KWAME NKRUMAH UNIVERSITY OF SCIENCE

HYDROLOGICAL MODELLING OF ZAÏ PLANTING PIT FOR RAINWATER HARVESTING IN AGROFORESTRY SCHEMES FOR CLIMATE CHANGE ADAPTATION IN THE SUDANO-SAHELIAN ZONE OF NIGER

By

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AND TECHNOLOGY, KUMASI, GHANA

DECLARATION

I hereby declare that this submission is my own work towards the PhD in Climate Change and Land Use and that, to the best of my knowledge, it contains no material previously published by another person, nor material which has been accepted for the award of any other degree of the University, except where due acknowledgment has been made in the text.

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Date

DEDICATION

DEDICATION

To my mother, Amina Nabiou

and

my late father and brother

May their souls rest in peace, ameen

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ABSTRACT

An estimated 23.5 % of global land area is affected by land degradation and this has resulted in 1 to

2.3 million hectares of agricultural land becoming unsuitable for cultivation. Situated in the SudanoSahelian zone, Niger is a landlocked area, experiencing the challenges of severe soil crisis in a context of water scarcity. To reverse the trend of land degradation in Niger, many sustainable land management practices are used, including rainwater harvesting techniques. So far, few studies consider the potentials of *in situ* rainwater harvesting in the establishment of agroforestry systems on degraded lands. The objective of this study was therefore to evaluate the biophysical viability of the forestry *zaï* technique (a water harvesting technique used to reclaim degraded lands) in the Sudano-Sahelian zone of Niger under current and future climatic conditions. A two-year field experiment was conducted on a degraded land in Niger using a randomized block design with four replications. The treatments included the traditional planting technique and the forestry *zaï* technique. Compared to the traditional planting technique, the forestry *zaï* increased the soil water storage in the root zone which in turn led to a significant improvement of millet grain yield that reached 1088 $kg.ha^{-1}$, compared to 668 kg ha^{-1} recorded under the traditional planting technique. In contrast to millet, *A. senegal* showed mild sensitivity to the water harvesting technique, while tree survival rate was 100 % for the traditional and *zai* systems. The study also revealed that the technique of the forestry *zaï* is a suitable rainwater harvesting technique even under changing climatic conditions. Therefore, it contributes both to adaptation (a solution to water scarcity and land degradation) and mitigation (carbon sink) for perennial tree species.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

AR: Assessment Report

CO_2: Carbon dioxide

FAO: Food Agriculture Organisation

GCM: Global Climate Model

GHG: greenhouse gases

HI: Harvest Index

IFPRI: International Food security Research Institute

IPCC: Intergovernmental Panel on Climate Change

NAPA: National Adaptation Program of Action

NGO: Non-Governmental Organisation

RCM: Regional Climate Model

RCP: Representative Concentration Pathways

RWH: Rainwater harvesting

SW: Soil Water

UNCCD: United Nation Convention to Combat Desertification

UNFCCC: United Nations Framework Convention on Climate Change

WOCAT: World Overview of Conservation Approaches and Technologies

WS: Water Scarcity

CHAPTER 1: INTRODUCTION

1.1. Background of the Study

Many regions (arid and semi-arid) in the world are facing the risk of landscape degradation and even desertification due to water scarcity (WS) and mismanagement. Water scarcity is becoming more and more severe with global implications (Sazakli et al., 2007). The distribution of water reserves is far from being homogeneous, both geographically and temporally. Consequently, many regions face water scarcity problems, affecting not only those located in arid areas but also those in which demand exceeds water supply (Angrill et al., 2012). Due to the uneven distribution of water reserves in time and space, an estimated two billion people live in highly water-stressed areas (Oki and Kanae, 2006) . In addition, climate change is expected to increase the problem of water scarcity in the future. Regional climate change predictions are often ambiguous for rainfall evolution, but for arid and semi-arid regions, all the Intergovernmental Panel on Climate Change (IPCC) scenarios (IPCC, 2007) predict an increase in temperatures of at least 1.5 °C by the end of the 21st century.

Water scarcity is one of the greatest challenges that agricultural food production is facing today. An estimate of 80% of global agricultural land is rainfed (Viala, 2008) and at present, nearly 80 % of the world's population is exposed to high levels of threat to water security (Vörösmarty et al., 2010) and world population increase will have a significant impact on water usage for food. In addition to water scarcity, the world now faces a modern soil crisis that eclipses those of the past (Koch et al., 2013). Soil degradation (the decline in soil function or its capacity to provide economic goods and ecosystem services) is a global phenomenon with many faces (Lal, 2010). The pressures on soil are widespread and varied. The challenges created by soil demand drive deep into our continued ability to provide sufficient resources for the world's growing population. Furthermore, 23.5 % of global land area is affected by land degradation (Bai et al., 2008). This has resulted in 1 to 2.3 million hectares of agricultural land becoming unsuitable for cultivation (Lambin and Meyfroidt, 2011).

In many regions of the world, since the balance between water demand and water availability has reached critical levels and increased demand for water and food production is likely to occur in the future, a sustainable approach to water resource management in agriculture is essential. The concept of sustainable water management is relevant to all practices that improve crop yield and minimise non-beneficial water losses (Mancosu et al., 2015). Conserving water and soil resources, while achieving food security is a high concern on the international research agenda (Pretty et al., 2010). In addition, increasing water scarcity and soil crisis point to the necessity of a more sustainable approach to soil and water management in agriculture at the global, regional and local level.

Rainwater harvesting (RWH) is a common soil and water conservation technique. RWH is massively promoted by NGOs, national agricultural extension services and government agencies in Africa (Stroosnijder, 2003) and India (Batchelor et al., 2002) where its practices already have a long tradition (Pandey et al., 2003). RWH is also one of the practices recommended by UNCCD to combat desertification.

In situ RWH belongs to the promising practices to support sustainable development in subSaharan Africa which is expected to be negatively impacted by climate change. Its practice improves hydrological indicators such as infiltration in the root zone (soil moisture) and below the root zone (groundwater recharge) (Vohland and Barry, 2009).

Rainfed agriculture is the dominant source of food in dryland Africa, which constitutes 43 % of the continent’s surface area (Wani et al., 2009). Within the agricultural system of drylands, rainfall is the main random production factor and water shortage often leads to reduced crop production. According to Critchley et al. (1991), farmers should therefore first reduce the rainfall-induced production risk, before investing in, for example fertilizer or improved planting material. In their excellent comprehensive assessment of water management in agriculture, Falkenmark et al. (2001) demonstrated that water shortages in rainfed agriculture can be tackled with low-cost methods referred to as *in situ* RWH .

Situated in Western Africa, in the Sahelian zone, Niger is a landlocked area, experiencing the challenges of water scarcity and soil crisis in a severe way. With a surface area of 1.26 million km^2, Niger is the largest country in West Africa (Merrey and Sally, 2014). However, 75 % of the land is desert. Its population is currently over 17 million and growing at a rate of around 3.3 % annually – the highest rate in the world (Merrey and Sally, 2014). Eighty percent of the population lives in rural areas, mostly engaged in agriculture (including growing crops, raising livestock, fishing, and forestry) (Merrey and Sally, 2014).

As population has grown, cultivation has been extended to drier and even marginal and degraded lands (Fatondji et al., 2006; Mansour and Fendrich, 2011) . Food is limited and crop yields are far below potential. Management of land to prevent or reverse degradation involves, to a large degree, management of water.

1.2. Justification of the Study

This dissertation explores the potential of *in situ* RWH techniques to address water shortage and soil degradation that inhibit Niger's ability to move toward greater food security for its population. The major techniques of *in situ* RWH disseminated in Niger, include *zaï* pits, halfmoons, contour bunds ("*banquettes*"), small dikes and stone bunds. This study will focus on the technique of *in situ* RWH called *zaï* in Burkina or *tassa* in Niger. In Niger, the traditional *tassa* system of cropping is used by digging small planting holes of 20–30 cm diameter and 20–25 cm depth about 1 m apart in each direction, to hold pockets of rainwater and moisten the soil (BaiduForson, 1999; Bouzou Moussa and Dan Lamso, 2004). *Zaï* systems are particularly well adapted to smallholder conditions, as this allows increasing production in the short term while restoring lands in the long term; implementation in small patches of land that can be gradually expanded; accommodating smallholders' strategies of concentration of scarce resources such as animal manure (Lahmar et al., 2012). There are 2 variants of *zaï*, namely the agricultural and the forestry *zaï*. This study focuses on the latter variant of *zaï*. It is an agroforestry planting technique used to reclaim degraded crusted lands that allows an intercropping of an annual and perennial species on a given farm. At the end of the rainy season, the annual crop is harvested and the stalks are cut at a height 1 m to protect the forest species against wind and animals (Roose et al., 1999). Pearl millet (*Pennisetum glaucum* (L.) R. Br.) will be used as annual crop, intercropped with the perennial species *Acacia senegal* (L.) Willd (Mimosaceae) in the case of this study. .

On one hand millet is the most important crop, occupying nearly half of the total harvested area in Niger. The International Food Policy Research Institute (IFPRI) projects that millet production will not keep pace with population growth; the deficit will continue growing for decades from about 2020s (Jalloh et al., 2013). The majority of food is produced by smallholder farmers. They are largely dependent on rainfed agriculture and are mainly located in the Tillaberi region, the southern, wettest part of the country (Gandah et al., 2003). Yields are often extremely low, averaging only 350 kg ha^{-1} for millet, while the potential yield is close to 1000 $kg.ha^{-1}$ (FAO, 2014).

On the other hand, dryland acacia species' ability to restore the land productivity is supported by evidence from scientific research and from traditional farming practices. The re-introduction of gum gardens and rehabilitation of degraded lands using *A. senegal* and other dryland acacia species can serve as a model for agricultural land rehabilitation for the entire Sudano-Sahelian zone (Elfadl and Luukkanen, 2005). Furthermore, promoting indigenous species is becoming more and more useful. It makes available to local people products such as fruits, vegetables, medicines, fire-wood, building material, etc. Despite their socio-economic importance, local people do not traditionally plant indigenous species (Nikiema, 2001).

Thus, sustainable intensification can play a significant role in enhancing millet production while restoring degraded/desertified soils. It mitigates global warming by sequestering atmospheric CO_2 in soils and vegetation (forests). It also adapts to climate change by using recommended management practices of the so called "climate-resilient" or "climate-strategic" agriculture. It helps in improving farm income and empowers women and other under-priviledged populations (Lal et al., 2015). Pasternak et al. (2009) also called this management practice "bioreclamation" of degraded land

(BDL)”. The BDL is basically an agroforestry system, improved with the incorporation of trees and crop under *in situ* RWH on degraded crusted lands (Fatondji et al., 2013).

Most of the studies on the *zaï* focussed on sole cropping systems. Yet, very few studies explore the forestry *zaï* for intercropping systems. Furthermore, there has been no study to investigate hydrological modelling under this technique. How does this technique minimise soil and nutrients loss both for agricultural and forestry *zaï* have not also been explored yet. There is also a research gap in the impact of climate change on this technique of *in situ* rainwater harvesting. This dissertation provides valuable insights into many of these issues. However, the gaps related to mono cropping are not covered in this dissertation. This research will contribute towards providing a better understanding of the interaction of *A. senegal* and pearl millet under the technique of forestry *zaï.*

1.3. Objectives of the Study

1.3.1. Main objective

The overall objective of this study was to evaluate the biophysical viability of the forestry zaï technique in the Sudano-Sahelian zone of Niger under current and future climatic conditions. The findings of this study will provide valuable insights into agricultural land, water and nutrient shortages that are key factors in the low crop productivity contributing to Niger’s food insecurity. Furthermore, through the association of pearl millet with *A. senegal* under the forestry *zaï* technique, lands would be reclaimed while increasing household income particularly with the benefits from the perennial species, contributing both to adaptation and mitigation in a context of climate change.

1.3.2. Specific objectives

This study specifically aimed to:

1. Determine the agronomic performances of pearl millet and *A. senegal* under the

technique of forestry *zaï*;

2. Determine the hydrologic behaviour of the "forestry *zaï*" using a simulation model;
3. Model the impact of climate change on the hydrologic behaviour of the "forestry *zaï*" under future climate scenarios.

Each of the specific objectives is addressed in one chapter (**Chapters 3, 4 and 5**) in this dissertation.

1.4. Research Questions

This study aims to provide answers to the following research questions:

1. Does the technique of forestry *zaï* increase the agronomic performances of pearl millet and *A. senegal*?
2. What is the hydrologic behaviour of the "forestry *zaï*" in the root zone?
3. What is the impact of climate change on the forestry *zaï* technique?

1.5. Layout of the thesis

Chapter 1 introduces this work within the international and the national contexts. **Chapter 2** presents an overview of RWH techniques and narrow down to the *in situ* RWH technique that is the subject of this study and justifies this study both within the framework of scientific research (deducted from research gaps) and real life manifestation. **Chapter 3** investigates the effect of the forestry *zaï* on millet yields, *A. senegal* growth and soil water storage. **Chapter 4** models the dynamic of soil water in the root zone under the *zaï* technique with regards to crop and tree responses. **Chapter 5** models the impact of climate change on the dynamic of soil water storage and crop and tree responses for the technique of forestry *zaï*. In **Chapter 6**, the general conclusions and recommendations of this thesis are presented.

CHAPTER 2: LITERATURE REVIEW

2.1. Rainwater Harvesting

RWH (Rainwater Harvesting) is "the collection of run-off water for its productive use" and generally consists of three components: a catchment area, a storage facility and a target (Oweis and Hachum, 2009). The catchment area, which can be a rooftop or a part of the land surface, produces run-off which is directed to the storage facility. This can be a cistern, pond or the soil profile and holds the water until it is used by a target, which, in case of agricultural production, is the crop or animal (Critchley et al., 1991).

A wide range of RWH systems exists and they have been classified in many ways. Critchley et al. (1991) gave a well-known overview of RWH techniques. Recently, also the World Overview of Conservation Approaches and Technologies (WOCAT) has published an overview of RWH systems (Mekdaschi Studer and Liniger, 2013). Critchley et al. (1991) have subdivided RWH systems into micro- and macro-catchment systems. Micro-catchment systems directly supply run-off water from a small catchment area to an adjacent cropping area, whereas macrocatchment systems divert water with dams and canals from a bigger catchment area or a Wadi (natural channel) to nearby land. Since micro-catchment systems are low-cost methods, individually implementable and efficient in reducing run-off water loss, they are generally preferred to macro-catchment systems (Oweis and Hachum, 2006). These micro-catchments are also called *in-situ* RWH.

Gowing et al. (2015) have defined *in-situ* RWH, as a soil and water conservation method that refers to a group of techniques for preventing runoff and promoting infiltration. It retains moisture that would otherwise be wasted as runoff from the cropped area. Rain is conserved where it falls. No additional runoff is introduced from elsewhere. This approach is appropriate where the main constraints are related to the soil but rainfall is sufficient. The acceptance of water may be hindered by low infiltration rate, caused by surface crusting (capping). The problem could also be caused by low percolation rate due to restrictive layers in the soil profile. These problems are caused by inherent soil characteristics or previous mismanagement (e.g. formation of plough pan, compaction by trampling). This system works better on soils with high water holding capacity and where the rainfall is equal to or higher than the crop water requirement, but moisture amount in the soil is restricted by the amount of infiltration and or deep percolation (Hatibu and Mahoo, 1999). *In-situ* RWH belongs to the promising practices for supporting sustainable development in sub-Saharan Africa but it is expected to be negatively impacted by climate change. Its practice improves hydrological indicators such as infiltration in the root zone (soil moisture) and below the root zone (groundwater recharge) (Vohland and Barry, 2009).

In situ RWH techniques have already been extensively investigated in scientific literature, but many research gaps remain. In order to formulate the research questions of this study, an extensive examination of international scientific literature on the RWH techniques have been done. A number of papers and technical reports provide good inventories of these techniques together with information for their implementation (Biazin et al., 2012; Critchley et al., 1991; Liniger and Critchley, 2007; Liniger et al., 2011; Mekdaschi Studer and Liniger, 2013; Reij et al., 2013). For the particular case of the *zaï* technique that is the subject of this study, most of the studies focus on crops and reported increase of crop yields (Fatondji et al., 2006; Lahmar et al., 2012; Roose et al., 1999; Sawadogo, 2011; Shemdoe et al., 2009), soil water balance (Fatondji et al., 2011; Oweis and Taimeh, 1996; Wildemeersch et al., 2015a), characterisation of drought stress (Wildemeersch et al., 2015b), manure decomposition and nutrient release and nitrate fate from organic amendment (Fatondji et al., 2011; Fatondji et al., 2009). Roose et al. (1999) also mentioned the effect of *zaï* on biodiversity. The effect of this technique on soil quality have also been explored by Wildemeersch et al. (2015d). Fatondji et al. (2011) reported that the agricultural *zaï* helps plants to escape from dry spells by improving soil water status. The study of Wildemeersch et al. (2015a) showed that the *zaï* technique significantly reduces runoff, stores more water in the catchment area and increases crop transpiration. For the agricultural *zaï*, high nutrients release of organic amendment that strongly exceed plant nutrients uptake, which could lead to important leaching losses of nitrogen during the first 4-5 weeks were reported by previous studies (Fatondji et al., 2011; Fatondji et al., 2009).

Comparably to crops production, few papers investigate the potentialities of this *in situ* rainwater harvesting technique for re-afforestation. Koutou et al. (2007) analysed the factors that control the adoption of the forestry zaï technology in Burkina Faso. The identified factors controlling the adoption of the forestry *zaï* were the number of hoes owned by a farmer, the number of small ruminants in the area and the acceptance of a farmer to lend the material used to dig the *zaï* to a farmer that does not have it. Avakoudjo et al. (2013) examined the best vegetal species and soil and water conservation techniques for the elaboration of the best strategies for reclaiming degraded Sudano-Sahelian ecosystems in the northern Benin. They showed that the species of *Jatropha curcas* and *Balanites aegyptiaca* grow faster under the forestry *zaï* technique. Doamba (2012) explored the effect of the forestry zaï on biodiversity and soil parameters. The results showed an improvement of plant diversity on plots of *zaï*. The study also showed the impact of termites with the construction of biogenic structures (increasing of soil porosity).

2.2. Pearl Millet (*Pennisetum glaucum*)

Pearl millet, or in short, millet, was domesticated since 4000 to 5000 years ago (Vadez et al., 2014) and is now widely distributed across the semi-arid areas of Africa and Asia, where it is principally grown for its grains. It was domesticated in the West African Sahelian zone, which is known to be the crop's main centre of diversity. India is the largest producer of pearl millet. The major millet producing countries in Africa are Burkina Faso, Chad, Mali, Mauritania, Niger, Nigeria and Senegal. In the United States of America, Australia, South America and Europe millet is grown as a highquality, forage crop (Vadez et al., 2014). In Niger, millet is used for human consumption. As, principal sources of energy, minerals and proteins for the rural population, millet grains are consumed as dough or porridge. Millet straw is used as thatching material and as a source of fodder during the dry season (Haussmann et al., 2012).

2.2.1. Taxonomy and description

Pennisetum glaucum belongs to the Poaceae family and the Paniceae tribe. Pearl millet grown in Africa can be classified into two groups: the early varieties reaching maturation between 75 to 100 days, and the late varieties maturing in 100 to 150 days. Millet is an annual crop and reaches a height of 3 to 6 m, although the most productive varieties are shorter (Hausmann et al., 2012). Pearl millet produces various tillers. The leaves are flat, green, and up to 8 cm wide; the grainbearing head of the plant forms a compact, cylindrical panicle. There are between 500 and 3,000 spikelets on a panicle, depending on the variety (Serraj et al., 2003).

The growing millet has a vegetative phase (sowing, germination, establishment, tillering and jointing) and reproductive stage (heading, flowering, grain filling and maturation).

The duration of each of these growth stages varies considerably and depends on variety and environmental conditions. In West-Africa, for late varieties, the vegetative phase typically lasts 50 to 80 days, whereas the grain-filling phase begins at 80 to 120 days after emergence (Maiti and Bidinger, 1981).

2.2.2. Millet ecology

Millet is tolerant to high temperatures. The optimal temperature for seed germination ranges between 37 to 44 °C (Loumerem et al., 2004). Millet endures low soil fertility and high soil acidity, but does not resist water-logged or seasonally-flooded soils. Due to its tolerance to challenging environmental conditions, millet is often found in marginal areas where other cereal crops, such as maize or wheat, do not survive. Millet is cultivated in the Sahel, on coarsetextured soil, containing more than 65 % sand (Brunken et al., 1977). The crop is generally grown in areas where annual rainfall varies from 200 to 800 mm and its optimal crop water requirement is estimated at 450 mm. Variability in inter-annual rainfall is extremely high in the Sahelian region, resulting in recurrent drought periods. The timing of these drought periods is of paramount importance for their effect on millet crop production, as the sensitivity of millet to drought stress changes throughout its development. During the vegetative phase, millet is little affected by drought stress. On the other hand, drought stress during germination, flowering and grain formation is one of the main threats to millet production (Maiti and Bidinger, 1981). Despite its sensitivity to drought during certain development stages, millet is well adapted to agricultural areas that are afflicted by severe drought and displays several strategies to resist drought stress.

2.2.3. Management of millet production

In Niger, millet is produced during the four-month rainy season and has a long-term yield average of 350 kg grain ha^{-1}. Under optimal conditions, experimental grain yields of 8000 kg ha^{-1} of some millet hybrids have been reported (Andrews et al., 1993), but yield levels can be increased 2.5 to 3 times on farmer fields if adequate plant material and improved management are applied. Millet is generally grown in monoculture, but can also be intercropped with cowpea or groundnut. It is seeded in pockets, which are opened by hand hoes. In each pocket, 5 to 40 seeds are placed and the clusters of plants emerging are thinned to 3 to 7 plants at first weeding. Farmers traditionally apply a low planting density (10 000 pockets ha^{-1}), as this induces tillering. The most important diseases and pests are downey mildew (caused by *Sclerospora graminicola*), head miner (*Heliocheilus albipunctella*) and stem borer (*Coniesta ignefusalis*), whereas *Striga asiatica* (L.) Kuntze and *Striga hermonthica* (Del.) Benth are known to parasitise pearl millet. Harvesting is usually done by clipping panicles from millet stems. Periodic clipping reduces crop damage by birds, pests and weather. Sowing, weeding, thinning and harvesting are in general executed manually and are very labour demanding (Maiti and Bidinger, 1981).

2.3. *Acacia senegal*

In many African countries, *Acacia senegal* (L.) Willd. (Mimosaceae) plays an important role in poverty reduction. In dryland Africa, the plant is used by rural people for ecological, economic, social and even cultural purposes. *A. senegal* is known as Arabic gum, and the tree produces gum which is used for food, medicine and in ceremonies. The gum is sold and procures revenues that are important for rural producers and can be seen even in the gross national product of Sahelian countries. Other species produce gum, but gum from *A. senegal* is usually regarded as having the best quality and has various uses in cosmetic, medicinal and food industries (Arbonnier, 2002). The firewood of *A.*

senegal is of high quality (energy value of 3,500 kcal/kg) and is considered the best in Mauritius and Senegal. As a nitrogen-fixing species, it is also used to re-establish vegetation cover in degraded areas, as well as to fix sand-dune and to control wind-erosion (Ruskin, 1980). During the 1970s, Niger was among the large producers of gum, and the annual export reached values above 2,500 tons. The export declined considerably during the following years, and in 2000 the official statistics in France, Nigeria and Côte d'Ivoire (the major buyers of gum from Niger) showed an export of only 115 tons. To this should be added an estimated unofficial export to Nigeria of about 1,000 tons. The decrease in export was attributed to droughts, decimating the tree populations, poor regeneration of the stands and poor organisation of the trade (Rossi, 2005). Lately, due to the recent crisis in Sudan, the world's largest producer of Arabic gum, there has been an increased interest in promoting the species for gum production and restoration of vegetation (Larwanou et al., 2010).

2.3.1. Botanic description of *A. senegal*

Arabic gum, *Acacia senegal* (L.) Willd. belongs to the genus *Acacia*, and is a leguminous tree species, belonging to the Family Fabaceae, sub-family Mimosoideae, consisting of more than 300 species that produce gum in commercial quantity (Ibrahim et al., 2014).

A. senegal, a deciduous shrub, grows up to 15 m tall and usually starts branching from the ground. The diameter of the trunk may reach up to 30 cm. At the early stage the bark of *A. senega*l is greyishwhite whereas for old trees it may be dark, scaly and thin, showing the bright green cambium layer just below the surface if scratched with a nail. With a mottled red slash, A. *senegal* has thorns of 35 mm long, with enlarged bases appearing at the nodes of the branches. The thorns are sharp, with some pointing forwards and others backwards (Orwa et al., 2009).

Varietal differences in *A. senegal* depends on differences in morphological characteristics (colour of the axis, shape of pod tips, presence or absence of hair on the axis of the flower spike, number of pinnae pairs, occurrence of a distinct trunk and shape of the crown) as well as on variation in natural distribution There are four varieties of *A. senegal:* var. kerensis Schweinf, var. rostrata Brenan, var. senegal, and var. leiorhachis Brenan. The generic name “acacia” derives from the Greek word “akis”, meaning a point or a barb (Nair, 1989).

2.3.2. Biology

A. senegal is pollinated by insects. The beginning of flowering is variable according to the spatial distribution (December to January in South Africa, February to March in Pakistan, June to July in Sudan and August to December in India). The fruits also ripen in July-September in Kenya, August in Pakistan, January in Burkina Faso, October in South Africa and November to December in southern and central Niger. The wind shakes seeds from the dehiscent pods and grazing animals may extend the seed dispersal range (Nair, 1989).

