and wood) for above and belowground had length values of the same magnitude. By so doing, the parametrization did not used an average value for link length for all components, but used an average link length for each component for above and belowground. The wood density for wood was included for the three components (twig, branch and wood) and this value was 0.72 (±0.03) in Yanfolila and 0.74 (±0.01) in Koutiala.

Table 15: Average (SD) *Vitellaria paradoxa* main branching parameters for FBA model for southern Mali, West Africa

Parameters	Koutiala				Yanfolila			
	Aboveground		Belowground		Aboveground		Belowground	
	Aver	SD	Aver	SD	Aver	SD	Aver	SD
Number of branch per branching point (nb)	2.3	0.27	2.6	0.50	2.2	0.34	2.5	0.43
P (change in cross section area)	1.01	0.83	1.17	1.13	1.05	1.03	1.27	1.10
Q (relative allocation to largest offspring)	0.50	0.25	0.53	0.22	0.53	0.23	0.59	0.21
Tapering coefficient	0.15	0.16	0.06	0.03	0.11	0.19	0.04	0.07
Twig (D above and below-ground ≤ 1.99 cm) length (cm)	13.24	9.20	26.85	23.79	14.07	9.99	35.14	31.07
Branch (D above and below-ground =2-10 cm) length (cm)	22.88	20.85	61.81	55.44	20.25	14.29	65.68	60.95
Wood (D above and belowground > 10 cm) length (cm)	66.78	54.73	31.17	28.77	70.65	60.45	48.70	44.15
Wood density (g cm^{-1})	0.74	0.01	0.74	0.01	0.72	0.03	0.72	0.03

SD: standard deviation, D: diameter

3.3.4. Fractional branch analysis output and allometric equations

The FBA model derived the scaling coefficients for aboveground and the proximal root biomass (belowground) of *V. paradoxa* (Table 16). These results of allometric scaling suggested a greater variation among the tree components (twig; branch and wood) for the "b" factor around the universal value of 8/3 (= 2.67) (Table 16). Our results of allometric scaling for *V. paradoxa* showed that, the values for aboveground biomass (2.64 and 2.65) were greater than those of the proximal root diameter biomass (2.35 and 2.38) in Koutiala and Yanfolila, respectively (Table 16). The FBA model for belowground only simulates the proximal root biomass and not the remaining biomass (like taproot and other roots related to taproot).

The ratios of cross-sectional area of the stem and sum of proximal roots varied according to the site. Thus in the Sudano Sahelian zone (Koutiala) with lower rainfall, the value of the ratio of cross-sectional area (CSA) of the stem and sum of proximal roots was 0.68 while the value for the Sudano Guinea zone (Yanfolila) was 0.70. The figure 18 shows that the sum of proximal roots explained 92% ($R^2 = 0.92$) of the variations in the CSA of the stem in Koutiala and 91% ($R^2 = 0.91$) in Yanfolila (Figure 18).

Based on the allometric equations developed (table 16) the carbon stocks of belowground biomass estimates were depicted against the stem diameter (Figure 19). This relationship between below-ground carbon stocks and stem diameter reveals a good relationship. It's explained 96% ($CSA = 0.0604D^{2.12}$; $R^{2 =}$ 0.96; n = 30, $p < 0.0001$) and 94% ($CSA = 0.0551D^{2.14}$; $R^2 = 0.94$; n = 40, $p < 0.0001$) of the variation in the belowground carbon stocks in Koutiala and Yanfolila, respectively (Figure 19). Therefore, the stem diameter could be a good predictor for belowground carbon stocks for *V. paradoxa* in the study sites.

Table 16: Allometric equations ($B=aD^b$) for *Vitellaria paradoxa* generated through FBA model for southern Mali, West Africa

	Koutiala		Yanfolila	
	Scaling	Coefficients	Scaling	Coefficients
Aboveground	a	b	a	b
Total biomass	0.062	2.64	0.052	2.65
Branch biomass	0.0014	2.90	0.0045	3.17
Twig biomass	0.0209	1.50	0.0242	2.10
Belowground				
Proximal root biomass	0.039	2.35	0.035	2.38

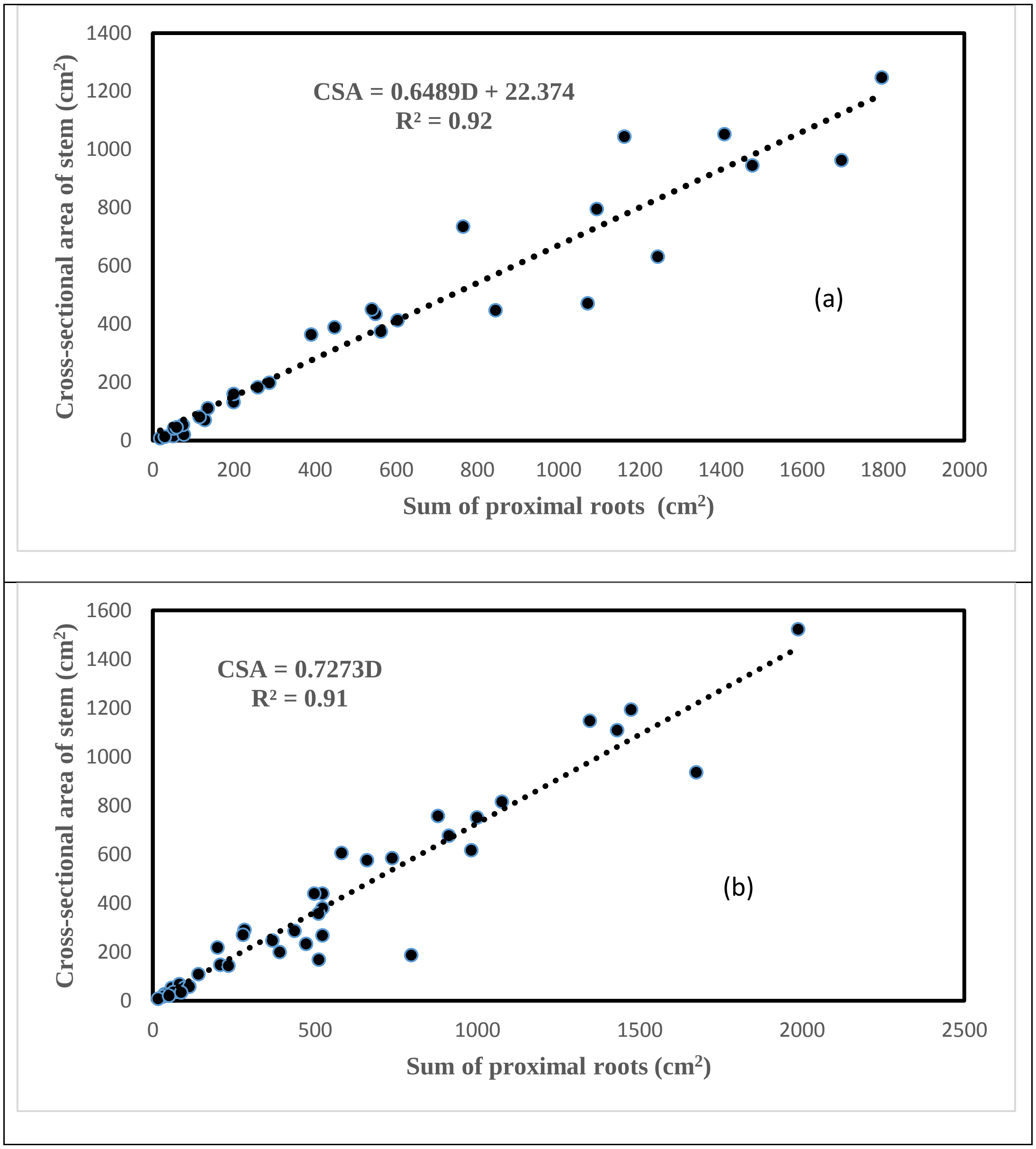


Figure 18: Relationship between cross-sectional area of the stem and sum of proximal roots of Vitellaria paradoxa in Koutiala (a) and Yanfolila (b) in southern Mali, West Africa

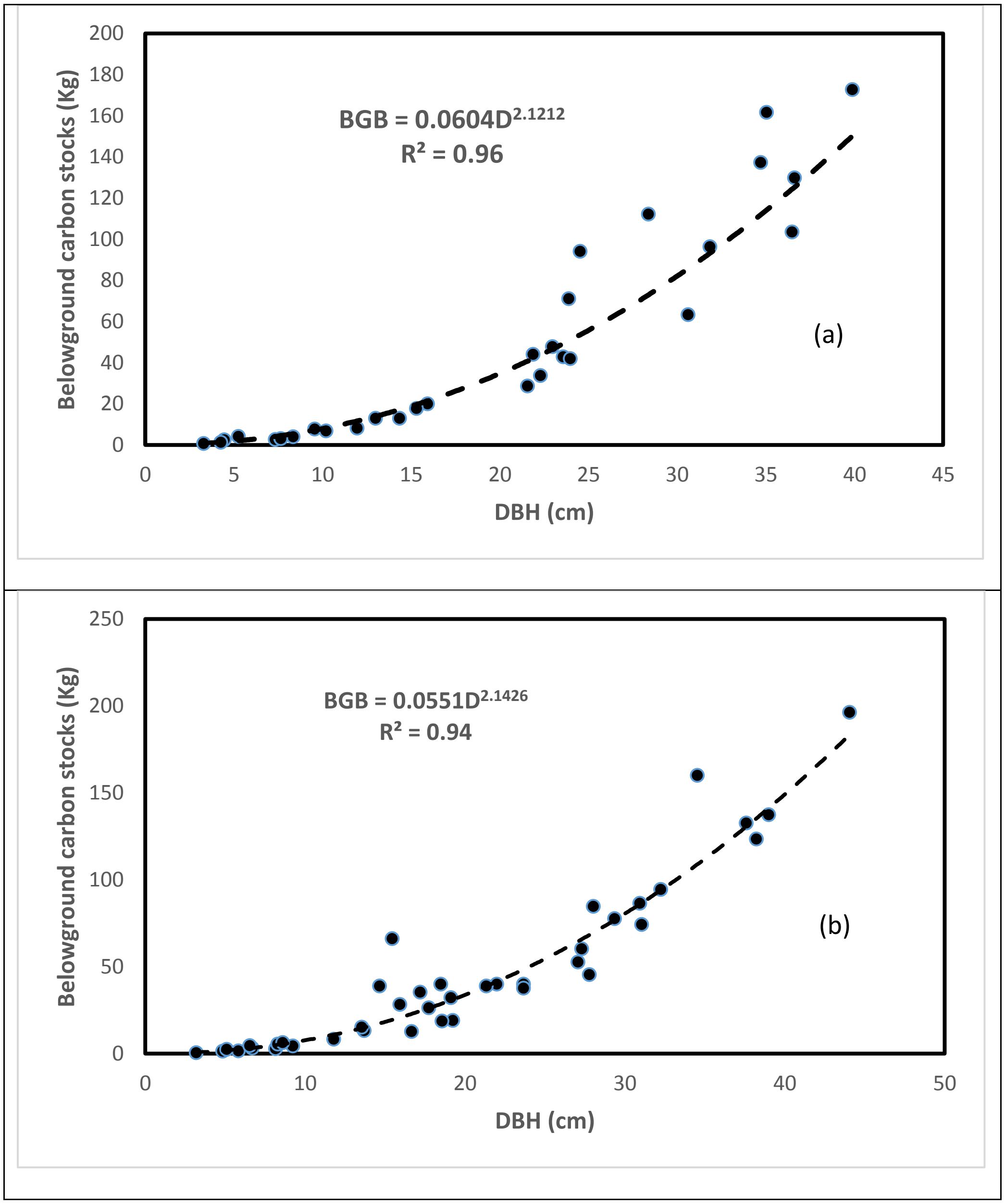


Figure 19: Relationship between belowground carbon stocks and stem diameter of *Vitellaria paradoxa* in Koutiala (a) and Yanfolila (b) in southern Mali, West Africa

3.3.5. Above and belowground carbon stocks estimation for *Vitellaria paradoxa*

The equations for estimating the aboveground biomass of *V. paradoxa* were $AGB = 0.062D^{2.64}$ and $AGB = 0.052D^{2.65}$ and for the belowground biomass $BGBi = 0.039D_i^{2.35}$ and $BGB_i = 0.034D_i^{2.38}$ in Koutiala and Yanfolila, respectively. The table 17 displayed the carbon stocks derived from the allometric equations developed for above and belowground. A pair-wise analysis showed no significant difference ($p > 0.05$) for the carbon stock in above and belowground for *V. paradoxa* between the study sites (Table 17).