2.4. Climate change, state of knowledge

Since 1990, the IPCC has confirmed in its 1st Assessment Report (AR1) the concerns about climate change, including the assumption that global warming is caused by the increase in the rate of greenhouse gases (GHG) into the atmosphere by human activities (IPCC, 1990). Later in 1992, the IPCC provided an additional report to the negotiators of the United Nations Framework Convention on Climate Change (UNFCCC). In this report, the IPCC reiterated the conclusions of the previous report and the understanding of the Green House Gas (GHG) effects. In its Second Assessment report (AR2) in 1995, the IPCC provided the basis of carbon trading at the Kyoto Protocol (1997) with targets, which forced the signatory countries to reduce their GHG emissions (Protocol, 1997).

Despite the implementation of this protocol, it is apparent from the AR3 (2001), AR4 (2007) and AR5 (2013) of the IPCC that global warming is increasing more and more (IPCC, 2001, 2007; Stocker et al., 2013). In addition, the value of the average speed of warming over the last hundred years (1906-2005), which is 0.74ºC, is greater than was the analogous value calculated at the time in AR3, which was 0.6 ºC. Furthermore there is an increase of global average ocean temperatures, widespread ice and snow melting and rising global average sea level (1.8 mm per year between 1961 and 2003 and 3.1 mm per year between 1993 and 2003). The rainfall regime is uncertain against this phenomenon. Long term observations (1900-2005) of rainfall volumes showed that more rainstorms were noted in eastern North America and South America, north Europe and North and Central Asia (IPCC, 2007). In the Sahel, the Mediterranean, southern Africa and parts of South Asia, drying has been noticed (IPCC, 2007). Similarly, studies of Ballouche (2004) showed a decrease in rainfall amounts and changes in their annual distributions in the Sahel. In the particular case of Niger where this study is conducted, a downward trend in rainfall over the past four decades (1961-2004) and an upward trend in the minimum and maximum temperatures from 1986 to 2005 were noted (PANA, 2006).

For the end of 21st century, global surface temperature is *likely* to exceed 1.5°C relative to 1850 to 1900 for all the Representative Concentration Pathways (RCP) scenarios except RCP 2.6. It will *likely* exceed 2°C for RCP 6.0 and RCP 8.5 and for RCP 4.5, *more likely than not* to exceed 2°C. Beyond 2100, warming will continue under all RCP scenarios, except RCP 2.6. Warming will not be regionally uniform and will continue to show inter annual and decadal variability. During the 21st century, there will be a rise of global mean sea level. All RCP scenarios showed that the rate of sea level is *very likely* to rise and exceed the observations of 1971 - 2010 caused by increased loss of mass from glaciers and ice sheets and increased ocean warming. Global mean surface temperature increases will cause more intense and more frequent extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions by the end of this century. Globally, it is likely that the area covered by monsoon systems will increase over the 21st century. Increase in the atmospheric moisture is likely to intensify monsoon whereas monsoon winds are likely to weaken.
The onset dates of monsoon are likely to become earlier or would not change much. In many regions, Monsoon retreat dates will likely be delayed, resulting in lengthening of the monsoon season **(**Stocker et al., 2013)**.** According to NAPA (2006) in Niger, average monthly rainfall would increase by 2025

compared to the normal for the period 1961-1990, except for the weather stations of Tillabéri and Niamey that will experience a decline. As for the monthly mean temperature by 2025 will experience a very slight increase compared to the normal for the period 1961-1990, with the exception of weather stations of Bilma and Gaya.

The increase in the frequency of heavy rainfall causing floods, violent winds (Carrega et al., 2004; IPCC, 2007) are counted among the main observed climate risks worldwide. According to the IPCC (2007), extreme temperatures (hot nights, hot days and heat waves have become more frequent), rising sea levels and increase of intense activity of tropical cyclone in the North Atlantic since 1970, and more severe and long droughts since the 1970s in tropical and subtropical regions are the key climate risks observed at the global scale. Some of these climatic phenomena are observed everywhere in Africa. Indeed, a study found that since 1943, climate change was marked by the reappearance of extended droughts in the countries of African Sahelian region in relation with the recurrent droughts that began in the 1970s (Durand-Dastès, 1986). Later, Tabet-Aoul (2008) indicated that there is a greater occurrence of droughts (one year on three), increased flooding (especially in Tunisia, Algeria, Morocco), an increasing number of heat waves in all seasons and a rise in sea level. Balouche (2004) showed that the hydrological functioning of Sahelian ponds and lakes indicates a drying trend. In Niger, the extreme events already observed are especially floods, droughts, sandstorms and / or dust, extreme temperatures and high winds (PANA, 2006).

2.4.1. Climate change impacts

The observed climatic phenomena have many impacts. In southern Africa, longer dry seasons and uncertain rainfall regimes are observed. Rising Sea level and human expansion together contribute to decreasing the coastal wetlands area and mangroves and increasing damage to many areas by coastal flooding. In the dry tropics, some areas are subject to water stress (IPCC, 2007). In the Sahel, shorter rainy seasons generated warmer and drier conditions, with detrimental effects on crops. In Niger, a decline in agricultural production, fodder deficit, insufficient water points, silting of water points, drop of the water table, reduction of forest formation areas, decrease in fish production, decrease of biodiversity (species extinction, degradation of wildlife habitat) and an increase in the frequency of some diseases such as meningitis, malaria, and respiratory diseases and formation of sand dunes are observed (PANA Niger, 2006).

Like the already observed impacts, forecasts for Africa are also pessimistic. Indeed, they indicate that by 2020, 75 to 250 million people will be subject to increased water stress, coupled with an increase in water demand. This will have adverse impacts on the livelihoods and will exacerbate water-related problems. Also, in many countries and regions of Africa, it is expected that agricultural production and access to food will be seriously compromised by the variability and the climate evolution. In some countries, where agricultural output depends on rainfall the production could decrease by 50 % by 2020 (IPCC, 2007).

These manifestations of increased variability and climate change have increased the number of vulnerable people. In the particular case of arid and semi-arid areas, that are distinguished from others by a higher degree of vulnerability; either due to greater climate uncertainty or to an excessive imbalance between population and resources distribution (soil erosion, overgrazing) or, conversely, because of too much dependence on a momentarily threatened resource (Cambrezy and Janin, 2003). Therefore, climate phenomena reveal, and amplify the underlying problems related to the vulnerability of societies (Carrega et al., 2004). A study by Nordhaus and Boyer (1999) referred to the agricultural sector as the most vulnerable. Agriculture will likely be significantly affected by climate change, because of the sensitivity of crops to climate variables. However, it is fairly well established that the yields in temperate crops, without adaptation, tolerate a warming of 2 to 3 ° C before declining, while yields of tropical crops declined immediately (Easterling et al., 2002) cited by Cloppet (2004). This reinforces the potential imbalance of climate impact between temperate and tropical regions. It is often the countries in tropical and equatorial regions that have the lower potential to adaptation, because they also depends heavily on resources and the stability of institutions (Cloppet, 2004). In the Sahel, Sultan et al. (2005) highlighted, by model simulations, a strong impact of dry spells on crop performance, depending on the stage of the crop development. Agriculture is the most climatedependent industry; the impact of climate change has become a major issue that goes beyond the scientific framework (Cloppet, 2004). However, across Africa, much of the population is directly dependent on the land for its survival. Therefore, climate change has an immediate impact on the livelihood of populations (Robison and Brooks, 2010).

2.4.2. Adaptation to climate change

There are many ways to define the concept of adaptation. In this concept, the important questions to answer are: ‘‘who and what adapts?’’ , ‘‘adapting to what?’’ and ‘‘how does adaptation occur?’’ (Smit et al., 2000). According to the IPCC (2007) adaptation refers to actions to reduce vulnerability or enhance resilience.

Worldwide, significant efforts for climate change adaptation have been undertaken in several areas at both national and local scales. These include the shift of sowing dates, displacement of populations of polar areas and cyclone warning systems (IPCC, 2007). However, the recent food crisis in countries such as, Niger reminds us of the continuing vulnerability of the region to the vicissitudes of the weather.

Niger, like the other countries of Africa, is one of the most vulnerable regions to the ravages of climate change. Poor and underdeveloped countries, like Niger, are increasingly deficient in terms of financial, technological and human resources capacities needed to address climate change (PANA, 2006). The dependence of majority of the population on agriculture in West Africa vis-àvis rainfed crops makes it particularly vulnerable country to such changes of rainfall regimes (d'Orgeval, 2008). Added to this, a difficult socio economic context weakens the adaptability of Niger.

2.5. Hydrological Modelling

2.5.1. Definition of hydrological modelling

River basin is an area where various hydrologic processes occur. These processes include precipitation, evapotranspiration, infiltration, interception, surface runoff and sub-surface flow. Hydrologic modelling necessitates formulation of mathematical models to represent, these hydrologic processes, as well as the interaction between them. Hydrologic models represent through mathematical abstraction the inter-relationship of soil, climate, water and land use (Gosain et al., 2009). Hydrologic modelling is challenging. It involves highly nonlinear processes, high spatial variability at basin scale and complex interactions. Hydrologic modelling started from the mid 19th century and continues to develop with the better understanding of the physical processes, data retrieving facilities and computational efforts.

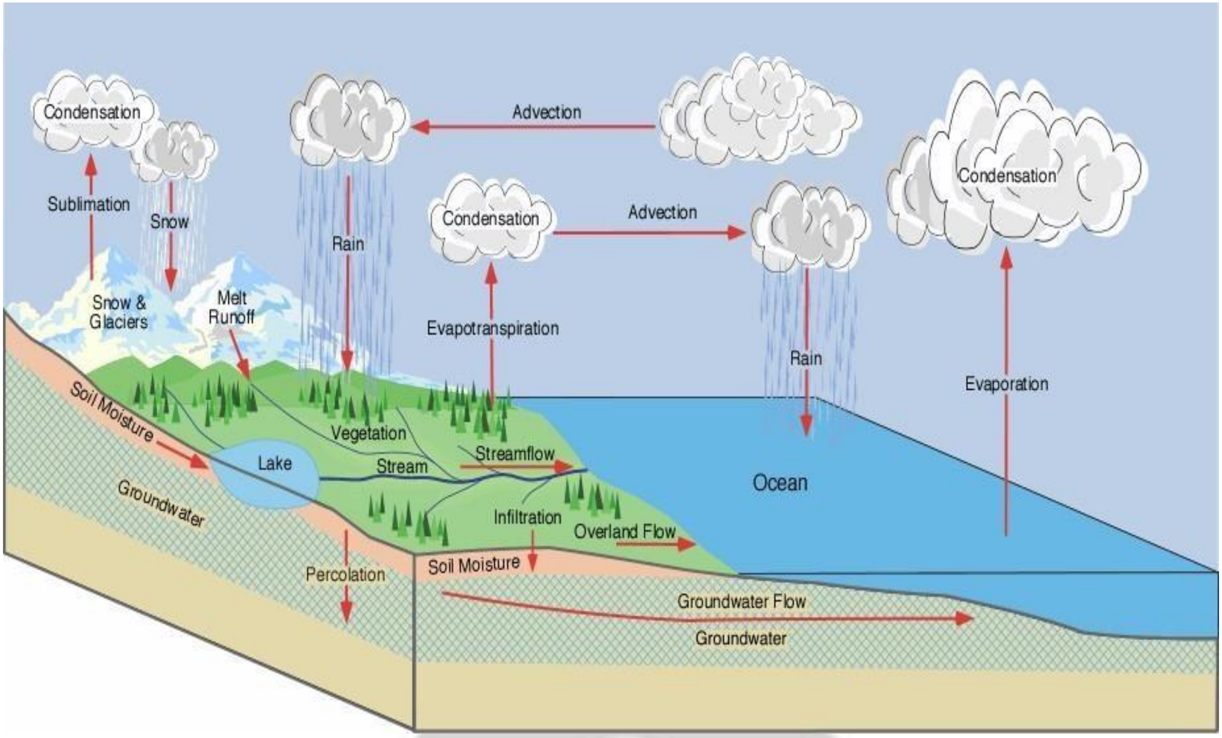


Figure 2. 1 : Hydrologic cycle

(Source : http://www.physicalgeography.net)

2.5.1. Classification of hydrologic models

Hydrologic models are either classified as conceptual or physically based according to the physical processes involved (Refsgaard, 1990). Conceptual models represent the hydrologic processes by simplified mathemat ical relationships, whereas physically based models represent the physical processes in a deterministic way by representations of mass, momentum and energy conservation (Refsgaard, 1990). Hydrologic models are classified as either lumped or distributed mod els, according to the spatial description of the watershed process. The lumped models ignore the characteristics of the spatial variability of the watersheds while the distributed models take into account the spatial variability of vegetation, soil, topography, etc.

2.5.3. Modelling concepts of hydrologic processes

The primary components of hydrologic cycle are: interception, snowmelt, evapotranspiration, subsurface runoff, groundwater flow, surface runoff and channel routing.

Interception Component

The interception component calculates the net precipitation reaching the ground through the canopy and canopy storage. Rainfall interception modifies the surface water balance by vegetative canopies. Over the forest canopies, interception loss can be significantly higher (Noilhan and Mahfouf, 1996). Muzylo et al. (2009) reviewed different approaches of rainfall interception modelling. The Rutter interception model (Rutter et al., 1975) is a reference for rainfall interception. In this model, the canopy interception is given by:

$= (-) - \;\; -\underline{\;\;} ; \leq \leq$ (2.1) where, C is the canopy interception, δ is the through fall coefficient, S is the canopy storage capacity or the maximum interception, is evaporation rate from intercepted water, $_1$ and b are the Rutter drainage parameters; δ and S are related to the leaf area index(LAI) of the canopy.

Evapotranspiration Component

Evapotranspiration component calculates actual evaporation from soil, canopy storage, and open water, sublimation from snow and transpiration from vegetation.

In energy balance method the evaporation rate (E_r) is given by (Chow et al., 1988): $=$ (

$- \;\; - !)$ (2.2) where, Er: Evaporation rate, "$_{\#}$: latent heat of vaporization, $\$_{\%}$: density of water, &': net radiation,

(): sensible heat flux and *: ground heat flux.

In aerodynamic method evaporation (E_a) is given by (Chow et al., 1988):

$$_{+} = , (e_{+} - e_{+}) \qquad (2.3)$$

Where $_{-)}$: saturated vapour pressure, $_{-}$: vapour pressure air temperature and $_{.}$: vapour transfer coefficient.

Penman (Penman, 1948) combined the energy balance and aerodynamic method of evaporation and developed a combination method which is known as the Penman combination method. In this method evaporation is given by:

= /01——/2₃ + /01——¹2₅ (2.4)

Where Δ: slope of the saturation vapour pressure versus temperature curve and 6: psychometric constant, E_r: Evaporation rate in energy balance method, E_a: Evaporation in aerodynamic method.

The model of Prie stley-Taylor (Priestley and Taylor, 1972) is a modified version of Penman's theoretical equation. This method uses an empirical approximation of the equation of Penman to eliminate the necessity of input data other than radiation.

Potential evapotranspiration given by the Priestley-Taylor model:

= 7 / (Rn – G) /01 (2.5)

where < : multiplying factor, *: ground heat flux, Δ: slope of the saturation vapour pressure versus temperature curve and 6: psychometric constant, &': net radiation.

The Penman -Monteith method (Monteith, 1965) is also a modification of Penman combination method (Penman, 1948)). In this method evaporation (*E*) is given by,

= [?(@AB)0C(=>DE)] => ?0C (2.6)

where *: ground heat flux, Δ: slope of the saturation vapour pressure versus temperature curve and 6: psychometric constant, &': net radiation, E_a: Evaporation in aerodynamic method, "#: latent heat of vaporization.

Unsaturated Zone Component

Unsaturated zone is refers to unsaturated and usually heterogeneous soil profile extending from the land surface to the groundwater table (Refshaard et al., 1995). Water in this zone represents the temporary storage of precipitation and is characterised by cyclic fluctuations in soil moisture. In hydrologic modelling, this zone is usually vertically subdivided into two layers: the upper layer (active layer or root zone layer), which exhibits rapid fluctuations in moisture content due to evapotranspiration and precipitation infiltration, and the lower layer (or the transmission zone), which characterises the relatively slow soil moisture behaviour (Biftu and Gan, 2001; Refshaard et al., 1995). Physical processes involved in unsaturated zone are precipitation, infiltration, evapotranspiration from the root zone, percolation to the saturated zone etc. Flow in the unsaturated zone is assumed to be vertical as gravity plays a major role during the percolation.

Most comprehensive physically based hydrologic models use Richards's equation for one dimensional vertical flow to update the soil moisture content and tension in unsaturated zone. The Richard's equation was developed by combining Darcy's law with the law of conservation of mass and includes the effect of soil evaporation and transpiration, gravity and soil suction, in the form (Refshaard et al., 1995):

$$C \frac{FG}{F} = \frac{F}{FH}\left(K \frac{FG}{FH}\right) + \frac{FI}{FH} - S \qquad (2.8)$$

where, J: soil moisture tension, K: time, L: vertical space coordinate, *C:* soil water capacity ($\overline{FM}$), FG N: volumetric water content, (N, L): hydraulic conductivity and S(L): source for root extraction and soil evaporation.

A number of hydrologic models calculate the infiltration separately and apply water balance to update the soil moisture and percolation to the ground water.

Saturated zone component

Saturated subsurface flow and groundwater level is calculated by the saturated zone component. Flow in saturated zone is assumed to be two dimensional horizontal. Saturated zone receives percolation flow from the unsaturated zone and updates the ground water table which in turn updates the lower boundary condition of the unsaturated zone component (Abbott et al., 1986).

Most comprehensive physically based models solve three dimensional ground water flow equation to calculate the spatial and temporal variation of hydraulic heads. Three dimensional groundwater flows in an anisotropic, heterogeneous aquifer or multi-layer aquifer system is given by (Refshaard et al., 1995):

$$S_{FOF} + R = {}_{FPF}\, (R_{S,U}\big({}_{FP} \frac{FO}{Q} \big)_{Q} \big) \quad i, j = 1, 2, 3 \qquad (2.9)$$

where $V(W_{XY})$ is the specific storage, $h(W_X)$ is the hydraulic head, W_X is the space coordinates, $R(W_{XY})$ is the hydraulic conductivity, and & (W_{XY}) is the volumetric flow rate via source or sink.

Surface runoff and routing Component

This component includes three physical processes: accumulation of water contributing surface runoff (known as overland flow), routing of overland flow to the nearest stream channel and routing of channel flow to the basin outlet. Surface runoff can occur in two ways: when the rate of precipitation is lower than the infiltration, the soil becomes saturated and runoff occurs (knows as Dunne runoff); when precipitation rate exceeds soil infiltration rate (known as Horton runoff). Distributed hydrologic model based on variable contributing area expresses the topographic index in distribution function form and thus generate hydrologically similar area based on similar values of topographic index. Contributing areas having the local water table above the surface considered as saturated zone and any rainfall falling upon that zone is taken to runoff.

Some physically based distributed hydrologic models (e.g. ISBA, MISBA, and LISTFLOOD) consider the sub-grid heterogeneity of moisture capacity of soil (x) to follow the Xinanjiang distribution (Ren-Jun, 1992):

$$F([) = -(-P\backslash]\hat{}P)_{\beta} \quad 0 << x << x_{max} \qquad (2.10)$$

where, β: empirical parameter and F (W): cumulative probability distribution of x completely defined by the maximum (W_{max}) and mean moisture capacity of the soil (W_{mean}). The scheme behaves like a multi-bucket model in which the buckets size distribution is defined by the Xinanjiang distribution (Ren-Jun, 1992). When a bucket is filled, surface runoff occurs (Kerkhoven and Gan, 2006).

2.6. Agroforestry Systems

Agroforestry system refers to land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately associated on same land management with agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In these systems, the components are related by ecological and economical interactions (Lundgren and Raintree, 1982) cited by (Nair, 1993). Furthermore, all agroforestry should theoretically possess the following three attributes namely, productivity, sustainability and adoptability. These attributes are the characteristics of all agroforestry systems. They are the basis to evaluate various agroforestry systems (Nair, 1993).

CHAPTER 3: PERFORMANCE OF PEARL MILLET AND *ACACIA SENEGAL* UNDER FORESTRY *ZAI* WATER HARVESTING TECHNIQUE

3.1. Introduction

Human pressure on the environment has led to severe soil crusting and desertification throughout Sahelian regions (Descroix et al., 2009; Valentin, 1995). Over the last three decades (19712000), land use in Niger is characterized by a continuous degradation and loss of tree cover (Hountondji et al., 2004; Ibrahim et al., 2015b). The high population growth (3.3 %) led to an increase of land allocated to cultivation from 10% of the total area in the 1950s to close to 80 % by 2009 (Cappelaere et al., 2009). The length of fallow periods has considerably decreased to an average of 2.6 years (Valentin et al., 2004) due to land shortage. Crop productivity consequently decreased in the absence of sufficient fertilizer input, increasing problems of food supply and cropped area requirements for the fast-growing population (Cappelaere et al., 2009). Limited availability of fertile lands forces farmers to rely on marginal and degraded lands for agricultural production (Fatondji et al., 2006). Furthermore Valentin et al. (2004) showed that fallowing does not invariably imply a reduction of soil crusts.

The *zaï* is an indigenous practice that consists of digging small basins of variable size, usually 20-40 cm in diameter and 10-20 cm deep in order to collect runoff water (Roose et al., 1999; Yameogo et al., 2011). Its application to crusted surfaces strongly degraded, is a simple solution to restore land productivity and agro-forest rehabilitation (Roose et al., 1999). There are generally 2 variants of *zaï*, namely agricultural and forestry *zaï*. On one hand most of studies focused on the agricultural *zaï* (Bayen et al., 2012; Fatondji et al., 2006; 2009; Roose et al., 1999; Wildemeersch et al., 2015c; Zougmoré et al., 1999) in comparison to forestry *zaï* that is poorly documented (Koutou et al., 2007). For this latter case that is the subject of this study, previous investigations were oriented towards analysing the factors leading to the adoption of the forestry *zaï* technology in Burkina Faso (Koutou et al., 2007), on the examination of the best plant species and techniques of soil and water conservation for the elaboration of the best strategies to reclaim degraded Sudano-Sahelian ecosystems in northern Benin (Avakoudjo et al., 2013), on the effect of this technique on biodiversity and soil parameters (Doamba, 2012).

In spite of the double advantage inherent in the establishment of agroforestry systems on degraded crusted land (arresting land degradation while increasing household income), forestry *zaï* has been poorly documented.

This study aims at determining the agronomic performances of pearl and *A. senegal* inter-crop under the technique of forestry *zaï*.

3.2. Materials and Methods

3.2.1. Study area

This study was conducted in Niger, a Sahelian country, located in West Africa. Niger is considered to be land-rich and water-poor. It is among one of the hottest and driest countries in the world. Over

75 % of the country is “hyper arid desert”, characterised by very little rainfall and low population densities. Soils are mostly poor, with insufficient organic matter and phosphorous and water holding capacity; more important, most are degrading. Indeed, World Bank studies have shown the close linkages among severe poverty, vulnerability, land degradation and low agricultural productivity. This observation is consistent with popular folklore in Niger that land degradation is a more important cause of poverty and vulnerability than are population growth and drought (World Bank, 2010).

The study site is located at Sadoré village (13°15’N, 2°17’E) 40 km south-east of Niamey) in the Tillabéri region of Niger. The region is situated in the south of the country (Figure 3.1). The region is in the Sudano-Sahelian zone. The hot dry season is long (from November to May) and the cropping season is short (from June to October). Rainfall is highly variable in space and time with an annual average of 550 mm. The intensity of rainfall is very high with 50 % of the events having intensities exceeding 27 mm h^{-1} and peak intensities of up to 386 mm h^{-1} (Sivakumar, 1989). Potential evaporation is also very high and varies between 2000 and 4000 mm per year. Daily temperature ranges between 25 and 41 °C. Small-scale farming relying on rainfed agriculture is dominant in the region. Pearl millet is the main crop, usually grown in monoculture or in association with groundnut or peanut.