3.3.6. Ratio below to aboveground carbon stocks of *Vitellaria paradoxa*

The root to shoot ratio (R/S) is used to estimate belowground carbon stocks. In the current study the ratio between belowground to aboveground carbon stocks were 0.36 and 0.39 in Koutiala and Yanfolila, respectively. The aboveground carbon stocks explained 90% ($R^2 = 0.90$) of the variation in the belowground carbon stocks in Koutiala and 89% ($R^2 = 0.89$) in Yanfolila (Figure 20). Thus, the stem diameter (aboveground) is a good predictor of the proximal root carbon stocks as shown in the figures 19 to 21.

3.3.7. Fractional branching analysis model validation

The regression coefficients were used to examine the strength and significance of the models. The linear model of the data for the above and belowground carbon stocks against the diameter at breast height/proximal root diameter has yielded R^2 values (Table 18, Figure 19) ranging from 0.87 to 0.93 between the carbon stocks and the diameters at both sites. Thus, the higher values of R^2 indicated that the carbon prediction model provides a good fit to the data. Moreover, the standard error of the estimate (SEE) was 0.051 (5.1%) in Koutiala as compared to 0.014 (1.4%) in Yanfolila for aboveground carbon stocks (Table 18). The results showed that the F-value for the regression model is significantly different from zero $F(1, 28) = 217.17$, $p < 0.0001$ in Koutiala and $F(1, 38) = 355.57$, $p < 0.0001$ in Yanfolila for aboveground carbon stocks which indicated a positive linear relationship between the carbon and diameter/proximal root diameter. Similar results (high value of R^2, low standard error of the estimate and F different from zero) were observed for the belowground carbon stocks which validate the models at both sites (Table 18).

Table 17: Carbon stocks (Mg C ha^{-1}) in above and belowground biomass by *Vitellaria paradoxa* in southern Mali, West Africa

Sites	Aboveground		Belowground	
	Mean	Standard Error	Mean	Standard Error
Koutiala	2.16a	0.44	0.80a	0.15
Yanfolila	3.21a	0.60	1.26a	0.21

Note: Data affected with the same letter in the same column are not statistically different at 95%.

Table 18: Parameter estimate and performance of developed model of *Vitellaria paradoxa* for southern Mali, West Africa

Sites		N	Fractal model	R^2	SEE	F value	Sign
Koutiala	Aboveground	30	$AGB=0.062D^{2.64}$	0.89	0.051	217.17	p<0.0001
	Belowground	30	$BGB_i=0.039D_i^{2.35}$	0.93	0.014	355.57	p<0.0001
Yanfolila	Aboveground	40	$AGB=0.052D^{2.65}$	0.87	0.052	245.92	p<0.0001
	Belowground	40	$BGB_i=0.035D_i^{2.38}$	0.90	0.016	336.74	p<0.0001

N = sample number; R^2 = coefficient of determination; SEE = Standard error of the estimate; Sign = level of significance.

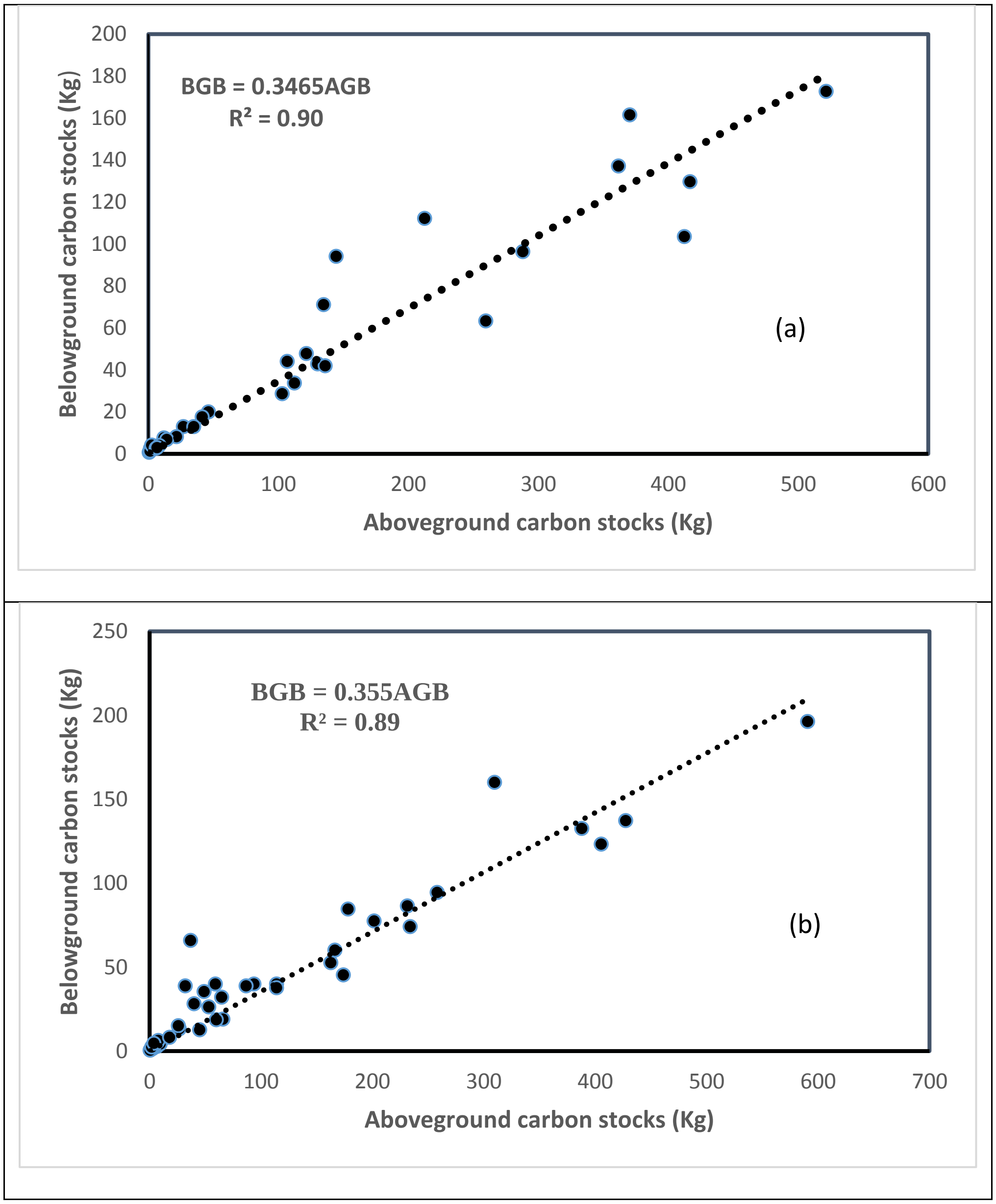


Figure 20: Relationship between aboveground and belowground carbon stocks of *Vitellaria paradoxa* in Koutiala (a) and in Yanfolila (b) for southern Mali, West Africa

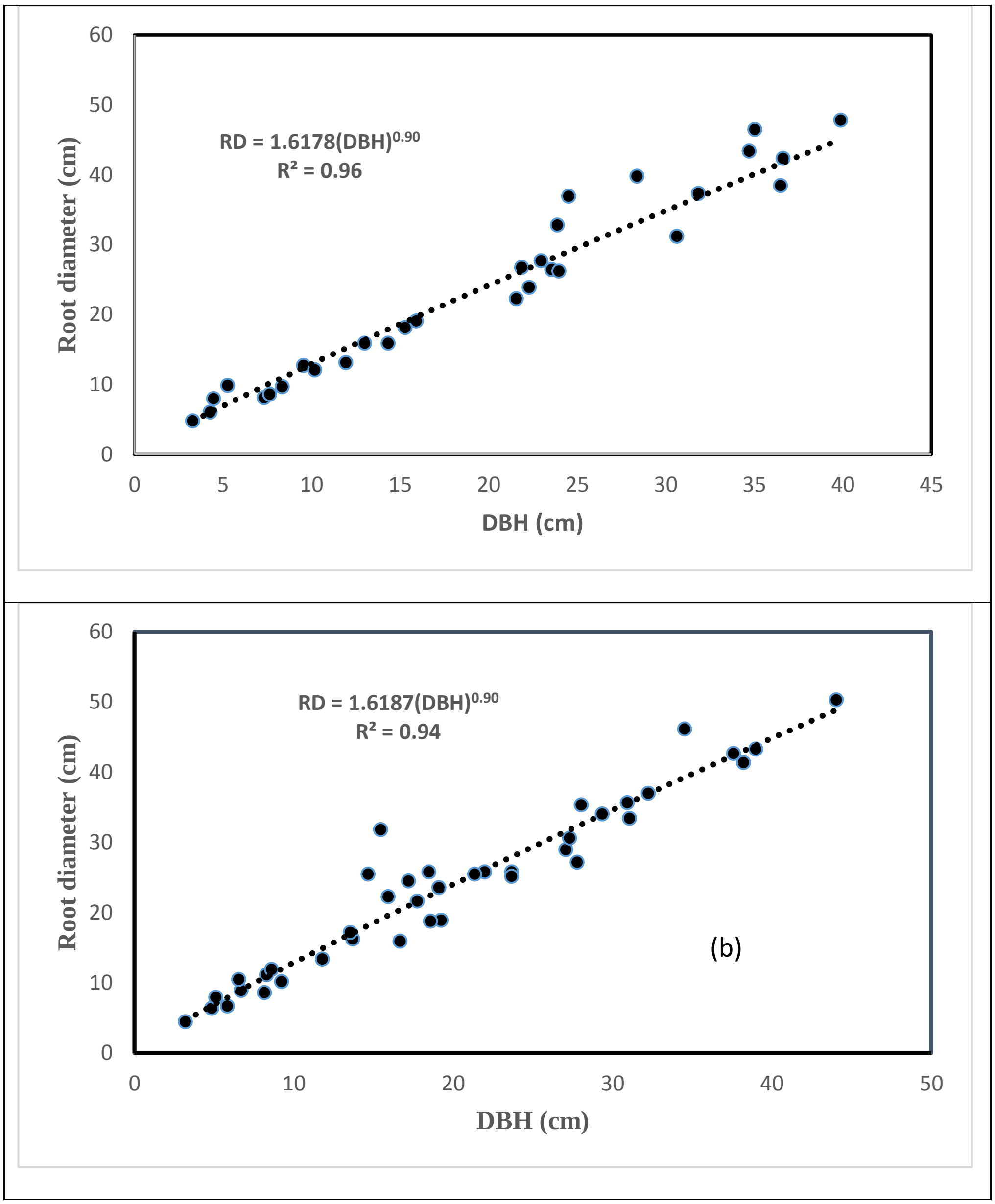


Figure 21: Relationship between DBH and root diameter of *Vitellaria paradoxa* in Koutiala (a) and in Yanfolila (b) for southern Mali, West Africa

3.4. Potential of dendrochronology in assessing carbon sequestration rates of *vitellaria paradoxa* under changing climate

3.4.1. Tree-ring structure

Wood anatomical analyses showed that *V. paradoxa* forms distinct growth rings on the samples of all land-use types (parklands, fallow and protected area) and sites (Figure 22). The growth ring boundary of *V. paradoxa* is characterized by smaller size vessels and thick cell walls at its end (Figure 22). The transition between early to late wood is gradual with more distinct transition in wider rings. Although we found few false, partially indistinct and locally missing rings near the bark in most samples from Yanfolila parklands, *V. paradoxa* forms distinct growth rings each year.

3.4.2. Annual radial growth of *Vitellaria paradoxa* in different land-use types

Tree-ring analyses revealed that the tree age ranges from 16 to 78 years in the study sites. The annual radial growth varied according to years (larger ring formed during good rainfall years and narrower rings in low rainfall years). The samples size (four per land-use type) is small to make statistically sound comparisons among the land-use types. Nevertheless, between land-use types, there was not a significant difference in annual radial growth for the same site. Whereas the mean annual radial growth of the parklands in Yanfolila was statistically different ($P < 0.05$) from that of the fallow in Koutiala (Table 19). Thus, there is a significant difference in ring width growth between the sites (df = 134, t-value = -3.9, p-values = 0.00007) with Koutiala displaying the lowest values. However, fallows displayed the lowest ring growth values and parklands the highest in both sites (Table 19).

3.4.3. Cross-dating

Cross-dating between radii of the same disk was successful for most of the disks from all land-use types, in both sites, except for all disks from the parklands in Yanfolila and one disk from the fallows in Koutiala. This corresponds to successful cross-dating of 7 out of 8 trees in Koutiala and 8 out of 12 trees in Yanfolila, i.e., a total of 15 out of 20 or 75% success for both sites. However, only 5 out of 15 disks were successfully cross-dated between the sites (Koutiala and Yanfolila) and were not correlated.