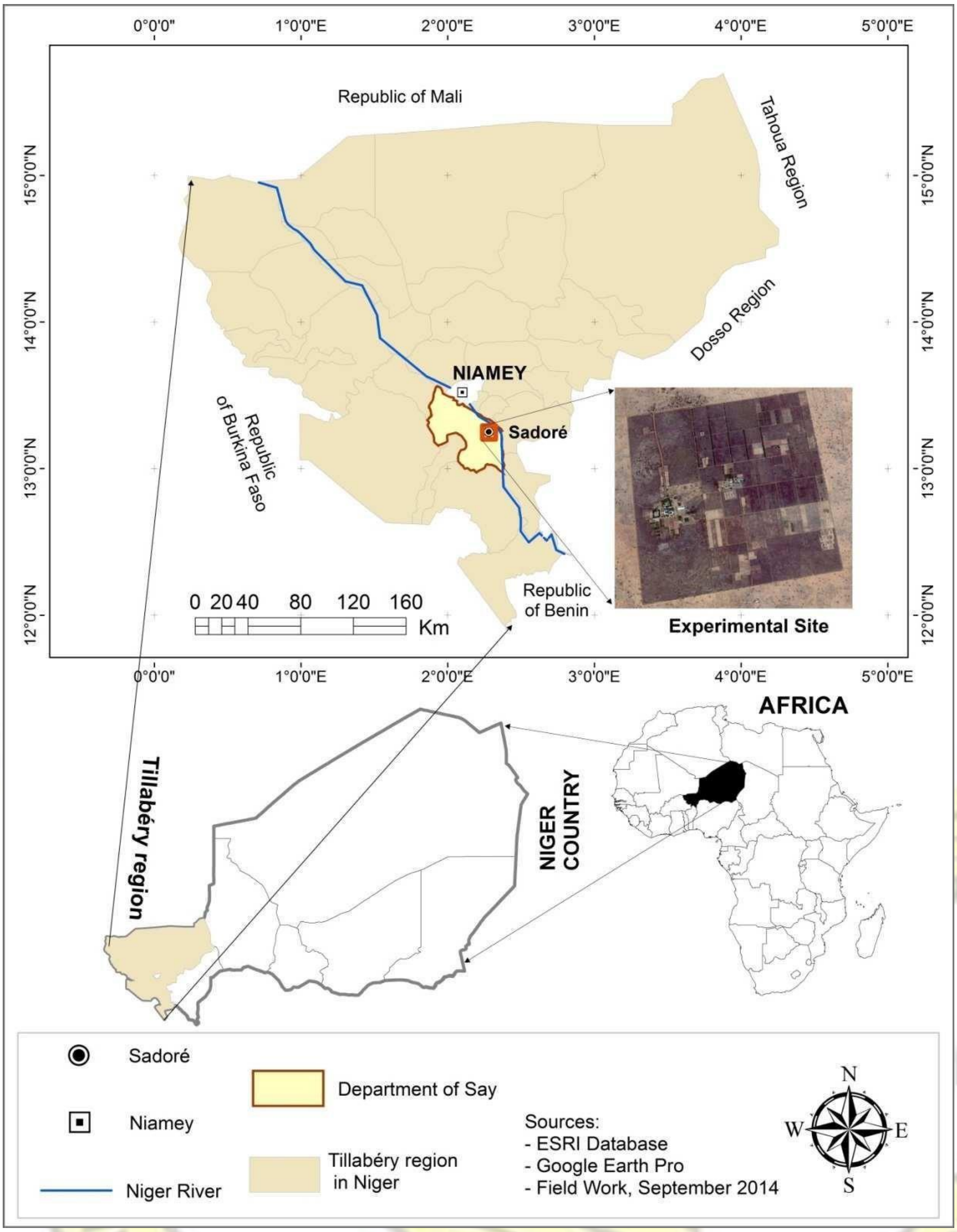


Figure 3 2 Map of Niger and the Tillabéri region (enlarged section). The experimental field is located near Sadoré village (13°15’ N 2°17’ E, 40 km south-east of Niamey) in the Say department of the Tillabéri region

3.2.2. Experimental site description

The experiment was established on a Plinthosol at Sadoré village. Plinthosols are marginal soils having petroplintithe at shallow depth (Michéli et al., 2006). These soils show major constraints for agricultural production and are locally referred to as "gangani" or "laterite" (Hiernaux, 1998). The field had a slope of 1% and a shallow root zone due to the presence of petroplinthite at a depth of 0.45 to 0.60 m. The soil type was classified using the USDA soil texture system as loamy sand (015 cm depth), sandy loam (15-30 cm and 30-45 cm depths) and sandy clay loam (45-60 cm depth). The soil is acidic, poor in organic Carbon and chemical nutrients (Table 3.1).

3.2.3. Experimental design

The study was carried out during two consecutive years (2014, 2015). To examine the effect of forestry *zaï* on the agronomic performances of *pearl millet* (PM) and *Acacia senegal*, an experimental field (Figure 3.2) with two treatments was set up. It comprises the forestry *zaï* (Z) and the control (C) treatments; details of their implementation on the experimental field are given below: (a) The forestry *zaï* (Z) is an indigenous practice used for *in situ* rainwater harvesting to reclaim degraded crusted lands. It is a variant of zaï that consists of keeping in one hole of five, a forest species and in the 4 other holes an annual crop. At the end of the rainy season, the annual crop is harvested and the stalks are cut at a height 1m to protect the forest species against wind and animals. In this experiment, it consisted of digging pits of 0.20 m diameter and depth of 0.20 m during the dry season in which manure was applied. Only one size of the *zaï* was selected because according to Fatondji (2014), studies conducted at ICRISAT in Niamey did not show any variations in the performance of crops grown under different sizes of the agricultural *zaï*. As a result, this experiment did not consider different sizes of *zaï* sizes. The pits were installed in a 1 m x 1 m grid. Pearl millet and Acacia were sown / planted in the zaï pits. Millet was sown at a density of 1 m x 1 m and *A. senegal* was planted at a density of 5 m x 5 m.

(b) Control (C): This is a conventional practice in the Tillabéri region. No land preparation was applied except for the application of organic manure which was superficially mixed with the top soil. Manure was only applied in a circle of 20 cm where plant pockets would be opened with hand

hoes at seeding/planting. Only small planting pockets (1 m x 1 m) were opened at seeding by hand hoes for sowing pearl millet and planting holes (5 m x 5 m) were opened at the planting of Acacia. Millet was sown at a density of 1 m x 1m and Acacia was planted at a density of 5 m x 5 m.

The experimental field was laid out in a randomized block design with 4 replications. The treatments were applied on plots of 10 m x 10 m size separated at intervals of 5 m x 10 m.

Farmyard manure at an annual application rate of 3 ton ha^{-1} was applied to all the treatments as suggested by Fatondji et al. (2009). It comprised of a mixture of urine and cow dung (see Table 3.2 for the quality of the applied manure).

The millet variety “ICMV IS 99001” (maturity 95 days) was sown at a density of 10 000 plant pockets ha^{-1} and the local variety of *A. senegal* was planted at a density of 2000 plants ha^{-1}.

The planting was done on 28th June 2014 and 6th July 2015. Three weeks after planting, the millet was thinned to three plants per hill. There were three hand weeding events during the growing period. Harvesting were done on 3th October in 2014 and 14th October in 2015.

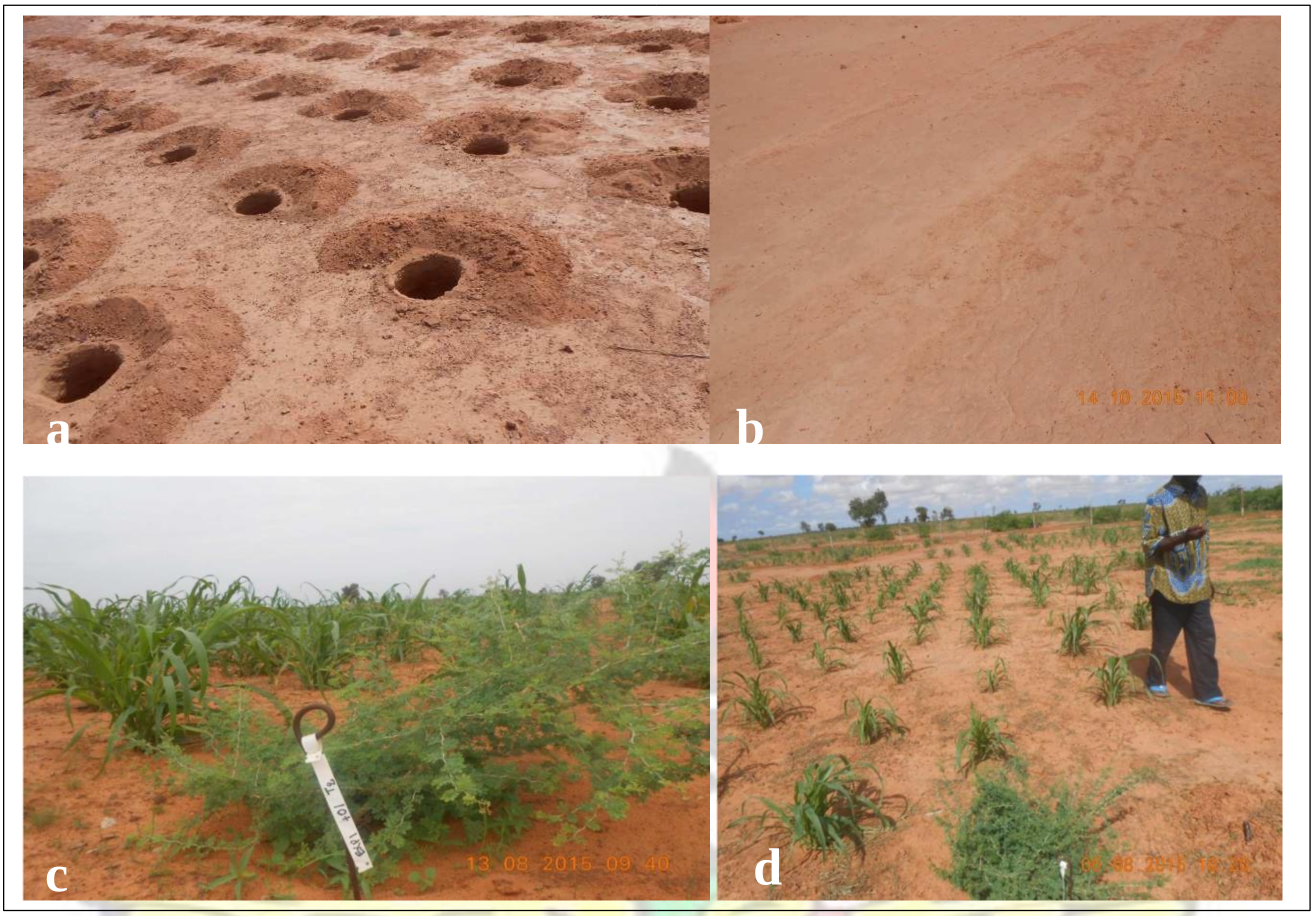


Figure 3. 2. Installation of the field experiment on a degraded crusted soil at Sadoré village. For the forestry zaï treatment (a), small pits of 20 cm diameter and 20 cm depth were dug at a density of 1 m x 1 m. For the control treatment (b) no land preparation was done. Millet was associated to *A. senegal* under both forestry *zaï* (c) and flat soil (d) planting techniques. Millet was sown at a density of 1 m x 1 m and *A. senegal* was planted at a density of 5 m x 5 m.

3.2.4. Soil sampling and analysis

Composite soil samples were taken at depths of 0–15 cm, 15–30 cm, 30–45 cm and 45-60 cm. The samples were analysed for pH-H_2O (soil/water ratio of 1:2.5). The method described by Walkley and Black (1934) was used to determine soil organic carbon. The Kjeldahl method (Houba et al., 1995) and the Bray 1 method (Reeuwijk, 1992) were used to determine, respectively, the total N and extractable phosphorus (Table 3.1).

Table 3. 1. Soil initial physical and chemical properties of the experimental field (0-60 cm depth)

Soil depths	**0-15 cm**	**15-30 cm**	**30-45 cm**	**45-60 cm**
		Soil physical properties		
% sand	82.7 ± 3.7	76.5 ± 4.4	73.2 ± 4.8	71.1 ± 4.8
% silt	8.1 ± 2.1	8.3 ± 2	8.3 ± 1.2	9.6 ± 1.2
% clay	9.2 ± 1.7	15.2 ± 2.8	18.5 ± 3.9	19.4 ± 3.9
Texture class	Loamy sand	Sandy loam	Sandy loam	Sandy clay loam
Bulk density (g/cm^3)	1.77	1.95	1.88	NA
		Soil chemical properties		
pH/H2O(1: 2.5)	4.5 ± 0.3	4.5 ± 0.2	4.6 ± 0.2	4.6 ± 0.2
N-Total (mg/kg)	206 ± 66	194 ± 32	181 ± 22	139.2 ± 30
P-Bray 1 (mg/kg)	2.7 ± 6	1.4 ± 0.2	1.1 ± 0.2	0.8 ± 0.2
C. Org(%)	0.29 ± 0.1	0.28 ± 0.1	0.26 ± 0.03	0.24 ± 0.04
Exchangeable captions (Cmol+/kg)	1.48 ± 0.37	1.35 ± 0.57	1.24 ± 0.36	1.24 ± 0.45

NA: Not available

Table 3. 2. Organic amendment (manure) quality

	N-total (%)	**P-total (%)**	**K-Total (%**
2014	1.5	2.6	1.1
2015	1.5	2.6	1.3

3.2.5. Data collection

Millet and A. senegal biomass data

At the end of each growing season, pearl millet was harvested using a subplot of 8 m x 8 m in each plot to exclude the border effect. The samples of millet straw and manually-threshed panicles were dried at 80 ºC for 48 hours using an oven. The dry weights were recorded and expressed in kg ha^{-1}. Using a destructive sampling one individual of Acacia was randomly selected from each system of all replications. The above-ground and below-ground biomasses were separated and oven dried at 80 °C for 48 h, weighed and recorded.

Soil water data

For the evaluation of soil water storage, the moisture content of the soil was monitored in 2014 and 2015 at different depths (15, 30, 45, 60, 75, 90, 105, 120, 135, 150 cm) using a calibrated neutron probe with two aluminium access tubes installed per plot. One was placed next to the plant and the other was positioned between plants or in the micro-catchment area (Figure 3.3). Measurements were taken on a weekly basis. Soil water storage over the root zone depth (45 cm) was computed using the measurement at 15 cm depth with the formula described by CPN International (2013) where the volumetric water content (N_c(%)) was calculated as follows:

$$N_c = a + b \text{ x } d \underline{e} f \qquad (3.1)$$

where, N_c: volumetric water content (%); a: intercept of the equation of the neutron probe calibration curve; b: slope of the equation; *C*: neutron count read with the probe in the field and *Cs*: standard count reading from the access tube installed in pure water.

Figure 3. 3. Access tube installation (a) in the plant pocket and (b) outside plant pocket for monitoring soil moisture.

3.2.6. Data analysis

The analysis of variance (ANOVA) was performed using the general linear model (GLM) procedure for biomass data. The analysed data were checked for normality distribution. Soil water data were analysed using the GLM Repeated Measures procedure. The mean effect of the variables were compared at a $p < 0.05$ level of significance to describe the differences of the soil moisture storage and the agronomic performances of millet and Acacia. The analyses were performed with the software package IBM SPSS Statistics version 22.

3.3. Results

3.3.1. Distribution of rainfall during the cropping periods

The total rainfall recorded in 2014 and 2015 are shown in Figure 3.4. The total cumulative rainfall recorded was 638 mm and 543 mm in 2014 and 2015, respectively. In 2015, the rainfall was lower compared to the long-term rainfall (550 mm) of the study area. The onset of the rainy season of 2015 was late and the cumulative rainfall was lower than that of 2014.

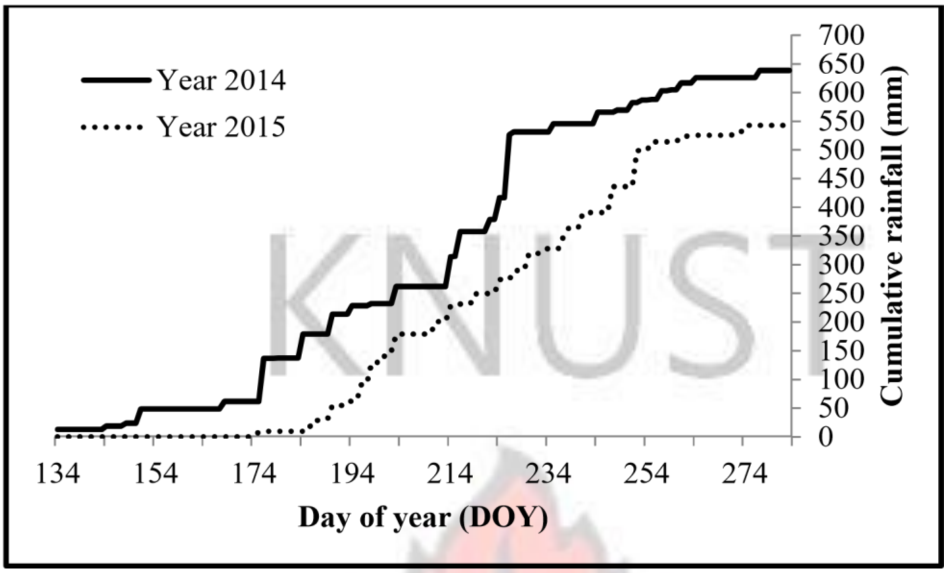


Figure 3. 4. Rainfall distribution during the cropping periods

3.3.2. Agronomic parameters

As seen from the biomass data for millet shown in Tables 3.3 and 3.4, there were statistically significant differences between the effects of the forestry *zaï* and the flat soil on the grain yield ($p = 0.019$ and 0.008 respectively in 2014 and 2015), the straw biomass ($p = 0.008$ and < 0.001 respectively in 2014 and 2015) and the total biomass of millet ($p = 0.009$ during both years). For millet, the forestry *zaï* technique produced better grain yield, straw and total biomass than the flat soil planting technique. The total dry biomasses for millet were the same for the two seasons in the control treatment. However, the millet straw biomass for 2014 was about a 1.5 times more than that of 2015 and the grain yield for 2014 was about a third that of 2015. For the forestry *zaï*, the total dry biomass for millet in 2014 was about two -thirds that of 2015. The millet straw biomass for 2014 was about the same as that for 2015. Yet, the grain for 2014 was about a third of that of 2015. The harvest index (HI) of both treatments was quite similar in 2014 and 2015 but the HI of 2015 is about 3 times more than that of 2014.

The *A. senegal* had 100 % tree survival rate for the traditional planting technique and the forestry *zaï* after being planted in 2014. The same trees had grown till the next season in 2015, leading to a cumulative biomass of the second season (Table 3.4). However, no significant difference was found with the biomass of Acacia (above, below-ground and total biomass) during both years (2014 and 2015). In 2014, the above-ground biomasses of both planting techniques were quite similar, whereas for the traditional planting technique the below-ground biomass of acacia was about 34 % higher than the biomass produced in the case of forestry *zaï* resulting in a higher root shoot ratio for the traditional planting technique compared to the forestry *zaï*.

The total biomass produced by the intercropping system is significantly ($p = 0.004$ and 0.012 respectively in 2014 and 2015) higher in the *zaï* treatment compared to the flat planting technique.

Table 3. 3 Effect of the forestry zaï on the agronomic performance of millet and Acacia in 2014

	Millet				Acacia senegal				Total biomass
Systems	Straw yield (kg.ha^{-1})	Grain yield (kg.ha^{-1})	Total dry matter (kg.ha^{-1})	Harvest* index	Above biomass (kg.ha^{-1})	Below biomass (kg.ha^{-1})	Total dry matter (kg.ha^{-1})	Root shoot ratio	Total biomass of the system (kg.ha^{-1})
Traditional system	1598.2 ± 103	225.5±21.7	1823.7±124.7	0.12	20.6±4.5	30.5±1.6	51.1±4.5	1.51 ± 0.2	1874.9±123.9
Zai forestry system	2062 ± 63.9	348.5 ± 31.9	2411.1±35.9	0.14	22.7±3.1	22.6±5.4	45.3±8.1	1.15 ± 0.2	2456.5±38.5
F. pr (0.05)	0.008	0.019	0.004	0.194	0.725	0.203	0.556	0.359	0.004

± Standard error

Table 3. 4 Effect of the forestry zaï on the agronomic performance of millet and Acacia in 2015

	Millet				Acacia senegal				Total biomass
Systems	Straw yield (kg.ha^{-1})	Grain yield (kg.ha^{-1})	Total dry matter (kg.ha^{-1})	Harvest* index	Above biomass (kg.ha^{-1})	Below biomass (kg.ha^{-1})	Total dry matter (kg.ha^{-1})	Root shoot ratio	Total biomass of the system (kg.ha^{-1})
Traditional system	1097±106	668 ±81	1765±186	0.37	143± 45	109 ± 23	139±31	1.09 ± 0.4	2016±249
Zai forestry system	2082 ± 82	1088± 69	3170±139	0.34	442±260	169 ± 59	252±68	0.74 ± 0.2	3781±430
F. pr (0.05)	< 0.001	0.008	0.009	0.057	0.301	0.372	0.359	0.469	0.012

g35Sh iSj

± Standard error

*Harvest index (HI) =

kl 5 3i m5 j3

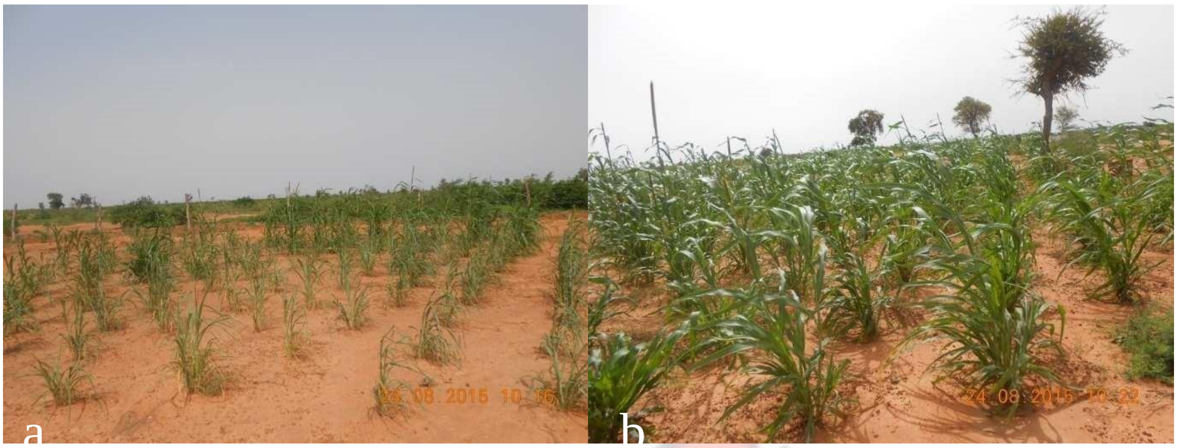


Figure 3. 5. Illustration of millet performance after a dry spell of 6 days under the flat soil (a) and the forestry zaï (b) planting techniques

3.3.3. Growth parameters of *A. senegal*

Figure 3.6 shows the height growth of *A. senegal* for 15 months after planting under the forestry *zaï* technique and the traditional planting technique. Statistical analysis did not show any significant difference for the height between the 2 planting techniques even though the forestry *zaï* treatment plants were higher by 10.3 %.

Figure 3.7 provides the girth growth of *A. senegal* for 15 months after planting under the forestry *zaï* technique and the traditional planting technique. Statistical analysis did not show any significant difference for girth between the 2 planting techniques. However, the *zaï* treatment plants increased in girth by 7.2 % over the control treatment girth.

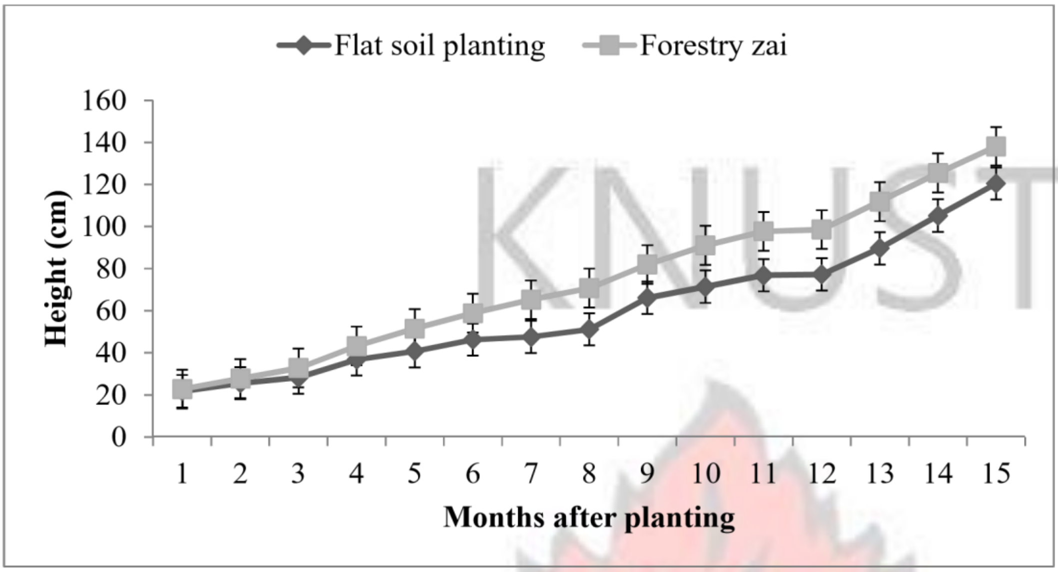


Figure 3. 6. The height growth of *A. senegal* 15 months after planting (MAP)

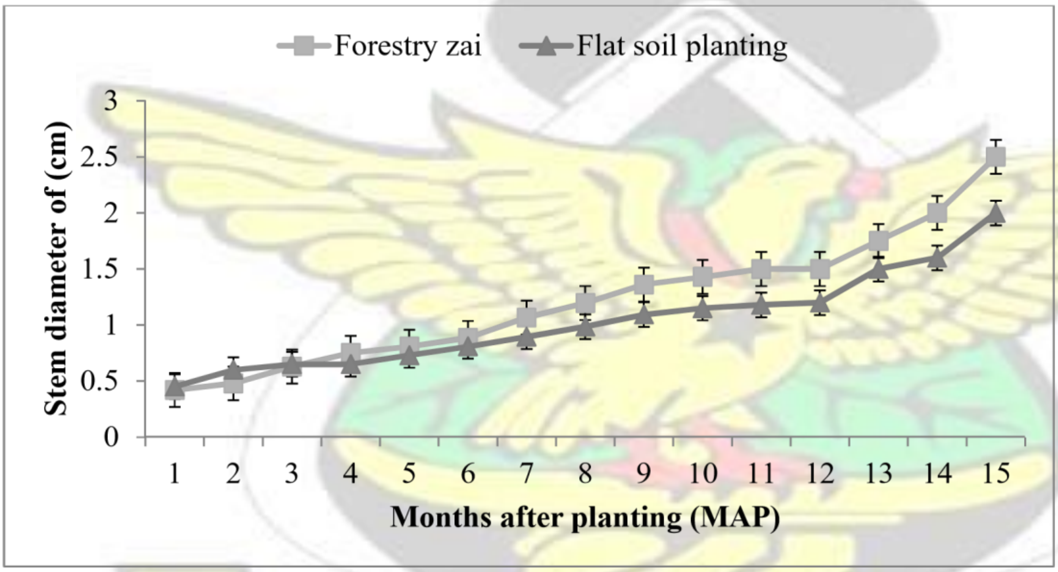


Figure 3. 7. The girth growth of *A. senegal* 15 months after planting

3.3.4. Soil water content in the root zone

In 2014, soil water content in the root zone in and between pockets of the forestry zaï remained, respectively, higher by averages of 20.98 % and 14.24 % over the control (flat soi l) during the whole cropping season although statistical analysis did not show any significant difference between them (Figure 3.8 and Figure 3.9).

In 2015 soil water content in the root zone in and between pockets of the forestry zaï remained respectively higher than by averages of 35.33 % and 31.22 % over the control (flat soil) during the

whole cropping season although the statistical analysis did not show a significant difference between them (Figure 3.10 and Figure 3.11).

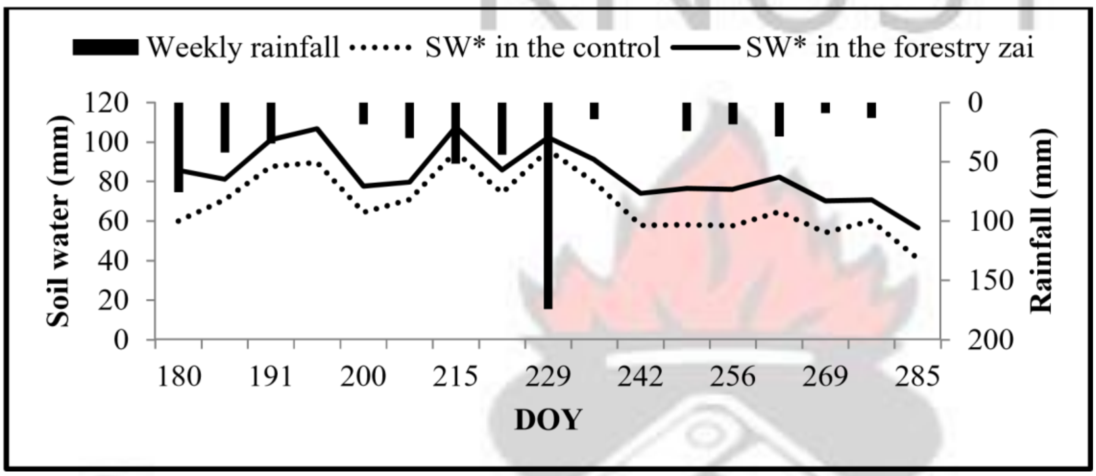


Figure 3. 8. Soil water storage in the plant pockets within the root zone (0-45 cm) in 2014
*Soil water

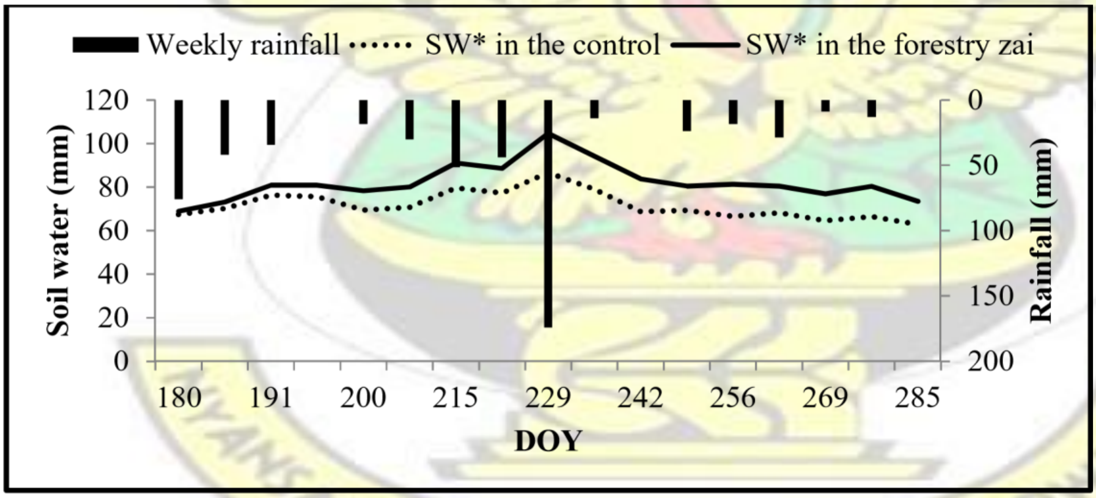


Figure 3. 9. Soil water storage between the plant pockets within the root zone (0-45 cm) in 2014
*
Soil water

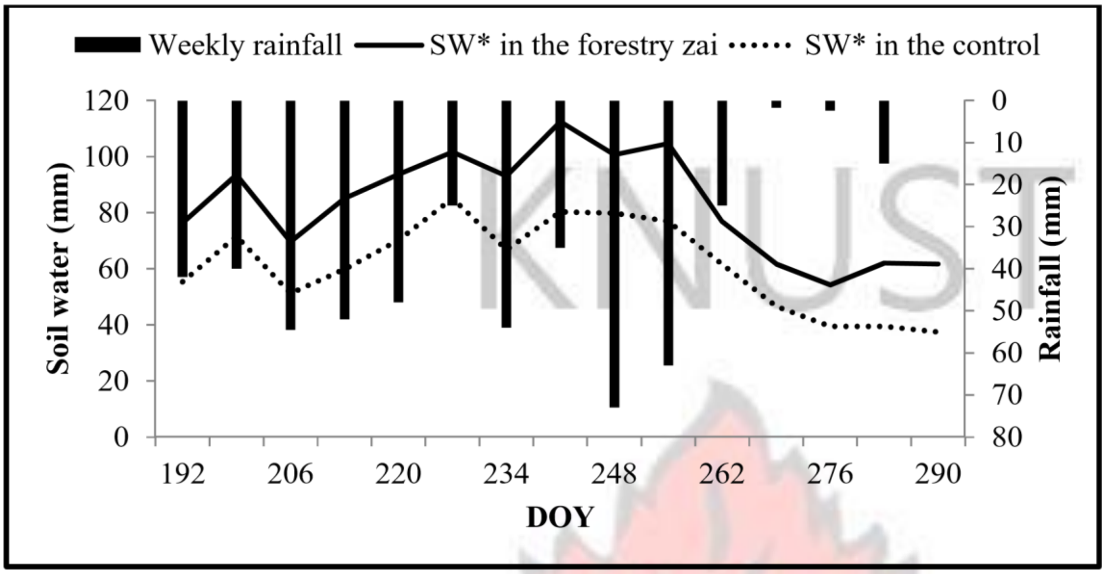


Figure 3. 1. Soil water storage in the plant pockets within the root zone (0-45 cm) in 2015
*Soil water

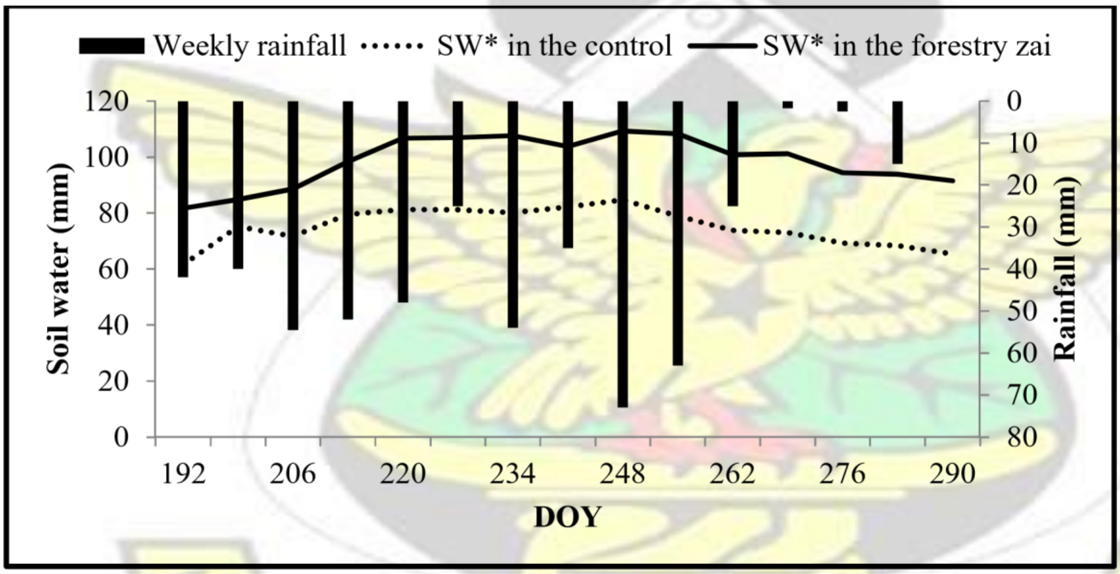


Figure 3. 2. Soil water storage between the plant pockets within the root zone (0-45 cm) in 2015
*Soil water

3.3.5. Soil water content below the root zone

In 2014, soil water content below the root zone in and between plant pockets was similar for both treatments (Figure 3.11 and Figure 3.12)

In 2015, soil water content below the root zone in and between pockets of the forestry zaï remained, respectively, higher by averages of 13.70 % and 2.64 % over the control (flat soil) during the whole cropping season, although statistical analysis did not show any significant difference between them (Figure 3.13 and Figure 3.14).

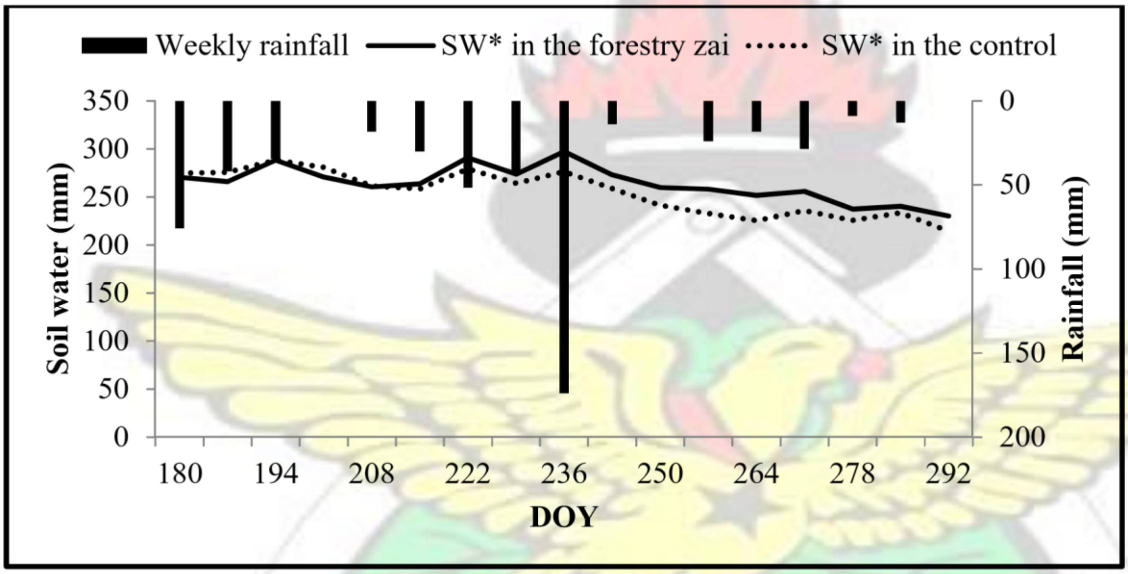


Figure 3. 3. Effect of the forestr y zaï on soil water storage in the plant pocket below the root zone (45 - 150 cm) in 2014

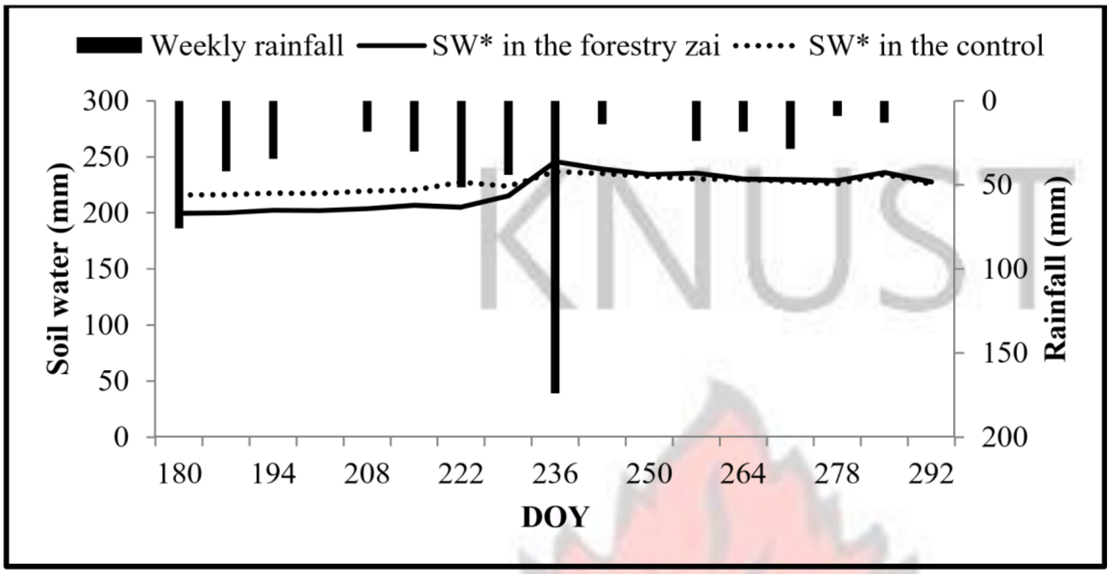


Figure 3. 4. Effect of the forestry zaï on soil water storage between the plant pockets below the root zone (45-150 cm) in 2014

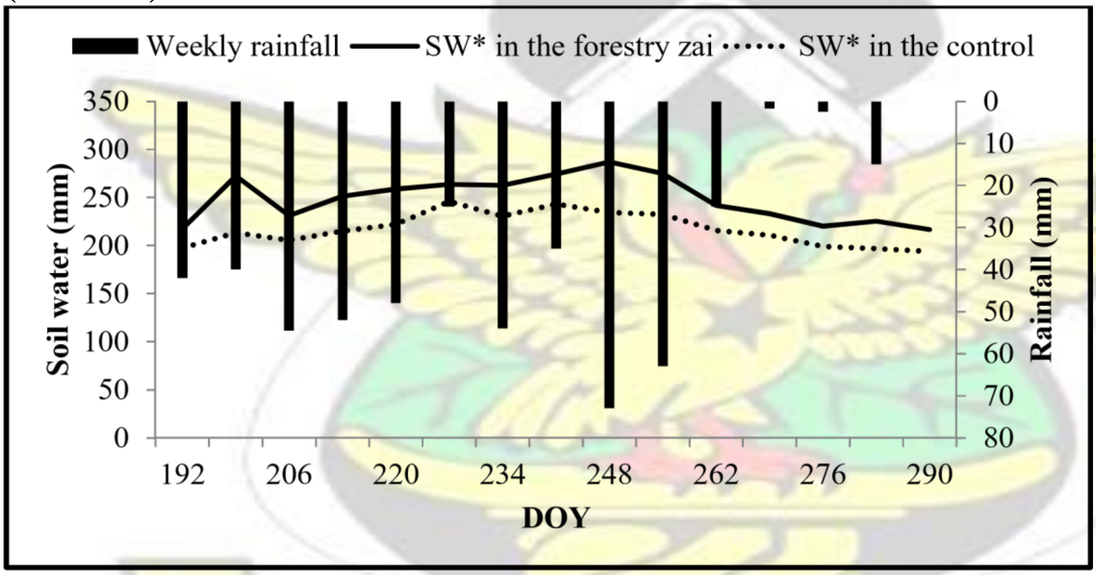


Figure 3. 5. Effect of the forestry zaï on soil water storage in the plant pocket below the root zone (45 - 150 cm) in 2015

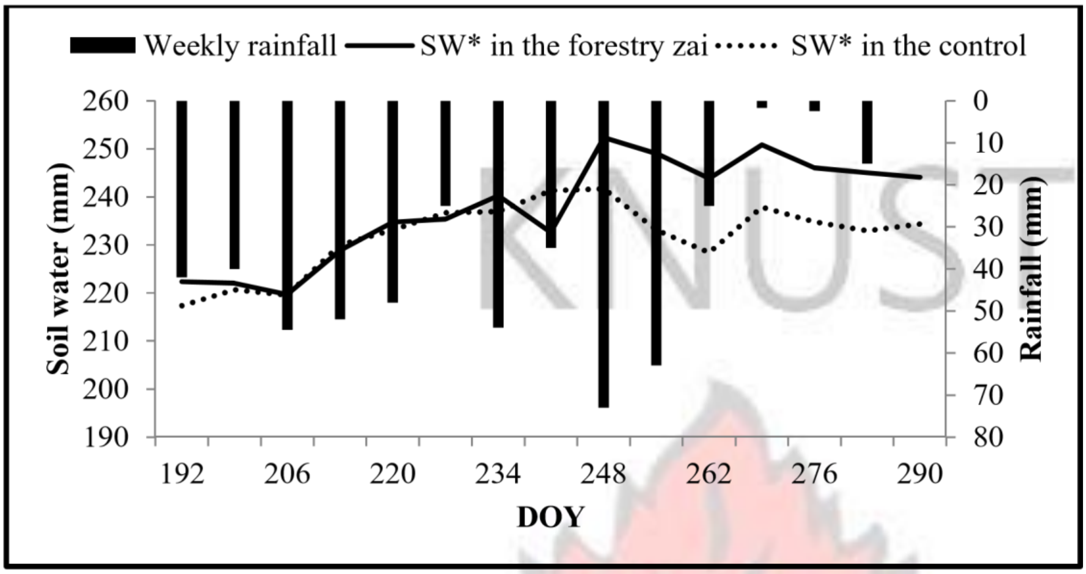


Figure 3. 6. Effect of the forestry zaï on soil water storage between plant pockets below the root zone (45-150 cm) in 2015

3.4. Discussion

This study showed that for the establishment of an intercropping system on a degraded crusted soil ("gangani"), the conventional planting technique (flat soil) considerably reduced grain yield and crop biomass production compared to the forestry *zaï*.

The yields for the annual crop are similar to those reported by Fatondji et al. (2006), Roose et al. (1999), and Wildemeersch et al. (2015b) in the case of the agricultural *zaï*, although this study was conducted with the forestry *zaï*. Therefore, in addition to emphasising the advantage of the *zaï* compared to the flat soil planting technique, these results also suggest that there is no prejudicial effect of competition between millet and *A. senegal* during the early stages of agroforestry system development. The second year millet yield reached 1,088 kg.ha^{-1}, which represents three times more than the millet average grain yield in Niger (Bationo et al., 2003). Comparable results were reported by Raddad and Luukkanen (2007) who highlighted that intercropping of *A.senegal* and crops does not have detrimental effect. These results also showed an inter-annual variability of millet grain yield, already mentioned by Ibrahim et al. (2015a) as related to the cumulative and rainfall distribution. However, in this case study even though rainfall of the first year (2014) of the experiment was greater than the second one, the second year millet grain yield is greater than the first one. These results could probably be induced either by the rainfall deficit during the reproductive stage of millet in 2014 compared to 2015 or by the residual effect of the manure applied the previous year (Eghball et al., 2004).

The total dry biomasses for millet were about the same for the two seasons in the control treatment. However, the millet straw biomass for 2014 was about 1.5 times more than that of 2015 and the grain yield for 2014 was about a third of that of 2015. The higher rainfall in 2014 might have contributed to a higher vegetative growth of the millet leading to a higher straw biomass but with reduced grain yields compared to 2015 probably due to shortage of rainfall during the reproductive stage of millet in 2014.

The harvest index (HI) of both planting techniques was quite similar in 2014 and 2015 but the HI of 2015 was about 3 times more than that of 2014. These results indicate the better performance of the millet for grain in 2015 compared to 2014, probably induced by the factors (rainfall distribution, residual effect or organic manure and the beneficial effect of *A. senegal* on crops) already mentioned above.

The results also showed that *A. senegal* survived in both treatments. In addition, the biomass of *A. senegal* and its growing parameters (height and girth) during both years of experimentation did not show any significant difference between the *zaï* and the flat soil planting techniques. These results suggest that water harvesting only has a minor influence on the growing of *A. senegal*. Similar results were reported by previous studies. For example, according to Elfadl and Luukkanen (2005), soil management does not have significant effect on seedling survival and growth of *A. senegal*.

They also mentioned that agricultural crops do not significantly affect seedling survival and growth of *A. senegal* and this was also observed in the case of this study. The higher root shoot ratio observed in the case of the traditional planting technique compared to the *zaï* during both years of experiment, indicates more growth of the roots that were probably exploring deeper soil layer for water and could indicate that this treatment was subject to water stress compared to the *zaï*. Similarly for *A. senegal* growth soil water in the root zone of the forestry *zaï* was higher than the soil water storage of the traditional planting technique even though statistical analysis did not show any significant difference between them.

3.5. Conclusion

This study showed that compared to the flat soil planting technique, the forestry *zaï* increased the available soil water in the root zone which in turn leads to a significant improvement of millet grain yield and millet straw biomass during the two consecutive years of field study. Moreover, there was no detrimental effect related to the intercropping of *A. senegal* and pearl millet. In contrast to millet, *A. senegal* did not show any sensitivity to the water harvesting technique.

For the *zaï*, intercropping millet with *A. senegal* showed significant increases of millet agronomic performances. Even though tree survival rate was 100 % in all treatments, the growth parameters were better for the plants under the *zaï* technique. Increased millet grain yield is therefore a good sign in improving food security for the farmer while deriving substantial environmental benefits from the agroforestry trees in the long term. The forestry *zaï* water harvesting technique can therefore be considered as a very useful intervention in establishing agroforestry systems on crusted degraded lands in Niger.

CHAPTER 4: HYDROLOGIC BEHAVIOUR OF THE “FORESTRY ZAÏ” USING A SIMULATION MODEL

4.1. Introduction

Since the 1970s, Sahelian countries have been facing droughts and desertification. Land and natural resources shortages as consequences of this situation are the causes of low agricultural productivity that leads to food insecurity in the region (Botoni and Reij, 2009).

Drought is the principal risk for food production in Niger and the country has experienced seven droughts between1980 and 2010, with adverse impact on national agricultural production. Over a period of 12 years, Niger has witnessed four droughts in 2001, 2005, 2010, and 2012 and severe food shortage that resulted in appeal for international humanitarian assistance and food relief.

Water losses intensify the difficulties of farming in dry tropical regions. Field research showed that 50 to70 % of rainfall does not reach crops but evaporates or becomes surface runoff (causing soil erosion). According to Wani et al. (2009), guiding more water to the root zone would lead to a dramatic improvement of food production**.**

There is growing consensus for a need to improve agricultural productivity and water resources management to meet new challenges posed by increasing demand and diminishing water supply (Ngigi et al., 2007). Effective soil and water conservation techniques in Niger have successfully contributed to (a) conserving rain water, (b) increasing its infiltration, and (c) enhancing plant growth, which improves the resilience of crop during water stress and serves as a useful drought mitigation intervention (World Bank, 2013). The *zaï* as an *in situ* RWH technique is one of the soil and water conservation techniques promoted in Niger (details on how to implement it were given in chapter 3 section 2).

The *zaï* is one of the easiest techniques of *in situ* rainwater harvesting mastered by local farmers and earlier studies have already shown the agronomic performance of millet under this practice in the study area for sole cropping (Fatondji et al., 2006). The results from this study also showed that forestry *zaï*, an agroforestry technique that consists of associating a perennial and an annual species is also a promising technique for land reclamation (see Chapter 2, section 3). Pearl millet is the major food cereal cultivated in the Sahelian agro-ecology of Niger on coarser textured soils using up to 90 % of the cropped area (Bationo et al., 1993), whereas *A. senegal* is also a local species in the area well known for its multipurpose uses and for its nitrogen fixation in the soil (Sprent et al., 2009).

It is important to provide a better understanding of the water distribution in the root zone in this dryland under the forestry *zaï* technique for users and policy makers. As an agroforestry and a farm household level technique, agroforestry models are key tools for providing insights into the distribution and the water use in space and time. This knowledge then must be incorporated into management practices by the development and use of management tools.

Although there are many agricultural models, few of them can be applied to simulate the interaction between the annual and the perennial species in space and time, specifically in terms of water and nutrients uptakes and light use for photosynthesis in dryland area.

Trees are typically not included in these models, and tree-crop interactions can generally not be simulated. An exception is the inclusion of Eucalyptus-crop interactions into the Agricultural Production Systems Simulator (APSIM) (Huth et al., 2002). Yet some other models have tackled the complexity of agroforestry systems: HyCAS (Matthews and Lawson, 1997); HyPAR (Mobbs et al., 1999) etc. Among these, the Water, Nutrient and Light Capture in Agroforestry Systems model (WaNuLCAS) (van Noordwijk et al., 2011) is capable of simulating tree–crop interactions in great
detail.