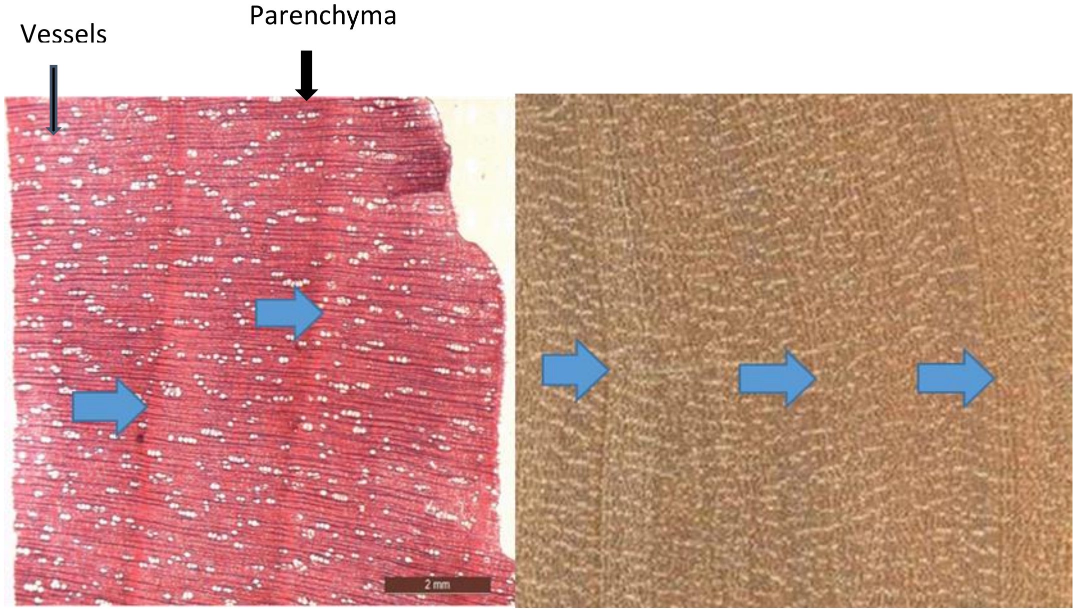


Figure 22: Image of the cross-sectional surface of wood samples of *Vitellaria paradoxa* from southern Mali, West Africa

"The arrows indicate growth ring boundaries"

Table 19: Annual radial growth of *Vitellaria paradoxa* in different land use types in southern Mali, West Africa

Sites	Land-use types	N	Annual radial growth ring width (mm)
			Mean±SE
Koutiala	Parklands	4	2.60±0.13ab
	Fallow	4	2.10±0.12b
Yanfolila	Parklands	4	3.25±0.33a
	Fallow	4	2.50±0.07ab
	Protected area	4	2.57±0.14ab

NB: N = number of stem disks collected per land use types. Values followed by the same letter are not statistically different at 95%

3.4.4. Tree-ring chronologies

Cross-dating of different samples was successful with GLK of 66 % in Koutiala and 76% in Yanfolila (Table 20). The mean length of chronology varied between 68 years in Yanfolila and 78 years in Koutiala. The mean sensitivity (MS) and standard deviation (SD) provide information on inter-annual variability on ring width. The high values of mean sensitivity and standard deviation in both sites indicate that *V. paradoxa* growth is sensitive to changes in environmental conditions and that external factors affected tree growth at both sites. The correlation coefficients values between all radii and between trees (Table 20) indicate similarity in annual growth patterns among sampled trees. The results revealed that *V. paradoxa* annual growth patterns were more similar among sampled trees from Yanfolila as compared to the samples of Koutiala. The autocorrelation is one of the most important parameter in dendrochronology as it measures the influence of previous year's growth on the current's growth. Among the two sites, the highest value of autocorrelation was recorded in Koutiala as compared to Yanfolila (Table 20). In general, the autocorrelation value remains lower at both sites (less than 0.5). While a high autocorrelation (i.e. more than 0.5) meaning that the tree-ring width in a given year is partially explained by the growth conditions during the previous year. Therefore the lower values of autocorrelation are more helpful for paleo-climatic studies.

Expressed population signal (EPS) value of our studied trees (0.93 in Koutiala and 0.94 in Yanfolila) is higher than the threshold standard (0.85) indicating strong coherency among the different time series included in the final tree ring chronologies.

Table 20: Descriptive statistics of tree ring width chronologies (average of Person's correlation, t-value ($p<0.05$) and GLK or coefficient of parallel variation for *Vitellaria paradoxa* in southern Mali, West Africa

Statistical parameters	Sites	
	Koutiala	Yanfolila
Number of samples	7	8
Mean length of series (year)	46	40
Time span (year)	(78)1936-2013	(68)1946-2013
Common interval time span (year)	(34)1980-2013	(44)1970-2013
Mean sensitivity (MS)	0.30	0.33
Standard deviation (SD)	0.73	0.77
Correlation among all radii	0.35	0.40
Correlation between-tree	0.23	0.30
Autocorrelation	0.20	0.01
Express population signal (EPS)	0.93	0.94
Radii vs mean	0.55	0.64
Mean T-value	2.00	2.00
Mean GLK (%)	66.00	76.00

GLK='*Gleichläufigkeitkoeffizient'* (coefficient of parallel variation between tree-ring series)

3.4.5. Climate and growth relationships

3.4.5.1. Correlation coefficient of standard chronologies with climate parameters

The standard chronologies of *V. paradoxa* of two sites and local recorded climate (mean annual rainfall and mean annual temperature) were analyzed per site. On both sites growth of *V. paradoxa* was positively correlated with moisture availability (Table 21). A significant relationship was found between *V. paradoxa* tree growth and annual rainfall amounts in Koutiala ($r = 0.50$, $n = 45$ years, $p < 0.01$; Figure 23a) and Yanfolila ($r = 0.66$, $n = 31$ years, $p < 0.01$; Figure 23b). However, no significant correlation was found for temperature either in Koutiala ($r = - 0.20$, $n = 31$ years, $p > 0.05$) or in Yanfolila ($r = 0.1$, $n = 31$ years, $p > 0.05$).

3.4.5.2. Correlation coefficient of residual chronologies with climate parameters

The residual chronologies of *V. paradoxa* of two sites and local recorded climate (mean annual seasonal rainfall) were analyzed per site. The correlation between seasonal rainfall and residual chronology was also significant in Koutiala ($r = 0.55$, $n = 45$ years, $p < 0.01$; Figure 24a) and Yanfolila ($r = 0.71$, $n = 31$ years, $p < 0.01$; Figure 24b). The most important positive significant correlation was recorded with the seasonal rainfall as compared to mean annual precipitation for *V. paradoxa* at both sites. This is the evidence that a decreased of rainfall will be very harmful on *V. paradoxa* growth on the study sites.

Table 21 : Correlations between selected climatic parameters and *Vitellaria paradoxa* chronologies in southern Mali, West Africa

Sites	Standard chronology index			Residual chronology index		
	Annual precipitation	Seasonal precipitation	Annual temperature	Annual Precipitation	Seasonal precipitation	Annual temperature
Koutiala	0.50**[3]	0.51**	-0.20	0.52**	0.55**	-0.20
Yanfolila	0.66**	0.70**	+0.1	0.67**	0.71**	+0.11

NB: ** P < 0.01

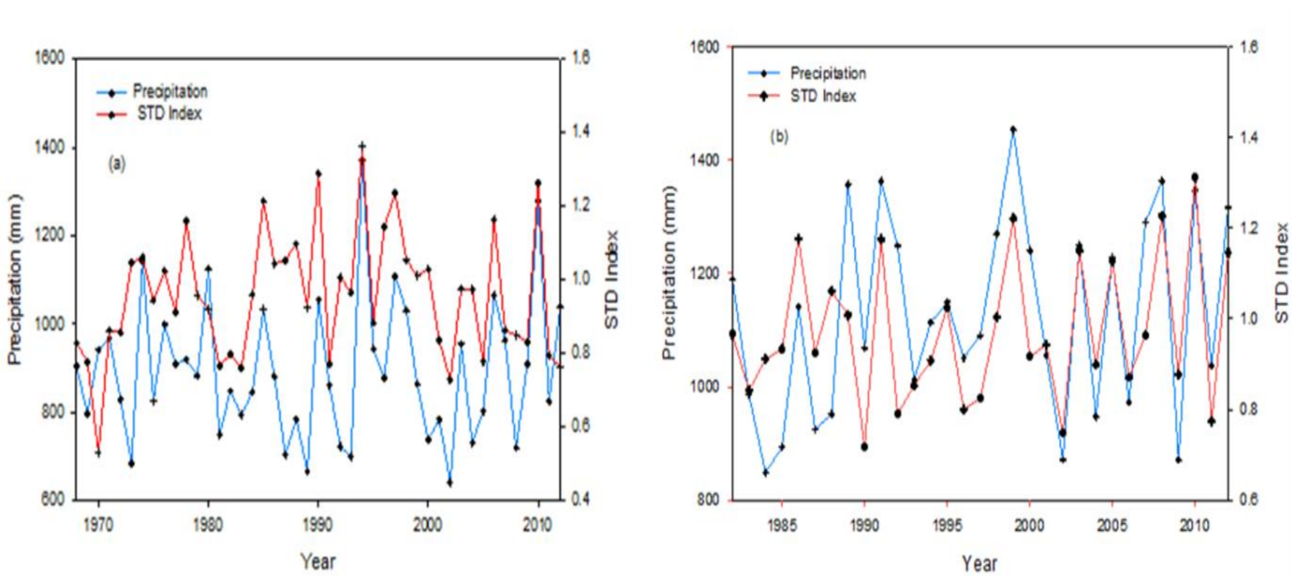


Figure 23: Correlation analysis between standard index (STD) of *Vitellaria paradoxa* and precipitation in Koutiala (a) and Yanfolila (b) in southern Mali, West Africa

[3] ** Significant levels of p < 0.01

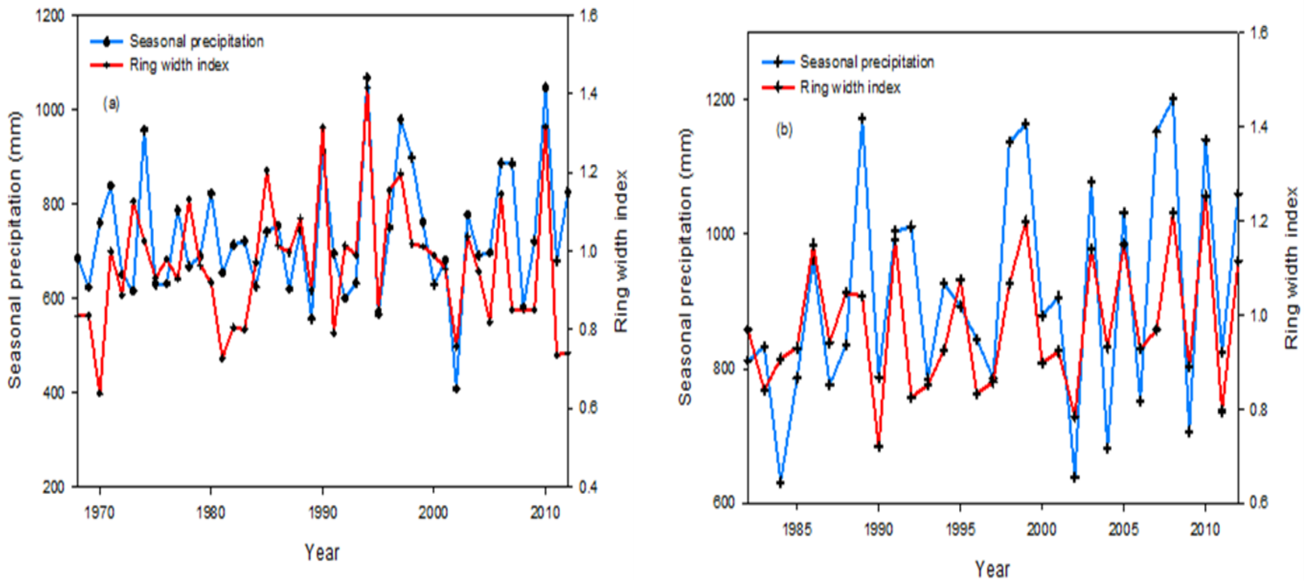


Figure 24: Correlation analysis between the residual chronology of *Vitellaria paradoxa* and rainy seasonal precipitation in Koutiala (a) and Yanfolila (b) in southern Mali, West Africa

3.4.6. Wood density of *Vitellaria paradoxa*

Wood density (specific gravity) distribution is related to the growth ring structure (latewood and earlywood). It is an important variable in the estimates of tree biomass and greenhouse-gas emissions from land-use types. Moreover, knowledge of wood density seems to improve the accuracy of estimates of tree biomass. The wood specific density of the current study varied from land-use to another as well as between sites. It ranged from 0.72 to 0.75 g cm^{-3} (Table 22) with an overall mean value of 0.74±0.007 g cm^{-3} in Koutiala. In Yanfolila it ranged from 0.70 to 0.76 g cm^{-3} with an overall mean value of 0.72±0.03 g cm^{-3}. Thus, it was not statistically different for both land-use types and study sites (Table 22) even though the low mean value of wood density of *V. paradoxa* was recorded in the humid zone (Yanfolila) as compared to the dry zone (Koutiala).