WaNuLCAS was selected for the simulation of hydrological processes and crop and tree response to these processes in Niger drylands because it simulates interactions between crop and tree based on above and below -ground resource capture and co mpetition for water, nutrients and light under different management scenarios in agroforestry systems at various temporal scales (daily and long

The objective of this study is to determine the hydrologic behaviour of the forestry zaï technique unde r current climatic conditions.

4.2. Materials and Methods

4.2.1. Site description

The study was conducted in the Sodano-Sahelian zone of Niger in the village of Sadoré (see Chapter 3 section 3.2 for more details on the study area).

4.2.2. Description of WaNuLCAS model

Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS) is a model that simulates interactions between crop and tree in agroforestry system. STELLA research modelling environment was used to formulate it. The model is freely available at: www.worldagroforestry.org/sea/Products/AFModels/wanulcas/download.htm. The model describes water and nutrient uptake on the basis of root length densities of both the crop and the tree, plant demand factors and effective supply by diffusion at a given soil water content (van Noordwijk et al.,

Vertically, the model represents a soil profile with four layers, horizontally four spatial zones, an uptake by a crop and a tree and water and nitrogen balance (Figure 4.1) . The user can adjust the term).

2011).

model to the type of system simulated by defining the width and depth of each zone. The model can serve both simultaneous and sequential agroforestry systems simulations. It may help to understand many types of agroforestry systems including improved fallow, rotational and simultaneous forms of hedgerow intercropping, relay planting of tree fallow. Management options such as choice of species, tree spacing, and pruning regime are explicitly incorporated in the model. The model als o allows the evaluation of crop growth at different tree spacing, densities or fertilizer application rates (van Noordwijk et al., 2011)

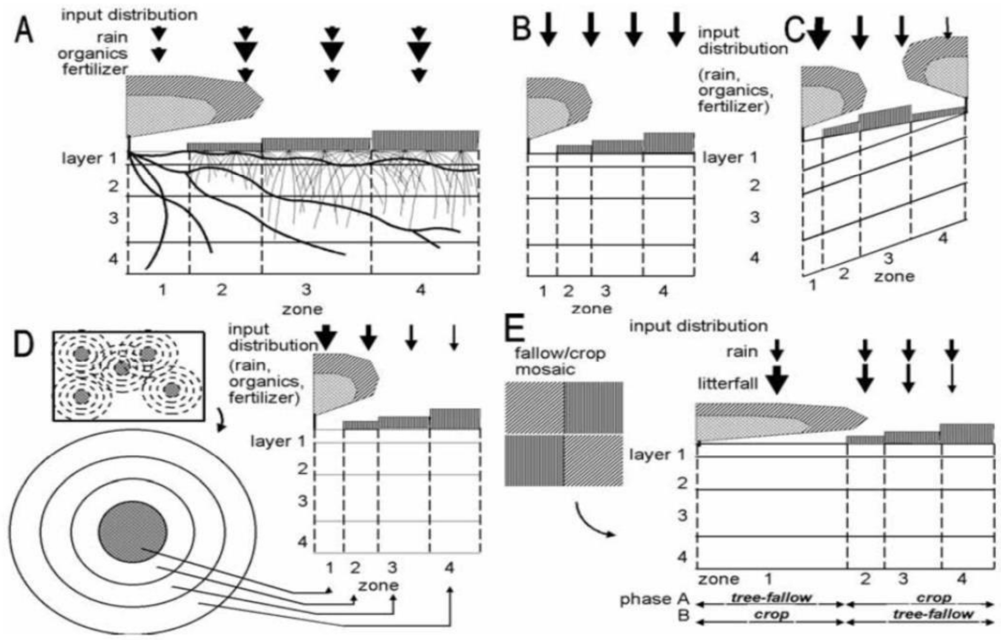


Figure 4.1. General presentation of the layers and the zones in WaNuLCAS model (A) applications to four types of agroforestry systems; (B) Alley cropping; (C) Contour hedgerows on slopes, with variable topsoil depth; (D) Parkland systems, with a circular geometry around individual trees; (E) Fallow-crop mosaics with border effects. (source: van Noordwijk et al. (2011)).

The input climatic data include daily potential evapotranspiration, rainfall and soil temperature data. They are read either from an excel spreadsheet. The rainfall data could also be generated on daily probability rainfall basis and on the expected monthly rainfall total. The system water balance includes rainfall, with the option of exchange between the tree zones by run -on and runoff, surface evaporation, uptake by the crop and tree and leaching. The soil water balance in soil plant models describes a number of processes that act on different time scales (van Noordwijk et al., 2011). Soils are represented in four layers. The depth can be chosen, with specified soil physical properties and initial water and nitrogen contents, for all the sixteen cells (van Noordwijk et al., 2011).

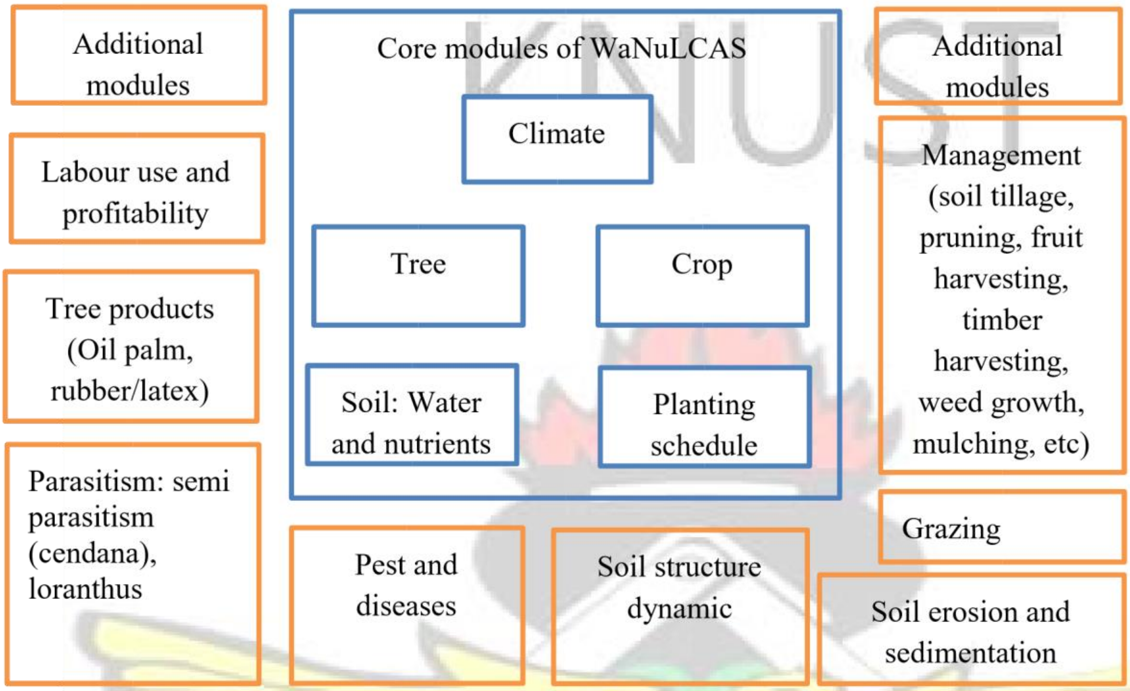


Figure 4.2: Core modules and additional modules of WaNuLCAS model

The governing equation for the crop yield in an agroforestry system is given below (van Noordwijk et al., 2011):

$$n_o = n \quad + q \quad + q_r + \quad + \quad {}_{s0} \quad + t \qquad (4.1)$$

where, Y_c: Crop yield in interaction; Y_0: Crop yield in monoculture; F_1: Direct fertility effect; F_ω: long term fertility effect; C_l: Competition for light; C_{w+n}: Competition for water and nutrients; M: Micro-climate effect.

The tree-soil-crop interaction is summarised in the equation 4.2, representing the balance for below and above-ground resources (water, light and nutrients) (van Noordwijk et al., 2011):

Δv l35wj= x'yzK + & {|{" — ~yK- •3l€ — ~yK- 3jj,•lm€ — ~yK- 3jj,hlh•lm€ —
•,))) (4.2)

Table 4. 1 Details of terms in equation 4.2

Term in equation 4.2	Water	Nitrogen	Light
Input	Rainfall, irrigation runon-runoff	Fertiliser and organic imports	Sum of daily radiation
Recycle	Hydraulic lift into crop root zone	Litterfall, tree prunings, crop residues	-
Uptake $_{crop}$	$\sum$W_Uptakecrop	N_fix(crop) + $\sum$N_uptakecrop	$\sum$Lightcap_crop
Uptake $_{tree,\ competitive}$	$\sum_{sub}$W_Uptaketree	$\sum$topN_uptaketree	$\sum$Lightcap_tree$_{1,2}$
Uptake $_{tree,\ NonComp}$	$\sum_{sub}$W_Uptaketree	N_fix(tree) + $\sum$subN_uptaketree	Lightcap_tree$_3$
Losses	$\sum$Percolation from lowest zone	Leaching from lowest zone	1 - $\sum$Lightcap
Δstorage	ΔWater content	ΔNmin & SOM	-

4.2.3. Agroforestry system to be modelled

The agroforestry system to be modelled is illustrated in Figure 4.3.

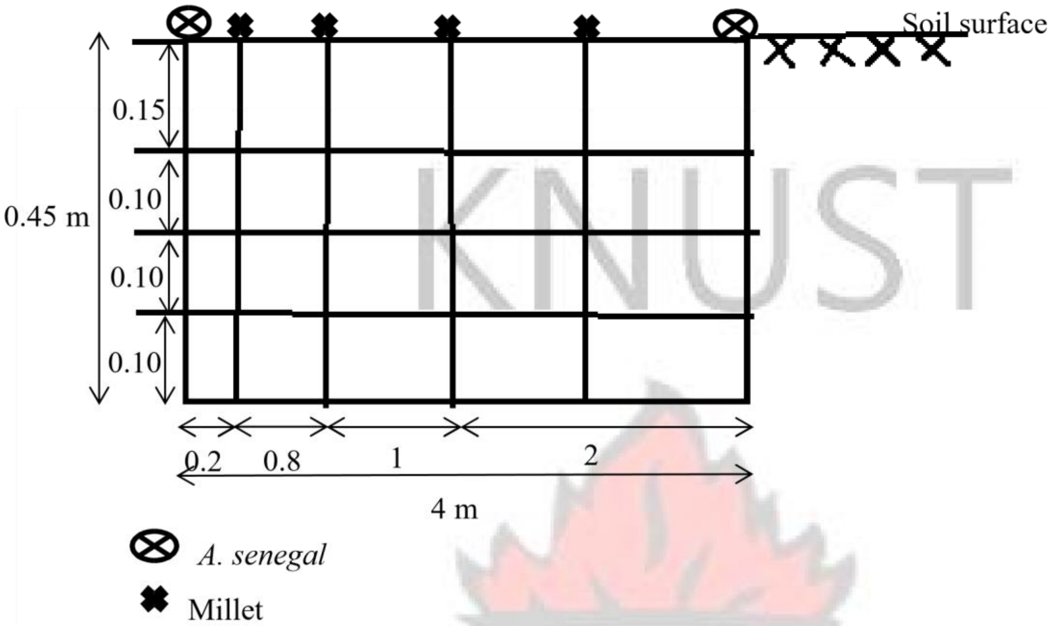


Figure 4.3: An illustration of the modelled agroforestry system

WaNuLCAS model is composed of two sub-models: WaNulCas Excel linked to WaNuLCAS STELLA. It was calibrated with millet and *A. senegal* data collected from the field experiment. For *A. senegal,* additional data of the adult tree of the variety used were collected from literature. The data were integrated in WaNuLCAS Excel file by filing the appropriate sheets with the appropriate parameters. It mainly concerns: millet parameters, *A. senegal,* parameters, soil parameters and weather parameters. The studied agroforestry system is also defined by specifying the dates (in Julian days) of millet sowing as well as the date of *A. senegal* planting. Millet was sown twice: the first year and repeated in the following year where *A. senegal* was planted only in the first year but remained for the following year. In this study the agroforestry system defined is that millet is growing with *A. senegal* seedling (90 days old). *A. senegal* was not pruned. The initial biomass of *A. senegal* was specified into WaNuLCAS STELLA. The widths of the 4 successive lateral zones were defined in WaNuLCAS Stella and were 0.2, 0.8, 1, and 2 m, respectively. *A. senegal* was planted in the first zone and millet was cultivated in the following three zones. The experiment was conducted on a shallow soil with a maximum depth of 60 cm. For the modelling purpose, the soil was divided into four horizontal layers with 0.15 m (0–15 cm), 0.1 m (15–25 cm), 0.1 m (25–35 cm) and 0.1 m (0.35_45 cm) thicknesses,

respectively, from the soil surface. After integrating the different inputs parameters of the model (WaNuLCAS Excel and Stella models), it was used to describe the interactions of plant - soilatmosphere and to simulate soil water in the root zone, millet biomass and grain yield and *A. senegal* biomass. The observed and simulated millet biomass, grain yield and*A. senegal* biomass as well as the soil water storage in the root zone were then compared to evaluate the model's accuracy to predict soil water in the root zone, the biomasses of *A. senegal* and millet and the millet grain

4.2.4. Input data

Crop and tree related input observation

The WaNuLCAS model requires data on biomass, phenology, root length density, grain yield, soil properties and crop management. The following sections describe field observations carried out to determine these data.

Characteristics and Biomass of A. senegal

At the beginning of the experiment, 18 seedlings were sampled from the seedlings stock, oven dried to estimate their initial biomass. At the end of each of the 2 rainy seasons of the experiment, seedlings *A. senegal* was also sampled, oven dried and weighed to estimate the biomasses after each rainy season (details of biomass estimation of *A. senegal* are given in Chapter 3, Section 2).

yield.

Characteristics and biomass of millet

The characteristics of the millet variety used for the experimentation were obtained from the research station at ICRISAT that provided the seeds. At the end of each of the 2 rainy seasons (2014 and

2015), for each treatment the straw biomass and grain yield of millet were harvested and oven dried (details are given in chapter 3 section 3.2). The harvest index was estimated by dividing the grain yield by the total biomass. The millet phenology was monitored from the field experiment and the dates of flowering, fruiting and maturation were noted.

Millet leaf area index

For the measurement of millet leaf area index, a millet plant close to an *A. senegal* tree was randomly selected from each treatment of each replication. A total of 4 millet plants were sampled. The leaves of each millet plant were manually removed one by one. The area of the leaves per millet plant was then measured with a calibrated Leaf area meter (LI-3100C Area Meter). Leaf area index was then calculated by dividing the leaf area by 1 m^2 as the millet was planted at a density of 10 000 plants.ha^{-1}.

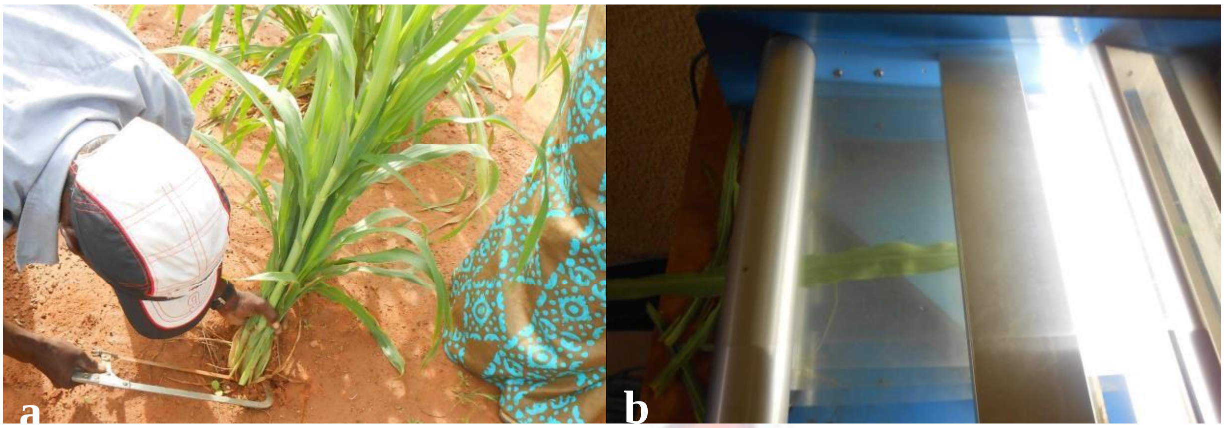


Figure 4.4. Process of leaf area determination. Millet was sampled (a) and taken to the laboratory, where leaves were removed and the leaf area was measured using a Leaf Area Meter (b).

Millet and A. senegal roots length density

For the measurement of millet root length density, a millet plant close to an *A. senegal* tree was randomly selected from each treatment of each replication. So a total of 4 millet plants were sampled. The roots were collected at the flowering stage with a metal frame measuring 15 × 10 × 10 cm^3 for the first depth (15 cm) directly under the hill. Below this depth, roots were collected at 10 cm depth increment with a metal tube of 8.5 cm in diameter. The root sampling was done down to 45 cm depth. The roots were washed; debris and dead roots were removed. The root samples collected were scanned through a scanner with 200 dpi resolution. The images of the roots were analysed using WinRhizo Pro software (Regent Instruments Canada Inc.) to calculate root length. The root length density (RLD) was determined by dividing the root length (R_L) by the soil core volume (V), as shown in equation 4.3.

$$RLD = \frac{R_L}{V} \tag{4.3}$$

For the case of *A. senegal,* the root sampling was done as previously described for millet. However, given the size (bigger diameter compared to millet) and the low number of *A. senegal* the root

samples were directly measured with a ruler and the length was divided by the core volume to calculate the root length density.

Figure 4. 5. Millet roots sampling process (a) directly under the hill for the first depth and (b) below the first depth. A sample of washed roots (c); Roots scanning using a scanner with 200 dpi resolution (d) for measuring roots length

Soil management and properties

Organic manure was applied for the growth of pearl millet and *A. senegal* at the same rate for both treatments (3 $t.ha^{-1}$ as recommended by Fatondji et al. (2009)) during the two consecutive years of experimentation. The soil initial properties were determined by sampling the soil of the field experiment for 4 depths (15 cm, 30 cm, 45 cm and 60 cm). The samples were then tak en to the laboratory for the determination of the soils properties. The soil properties are indicated in the Table 3.1 (Chapter 3, Section 3.2.2).

Weather data

The rainfall data were recorded with rain gauge installed on the experimental field. Soil temperature data was also daily monitored with a soil thermometer down to 45 cm. The daily potential evapotranspiration data was derived by collection of the daily pan data at ICRISAT research centre situated about 2 km from the experimental field.

Input parameters of WaNuLCAS model are:

a) Weather data (daily potential evapotranspiration, daily rainfall and daily soil temperature);

b) Crop parameters (details in Table 4.2);

c) Tree parameters (details in Table 4.3);

d) Soil parameters (soil texture, bulk density, percentage of organic C, pH, CEC);

e) Management parameters (dates of sowing / planting, dates and type of amendment, weeding events).

The interfaces for the input data are shown in Figures 4.6 and 4.7, namely the input sections of WaNuLCAS Excel and WaNuLCAS Stella.

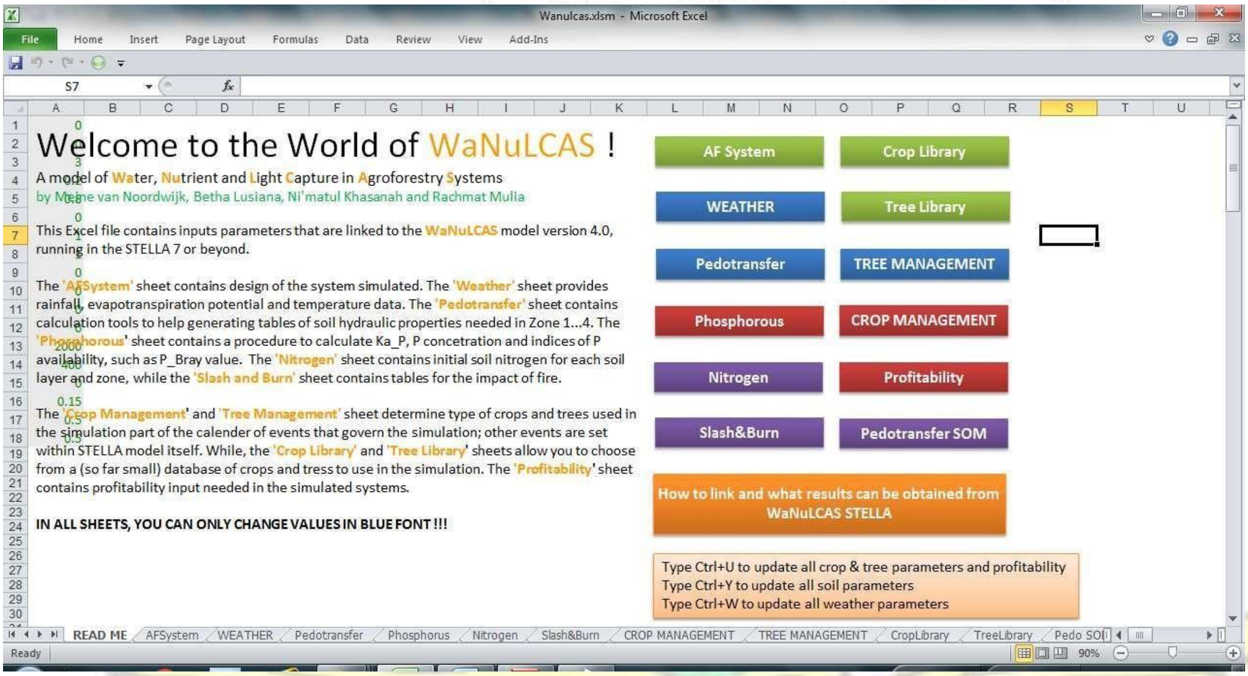


Figure 4. 6. Upper level view of WaNuLCAS Excel model input section

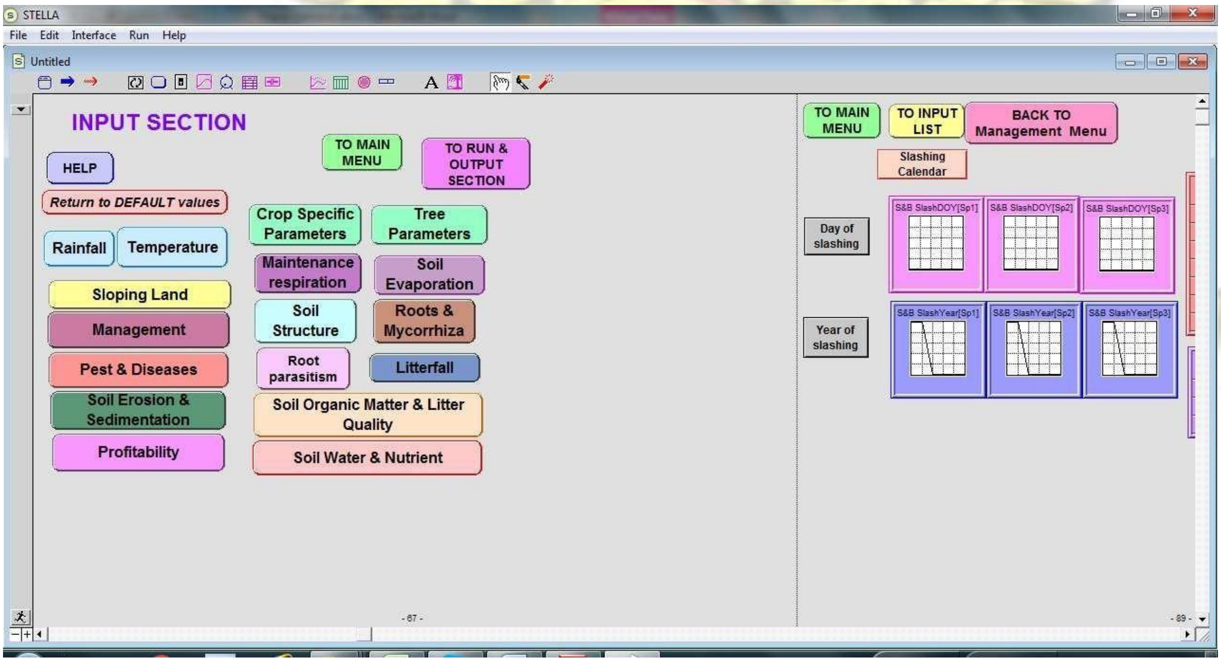


Figure 4. 7. Upper level view of WaNuLCAS Stella model input section Table 4. 2 Crop input parameters

Parameters	Units	Millet parameters
Length of generative stage	days	35
Length of vegetative stage	days	60
Is it annual crop? 1=yes, 0 = no	[]	1
Earliest day to flower in a year	Julian day	1
Latest day to flower in a year	Julian day	365
Production of dry matter per day	$kg/(m^2.day)$	0.005789
Seed weight	kg/m^2	0.00375
Water requirement for dry matter production	l/kg	300
Ratio of height increment to biomass incr.	m/kg	7
Maximum proportion of crop biomass remobilized as storage component	1/day	0.027
Extinction light coefficient	[]	0.5
Relative light intensity at which shading starts to affect crop growth	[]	1
Maximum Leaf Area Index	[]	5
Rainfall water stored at leaf surface	Mm	1
Hydraulic conductivity of roots	cm/day	1.00E-05
Maximum plant potential	cm	-5000
Minimum plant potential	cm	-15000
Type of N2 fixation	[]	0
Root tip diameter	Cm	0.027
Max. root length density in layer1	cm/cm^3	5.77
Max. root length density in layer2	cm/cm^3	1.53
Max. root length density in layer3	cm/cm^3	1
Max. root length density in layer4	cm/cm^3	0.3
Root half life	days	50
Root affected by water or nutrient stress	[]	0
Lignin fraction of crop residue	[]	0.2
Lignin fraction of crop root residue	[]	0.2
Standard moisture content	[]	0.1

Table 4. 3 Input parameters of the tree

Parameters	Units	Input parameters of *A. senegal*
Length of vegetative cycle	Days	1460
Length of generative cycle	Days	120
Earliest day to flower in a year	Julian day	150
Latest day to flower in a year	Julian day	300
Initial stage	[]	0.0625
Stage after pruning	[]	0.05
Max. growth rate	kg m^{-2}	0.008889
Fraction of growth reserve	[]	0.05
Leaf weight ratio	[]	0.494975
Specific leaf area	m^2/kg	10.5
Water requirement for dry matter production	l kg^{-1}	212.132
Maximum leaf area index	[]	2.66666
Ratio leaf area index min. and max.	[]	1
Relative light intensity at which shading starts to affect tree growth	[]	0.5
Extinction light coefficient	[]	0.5
Rainfall water stored at leaf surface	Mm	0.8
Intercept for total biomass equation	kg	0.332
Power for total biomass equation	cm_{-1}	2.084
Intercept for branch biomass equation	kg	0.283
Power for branch biomass equation	cm_{-1}	2.082
Wood density	kg m^{-3}	700
Root tip diameter	Cm	0.1
Max. root length density in layer1-zone1	cm cm^{-3}	0.392
Max. root length density in layer1-zone2	cm cm^{-3}	0.05
Max. root length density in layer1-zone3	cm cm^{-3}	0
Max. root length density in layer1-zone4	cm cm^{-3}	0
Max. root length density in layer2-zone1	cm cm^{-3}	0.403
Max. root length density in layer2-zone2	cm cm^{-3}	0.1
Max. root length density in layer2-zone3	cm cm^{-3}	0
Max. root length density in layer2-zone4	cm cm^{-3}	0
Max. root length density in layer3-zone1	cm cm^{-3}	0.346
Max. root length density in layer3-zone2	cm cm^{-3}	0.01
Max. root length density in layer3-zone3	cm cm^{-3}	0
Max. root length density in layer3-zone4	cm cm^{-3}	0

Max. root length density in layer4-zone1	cm cm^{-3}	0.1
Max. root length density in layer4-zone2	cm cm^{-3}	0.01
Max. root length density in layer4-zone3	cm cm^{-3}	0
Max. root length density in layer4-zone4	cm cm^{-3}	0

4.2.5. Output data for the model

The output data for the model can be produced in tabular or graphical forms. The output data include soil water, soil carbon, nitrogen and phosphorus, crop biomass and yield and tree biomass.