3.4.7. Dendrometric parameters of shea tree

- **Diameter at breast height (DBH)**

The diameter at breast height (DBH) of the samples of shea trees ranged from 11.39 to 34.16 cm (Table 23) with an overall mean of 22.91±12.43 cm in Koutiala. In Yanfolila the DBH ranged from 9.03 to 38.23 cm with an overall mean of 21.53±12.60 cm. The high value of the standard deviation at both sites indicated that the sample size was very variable around the mean.

- **Age**

Tree-ring analyses revealed that the tree age varied from 21 to 78 years with an overall mean of 51.13±20.26 in Koutiala against 16 to 68 years with the overall mean of 35.83±16.22 in Yanfolila (Table 23). It was found that shea tree diameter is significantly correlated with its age ($R^2 = 0.84$; $p < 0.0002$, $n = 20$) (Figure 25a).

- **Height**

Shea tree height (H) ranged from 4.12-9.22 m and 3.31-12.37 m with an overall mean of 6.63±1.92 and 7.14±2.43 m in Koutiala and Yanfolila, respectively. Like the diameter, the height was significantly correlated ($R^2 = 0.52$; $p < 0.001$, $n = 20$) to its age (Figure 25b).

3.4.8. Estimation of carbon stocks and sequestration in aboveground biomass (AGB)

V. paradoxa density varied according to land-use types and sites. Higher density was observed in the parklands with 16 individuals ha^{-1} compared to the fallows with 13 individuals ha^{-1} in Koutiala. In Yanfolila, the species displayed a density of 27, 23 and 18 individuals ha^{-1} respectively in parklands, fallows and in protected areas. The higher density of *V. paradoxa* in parklands indicates the impacts of human beings who preserve and nurture it as compared to the fallows and protected areas where such intentional management action doesn't exist.

AGB was estimated using generic allometric equation (8) and site-specific allometric equations associated with tree-ring analysis. Diameter ($n = 20$, $r^2 = 0.84$, $p < 0.0002$; Figure 25a) and height ($n = 20$, $r^2 = 0.52$, $p < 0.001$; Figure 25b) were significantly correlated with age. Consequently, the older trees stocked more carbon but sequestered less compared to the younger ones. There was no significant difference for C-sequestration in AGB ($p > 0.05$) for both land-use types and sites using generic model and sites specific allometric models (Table 24). Similar trend was observed for the amount of carbon stocks when comparing the two sites (Table 24).

Table 22: Wood density of *Vitellaria paradoxa* in different land-use types in southern Mali, West Africa

Sites	Land-use types	N	ρ (g cm^{-3}) Mean±SE
Koutiala	Parklands	4	0.72±0.03a
	Fallow	4	0.75±0.02a
Yanfolila	Parklands	4	0.76±0.01a
	Fallow	4	0.71±0.03a
	Protected area	4	0.70±0.04a

NB: N = number of stem disks collected per land use types; Mean values within each site followed with the same latter in the same column are not statistically different at 95%

Table 23: Characteristics of sampling of *Vitellaria paradoxa* in different land-use types in southern Mali, West Africa

Sites	Land-use types	N	Age range	DBH (cm) range	Height (m) range
Koutiala	Parklands	4	21-78	11.39-34.16	4.71-9.22
	Fallow	4	35-72	12.94-33.15	4.12-8.28
Yanfolila	Parklands	4	19-43	11.39-33.64	6.15-10.10
	Fallow	4	22-54	11.72-25.16	4.24-8.40
	Protected area	4	16-68	9.03-38.23	3.31-12.37

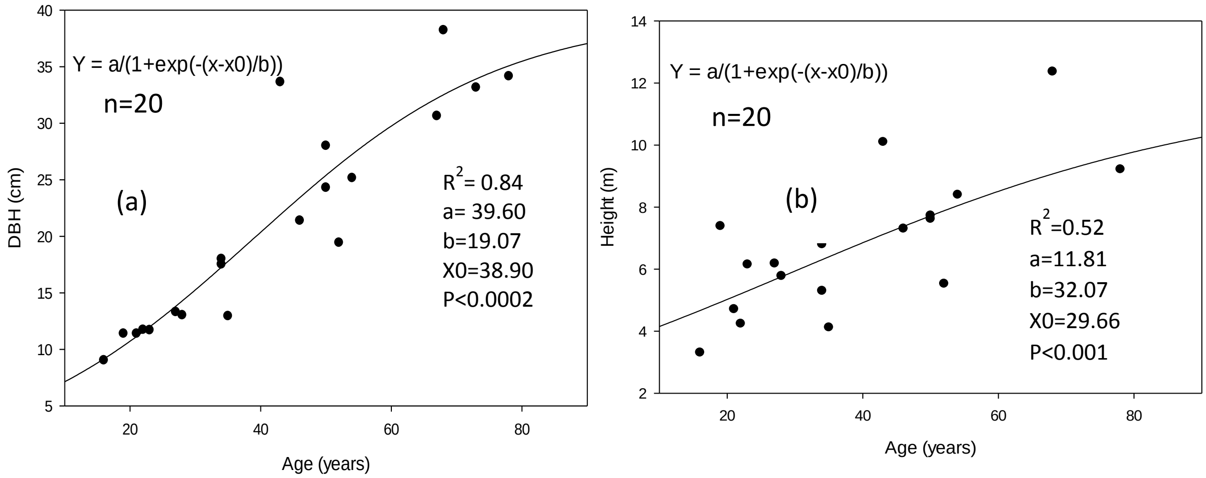


Figure 25: Relationship between age and DBH (a) and height (b) of *Vitellaria paradoxa* for southern Mali, West Africa

Table 24: Carbon stocks (Mg C ha^{-1}) and carbon sequestration (Mg C ha^{-1}yr^{-1}) in aboveground biomass by *Vitellaria paradoxa* in different land use types in southern Mali, West Africa

Land use types	Sites: Koutiala		Sites: Yanfolila		Allometric Models
	Carbon stocks	Carbon sequestration	Carbon stocks	Carbon sequestration	
Parklands	3.810±1.76**a**	0.068±0.020**a**	4.148±3.071a	0.112±0.065a	Generic model (**Chave *et al*. 2014)**
Fallow	3.431±1.41**a**	0.053±0.017**a**	3.398±1.211a	0.075±0.018a	
Protected area			3.473±2.224a	0.064±0.028a	
Parklands	0.03±0.013**a**	0.001±0.0001**a**	0.033±0.01**a**	0.0011±0.0002**a**	Site-specific allometric equations
Fallow	0.025±0.010**a**	0.0004±0.0003**a**	0.024±0.007**a**	0.0010±0.0001**a**	
Protected area			0.032±0.005**a**	0.0010±0.001**a**	

NB: Mean values followed with the same latter in the same column are not statistically different at 95%

CHAPTER IV: DISCUSSION

4.1. Farmers' perceptions of climate change on parkland ecosystem services and coping strategies

According to our findings, farmers are well aware of climate change and its effects such as frequent drought and floods, increase in temperature and number of hot days, stronger winds as well as the rainfall patterns (late start and early cessation of the rainy season). Similar results were reported in West Africa **(Mertz *et al*. 2009; Ayanwuyi *et al*. 2010; Sofoluwe *et al*. 2011; Odewumi** *et al*. **2013)** and East Africa **(Mengistu 2011)**. Increase in temperature observed in our sites was attributed by the interviewees to a decrease in the vegetation cover. Indeed, these farmers have observed that when they were young the vegetation cover was denser and the temperature was lower than what they currently experience. Farmers have also observed an increase in the number of hot days corroborating the findings of previous workers in West Africa **(Jenkins *et al*. 2002; Akponikpè *et al*. 2010)** including southern Mali **(Butt *et al*. 2006).** According to **Rahman (2006)** high temperatures are often associated with drought while increase in temperature is expected to reduce crop yields and increase levels of food insecurity **(IPCC 2007; Ogalleh *et al*. 2012)**. A Chi-square analysis revealed no significant difference in farmers' perceptions about climate change between the study sites indicating that their knowledge might be similar. This agrees with **Odewumi *et al*. (2013)**, who observed no significant difference in farmers' perceptions of climate change between two sites in Nigeria.

The results of multinomial logit regressions revealed that age, education level, farm size and gender are the main factors significantly influencing farmers' perceptions of climate change in our sites. This finding is consistent with the fact that the socio-demographic characteristics influence farmers' perceptions of climate change as reported by previous authors **(Ayanwuyi *et al*. 2010; Legesse *et al*. 2010; Olayemi 2012; Sahu and Mishra 2013)**. In contrast, our results are not in agreement with **Odewumi *et al*. (2013)**, who found no influence of any of the explanatory variables (age, education level and gender) on farmers' perception of climate change. This disagreement with our findings may be attributed to the small sample size (145 against 400 farmers for the current study), which may affect the results. From these logit regression results, the age of farmers is also a good predictor associated with the perception of the occurrence of drought, increase in temperature, wind and dust in Koutiala and change in rainfall patterns in Koutiala and Yanfolila. Indeed, older farmers have been exposed more to changes in the climate than the younger farmers **(Nhemachena and Hassan 2007; Varadan and Kumar 2014)** but the findings of **Sahu and Mishra (2013)** contradicted any relationship between the above mentioned factors. The multinomial logit results show that men are more likely to perceive the climate hazards such as drought, flood, temperature, hot days, wind and dust and rainfall induced by changes in climate compared to women, and this agrees with the results of **Villamor *et al*. (2015).** This is related to the fact that men are the main actors in rainfed agriculture, hence they are more active in taking adaptation strategies to cope with climate change and variability than women in the agricultural sector. However, vulnerability is high among women due to their reliance on non-wood forest products including those of shea trees as source of food and income. The third determinant that influences farmers' perception of climate change is the level of their education. Better educated farmers perceived more climate changes because they have several ways to document and remember past events **(Habiba *et al*. 2012)**. Farm size showed significant negative influence on farmer's perceptions in Koutiala. This might be due to the fact that this variable affects the timely completion of some field operations in case of late onset of the rainy season thus shortening the duration of the sowing period. This often leads to reduced farm size for the majority of the farmers who do not have the necessary financial resources to hire additional labour **(Graft Acquah 2011; Olayemi 2012).**

Most observed changes in rainfall patterns (drought, late start and early cessation of rains) frequently lead to decrease water availability and tree density **(Maranz 2009; Gonzalez *et al*. 2012).** This will ultimately affect negatively the delivery of ecosystem services to rural farmers and communities **(Okullo *et al*. 2004; Dawson *et al*. 2011). Okullo *et al*. (2004)** found that *V. paradoxa* production was strongly correlated with both relative humidity and wind speed which affects the shedding of flowers. Therefore these climate changes induced reduction in water and increase in wind speed which often lead to poor fruit formation and reduced yield of trees are unique as previous work in parts of Africa has been more on tree mortality alone **(Maranz 2009; Gonzalez *et al*. 2012)**. Low yield of non-timber forest products as a consequence of reduced water availability will negatively impact rural people in general and women in particular because these products are the mainstay of rural women who commonly use them to generate income to meet their expenditures. Besides the provisioning services, parklands provide a microclimate through tree shade. More than 60% of the farmers interviewed in both sites argued that parklands are widely used as wind breaks to protect farmlands against soil erosion. Similarly, **Bayala *et al*. (2014)**

reported that trees contribute to reduce wind speed and increase soil fertility. However, 25% of the respondents did not agree with the opinion that soil fertility may be improved through tree biomass. This must be due to the fact that such soil fertility improvement is more important on poor soils **(Bayala *et al*. 2012; 2014).**

Deforestation has been perceived as the main cause of climate change by 63% of the respondents in Koutiala against 49% in Yanfolila. In other studies, deforestation was associated with the loss of tree related indigenous knowledge in Nigeria and in Senegal **(Codjoe *et al*. 2013; Ofuoku 2011; Ugwouke 2013)**. Deforestation in southern Mali is due to a range of factors, including but not limited to agricultural mechanization, fuel wood harvest and charcoal production.