For the purpose of this study, the details of the soil water output data and biomass of millet and *A. senegal* are, respectively, shown in Appendices 1, 2 and 3.

The interface of the run and output section is given in Figures 4.8 and 4.9.

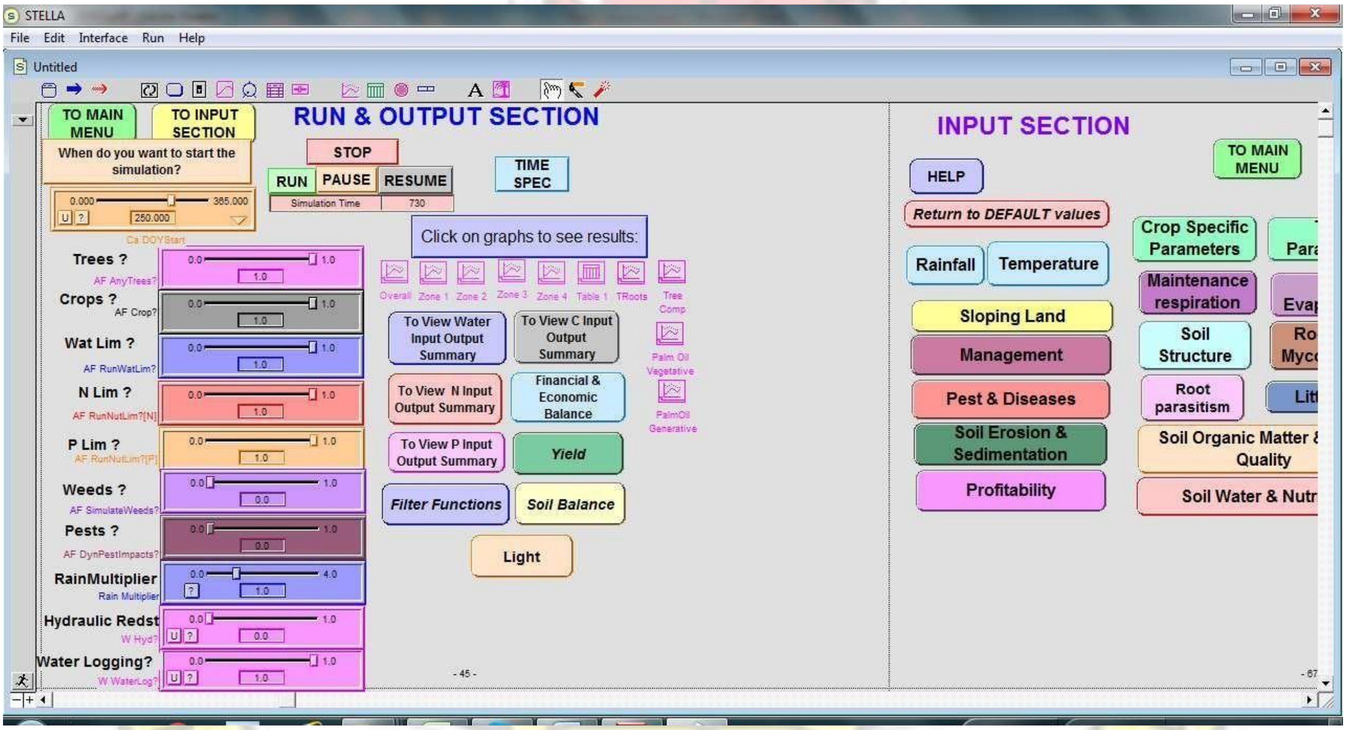


Figure 4. 8. Upper level view of WaNuLCAS Stella run and output section

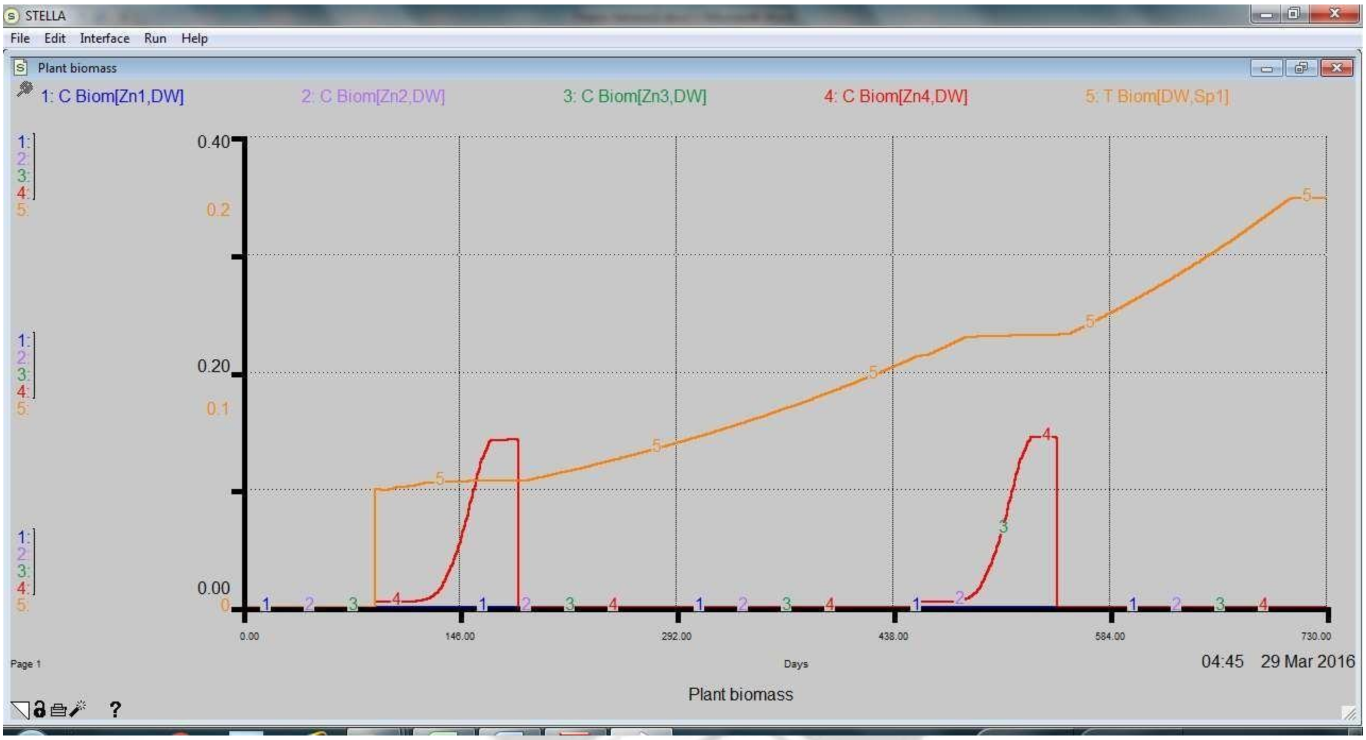


Figure 4. 9. Upper level view of WaNuLCAS Stella showing an example of output

4.2.6. Model validation

The statistical criteria used to evaluate the model are given below: The

root mean square error (RMSE)

RMSE = d∑hSš———‡Qˆh Q ‰f‰x ^\•]žŒŒ ≥ 0 with the optimum = 0 (4.4)

where, P_i = predicted values, O_i = Observed values, n = number of samples and O_{mean} = mean of observed data.

4.3. Results

4.3.1. Soil water storage in the root zone

Figure 4.9 shows the observed and simulated soil water storage in the root zone (45 cm) during the two consecutive years (2015 and 2014) of experimentation. Additionally, WaNulCas model's performance is reflected by corresponding RMSE values as summarized in Table 4.4. Although simulations slightly underestimated soil water in the root zone compared to the observations, WaNulCas shows a good performance in simulating soil water dynamics in the root zone. The relatively low RMSE values (< 50 %) indicate tha t the model performance is good in mimicking soil water behaviour in the root zone. In addition the R^2 values (> 50 %) are in agreement with the RMSE values.

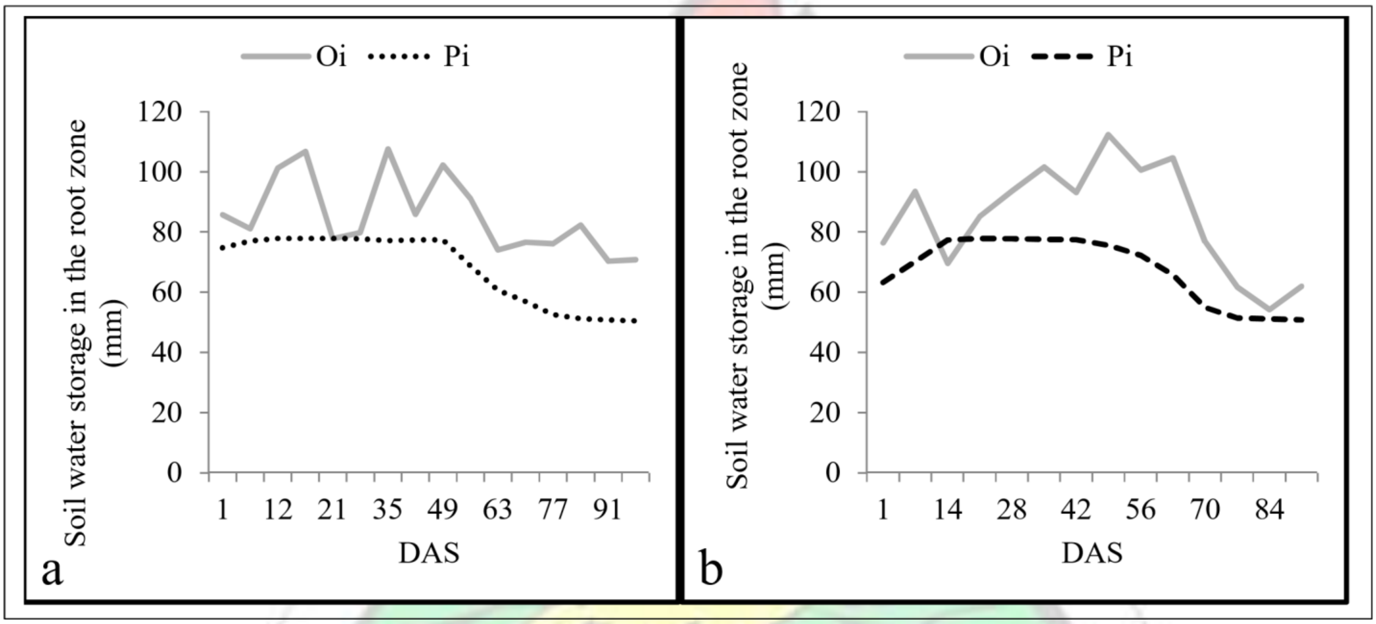


Figure 4. 9. Observed (Oi) and predicted (Pi) soil water storage in the root zone in 2014 (a) and 2015 (b)

Table 4. 4 Root mean square error of the soil water prediction in the root zone for 2014 and 2015

Year	**2014**	**2015**

RMSE (%)	22.83	25.03

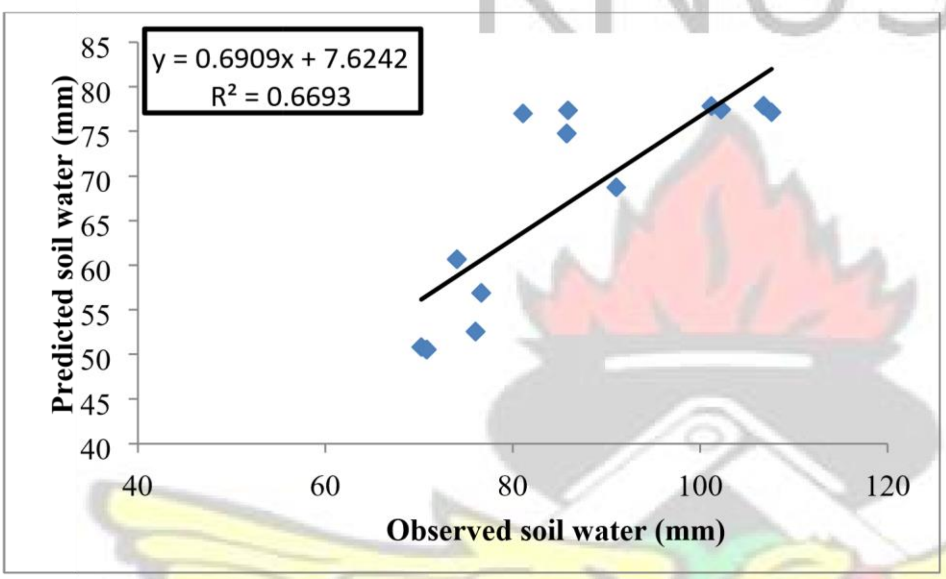


Figure 4. 10. Relationship between simulated and observed soil water in 2014

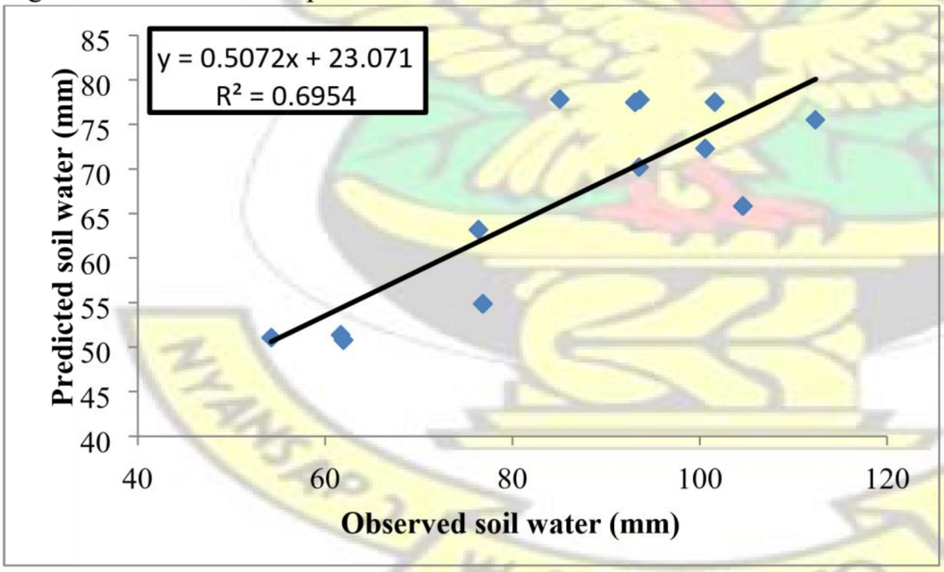


Figure 4. 11. Relationship between simulated and observed soil water in 2015

4.3.2. Millet and *A. senegal* response

and the cumulative grain yield produced during the 2 years. Figure 4.13 provides the predicted and the observed millet straw biomasses for the years 2014 and 2015 and the cumulative straw biomasses produced during the 2 years. The low RMSE values in Table 4.5 highlights the model's good performance in predicting the millet yield in 2015, the cumulative millet yield for the 2 years, the millet straw biomass for both years and for the cumulative straw biomass for the 2 years. In Table 4.5 the high value of RMSE > 1, also indicates that WaNulCas failed to provide a good simulation of millet grain yield in 2014, with an under estimation of the observed grain yield.

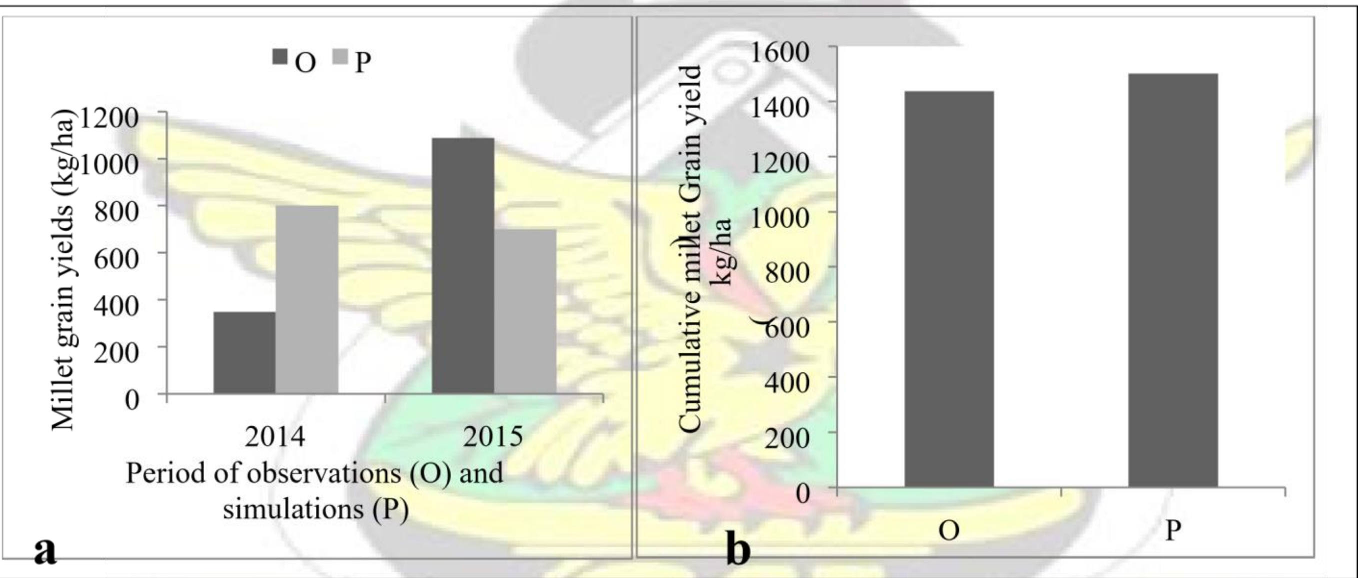


Figure 4. 12. (a) Observed (O) and simulated (P) millet grain yield for each of the 2 consecutive years of experimentation and (b) Cumulative observed and predicted millet grain yields

In Figure 4.12, the simulated and observed millet grain yields are given for the years 2014 and 2015

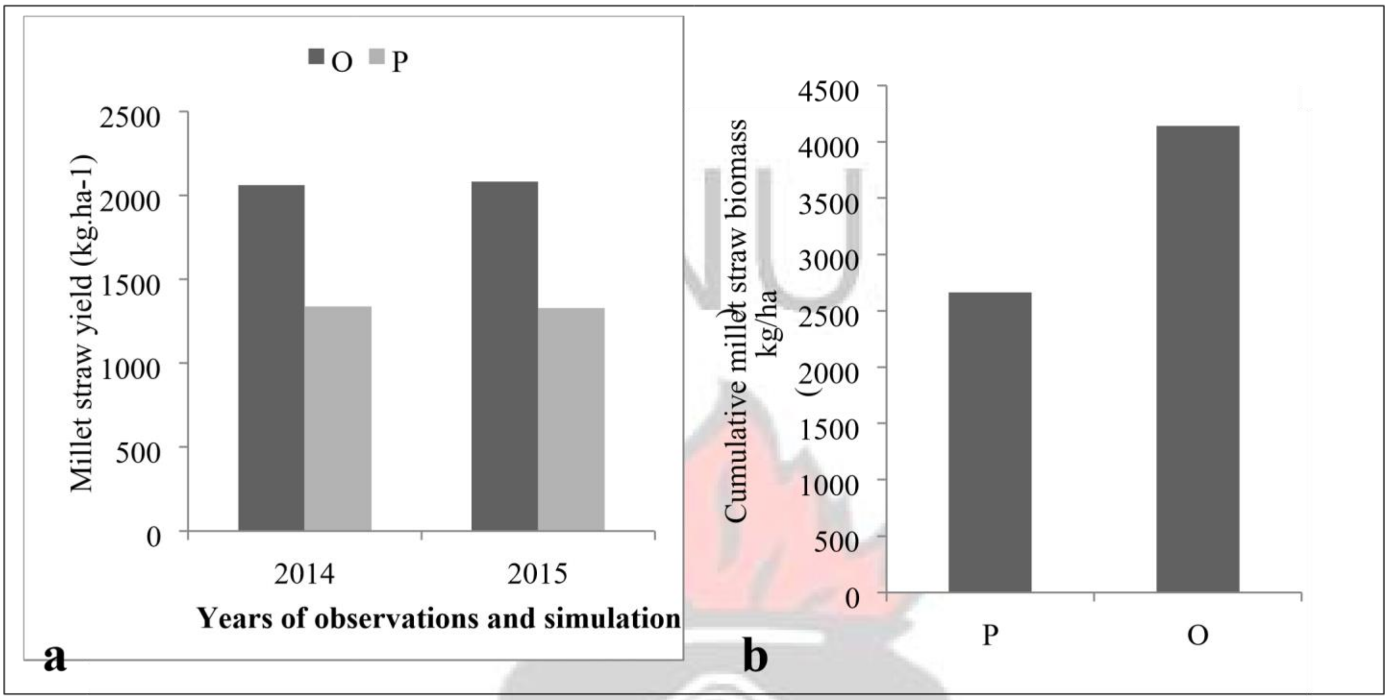


Figure 4. 13. (a) Observed (O) and simulated (P) millet straw biomasses for each of the 2 consecutive years of experimentation and (b) Cumulative observed and cumulative millet straw biomass

Table 4. 5. Root mean square error (RMSE) for model evaluation of millet straw biomass and grain yield

	Straw biomass	**Grain yield**
RMSE of 2014	35.17%	129.55%
RMSE of 2015	36.20%	35.67%
RMSE of the Cumulative millet grain yield (2014-2015)	35.69%	4.40%

A. senegal's response

The observed and the predicted biomasses of A. *senegal* after the 2 consecutive rainy seasons are given in Figure 4.14. With a RMSE of 13.98 % (Table 4.6), the model shows a good performance in simulating the biomass of *A. senegal*.