The results also revealed that farmers in the study sites are concerned about crop failure due to climate variability and therefore adopt different responses to tackle this issue. The main adaptation strategies were the diversification of crops and adoption of new crop varieties in Yanfolila and Koutiala, respectively. These two strategies seem to be common practices to cope with the vagaries of climate across the Sub-Saharan Africa **(Lacy *et al*. 2006; Halsnæs and Verhagen 2007; Thornton *et al*. 2007; Graft Acquah 2011; Olayemi 2012; Juana *et al*. 2013; Kalungu *et al*. 2013; Okonya *et al*. 2013).**

More than 11% of the farmers in both sites indicated that mixed tree-crop systems constitute a strategy to adapt to climate change due to their delivery of some ecosystem services. According to the farmers parkland increases crop yield and/or sustains it through its buffering effects on the ecological conditions and soil fertility improvement. Despite this buffering effect, only a small proportion of farmers in Koutiala (8%) and Yanfolila (16%) have adopted afforestation to adapt to climate change by planting species like *Eucalyptus camaldulensis***,** *Mangifera indica* and *Anacardium occidentale*. Our findings are slightly higher than the 5% reported with *Eucalyptus camaldulensis* and *Anacardium occidentale* in northen Nigeria (**Ayanwuyi *et al*. 2010)**. Even if farmers plant less trees due to a range of reasons (cost, survival, etc.), they are more active in preserving naturally occurring trees through what is known as farmers' managed natural regeneration or FMNR. The mixed systems go beyond tree and crops to include livestock as a coping option to erratic climate and ecological conditions of drylands **(Hassan and Nhemachena 2008)**. Such diversification approach makes the production as well as the livelihood systems more robust to climate hazards **(Boffa 2000; Bayala *et al*. 2014).**

In this study, applying soil and water conservation techniques to mitigate climate change induced crop yield increase was adopted by 16% of the farmers interviewed in Koutiala and 4% in Yanfolila. Similarly, farm size reduction was also limited to small number of farmers with 7% of the farmers interviewed in Koutiala and 10% in Yanfolila. Our values are far below the 55% of farmers in northern Ghana applying farm size reduction as reported by **Codjoe *et al*. (2013).**

About 63% of the respondents in both sites carried out off-farm activities in order to reduce their vulnerability to climate change. Our findings concur with **Ayanwuyi *et al*. (2010)** who stated that off-farm activities stabilize income in low crop production years as a result of climate change. Furthermore 8% of farmers in Koutiala as against 11% of farmers in Yanfolila often migrate after the rainy season in search of alternative income generating activities elsewhere.

4.2. *Vitellaria paradoxa* yield dynamics in agroforestry parkland systems and socio-economic characteristics of the households

Two categories of households have been derived by K-means cluster analysis. If the first type (82%) is poor compared to the second type (18%) based on their annual gross income per capita. The average annual gross income per capita varied from 397.95 (US dollars) for poor households to 553.82 (US dollars) for rich households in Koutiala. In Yanfolila the average gross income per capita was 413.57 (US dollars) for poor households against 722.26 (US dollars) for rich households. This difference between both sites in terms of gross income per capita could be explained by the rainfall distribution and availability of arable lands. The household type 2 is based on cash crops like cotton and is self-sufficient in terms of food security. Therefore, the contribution of shea tree to annual gross income of rural households is about 7% and 8% for the type 1 against 5% and 4% for type 2 in Koutiala and Yanfolila, respectively. Our values are lower than those of **Pouliot (2012)** who reported 7% of total gross income of richer household farmers against 12% of total income of poorest households derived from shea tree in Burkina Faso. In contrast, our findings are slightly higher than those of **Schreckenberg (2004),** who reported 2.8% as contribution of shea tree to annual household income in the Bassila region of Benin. However, recently other studies reported 36 to 46% **(Dah-Dovonon and Gnangle 2006; Gnanglé *et al*. 2009)** in Benin and 26 to 73 % in Mali **(Faye *et al*. 2010)** as the contribution of shea tree in annual gross income.

The present study revealed that two main cash crops (cotton and groundnut) are grown under agroforestry parkland systems at both sites. Other crops (maize, sorghum, millet) are used to reach self-sufficiency of food security. In Koutiala 98% of farmers against 32% in Yanfolila used organic manure in their fields while all (100%) fertilize their plots of cotton and maize with mineral fertilizer (external inputs). Cotton and maize are demanding crops concerning fertilizers as compared to others (groundnut, sorghum and millet). The inputs of fertilizers could have double benefits to soil fertility with high crop production and positive impact on shea tree yield. Agreeing with the findings of **Soro *et al*. (2012),** who reported that shea tree fruit production was influenced by the availability of nutrients in the north of Côte d'Ivoire.

The yield of shea tree in Yanfolila (298.57±272.73 kg ha^{-1} $year^{-1}$) is much higher than that of Koutiala (219.11±146.50 kg ha^{-1} $year^{-1}$). Furthermore, a higher labor availability (82±20 woman-day ha^{-1} $year^{-1}$) was observed in Yanfolila associated to better shea tree yield while the opposite (72±17 woman-day ha^{-1} $year^{-1}$) was observed in Koutiala. Our estimated yield based on Cobb-Douglas are lower than those of **Byakagaba *et al*. (2012),** who reported 921.00±20.40 kg ha^{-1} $year^{-1}$ in old fallow and 792.00±204.00 to 1349±328 kg ha^{-1} $year^{-1}$ in young fallow in Uganda. The difference may be related to the methods used to calculate yields. The cobb-douglas formula is based on labor input and capital input for yield estimation whereas, the methods used by **Byakagaba *et al*. (2012)** for shea yield estimation are based on dendrometric variables (diameter at breast height and crown diameter).

The simulation of shea tree yield varied according to the climatic gradient and the amount of rainfall. In Koutiala the yield estimated from the field survey was 219.11±146.5 kg ha^{-1} $year^{-1}$ while the simulation result was 186.6±97.50 kg ha^{-1} $year^{-1}$. In Yanfolila the yield of shea tree was 298.57±272.73 kg ha^{-1} $year^{-1}$ and 227.82±148.24 kg ha^{-1} $year^{-1}$ derived from survey and simulation, respectively. These findings confirmed that the rainfall distribution and amount have an influence on shea tree yield in agroforestry parkland systems. The yield in the Sudano Guinea zone (Yanfolila) was higher than those in the Sudano Sahelian zone (Koutiala). This difference of shea tree yield between the sites could be explained by the difference of shea tree density and amount of rainfall. In addition, this difference may be due also to the difference in pollinator (bees) abundance in the Sudano Guinea zone than in the Sudano Sahelian zone. In contrast, **Boffa (1995)** reported only 48 to 65 kg ha^{-1} $year^{-1}$ of shea tree dry nut in Burkina Faso. The latter results may be explained by the difference in shea tree density, tree diameter at breast height (DBH), land-use management practices and rainfall distribution. There is evidence that the nut yield of shea trees located in agroforestry parklands are around 4 kg tree^{-1} against shea trees located in natural formations (1.5 kg tree^{-1}) in Burkina Faso **(Lamien *et al*. 2004)**. In recent studies on shea tree yield by **Byakagaba *et al*. (2012) and Naughton *et al*. (2015),** for parklands a range of 131.1±29.4 kg ha^{-1} year^{-1} to 207.9±36.8 kg ha^{-1} year^{-1} and 32 kg ha^{-1} year^{-1} to 240 kg ha^{-1} year^{-1} in Uganda was reported and across sub-Saharan Africa, respectively. Our results are within the range reported by **Byagakaba *et al*. (2012)**, even though its maximum values are much higher than our simulations. In general our findings derived from simulations are consistent with those of the survey and those of the literature.

4.3. Fractal branch analysis model

The lack of relationship between p and q with parent diameter/root diameter confirmed the applicability of FBA model to *V. paradoxa*. Similar results were found for *Acacia mearnsii*, *Eucalyptus grandis/saligna* and *Mangifera indica* in Kenya **(MacFarlane *et al*. 2014)**, for *Terminalia chebula*, *Emblica officinalis* in India **(Panwar *et al*. 2014)**, for *Androstachys johnsonii* in Mozambique **(Magalhães and Seifert 2015)**, for *Jatropha curcas* in Indonesia **(Tjeuw *et al*. 2015)**. The p values are widely distributed in aboveground as well as in belowground at both sites. Therefore, the average of p in aboveground was 1.01±0.83 and 1.05±1.03 against 1.17±1.13 and 1.27±1.10 in belowground in Koutiala and Yanfolila, respectively. Values of similar magnitude of p (1.70±0.40; 1.8±0.40 and 1.80±0.40) were found in *Acacia angustissima*, *Gliricidia sepium* and *Leucaena collinsii*, respectively **(Kaonga 2012).** However, the q values are bounded between 0 and 1, with the average values > 0.50 indicating that one branch was larger than the others. This value of q in belowground is more widely distributed in Koutiala than in Yanfolila which could be related to soil characteristics, rainfall and land-use management practices. This result is in accordance with the findings of previous studies **(Smith 2001; Soethe *et al*. 2007; Martin *et al*. 2010; MacFarlane *et al*. 2014)**. Furthermore, mean link length increases with link diameter class for different components (twig, branch and trunk) of *V. paradoxa* agreeing with **MacFarlane *et al*. (2014) and Tjeuw *et al*. (2015).**

The relationships between the cross-sectional area of the stem and sum of proximal roots diameter was found to be linear for *V. paradoxa* at both sites. This is due to the fact that the sum of proximal roots diameter could be used to predict the cross-sectional area of the stem. The current study findings are in line with those of **Ozier-Lafontaine *et al*. (1999)**, who reported a higher positive relationships between the cross-sectional area of the branched link and cross sectional area of the diameter link of *Gliricidia sepium*.

The value of the scaling coefficient "b" is close to the universal value 8/3 (= 2.67), and its values were greater in above than belowground at both sites. The results revealed also a variation of "b" factor among the tree components (twig, branch and trunk). Allometric equations for total biomass had a higher value of "b" than those for branch biomass and twig biomass. This result is in agreement with the findings of **Tjeuw *et al*. (2015)** but not with those of results of **Martin *et al*. (2010)** who reported a higher value of "b" for branch than total biomass for *Shorea contorta* and *Vitex parviflora* in Philippines.

Our results revealed that the aboveground/belowground carbon stocks increase with increasing stem diameter corroborating **Jibrin and Abdulkadir (2015)**. The aboveground carbon stock (3.21±0.60 Mg C ha^{-1}) in Yanfolila was not significantly ($p > 0.05$) different from that recorded (2.16±0.44 Mg C ha^{-1}) in Koutiala. Our values are lower than those of **Shepherd and Montagnini (2001)** and **Kuyah *et al*. (2012)**, who reported 17.40 Mg C ha^{-1} and 17±0.02 Mg C ha^{-1} in aboveground of plantations (*Dorstenia panamensis*) in the humid tropics and agricultural landscapes in Kenya, respectively. Moreover, both values of our carbon stock estimates in aboveground are lower than the range of 22.2 to 70.8 Mg C ha^{-1} reported by **Luedeling and Neufeldt (2012)**, 22.4 to 54.0 Mg C ha^{-1} by **Takimoto *et al*. (2008)** in southern Mali, and 24 Mg C ha^{-1} found by **Traore *et al*. (2004)** in southern Mali. Such differences are plausible as our estimates are based on one species while the parkland is diverse in species composition. Furthermore, carbon stocks in these studies were estimated using generic allometric equations which are prone to overestimation. Our results are close to those reported by **Peltier *et al*. (2007)** in Cameroon (5.046 Mg C ha^{-1} aboveground biomass for *V. paradoxa*) whereas they are smaller than those of **Saïdou *et al*. (2012)** in Benin (20.17 Mg C ha^{-1} for *V. paradoxa*). As for belowground carbon stocks by *V. paradoxa* there was not a significant difference ($p > 0.05$) between Yanfolila (1.26±0.21 Mg C ha^{-1}) and Koutiala (0.80±0.15 Mg C ha^{-1}). These values are lower than the value recorded (4.25±0.74 Mg C ha^{-1}) by **Saïdou *et al*. (2012)** in Benin**.**

The ratio below to aboveground of 0.36 in Koutiala and 0.39 in Yanfolila were slightly higher than (0.26; 0.28) those reported by **Kuyah *et al*. (2012)** in Kenya and root to shoot (R/S) recommended by **IPCC (2006)** for subtropical dry forests, respectively. Then our findings are within the range of 0.35 to 0.5 for woodland of Mozambique **(Ryan *et al*. 2011)** and *Jatropha* *curcas* in Indonesia **(Tjeuw *et al*. 2015)**. In this later study, the 83% of the variation in the belowground carbon stocks explained by the aboveground carbon stocks was lower than the range of the values of our investigation (90% in Koutiala and 91% in Yanfolila). This difference with our findings could be related to environmental conditions (moisture, nutrient availability), tree species and tree age. Indeed, plants respond to nutrient limitation by modifying branching and root architecture (**Lynch and Ho 2005; Trubat *et al*. 2012**). In spite of a lowest root to shoot ratio, our findings are consistent with the existence of equilibrium between the above and belowground parts of trees through growth resources allocation (**van Noordwijk *et al*. 2015**).

4.4. Potential of dendrochronology for assessing climate change impacts on *Vitellaria paradoxa* growth

V. paradoxa showed distinct ring boundaries at both sites characterized by small size vessels and thick cell walls. Despite the distinctiveness of the growth ring boundaries some disks were not cross-dated successfully. Our samples from protected areas presented no missing rings as opposed to those from parklands and fallows, especially, in Yanfolila. Factors that may have caused these differences are the land-use management inducing, in some cases, growth ring anomalies (missing rings). Indeed, most of the non-cross-dated disks were collected from parklands where more active management operations are applied to both land (e.g. manure, tillage) and to the preserved trees (e.g. pruning). These assertions are in agreement with **Gebrekirstos *et al*. (2008)** who reported difficulty of cross-dating stem disks collected from communal grazing and cultivated lands due to possible missing rings. They also corroborate the findings of **Schweingruber (1996)**, who reported that only samples from undisturbed areas provide the best information for dendroclimatological studies.

In the absence of reference chronologies for tropical tree species (including our studied species), we have compared our data to some values from temperate and boreal regions. We thus realized that the thresholds of GLK and T-value applied in this study remain lower compared to those of temperate and boreal regions (GLK 70% and $T > 3.5$). In turn, the GLK values of our study are close to those reported by **Gebrekirstos *et al*. (2008)** ranging from 61% to 75% for four tree species in Ethiopia but higher than the 60% found by **Trouet *et al*. (2010)** in *Brachystegia spiciformis* in south central Africa.

The distinct growth zones are an indication of periodic dormancy induced by the following factors. First, both study sites are characterised by seasonal climate, i.e., there is a distinct seasonality between dry and rainy season. Second, the species displays a leaf phenology that matches the distinct seasonality of rainfall pattern, shedding its leaves during the dry season, between December and March and new leaf flushing as soon the next rainy season starts **(Hall *et al*. 1996)**. Hence, the coherent pattern of tree-ring series among the chronologies of land-use types within a site suggests that an external factor, which is the seasonal precipitation, affected the trees in a similar way. Similar findings were reported by other dendrochronological studies on tree species from Africa **(Fichtler *et al*. 2004; Trouet *et al*. 2006; Gebrekirstos *et al*. 2008)**. Considering all the above factors, it can be concluded that tree rings in *V. paradoxa* grown in the study sites, in southern Mali, are annual.

However, the weak cross-dating success (33%) and correlation ($r = 0.20$, $p > 0.05$) between the sites indicates that *V. paradoxa* growth is not only influenced by the precipitation amount but probably by other factors such as soils and management practices. Similar findings were reported by **Fichtler *et al*. (2004)** in southern Africa for *Burkea africana*, and **Trouet *et al*. (2010)** in Miombo woodland for *Brachystegia spiciformis*.

In both sites, regardless of the type of chronology (standard or residual), significant correlations were established ($r = 0.51$, $r = 0.70$, $p < 0.01$, $r = 0.55$, $r = 0.71$, $p < 0.01$) with major seasonal precipitation, which seems to be one of the most influential factors determining tree (*V. paradoxa*) ring growth in southern Mali. This study agrees with **Krepkowski *et al*. (2011)** who found that tropical tree growth is sensitive to the amount of rainfall received. The fact that major seasonal precipitation displayed higher correlation coefficient values with ring growth compared to annual precipitation also agrees with findings of previous tree dendrochronological studies in Africa **(Fichtler *et al*. 2004; Gebrekirstos *et al*. 2008; Nicolini *et al*. 2010; Trouet *et al*. 2010)**. In contrast, the studies of **De Ridder *et al*. (2013)** on *Terminalia superba* did not find any correlation between precipitation and tree growth in Côte d'Ivoire while the same species showed a positive correlation with the rainfall in the Democratic Republic of Congo (DRC). Significant positive correlation with major seasonal precipitation suggested that soil moisture, which depends on the amount of rainfall, may be one of the major factor affecting tree growth **(Therrell *et al*. 2006)**. Non-significant lower growth rates and carbon stocks in the northern site may be due to lower (soil) water availability while correlations with temperature in both sites was also not significant.

The lack of significant correlation with temperature corroborates the findings of **Gebrekirstos *et al*. (2008)** from Ethiopia but in our case this could also be an artefact of the number of tree samples and sites (only 2). In contrast, **Fichtler *et al*. (2004)** reported a negative correlation with temperature indicating a loss of assimilated carbon as a source of energy through respiration.

The difference between the means C-sequestered in parklands (0.112±0.065 Mg C ha^{-1} yr^{-1}), fallows (0.075±0.018 Mg C ha^{-1} yr^{-1}) and protected areas (0.064±0.028 Mg C ha^{-1} yr^{-1}) was not statiscally significant in Yanfolila (generic model). Similarly, the carbon sequestered in parklands (0.068±0.020 Mg C ha^{-1} yr^{-1}) was also not statiscally different from that of the fallows (0.053±0.017 Mg C ha^{-1} yr^{-1}) in Koutiala (generic model). In rurn, similar trend was displayed with the site-specific allometric equations. However, our estimates of carbon stocks with the generic model was higher than that of the site-specific allometric equations. This is the fact that the generic model over estimates the carbon compared to site-specific allometric equation (**Preece *et al*. 2012**). Parklands are derived from human agricultural activities. Hence, the highest amount in parklands could be due to management practices that increase the density of *V. paradoxa*. In Koutiala, the estimates of carbon stocks in AGB ranged from 3.431 to 3.810 Mg C ha^{-1} and 0.025 to 0.030 Mg C ha^{-1} whereas in Yanfolila the estimates were 3.398 to 4.148 Mg C ha^{-1} and 0.024 to 0.033 Mg C ha^{-1} The lack of significant difference for carbon stocks and sequestered among land-use types could be due to the limited number of samples collected that did not represent the structure of the population sampled. Nevertheless, our results revealed that the amount of carbon stocks as well as carbon sequestration is higher in Yanfolila (with higher rainfall amount) as compared to Koutiala. The carbon estimates of the current study are within the range reported by **Peltier *et al*. (2007)** in Cameroon (5.046 Mg C ha^{-1} in AGB in the parklands of *V. paradoxa*) and lower than those of **Saïdou *et al*. (2012)** in Benin (20.17 Mg C ha^{-1} in the parklands of *V. paradoxa*). In turn, they are lower than other reported carbon ranges, which are 22.4 to 54.0 Mg C ha^{-1} for parklands of *V. paradoxa* and *Faiderbia albida* in southern Mali **(Takimoto *et al*. 2008)**, 22.2 to 70.8 Mg C ha^{-1} for parklands **(Luedeling and Neufeldt 2012)**, and within to 3.1- 86.5 Mg C ha^{-1} for the genera of Acacia and Combretum in Mozambique **(Ryan *et al*. 2011)**. The range of carbon sequestered found in the literature in areas ecologically close to ours evolves from 0.4 Mg C $ha^{-1}yr^{-1}$ **(Luedeling and Neufeldt 2012)** to 1.09 Mg C $ha^{-1}yr^{-1}$ **(Takimoto *et al*. 2008)** in southern Mali. The difference between our values and the ones reported in the literature may be explained by the difference in allometric equations used, the density of tree species, the difference in tree growth rates and climatic zones and the fact that our study focused on a single species. In addition to the above-cited investigations conducted on natural stands, there are emerging data from commercial planted stands. For instance, **Bakayoko *et al*. (2012)** estimated the biomass of 12-year old planted in Côte d'Ivoire of *Cedrela odorata* to be 1.6 Mg C ha^{-1} and 5.95 Mg C ha^{-1} for 18-year old planted *Gmelina arborea*. Similarly in Ghana, the aboveground carbon stocks were estimated to be 10.3 Mg C ha^{-1} and 15.9 Mg C ha^{-1} for 8-year and 15-year planted of *Theobroma cacao*, respectively **(Isaac *et al*. 2007)**. The results of the last two studies constitute an indication of the relationship between the accumulated amount of biomass (carbon) and tree age agreeing with our findings. Moreover, our results using ring analysis may be more accurate compared to those of most of the above carbon estimates which used only the diameter as a main predictor of the biomass. As reported by **Williams *et al*. (2008)** the allometric model can strongly influence biomass estimate. However, environmental conditions like climate constitutes a key factor affecting carbon sequestration **(Nair *et al*. 2009; Luedeling and Neufeldt 2012)**. In our case, lower rainfall amount was associated with narrow rings regardless of the sites and land-use types and this is in agreement with **Woomer *et al*. (2004)** who have observed an important reduction of AGB in the Sahel.

Overall, the potential of the most dominant parkland species in carbon stocks in southern Mali is modest as well as that of the whole system under the dryland conditions (**Luedeling and Neufeldt 2012**). If this potential is feeble compared to other agro-ecosystems in other climatic conditions, the contribution of the carbon sequestered by *V. paradoxa* and indeed the parkland tree species in general (**Bayala *et al*. 2014**) in maintaining the soil conditions (soil carbon) is very critical for the sustainability of the production systems in the drylands.

CONCLUSION, RECOMMENDATIONS AND PERSPECTIVES

Conclusion and recommendations

The results revealed that farmers have observed an increase in drought frequency, temperature, the number of hot days and frequency of strong wind and dust. Similar findings have already been reported together with their effects on annual crops by previous workers. However, the present study is the first to reveal the impact of limited water availability due to drought and early cessation of the rainy season and wind/dust on the shedding of the flowers and poor fruit yield of Shea tree in the parklands. This ultimately affects the most important provisioning service which is the shea butter for self-consumption and income generation of farmers in general and women in particular. To overcome these adverse effects of climate change, farmers have adopted some adaptation measures like the diversification of crops as well as the adoption of new crop varieties, seasonal migration, etc. Without adaptation strategies, food insecurity and poverty will increase because of the erratic rainfall. The results also show that four out of seven variables studied were the most influential in explaining farmers' perceptions of climate change: age, educational level, farm size and gender. The most common causes of climate change were deforestation and human behaviour according to farmers' perceptions. Almost all respondents perceived drought as the main recurrent phenomenon of climate change which affects crop production and the delivery of ecosystem services of the parklands with dire consequences on the wellbeing of rural communities.

As gender was found to be significant in the way climate change is perceived, we recommend that, within the frame of the National Adaptation Programmes of Action (NAPAs), the government supports farmer's local gender sensitive adaptation strategies to climate vagaries (afforestation, diversification of crops, erosion control, new varieties, etc.). Thus, diversification of vegetables, use of drought tolerant crop varieties and support in adding value to non-timber forest products should be more women focused. Moreover, off-farm income earning activities should be created for rural farmers to protect the active household population from seasonal migration and reduce their vulnerability to climate change. For off-farm activities, women are more active in processing and commercialization of crop and tree products and therefore should be the key targets. Farmers should be encouraged to plant more shea trees on their farms, as a guaranty of future stable shea tree density in order to offset the deforestation and enhance the provision of the ecosystem services for their livelihood.

Meanwhile, the lack of accurate data on the production of the estimating stands constitutes a bottleneck for the value claim of this species calling the development of methods to estimate its yields.

The Land-Use Dynamics Simulator (LUDAS) based model was found to be a useful tool to simulate shea tree yield dynamics while capturing the labour availability of the households. Thereby, the models produced usable estimations of shea tree yield in both sites. The simulation results showed that shea tree yield in agroforestry parkland systems is related to rainfall amount and distribution. As a consequence, simulated shea tree yield was higher in the Sudano Guinea zone (Yanfolila) compared to the Sudano Sahelian zone (Koutiala). This study is the first which attempted to use an agent-based model to estimate shea tree yield in agroforestry parkland systems in Sub-Saharan Africa. The model was validated by the consistency of the results between the simulated shea tree yield of the model and the survey and those of the literature.