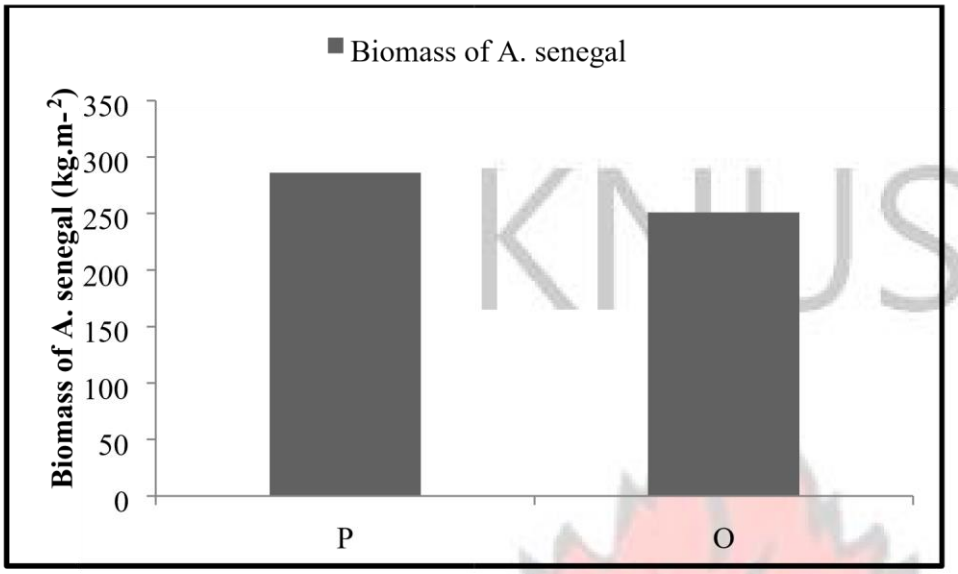


Figure 4. 14. Observed and simulated biomasses of A. *senegal* after the 2 consecutives rainy seasons

Table 4. 6 Root mean square error (RMSE) for model evaluation of A. senegal biomass prediction

RMSE of *A. senegal* biomass (%)	13. 98

4.4. Discussion

Although there is an underestimation of soil water, it could be concluded that there is a good agreement between the observed and simulated soil water in the root zone for the two rainy seasons (2014 and 2015). This can be explained by the use of the default pedotransfer functions (PTF) of Hodnett and Tomasella (2002), calibrated and validated using tropical soils database to predict volumetric soil water content in the root zone. These results are in agreement with those reported by Muthuri et al. (2004) who reported that the prediction of the overall water balance of WaNuLCAS model is extremely good.

The model showed a good reliability for simulating millet biomass (straw) during both years of simulations and observations. However, WaNuLCAS slightly under-estimated the measured biomasses of millet during both years. Similar results for the same model were reported for maize in a study conducted by Coulibaly et al. (2014) in Burkina Faso. Although these results are similar, Coulibaly et al. (2014) reported a lower RMSE (9%) than in the case of this study. This might be explained by the underestimation of the soil water in root zone. The performance of WaNuLCAS to predict soil water in the root zone may mean higher or lower water availability to crops and the consequence of under or over-estimation of their growth (Pinto et al., 2005). In addition, the trend for simulated biomasses was consistent with those observed in the field experiment as millet biomass of first year experimentation was almost equal to the one of the second year during the cropping seasons. Muthuri et al. (2004) also highlighted the performance of WaNuLCAS in simulation of crop biomass trend over years (5 years). However, in this latter case, biomass production was lower during the second season than during the first. WaNuLCAS underestimated too the crop biomass in this case of study.

Contrary to millet straw biomasses, millet grain yields simulation did not show the same trend as compared to the observed ones. In 2014, WaNuLCAS overestimated millet grain yield with a high RMSE compared to the observed one. In 2015, despite an underestimation, the model showed a good performance in simulating millet grain yield. In fact, the simulated values of millet grain yield for both years (800 kg.ha-^{1}for 2014 and 700 kg.ha-1 for 2015) are quite similar while the observed yields are significantly different. The observed millet grain yield of 2015 (1088.3 kg.ha-^{1}) is better than the one of 2014 (348.5 kg.ha-^{1}). The difference between the experimental results is explained by the residual effect of the applied organic manure and rainfall shortage during the reproductive stage of millet (see Chapter 3, Section 3.4). In the case of the simulations, the first year grain yield is even a bit better than the second one. This may be explained by the higher rainfall amount in 2014 than 2015. The overestimation of the first year grain yield by the model compared to the observed yield could be explained by a high decomposition rate of the organic manure by the model while it was not the case in the experimentation. In case of the experimentation there was residual part of the organic manure applied in 2014 in addition to the organic manure applied in 2015. This may have contributed to increase the soil fertility and led to a higher grain yield in 2015. The model could not account for the residual effect of organic manure and that could be the reason why despite its good performance, it underestimated the grain yield of 2015. Better estimates for biomass compared to harvestable grain yield of the model have already been reported by Coulibaly et al. (2014). Thus, further refinement is clearly needed to improve the model precision for the harvestable yield. As millet had been intercropped with *A. senegal* in the experimentation and as *A. senegal* continued to grow after the first year of millet harvesting, a continuous simulation of both represents better system performance. Interestingly the comparison of the observed cumulative grain yield produced during the 2 consecutive years and the simulation showed a good agreement, with a low RMSE value of 4.4%. This suggests that model performance in predicting cumulative grain and biomass may be better.

After the 2 consecutive years of observation and simulation, WaNuLCAS shows a good performance to simulate the biomass of *A. senegal* with a RMSE of 13.98% with a some overestimation. Similar results were reported by Walker et al. (2007) who stated that

WaNuLCAS predicts tree biomass quite well.

4.5. Conclusion

WaNuLCAS showed a good performance in simulating soil water in the root zone under the technique of forestry zaï during the 2 consecutive years. However, simulated annual yields for millet did not agree with the observed yields whereas the cumulative predictions over the two years tended to agree with observed cumulative yield values. Despite this situation, WaNuLCAS still remains a good model for simulating the forestry *zaï* technique as it simulates well the cumulative millet yield produced during the 2 consecutive years of experimentation. However further refinement is clearly needed to improve the model precision for the harvestable yield.

CHAPTER 5: IMPACT OF CLIMATE CHANGE ON THE HYDROLOGY OF THE FORESTRY

5.1. Introduction

In the last decade (2005-2014), an overwhelming consensus have emerged among scientists that the world has entered an era of rapid global climate change, much of which is attributable to greenhouse gas (GHG) emissions from human activities. Changes in rainfall distribution, with longer dry spells and more intense precipitation, are expected everywhere. This may lead to an increased occurrence of extreme events (floods and droughts). This will directly affect soil moisture and the productivity of rainfed crops. These changes will be felt mostly in areas already subject to climate variability, such as in the semi-arid and sub-humid areas of sub-Saharan Africa and South Asia, where, in the absence of alternative sources of water, the risk of increased frequency of crop failures is high

ZAÏ

(Reddy, 2015). According to the IPCC report (2007) there will likely be an increase of global temperature in the range of 1.4 - 6.4 °C by 2100, with a corresponding atmospheric CO_2 concentration increase of 600 ppmv to 1550 ppmv (IPCC, 2007). Although increased atmospheric CO_2 will increase photosynthesis, adverse impacts resulting from increasing temperature and changing water availability will probably outweigh the advantages of higher CO_2 concentration (Wassmann et al., 2009), especially if the average temperature increases by more than 3 °C (Attri and Rathore, 2003).

Rainfall in Niger was subjected to a prolonged period of below average rainfall from 1970 to 1990. Recent analysis of long-term rainfall trends shows that this trend has now reversed, with average rainfall increasing again from 1990 to 2007 (Lebel and Ali, 2009). Despite this recovery, the rainfall variability in semi-arid Niger is great both spatially and temporally and is considered to be one of the main limiting factors in agriculture (Graef and Haigis, 2001). Niger is one of the world's most vulnerable countries because of its landlocked position and its exposure to climate risks.

In 2011, the population of Niger was estimated to be 16.5 million people (CIA, 2011). In Niger, the birth rate is the highest of any country, with second highest population growth rate in the world (3.6 %). The population will double every 20 years at this rate. The yields of cereals are extremely low, and show no positive trends. By 2025, Niger's projected population of 26 million people could face substantial food shortage, if the rapid expansion of farmland slows while the yield growth remains stagnant (Funk et al., 2012).

As climate change is projected to affect agricultural and natural ecosystems around the world, there is no reason to expect that agroforestry systems will be spared (Luedeling et al., 2014). There is thus great need to project climate change impacts on agroforestry systems.

In Sahelian areas, where it is estimated that only 10 – 15 % of rainwater is used productively for plant growth (Breman et al., 2001), RWH could help to mitigate the impacts of climate change on crop production. *In situ*

RWH techniques, such as *zai* implemented at the field level, can act to shift a fraction of surface runoff water to productive purposes by storing water in the form of soil moisture (Rockström et al., 2002).

Several studies have investigated the siting of RWH techniques under current climatic conditions, but most fail in the assessment of the performance of these systems under changing climatic conditions (Lebel et al., 2015). The aim of this study therefore, is to model the impact of climate change on the hydrologic behaviour of the forestry *zaï* under future climate scenarios.

5.2. Materials and Methods

5.2.1. Data for model calibration

The model WaNuLCAS previously used in Chapter 4 will also serve for the simulations under future climate scenario. So all the data previously described remain the same except the climate data.

Rainfall and temperature data

Future climate daily rainfall and daily average temperature were downloaded from the Coordinated Regional Climate Downscaling Experiment (CORDEX) using the method of the nearest grid point (Willmott et al., 1985) for two Representative Concentration Pathways (RCPs): RCP 4.5 and RCP 8.5

RCPs concern the portion of the concentration pathway extending up to 2100, for which Integrated Assessment Models have produced corresponding emission scenarios (Stocker et al., 2013). The RCP 8.5 is a high emissions scenario, corresponding to projections of high human population (12 billion by 2100), high rates of urbanization and limited rates of technological change, all resulting in emissions approaching 30 Gt of carbon by 2100 compared with 8 Gt in 2000 (Riahi et al., 2007). The RCP 4.5 scenario is an intermediate mitigation scenario characterised by continuously increasing human popul ation but at a rate lower than in the RCP 8.5 scenario, intermediate levels of economic development and less rapid and more diverse technological change (Moss et al., 2010).

CORDEX is an initiative of the World Climate Research Program (WCRP) to provide reliable and high resolution datasets for supporting decision making in response to climate change. Early results from CORDEX over West Africa showed improvement of the models in capturing the African monsoon systems (Gbobaniyi et al., 2014) and precipitation (Nikulin et al., 2012).

The nearest grid point interpolation method was used to extract the future scenarios data from CORDEX using geographical coordinates of ICRISAT research centre weather station with R platform. The daily future climate data of he study area extracted from CORDEX are listed in Table

5.1.

Table 5. 1. List of regional climate models (RCMs) of CORDEX used for the simulations

Nº	RCMs	Institution	GCM driven	Variables	Historical	Rcp 4.5	Rcp 8.5
1	SMHI-RCA35	Swedish Meteorological and Hydrometeorological Institute	CanESM2	Pr, tas	1971-2005	2006-2100	2006-2100
2	CLMcom-CCLM4	Climate Limited-area Modelling Community	CNRM-CM5	Pr, tas	1950-2005	2006-2100	2006-2100
3	SMHI-RCA35	Swedish Meteorological and Hydrometeorological Institute	CNRM-CM5	Pr, tas	1950-2005	2006-2100	2006-2100
4	KNMI-RACMO	Royal Netherlands Meteorological Institute	EC-EARTH	Pr, tas	1971-2005	2006-2100	2006-2100

5	CLMcom-CCLM4	Climate Limited-area Modelling Community	EC-EARTH	Pr, tas	1971-2005	2006-2100	2006-2100
6	CLMcom-CCLM4	Climate Limited-area Modelling Community	HadGEM2-ES	Pr, tas	1971-2005	2006-2100	2006-2100

7	SMHI-RCA35	Swedish Meteorological and Hydrometeorological Institute	HadGEM2-ES_	Pr, tas	1971-2005	2006-2100	2006-2100
8	SMHI-RCA35	Swedish Meteorological and Hydrometeorological Institute	NorESM1	Pr, tas	1950-2005	2006-2100	2006-2100

GCM: Global Climate Model

Considering the unavailability of potential evapotranspiration data for future climate, it has been computed using R platform. There are many options for estimating reference evapotranspiration: Blaney-Criddle (1950), Kimberly-Penman (Wright, 1982), Penman-Monteith (Monteith, 1965) and many others cited by (Oudin et al., 2005). The method of Hamon (1961) cited by (Oudin et al., 2005) has been used in this study due to limited data of future climate. The algorithm of this method is given below:

$$PE = (..)^2 \exp({}^{k5}) \qquad (5.1)$$

Where, PE= potential evapotranspiration (mm.day^{-1})

DL= day length (h.day^{-1})

Ta= air temperature (ºC)

Simulated rainfall data from Regional Climate Models (RCMs) are biased (e.g. due to limited process understanding or insufficient spatial resolution; Rauscher et al., 2010) and therefore need to be post processed (i.e. statistically adjusted, bias corrected) before being used for climate impact assessment (Gudmundsson et al., 2012).

For this study, the quantile mapping (QM) method (Dosio and Paruolo, 2011; Piani et al., 2010) was used to bias-correct the data with R plat-form. QM method is routinely applied to correct biases of regional climate model simulations compared to observational data (Maraun, 2013). Extending the correction from means to the entire distribution, QM corrects for errors in the shape of the distribution and is therefore capable of correcting errors in variability as well. The observational data used for the bias correction of the RCMS are daily precipitation data from 1983 to 2012. After the bias correction, the data of the RCMs were divided into 3 data sets to represent the near term (2006-2038), the mid-century (2039-2070) and end-century (2071-2100). Then, the average daily precipitation and temperature were computed for each period of each model. The daily average data were then used as input data in WaNuLCAS model to simulate 2 consecutive years of intercropping of pearl millet and *A. senegal* under the technique of forestry *zaï*. The outputs of the simulation namely soil water dynamic, millet biomass and yield and *A. senegal* biomass where then compared to outputs of the 2 consecutive years of experimentation (2014 and 2015).

5.3. Results

5.3.1. Prediction of soil water, predicted millet and *A. senegal* response for near term (2006-2038) of the average emission scenario (RCP 4.5)

Figure 5.1a shows that for the near term (2006-2038) of the emission scenario RCP 4.5 the predicted soil waters in the root zone of all the regional climate models (CRMs) are below the observed under current climate scenario. In Figure 5.1b, the observed average annual millet straw under current climate is higher than the simulated ones of all near term CRMs of RCP 4.5. For the near term prediction under the RCP 4.5, the predicted average annual millet grain yields are almost all higher (18 to 25 %) than the current average annual millet yield for almost all the RCMs except for the following ones: CLMcom-CCLM4-CNRM-CM5 (- 37 %) and SMHIRCA35- HadGEM2-ES (- 37 %) (Figure 5.1c). The predicted biomass of *A. senegal* of all the CRMs are all almost equal or higher than the biomass produced under the technique of forestry zaï under current climate conditions

(Figure 5.1d).

5.3.2. Prediction of soil water, predicted millet and *A. senegal* response for near term (20062038) of the extreme emission scenario (RCP8.5)

Figure5.2a shows that for the near term (2006-2038) of the emission scenario RCP 8.5 the predicted soil waters in the root zone of all the regional climate models (CRMs) are below the observed under current climate condition. In Figure 5.2b, the observed millet straw under current climate is higher than the simulated ones for all near term CRMs of RCP 8.5. For the near term prediction under the RCP 8.5, the predicted average millet grain yields are almost equal to or higher (4 to 32 %) than the current average millet yield of all the RCMs (Figure 5.2c). The predicted biomass of *A. senegal* of all the CRMs are all almost equal or higher than the biomass produced under the technique of forestry zaï under current climate conditions (Figure 5.2d).

5.3.3. Prediction of soil water, predicted millet and *A. senegal* response for mid-century (20392070) of the average emission scenario (RCP 4.5)

Figure 5.3a shows that for the mid-century (2006-2038) of the emission scenario RCP 4.5 the predicted soil waters in the root zone of all the regional climate models (CRMs) are below the observed under current climate condition except for the models SMHI-RCA35- NorESM1 (- 16 %) and CLMcom-CCLM4- HadGEM2-ES (- 9 %) where the predicted and the observed soil water were quite similar between 70 to 77 days after sowing (DAS). In Figure 5.3b the observed average annual millet straw under current climate is higher than the simulated ones of all midcentury CRMs of RCP 4.5. For the mid-century prediction under the RCP 4.5, the predicted average millet grain yields are almost all higher (18 to 32 %) than the current average millet grain yield for almost all the RCMs except for the following ones: CLMcom-CCLM4- HadGEM2-ES and SMHI-RCA35- HadGEM2-

ES (Figure 5.3c). The predicted biomass of *A. senegal* of all the CRMs are all almost equal or higher than the biomass produced under the technique of forestry zaï under current climate conditions (Figure 5.3d).

5.3.4. Prediction of soil water, predicted millet and *A. senegal* response for mid-century (20392070) of the extreme emission scenario (RCP 8.5)

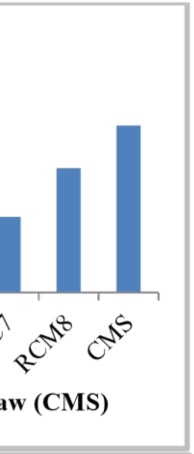
Figure 5.4a shows that for the mid-century (2039-2070) of the emission scenario RCP 8.5 the predicted soil waters in the root zone of all the regional climate models (CRMs) are below the observed under current climate condition. In Figure 5.4b, the observed average annual millet straw under current climate is higher than the simulated ones of all mid-century CRMs of RCP 8.5. For the mid-century prediction under the RCP 8.5, the predicted average millet grain yields are almost equal to or higher (4 to 32 %) than the current average millet grain yield for almost all the RCMs (Figure 5.4c). The predicted biomass of *A. senegal* of all the CRMs are all almost equal or higher than the biomass produced under the technique of forestry zaï under current climate conditions (Figure 5.4d).

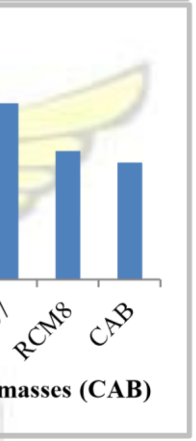
5.3.5. Prediction of soil water, predicted millet and *A. senegal* response for end-century (20712100) of the average emission scenario (RCP 4.5)

Figure 5.5a shows that for the end-century (2070-2100) of the emission scenario RCP 4.5 the predicted soil waters in the root zone of all the regional climate models (CRMs) are below the observed under current climate condition. In Figure 5.5b, the observed average annual millet straw under current climate is higher than the simulated ones of all end-century CRMs of RCP 4.5. For the end-century prediction under the RCP 4.5, the predicted average millet grain yields are almost equal (- 2 %) to or higher (18 to 32 %) than the current average millet grain yield for all the RCMs (Figure 5.5c). The predicted biomass of *A. senegal* of all the CRMs are all almost equal or higher than the biomass produced under the technique of forestry zaï under current climate conditions (Figure 5.5d).

5.3.6. Prediction of soil water, predicted millet and *A. senegal* response for end-century (20712100) of the extreme emission scenario (RCP 8.5)

Figure 5.6a shows that for the end -century (2071-2100) of the emission scenario RCP 8.5 the predicted soil waters in the root zone of all the regional climate models (CRMs) are below the observed under current climate one except for the model SMHI -RCA35 - CanESM where the predicted soil water was slightly below the observed one between 70 to 77 days after sowing (DAS). In Figure 5.6b, the observed average annual millet straw under current climate is higher than the simulated ones of all mid-century CRMs of RCP 4.5. For the end-century prediction under the RCP 8.5, the predicted average millet grain yields are almost equal (- 9 %) to or higher (4 to 32 %) than the current average millet grain yield for almost all the RCMs except for the model CLMcom - CCLM4-EC-EARTH where the average annual millet grain yield was slightly above the observed one (Figure 5.6c). The predicted biomass of *A. senegal* of all the CRMs are all almost equal or higher than the biomass produced under the technique of forestry zaï under current climate conditions (Figure 5.6d).





(rcp4.5) of regional models for the
c); A. senegal biomass production 15

RCM3: SMHI -RCA35CNRM-CM5;
adGEM2-ES; RCM7: SMHI -RCA35-

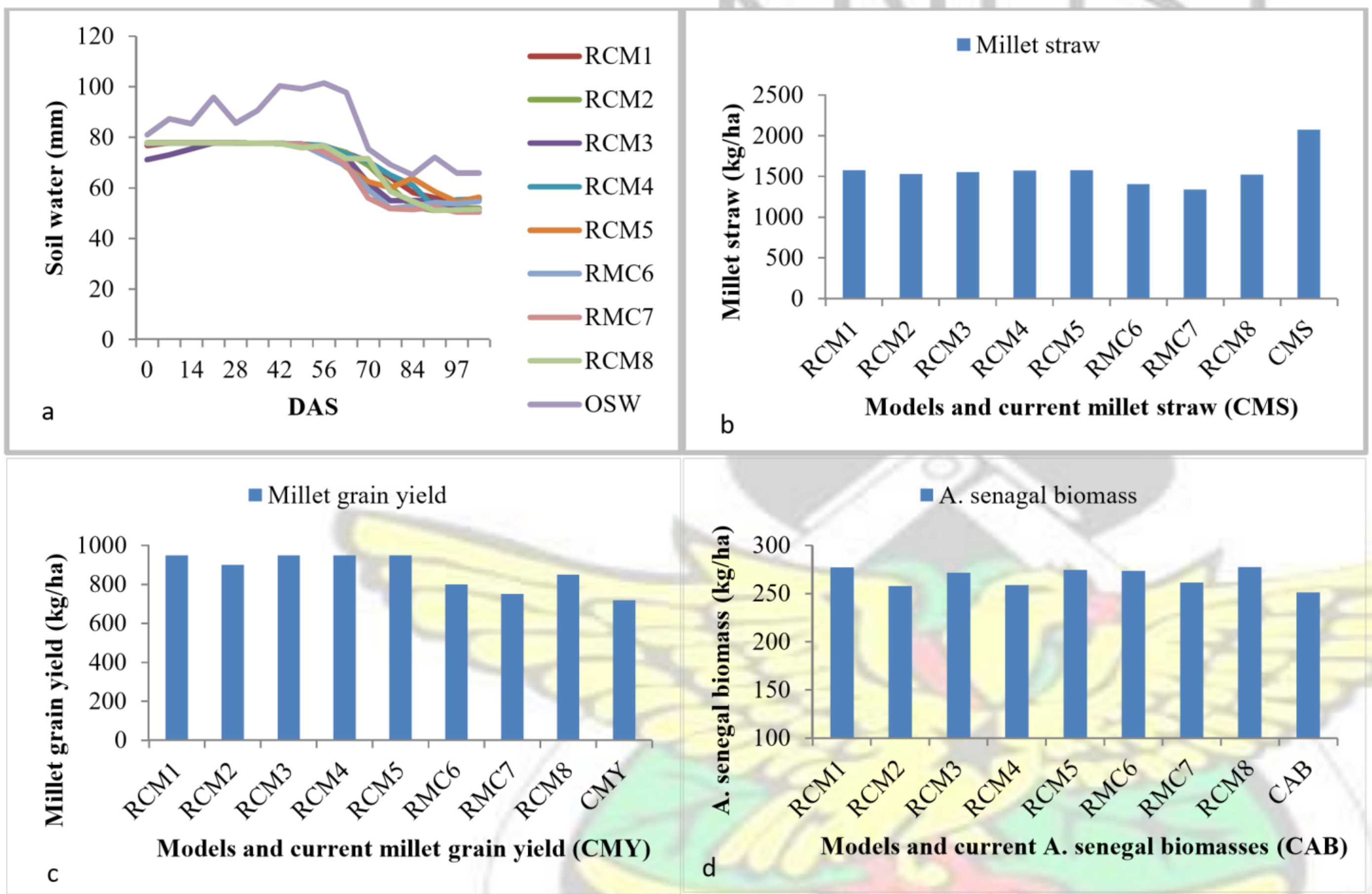


Figure 5. 2. Predicted average soil water storage during the growing seasons of the extreme emission scenario (rcp8.5) region al models for the period 2006 - 2038 (a); pearl millet response in term of annual average straw (b) and grain yield production (c); A. senegal biomass production 15 months after planting (d).

Note: RCM1: SMHI-RCA35 - CanESM2; RCM2: CLMcom-CCLM4- CNRM-CM5; RCM3: SMHI-RCA35-CNRM-CM5; RCM4: KNMI-RACMO-EC-EARTH; RCM5: CLMcom-CCLM4-EC-EARTH; RCM6: CLMcom-CCLM4- HadGEM2-ES; RCM7: SMHIRCA35- HadGEM2-ES; RCM8: SMHI-RCA35- NorESM1.