Besides the provisioning services, a dominant species like shea tree also contributes to the carbon stocks but there is dearth of methods to accurately estimate such stocks. As generic methods tend to provide poor estimates, site-specific allometric equations for *V. paradoxa* are required. The established allometric models will significantly improve the accuracy of carbon stocks estimation of *V. paradoxa* in West Africa Savanna for REDD++ (Reducing Emissions from Deforestation and Forest Degradation) activities. In addition, our models can be applied to *V. paradoxa* on sites with similar environmental conditions. FBA model is a reliable method of biomass estimation and its accuracy depends on the sample size. The results revealed that the shoot/ratio systems were fractals, suggesting that the above and belowground biomass can be predicted based on fractal properties. Our findings showed that the carbon stock by *V. paradoxa* is directly related to its diameter at breast height. The aboveground carbon stock in Yanfolila was not significantly different from that of Koutiala. Similarly, no difference was in carbon stocks in belowground between Yanfolila and Koutiala. Strong linear relationships were observed between carbon stock (above and belowground) and diameter/proximal root diameter with low standard error of the estimate (SEE) and F-values significantly different from zero which indicate that the models are valid. Fruit biomass was not included in the model therefore research is required on fruit to fine-tune the model.

As many other species in the region still have no specific allometric equations, we recommend the elaboration of site-specific allometric equations development using FBA model as a non-destructive method. We also recommend developing and using site-specific allometric instead of using generic allometric models. If accurate estimates of the local biomass is important, data on the impacts of the environmental conditions on its accumulation has management pratical implications. And one of the most critical environmental conditions of concern these days is climate change and variability (rainfall) that is why our focus was on understanding its impacts on shea tree growth using the tree-ring chronology approach. As far as we know, the tree-ring chronology presented is the first for *V. paradoxa* for southern Mali, and probably, so far, the first for West Africa. This pilot study revealed that *V. paradoxa* forms annual rings. The tree-ring chronologies were significantly correlated with precipitation indicating that it is one of the most important climatic factors affecting tree growth patterns in the study sites. Higher values were observed for AGB and C-sequestration rate in the more humid site (Yanfolila) compared to Koutiala. Our study clearly demonstrated the applicability of dendrochronology approaches to *V. paradoxa*, despite some of its weaknesses, which are small tree sample size, limited number of sites and the use of rainfall data far away (80 km) from Yanfolila. Future studies of the same nature (comparing land-uses) should be based on larger samples that closely mimic the structure of the vegetation. This pilot study may contribute to increase scientific knowledge and will be a reference in the dendrochronology application for this common species in the West African drylands. There is also a need to extend such approach to other species in different ecologies of the whole West Africa.

Perspectives

The current study revealed that farmers already adopted some strategies to deal with the climate change impacts. However, some of these strategies are jeopardized by the lack of financial and technical support. It is therefore suggested that the improvement of farmers' adaptation strategies to climate change should be a major concern of policy makers when planning activities for rural development. On the other hand, this study suggests to develop a conducive environment that can help create agricultural related off-farm income earning activities that could protect active households from the impacts of climate change and variability. Due to the key role of *V. paradoxa* in farmer resilience to climate change there is a need to pay attention on the regeneration of this species (*V. paradoxa*) in agroforestry parklands which appears as a new challenge in the Sahel countries and particularly in Mali.

Even though the study reached the objective of developing allometric equations of *V. paradoxa* for carbon stocks estimation:

- We recommend testing the applicability of FBA across a wider range on other species in the region in order to increase the accuracy of carbon estimation.
- An analysis of error propagation effects of the allometric equations that may occur during field measurement is recommended in the future. Because the study evaluate the performance of this allometric equation based on the standard error of the estimate and the determinant of coefficient (R^2).

The dendrochronology approaches remain untested for many species in West Africa and particularly in Mali. Its application on shea tree was successful and revealed climate change impacts on its tree-rings growth. Given the limited size of our sample, the amount of carbon are indicative calling for applying the tested approaches to larger samples and also to other tree species in West Africa. The use of oxygen and carbon isotopes jointly with dendrochronology approaches will help better explore the climate reconstruction in future similar studies.

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APPENDIX

Appendix 1: Rotated component matrix using Varimax method of principal component analysis of data from Koutiala in southern Mali, West Africa

Variable	Principal component						
	1	2	3	4	5	6	7
	Land factor 29.82%	Income factor 10.82%	Cotton factor 8.06%	Distance factor 7.41%	Ground-nut factor 6.69%	Education factor 6.08%	Depend-ency ratio 5.21%
Age of the respondent	.033	-.238	.141	.394	-.309	-.445	-.241
Education level	-.029	.092	-.027	-.270	.271	.694	.107
Labor availability	.871	-.165	-.148	.035	.159	.030	-.251
Dependency ratio	.047	.311	.290	-.365	-.341	-.130	.567
Ethnic group	.127	.271	-.446	-.515	.253	-.268	-.178
Household size	.921	-.103	-.075	-.028	.095	.003	-.155
Landholding per capita	.001	.071	.177	.307	.602	-.223	.352
Maize area (ha)	.740	-.156	.088	.151	-.239	-.134	.243
Sorghum area (ha)	.818	.184	.074	-.071	-.041	.182	-.064
Millet area (ha)	.804	.233	.116	-.163	.095	-.102	-.042
Cotton area (ha)	.860	-.057	.242	.081	-.056	.170	.029
Groundnut area (ha)	.171	.166	-.178	.280	.583	-.280	.284
Cowpea area (ha)	.225	-.067	-.671	.249	-.283	.063	.276
Other area (ha)	-.060	-.187	-.599	.417	-.078	.305	.174
Gross income (US dollars)	.692	.537	.043	.249	-.111	.049	-.062
Gross income per capita (US dollars)	-.336	.694	.138	.314	-.169	.196	-.006
% income from shea	.157	-.726	.056	-.080	.082	.072	-.023
% income from cotton	.154	-.632	.331	-.086	.030	.111	.307
House distance (km) to the village	-.259	.023	.436	.454	.216	.266	-.220
Farmland size (ha)	.972	.084	.024	.062	-.026	.058	.091

Appendix 2: Rotated component matrix using Varimax method of principal component analysis of data Yanfolila in southern Mali, West Africa

Variable	Principal component					
	1	2	3	4	5	6
	Land factor 25.48%	Income factor 12.63%	Dependency ratio 9.32%	Education factor 7.92%	Member-ship factor 7.33%	Labor factor 6.03%
Age of the respondents	-.056	.155	-.038	-.631	-.247	.008
Education level	.149	-.113	.400	.516	.348	-.125
Labor availability	.723	.453	.250	.037	.178	.242
Dependency ratio	.095	-.167	.575	-.080	-.558	-.329
Ethnic group	-.036	.341	-.557	.234	.233	-.115
Household size	.734	.276	.516	.045	-.092	.068
Landholding per capita	-.463	.387	.455	-.056	.361	.217
Maize area (ha)	.758	-.060	.120	-.054	.094	-.131
Sorghum area (ha)	.217	-.081	-.304	.409	-.428	.073
Millet area (ha)	.006	.264	.112	.683	-.123	-.231
Cotton area (ha)	.787	.269	-.236	-.156	.020	-.183
Groundnut area (ha)	.604	-.393	-.004	.072	-.156	.365
Cowpea area (ha)	.291	-.154	-.163	.091	-.178	.694
Other area (ha)	.596	-.027	-.158	-.232	.034	-.149
Gross income (US dollars)	.667	-.464	.215	-.029	.354	-.016
Gross income per capita (US dollars)	.142	-.704	-.273	-.032	.513	-.087
% income from shea	-.076	.704	-.033	.007	.155	.329
% income from cotton	.501	.560	-.381	.052	-.048	-.276
House distance (km) to the village	.309	.250	.116	-.338	.233	-.133
Farmland size (ha)	.959	-.045	-.139	.063	-.116	.046

Appendix 3: DBH, and Height of *Vitellaria paradoxa* in southern Mali, West Africa

Sites	Land-use types	Sample N^0	DBH (cm)	Height (m)
Koutiala	Parklands	1	28	7.73
		2	17.99	5.3
		3	34.16	9.22
		4	11.39	4.71
	Fallow	1	30.64	8.13
		2	33.15	8.28
		3	19.43	5.53
		4	12.94	4.12
Yanfolila	Parklands	1	11.39	7.39
		2	13.30	6.80
		3	11.70	6.15
		4	33.64	10.10
	Fallow	1	25.16	8.40
		2	17.52	6.8
		3	24.30	7.62
		4	11.72	4.24
	Protected area	1	9.03	3.31
		2	13.02	5.78
		3	21.38	7.31
		4	38.23	12.37

SYNTHESE DE LA THESE EN FRANÇAIS

Titre: Validation de méthodes pour l'estimation de la séquestration du carbone et le potentiel de *Vitellaria paradoxa* CF. Gaertn. dans la provision de services écosystémiques des systèmes parcs agroforestiers dans le sud du Mali, en Afrique de l'Ouest

RESUME : *Vitellaria paradoxa* est un arbre endémique des savanes africaines. Cette espèce joue un rôle important dans l'atténuation et dans l'adaptation des agriculteurs au changement climatique à travers ses services écosystémiques. Malheureusement, l'espèce est en déclin dans le Sahel, surtout dans le sud du Mali, en raison de sa sensibilité aux sécheresses récurrentes dues aux changements climatiques. La compréhension des processus qui induisent ce déclin et leurs conséquences sur les moyens de subsistance des agriculteurs ruraux exige l'élaboration d'approches et de méthodes appropriées. C'est pourquoi notre étude vise à valider les méthodes d'estimation de la séquestration du carbone et l'évaluation du potentiel de *V. paradoxa* dans la provision des services écosystémiques pour le bien-être de la population dans le sud du Mali. Mais avant cela, nous avons tenté d'élucider la perception paysanne du changement climatique et leurs mesures d'adaptation. Nos résultats ont révélé une série de mesures utilisées par les agriculteurs pour s'adapter aux effets du changement climatique incluant, l'utilisation de variétés améliorées résistantes à la sécheresse, la diversification des cultures, les activités non agricoles et la migration saisonnière. La contribution de *V. paradoxa* dans le revenu brut annuel des ménages ruraux varie de 4% à Koutiala (site du Nord) à 8% à Yanfolila (site du sud). Cela semble indiquer une augmentation de l'importance de cette espèce proportionnellement à celle des précipitations et à la densité allant du nord au sud du Mali. Le test des méthodes a révélé que le modèle « agent-based » pourrait être utilisé pour l'estimation de la dynamique du rendement de *V. paradoxa* d'une part et, d'autre part que l'analyse fractale de branche (FBA) pourrait être employée pour l'estimation de la biomasse et du carbone aérien et souterrain de cette espèce. Le stock de carbone aérien du karité à Koutiala (2.16±0.44 Mg C ha^{-1}) n'était pas significativement différent de celui de Yanfolila (3.21±0.60 Mg C ha^{-1}). Une tendance similaire a été observée pour les stocks de carbone souterrains entre des deux sites. Cette étude a montré un risque de surestimation de la biomasse en utilisant le modèle générique, vu que toutes les valeurs de b étaient en dessous de 2.67. En plus, elle a permis de démontrer que la dendrochronologie peut être appliquée á l'étude de l'impact des changements climatiques sur la croissance de *V. paradoxa*.

Mots clés: Cernes, distribution des précipitations, équations allométriques, stratégie d’adaptation, vulnérabilité

1. Introduction

Le Mali, pays enclavé, est dominé par les systèmes des parcs agroforestiers (PA) traditionnels. Ces parcs agroforestiers occupent environ 90% des terres agricoles (**Boffa 2000**). La gestion de ces parcs contribue à l’ajustement des conditions environnementales (atténuation des changements climatiques). La densité des arbres au sein des parcs est généralement faible **(Kelly *et al*. 2004)** ainsi que la composition des espèces. Ces systèmes de parcs sont généralement dominés par deux espèces connues comme le Karité (*Vitellaria paradoxa*) et le néré (*Parkia biglobosa*) tel que rapporté par **Bayala *et al.* (2011)**. A l’instar de l'ensemble du système agroforestier, ces deux principales espèces sont également menacées (**Gonzalez *et al*. 2012**). Le couvert végétal a diminué dans les parcs au cours des quatre dernières décennies, en raison de la réduction de la densité des espèces et de la sécheresse **(Boffa 2000; Maranz 2009)** dans le contexte d’une baisse continue des précipitations selon **Meehl *et al.* (2007).**

Le Mali, comme d'autres pays du Sahel, est vulnérable aux changements climatiques en raison de sa forte dépendance à l'égard des ressources naturelles et la pratique de l'agriculture pluviale de subsistance. Par exemple **Butt *et al.* (2003)** ont rapporté que d'ici l'an 2030, les températures moyennes annuelles au Mali peuvent augmenter de 1 ^{0}C à 2,75 ^{0} C, avec des précipitations légèrement en baisse. Cette tendance aura également un impact sur le potentiel de séquestration du carbone dans les parcs agroforestiers.

Le sud du Mali est également caractérisé par plusieurs types d’utilisations des terres telles que les parcs, les jachères et les aires protégées. Outre le développement et la validation des méthodes d'évaluation du carbone, les approches doivent prendre en considération les différentes utilisations des terres mentionnées ci-dessus. Celles-ci vont affecter le potentiel de séquestration du carbone des arbres, en particulier celui de *V. paradoxa*. Toutefois, les données sur le potentiel de séquestration du carbone dans la partie aérienne et souterraine (racines) des arbres sont peu abondantes au Mali. En outre, aucune étude n'a comparé ces types d'utilisation des terres (parc agroforestier, jachère et aire protégée) pour voir dans quelle mesure leur capacité de séquestration du carbone peut être différente. Cette étude porte sur le potentiel de séquestration du carbone du karité dans les parcs parce que ces systèmes ont été reconnus comme l'une des stratégies d'adaptation les plus importantes aux changements climatiques dans le Sahel **(Albrecht *et al.* 2003; Montagnini *et al*. 2004)**. L'étude examine aussi au-delà du carbone, comment d'autres produits et services fournis par cette espèce affectent les moyens de subsistance des populations rurales dans leurs systèmes d'exploitation.

2. MATERIELS ET METHODES

2.1. Localisation des sites d'étude

L'étude a été réalisée dans deux districts (Koutiala et Yanfolila) du sud du Mali. Koutiala est situé à 12^0 38'N et 5^0 66'W et, Yanfolila, à 11^0 10'N et 8^0 09'W. Ils ont été choisis pour représenter deux zones climatiques différentes de distribution du karité.

2.2. Méthodes

2.2.1. Perception paysanne des impacts du changement climatique sur la provision des services écosystémiques des parcs

Sur la base de la formule de **Dagnelie (1998)**, la taille totale de l'échantillon (N) a été estimée à 400 agriculteurs pour les deux sites. La taille de l'échantillon dans chaque site a été déterminée au prorata du nombre total de ménages. Ainsi 240 et 160 producteurs/productrices ont été considérés, respectivement à Koutiala et à Yanfolila. Une interview structurée a été menée pour collecter des informations sur la perception paysanne du changement climatique. Le modèle de régression multinomial a été utilisé pour identifier les facteurs qui influencent la perception paysanne du changement climatique.

2.2.2. Dynamique de rendement du karité dans les systèmes de parcs agroforestiers

L'échantillon mentionné ci-dessus a été utilisé pour la collecte de données de cette sous-section. Deux types de données ont été collectées à savoir: les données socio-économiques et biophysiques. L'analyse de cluster (KCA) a été utilisée pour générer les groupes des ménages. Les données entrées dans le modèle (modèle multi-agents) sont celles des précipitations sur 30 ans (1982-2012) et les paramètres socio-économiques et biophysiques. Les deux derniers types de données ont été transférés dans le programme NetLogo (version 5.2.0) pour les simulations.

2.2.3. Analyse fractale de branche (FBA) pour l'estimation des stocks de carbone du Karité

Au total, 70 pieds de Karité ont été sélectionnés dans les sites d'étude, avec 30 pieds à Koutiala et 40 pieds à Yanfolila. Les 70 arbres ont été regroupés en six catégories en fonction du diamètre à hauteur de poitrine (DBH) comme suit: 3 à 7; 7 à 10; 10 à 14; 14 à 24; 24 à 32 et > 32 cm. Les données collectées concernent la partie aérienne et souterraine (racines) du karité. Les équations allométriques spécifiques des deux sites ont été évaluées en utilisant le coefficient de détermination (R^2); l'erreur standard de l'estimation (SEE) et les valeurs de F générées par l'analyse de régression linéaire.

2.2.4. Potentiel de la dendrochronologie pour évaluer le taux de séquestration du carbone du karité dans le sud du Mali

Au total, 20 disques de karité ont été collectés dans le sud du Mali, 8 à Koutiala et 12 à Yanfolila. La méthode standard de dendrochronologie a été utilisée pour préparer les échantillons pour la mesure des cernes **(Cook *et al.* 1990)**. Nous avons combiné l'approche dendrochronologique avec les équations allométriques pour estimer la biomasse. Les relations entre le climat et la croissance ont été explorées à travers la corrélation de Pearson entre la largeur des cernes et les facteurs climatiques (précipitations et température).

3. Résultats et Discussion

3.1. Perception paysanne du changement climatique

Les résultats ont montré que plus de 60% des personnes interrogées estiment que la sécheresse, la température, le nombre de jours chauds, la vitesse du vent et la poussière ont augmenté dans le sud du Mali. La plupart des répondants (89% à Koutiala contre 67% en Yanfolila) ont également mentionné la diminution des quantités de précipitations au cours des deux dernières décennies. Ailleurs, en Afrique de l'Ouest des résultats similaires ont été rapportés par **Mertz *et al.* (2009); Ayanwuyi *et al.* (2010); Sofoluwe *et al.* (2011); Odewumi *et al.* (2013).**

Les résultats de la régression multinomiale ont révélé que l'âge, le niveau scolaire, la taille des exploitations et le sexe sont les principaux facteurs qui influencent de manière significative la perception paysanne du changement climatique dans le sud du Mali. Ce résultat corrobore de nombreuses études antérieures sur la perception paysanne du changement climatique **(Ayanwuyi *et al.* 2010; Legesse *et al.* 2010; Olayemi 2012; Sahu et Mishra 2013).**

Nos résultats ont montré que 100% des personnes interrogées dans les deux sites ont rapporté que les parcs à karité contribuent à améliorer leurs moyens de subsistance. Les fruits sont utilisés comme nourriture et le beurre de karité pour la cuisine et la production de savon. Les parcs à karité fournissent également des services de régulation qui pourraient potentiellement réduire la vulnérabilité des agriculteurs aux impacts du changement climatique. Les services de régulation les plus fréquemment cités par les agriculteurs sont la protection des sols contre l'érosion éolienne et hydrique, la réduction de la température grâce à leur ombrage et l'amélioration de la fertilité des sols. Plus de 90% des agriculteurs dans les deux sites ont reconnu que les parcs à karité offrent un ombrage et créent de bonnes conditions de microclimat. Près de 93% des agriculteurs de Koutiala contre 61% des agriculteurs de Yanfolila ont fait savoir que les parcs à karité sont largement utilisés comme brise-vent qui protègent les terres agricoles contre l'érosion des sols.

3.2. Evaluation de la productivité en noix d'un certain nombre de pieds de Karité

3.2.1. Types de ménages

A partir des données collectées, deux types de ménages ont été identifiés, à savoir, le type 1 ménage pauvre, et le type 2 ménage riche. Le type 1 est composé de 83% (n = 97) des ménages de Yanfolila contre 81% (n = 64) des ménages de Koutiala. Le coton est la principale culture de rente pour les ménages de type 2. Contrairement aux ménages de type 1, la contribution du karité au revenu annuel brut du type 2 est peu élevée.

3.2.2. Rendements simulés du karité et validation du modèle

A Koutiala la moyenne des simulations est de 186.60 ± 97.50 kg ha^{-1} an^{-1} contre 227.57 ± 149.24 kg ha-^{1} an^{-1} à Yanfolila. Les résultats des simulations ont des tendances similaires à celles dérivées des enquêtes (219.11 ± 146 kg ha^{-1} an^{-1} à Koutiala contre 298.57 ± 272.73 kg ha^{-1} an^{-1} à Yanfolila). Ainsi, les résultats issus de nos simulations sont compatibles avec ceux de l'enquête, ce qui explique la validité du modèle.

3.3. **Analyse fractale de branche (FBA) pour l'estimation des stocks de carbone du karité**

3.3.1. Estimation du stock de carbone aérien et souterrain du karité

Le stock de carbone aérien du karité à Koutiala (2.16±0.44 Mg C ha^{-1}) n'était pas significativement différent de celui de Yanfolila (3.21±0.60 Mg C ha^{-1}). Nos résultats sont proches de ceux de **Peltier *et al*. (2007)**, qui ont rapporté, 5.046 Mg C ha^{-1} de biomasse aérienne dans les parcs de karité au Cameroun. Aucune différence significative n'a été trouvée entre les stocks de carbone souterrains des deux sites (0.8±0.15 Mg C ha^{-1} à Koutiala contre 1.26±0.21 Mg C ha^{-1} à Yanfolila).

3.3.2. Validation du modèle d'analyse fractale de branches (FBA)

Les résultats de la regression linéaire entre le stock de carbone aérien et souterrain par rapport au diamètre à hauteur de poitrine / diamètre de la racine, a donné des valeurs de R^2 allant de 0,87 à 0,94 au niveau des deux sites. En outre, l'erreur standard de l'estimation (SEE) est de 0.051 (5.1%) à Koutiala, comparativement à 0.052 (5.2%) à Yanfolila pour les stocks de carbone dans la partie aérienne. Les résultats ont montré que la valeur de F pour le modèle de régression est significativement différente de zéro, ce qui valide le modèle.

3.4. Potentiel de la dendrochronologie pour évaluer le taux de séquestration du carbone du karité dans le sud du Mali

3.4.1. Croissance radiale annuelle du karité dans les différents types d'utilisation des terres

Les résultats ont montré qu'il n'y a pas de différence significative entre la croissance radiale annuelle pour un même site. Par contre, la croissance radiale moyenne annuelle des parcs de Yanfolila est statistiquement différente ($P <0.05$) de celle de la jachère à Koutiala.

3.4.2. Chronologies des cernes

La datation a été un succès pour 7 arbres sur 8 à Koutiala contre 8 arbres sur 12 à Yanfolila. Cela indique que la datation correspond à un succès de 15 sur 20 ou 75% de réussite pour les deux sites. La longueur de la chronologie était 68 ans à Yanfolila contre 78 ans à Koutiala. La valeur du signal exprimée de la population (EPS) de nos arbres d'étude (0.93 à Koutiala et 0.94 à Yanfolila) est supérieure au seuil standard (0.85). Cela signifie que la chronologie de la présente étude est fiable pour les deux sites.

3.4.3. Relations climat-croissance de karité

Une relation significative a été trouvée entre la croissance du karité et les précipitations annuelles à Koutiala ($r = 0.50$, $n = 45$ ans, $p < 0.05$) et à Yanfolila ($r = 0.66$, $n = 31$, $p < 0.05$). La corrélation entre la pluviométrie saisonnière et la chronologie résiduelle est aussi importante à Koutiala ($r = 0.55$, $n = 45$ ans, $p < 0.05$) et à Yanfolila ($r = 0.71$, $n = 31$, $p < 0.05$). Nos résultats corroborent des études antérieures en dendrochronologie en Afrique **(Fichtler *et al.* 2004; Gebrekirstos *et al.* 2008; Nicolini *et al.* 2010; Trouet *et al*. 2010).** Par contre, aucune corrélation statistiquement significative n'a été trouvée entre la température et la chronologie résiduelle ni à Koutiala ($r = -0,20$, $n = 31$, $p > 0,05$) ni à Yanfolila ($r = 0.10$, $n = 31$, $p > 0.05$).

3.4.4. Estimation des stocks de carbone et la séquestration de la biomasse aérienne (AGB)

Il n'y a pas de différence significative pour la séquestration du carbone de la biomasse aérienne ($p > 0,05$) entre les deux sites et entre les types d'utilisation des terres. Une tendance similaire a été observée pour la quantité de carbone stockée lorsque l'on compare les deux sites.

4. Conclusion et perspectives

Les résultats ont révélé que les agriculteurs sont conscients du changement climatique et ont déjà entrepris des mesures d'adaptation comme la diversification des cultures, ainsi que l'adoption de nouvelles variétés de cultures.

En raison du rôle clé du karité dans le revenu des ménages des agriculteurs, il est nécessaire pour eux d'investir dans les activités de plantation de karité.

Notre étude a fourni de nouvelles perspectives sur l'estimation de la biomasse en développant des équations allométriques spécifiques pour le karité. Cette méthode doit être étendue sur d'autres espèces dans la région.

Les résultats de la dendrochronologie ont révélé que la largeur des cernes est significativement corrélée aux précipitations dans les sites d'étude. L'utilisation des isotopes de l'oxygène et de carbone conjointement permettra de mieux explorer la reconstruction du climat dans les futures études similaires.