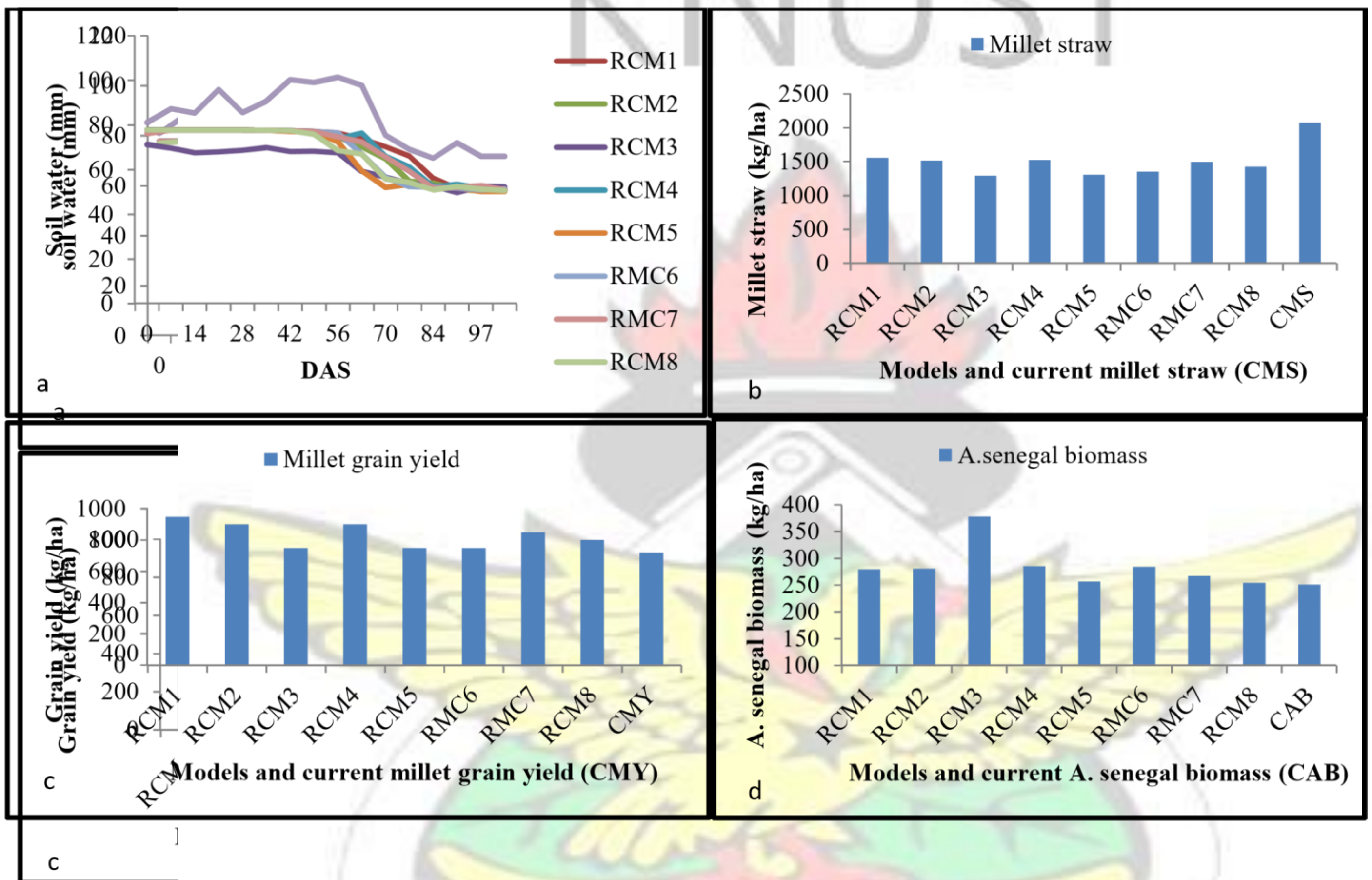


Figure 5. 4. Predicted average soil water storage during the growing seasons of the extr eme emission scenario (rcp8.5) regional models for the period 2039 - 2070 (a); pearl millet response in term of annual average straw (b) and grain yield production (c);*A. senegal* biomass production 15 months after

Figure 5. 3. Predicted ave al models for the period 2039 - 2070 (a); pearl mil production 15 months after

Note: RCM1: SMHI-RCA35 - CanESM2; RCM2: CLMcom-CCLM4- CNRM-CM5; RCM3: SMHI-RCA35-CNRM-CM5; RCM4: KNMI-RACMO-EC-EARTH; RCM5: CLMcom -CCLM4-EC-EARTH; RCM6: CLMcom -CCLM4- HadGEM2-ES; RCM7: SMHIRCA35 - HadGEM2-ES; RCM8: SMHI-RCA35- NorESM1.

Note: RCM1: SMHI-RCA CM4: KNMI-RACMO- EC-EARTH; RCM5: CLN adGEM2-ES; RCM8: SMHI-RCA35- NorESM1

planting (d). planting (d).

planting (d).

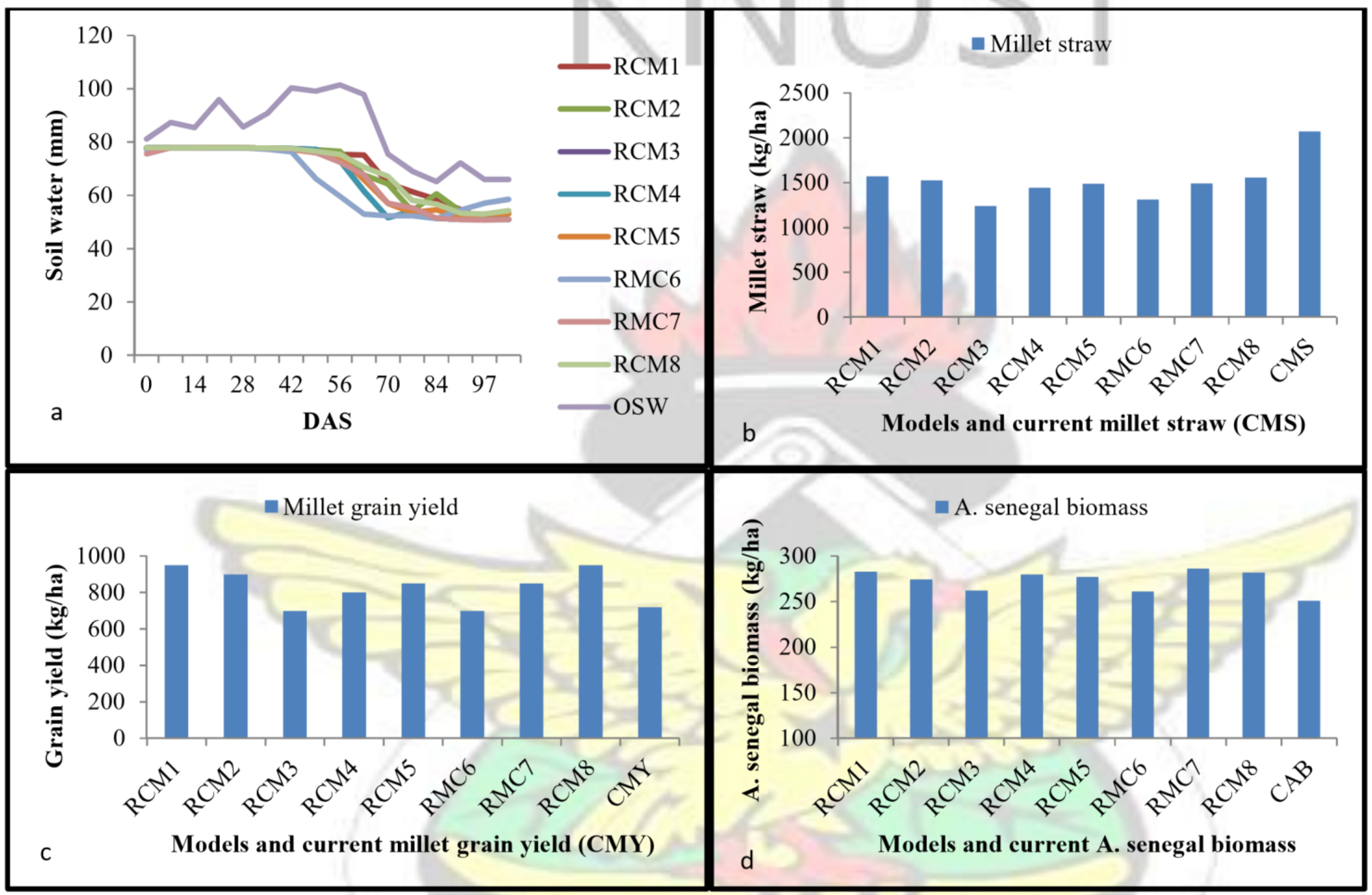


Figure 5. 5. Predicted average soil water storage during the growing seasons of the average emission scenario (rcp4.5) region al models for the period 2071 - 2100 (a); pearl millet response in term of annual average straw (b) and grain yield production (c);*A. senegal* biomass production 15 months after

Note: RCM1: SMHI-RCA35 - CanESM2; RCM2: CLMcom-CCLM4- CNRM-CM5; RCM3: SMHI-RCA35-CNRM-CM5; RCM4: KNMI-RACMO-EC-EARTH; RCM5: CLMcom -CCLM4-EC-EARTH; RCM6: CLMcom -CCLM4- HadGEM2-ES; RCM7: SMHIRCA3 5- HadGEM2-ES; RCM8: SMHI-RCA35- NorESM1.

planting (d).

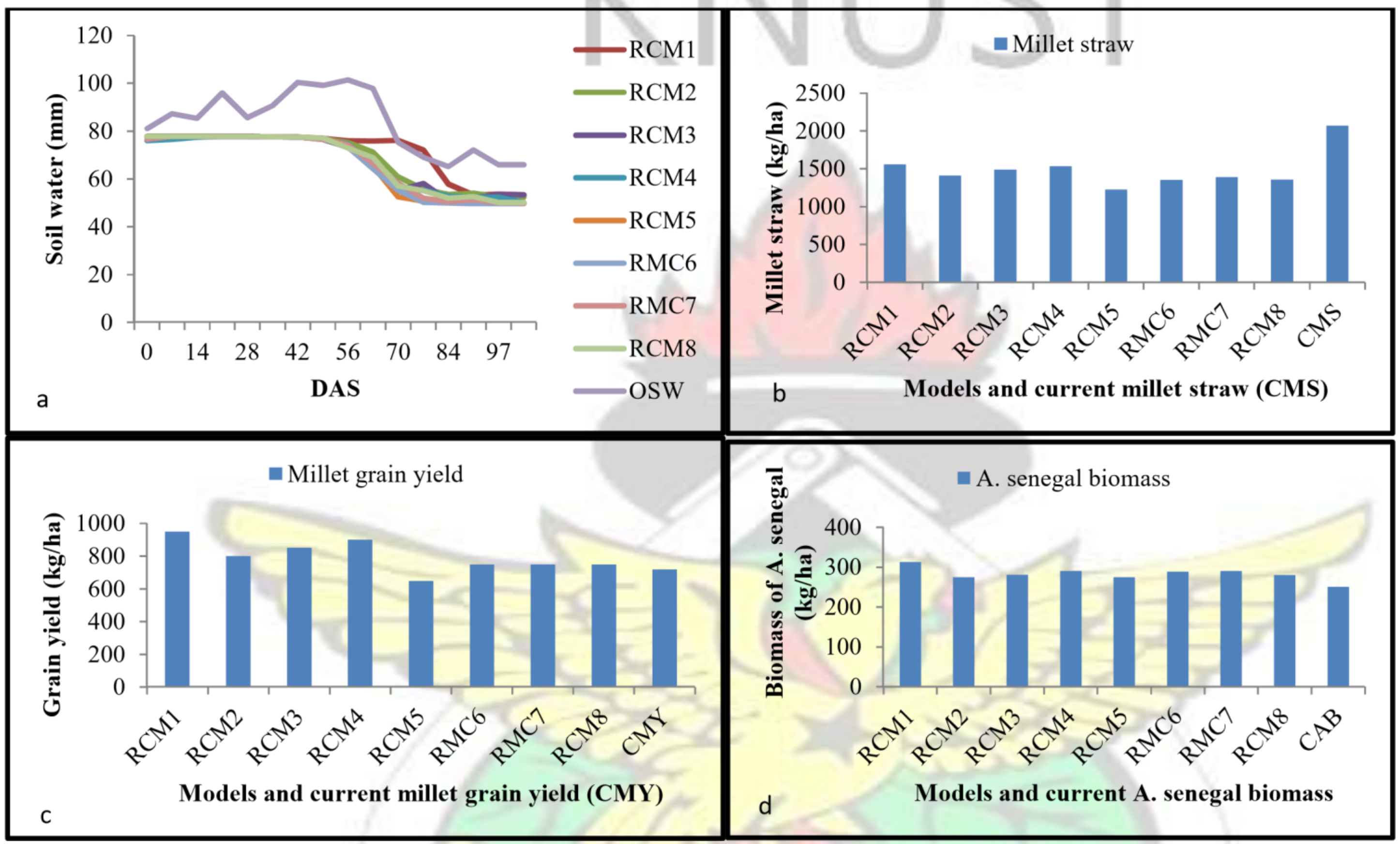


Figure 5. 6. Predicted average soil water storage during the growing seasons of the average emission scenario (rcp8.5) region al models for the period 2071 - 2100 (a); pearl millet response in term of annual aveage straw (b) and grain yield production (c); *A. senegal* biomass production 15 months after

Note: RCM1: SMHI-RCA35 - CanESM2; RCM2: CLMcom-CCLM4- CNRM-CM5; RCM3: SMHI-RCA35-CNRM-CM5; RCM4: KNMI-RACMO-EC-EARTH; RCM5: CLMcom -CCLM4-EC-EARTH; RCM6: CLMcom -CCLM4- HadGEM2-ES; RCM7: SMHIRCA35 - HadGEM2-ES; RCM8: SMHI-RCA35- NorESM1.

5.4. Discussion

For almost all the RCMs under both RCPs, the projected means of millet grain yields are always higher than the observed mean under current climate. These results suggest that climate change is not likely to affect millet production under the technique of forestry *zai*. The results showed increased millet grain yield ranging from a minimum of 4 % to a maximum of 32 %. This is consistent to results reported by Walker and Schulze (2006) who used the CERES-Maize model to predict crop sustainable production in smallholder farmers with different climate scenarios by the Mann-Kendall non-parametric test in South Africa, and the result shows that increasing inorganic nitrogen and rainwater harvesting can increase crop yield for smallholders in the long run. Similar results were also reported by Jägermeyr et al. (2016) who predicted an average yield increase of 5 to 13 % under RWH technique under climate future scenarios. In contrast, a large scale study conducted in sub-Saharan Africa reported negative impact of climate change on millet production (Schlenker and Lobell, 2010). Knox et al. (2012) also observed significant projected yield reduction (-10%) for millet in Africa. However, a quantitative projections study showed both negative and positive impacts of climate change on millet yield (Adhikari et al., 2015). According to the authors, the discrepancy might be attributed to the difference in scenarios, models and time periods used in future projections and the extent of the area considered in the study. The disparities between the results of the above-mentioned studies and the results of this study are probably due to the fact that this study is conducted under an *in situ* rainwater harvesting technique that is known to improve soil water for crop production. In addition to water harvesting that could maintain millet productivity under climate change, this crop is also known to be more resilient to climate change than maize or wheat but less resilient than sorghum (Adhikari et al., 2015).

Projected means of millet straw change showed a consistent decline for all the RCMs under both RCPs. This might probably be explained by the model's error (see chapter 4) to predicted millet straw biomass.

Lower soil water in the root zone projected by almost all RCMs under both RCPs compared to the baseline, may be attributed to WaNuLCAS model's small error to underestimate soil water in the root zone (Chapter 4, section 4.3).

The predicted average annual biomass of *A. senegal* of all the RCMs under both RCPs showed a persistent stability or increase compared to the annual average biomass produced under current climate conditions. This suggests that climate change may not have a detrimental effect on the growth of *A. senegal*. These results reflect the inherent properties of *A. senegal* to cope with even very harsh climatic conditions. Thus, its growing might not be affected under a water harvesting technique under future climate scenario.

5.4. Conclusion

For almost all the RCMs under both RCPs, the projected soil water dynamic in the root zone and the biomass of millet under the technique of forestry zaï are quiet good. Moreover, millet grain yield (the most important part for the farmer) and *A. senegal* biomass showed an increased trend in the future. Thus, the technique of the forestry zaï is a suitable *in situ* RWH technique even under changing climate condition. It contributes both to adaptation (a solution to water and land shortage) and mitigation (carbon sink) as a perennial tree.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

The main objective of this dissertation was to evaluate the biophysical viability of the forestry *zai*, under current and future climate conditions. The following conclusions can be drawn from this study:

(a) This study first explored the effects of the forestry zaï technique on soil water storage in the root zone and on the agronomic performances of pearl millet and *A. senegal* for the establishment of agroforestry systems on marginal lands to alleviate the problem of water scarcity and land degradation in the Sudano-Sahelian zone of Niger. The results showed that the forestry *zaï* improves soil water storage in the root zone which in turn leads to better significant increase of millet yield. However, *A. senegal* as very drought tolerant species did not significantly improve growth parameters under *zaï* technique compared to the traditional planting technique.

(b) WaNulCas, an agroforestry model, was used to simulate soil water in the root zone of millet and *A. senegal* under the forestry *zaï* technique. The model predictions agreed well with observed values. The study showed that WaNulCas is a good tool for simulating agroforestry systems under the technique of forestry *zaï* in the Sudano-Sahelian zone of Niger and could help in decision making for suitable management of these systems.

(c) The viability of the forestry *zaï* technique was investigated under future climatic conditions. The results showed that future millet grain and *A. senegal* are not likely to decrease in the long term under the forestry *zaï*. The forestry *zaï* technique could therefore be an adaptation method to the effect of climate change on agroforestry systems, while also contributing to mitigation.

6.2. Recommendations

6.2.1. Further research

(a) This study was conducted for only 2 consecutive rainy seasons. At the time of the experimentations the seedling of *A. senegal* were still at a juvenile stage and did not show any harmful effect on millet production. Therefore, a longer term research is needed to explore if the adult trees do not have any detrimental effect on millet production.

(b) *A. senegal* is known to be a nitrogen fixer. Periodic soil analyses could inform on how it improves soil quality for the benefit of millet production.

(c) Drought analysis can also be undertaken to establish the effect of extreme droughts on the *zai* system.

6.2.2. Policy

To tackle food security in Niger, restoring degraded land while improving incomes in household is a rational approach. The findings in this research showed that the forestry *zaï* is a promising water harvesting technique for this purpose. The following policy recommendations are therefore being made:

(a) A forestry *zaï* project is needed to encourage and disseminate the technology;

(b) A participatory approach should be used to ensure long term adoption;

(c) Specific education of local farmers on the method of implementation of this technique should be undertaken;

(d) Affordable tools should be used to implement this technique with regards to the means of local farmers.

(e) Material and financial support should be provided to motivate large scale and long term adoption.

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APPENDICES

Appendix 1: Simulated soil water storage in the root zone in 2014 and 2015

Days	Soil water in the root zone in 2014 (mm)	Soil water in the root zone in 2015 (mm)
0	89.35	89.35
1	79.51	79.32
2	73.70	73.31
3	71.32	71.33
4	69.14	68.89
5	67.61	67.88
6	67.32	67.38
7	69.58	67.27
8	69.26	67.22
9	67.74	67.21
10	67.34	67.21
11	67.23	67.21
12	67.21	67.21
13	67.21	67.21
14	67.21	67.21
15	67.21	68.91
16	67.21	70.24

17	68.71	70.38
18	68.16	70.38
19	67.46	70.38
20	67.21	70.38
21	68.33	70.38
22	67.58	70.38
23	67.23	70.38
24	69.70	70.38
25	69.86	70.38
26	67.58	72.53
27	67.44	73.92
28	67.28	73.92
29	67.23	74.48
30	67.21	76.82
31	67.21	77.84
32	67.21	77.84
33	67.21	77.84
34	67.21	77.84
35	67.21	77.84
36	67.21	77.84
37	67.21	77.84
38	67.21	77.84
39	67.21	77.85
40	67.21	77.84
41	69.24	77.85
42	68.77	77.84
43	67.50	77.83

44	67.50	77.82

45	67.50	77.82
46	67.50	77.81

47		67.50	77.84
48		67.50	77.83
49		72.70	77.82
50		74.74	77.80
51		74.74	77.83
52		74.93	77.83
53		74.99	77.80
54		74.99	77.83
55		74.99	77.80
56		74.98	77.75
57		77.00	77.81
58		77.84	77.78

59	77.84	77.80
60	77.84	77.77
61	77.84	77.68

62	77.83	77.77
63	77.85	77.73
64	77.84	77.74
65	77.84	77.72
66	77.84	77.56
67	77.84	77.72
68	77.84	77.65
69	77.82	77.34
70	77.81	77.52
71	77.83	77.40
72	77.82	76.87
73	77.80	77.36
74	77.77	77.34
75	77.73	76.66
76	77.82	75.91
77	77.79	77.15
78	77.74	77.02
79	77.69	77.04
80	77.62	75.65
81	77.55	77.02
82	77.47	76.79
83	77.36	75.45
84	77.25	73.60
85	77.14	71.78
86	76.99	70.44

87	77.82	73.58
88	77.73	74.20
89	77.79	72.26

90	77.61	70.24
91	77.34	67.68
92	77.02	70.22
93	76.55	69.28
94	76.08	66.90
95	77.58	67.58
96	77.29	66.90
97	77.72	64.77
98	77.15	61.68
99	77.45	58.60
100	77.27	55.02
101	76.01	53.84
102	74.68	52.32
103	73.41	51.25
104	71.96	51.15
105	70.37	50.84
106	68.71	50.74
107	67.05	50.65
108	68.62	50.57
109	67.32	50.50
110	65.41	50.43
111	63.43	50.36
112	60.66	50.77
113	58.08	50.63
114	55.56	50.27
115	55.56	50.09

116	55.55	50.08
117	60.22	52.87
118	59.18	51.75

119		56.87	49.99
120		55.36	49.99
121		55.73	49.98
122		53.67	49.97
123		52.01	49.96
124		54.91	49.96
125		53.10	
126		52.55	
127		51.75	
128		51.74	
129		51.47	
130		54.73	

days	Biomass of millet straw in 2014 (kg.ha-1)	Biomass of millet straw in 2015 (kg.ha-1)

131	53.22	
132	51.97	
133	51.22	
134	53.83	
135	52.18	
136	50.93	
137	52.98	
138	51.53	
139	50.78	
140	50.74	
141	50.70	
142	50.66	
143	50.63	
144	50.58	
145	50.54	
146	50.51	

Appendix 2: Simulated millet straw biomass in 2014 and 2015

0	0.0	0.0
1	0.0	0.0
2	0.0	0.0
3	0.0	0.0
4	0.0	0.0
5	0.0	0.0
6	0.0	0.0
7	0.0	0.0
8	0.0	0.0
9	0.0	0.0
10	0.0	0.0
11	0.0	0.0

12	0.0	0.0
13	0.0	0.0
14	0.0	0.0

15	0.0	0.0
16	0.0	0.0
17	0.0	0.0
18	0.0	0.0
19	0.0	0.0
20	0.0	0.0
21	0.0	0.0
22	0.0	0.0
23	0.0	0.0
24	0.0	0.0

25	0.0	0.0
26	0.0	0.0
27	0.0	0.0
28	0.0	37.5
29	0.0	37.5
30	0.0	37.5
31	0.0	37.5
32	0.0	37.5
33	0.0	37.5
34	0.0	37.5
35	0.0	37.5
36	0.0	37.5
37	0.0	37.5
38	0.0	37.5
39	0.0	37.5
40	0.0	37.6
41	0.0	37.6
42	0.0	37.7
43	0.0	37.8
44	0.0	38.0
45	0.0	38.2
46	0.0	38.2
47	0.0	38.5
48	0.0	38.8
49	0.0	39.2
50	37.5	39.7
51	37.5	40.3
52	37.5	41.1

53	37.5	41.9

54	37.5	42.9
55	37.5	44.2
56	37.5	45.7
57	37.5	47.5
58	37.5	49.5
59	37.6	51.9
60	37.6	54.7
61	37.6	58.0
62	37.6	61.9
63	37.6	66.3
64	37.6	71.5
65	37.6	77.4
66	37.6	84.4
67	37.8	92.5
68	38.0	102.0
69	38.2	113.1
70	38.6	126.0
71	39.0	141.1
72	39.5	158.6
73	40.1	178.7
74	40.8	201.9
75	41.7	228.6
76	42.7	259.1
77	43.9	293.9
78	45.4	312.2
79	47.2	338.4
80	49.2	367.5
81	51.6	399.2
82	54.4	433.2
83	57.7	469.3
84	61.5	507.7
85	66.0	548.1
86	71.1	590.7
87	77.0	635.3

88		83.9	681.9
89		92.0	730.3

90		101.5	779.7
91		112.5	829.8
92		125.4	880.4
93		140.4	931.2
94		157.8	981.9
95		177.8	1032.5
96		200.9	1082.7
97		227.4	1131.7
98		257.8	1179.6
99		292.5	1226.3
100		310.7	1259.2
101		336.8	1287.7
102		365.8	1314.1
103		397.4	1328.2
104		431.2	1329.8

105	467.2	1331.1
106	505.5	1332.1
107	545.8	1333.0
108	588.2	1333.8

109	632.7	1334.5
110	679.1	1335.2
111	727.4	1335.8
112	776.7	1336.3
113	826.7	1336.7
114	877.1	1338.4
115	877.2	1338.6
116	877.3	1338.8
117	877.4	1338.8
118	957.8	1340.9
119	1018.8	1342.0
120	1072.4	1342.0
121	1121.7	1342.0
122	1166.6	1342.0

123	1166.6	1342.0
124	1166.6	1342.0
125	1207.4	
126	1241.7	
127	1252.6	
128	1254.4	
129	1256.4	
130	1258.1	
131	1282.5	
132	1304.3	
133	1310.6	
134	1311.4	
135	1326.7	
136	1333.9	
137	1334.2	
138	1339.6	
139	1340.7	
140	1340.8	
141	1340.8	
142	1340.8	
143	1340.8	
144	1340.8	
145	1340.8	
146	1340.8	

Appendix 3: Simulated *A. senegal* biomass from 2014 to 2015

days	Simulated biomass of *A. senegal* (kg.ha^{-1})
0	0
1	0

2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0
12	0

13	0
14	0
15	0
16	0

17	0
18	0
19	0
20	0
21	0
22	0
23	0
24	0
25	0
26	0
27	0
28	0
29	0
30	0
31	0
32	0
33	0
34	0
35	0
36	0
37	0
38	0
39	0
40	0
41	0
42	0
43	0
44	0
45	0
46	0

47	0
48	0
49	0
50	125

51	125
52	125.15
53	125.25
54	125.44
55	125.76
56	126.12
57	126.51
58	126.91
59	127.3
60	127.7
61	128.09
62	128.47
63	128.86
64	129.23

65	129.61
66	129.98
67	130.35
68	130.72
69	131.09
70	131.45
71	131.81
72	132.17
73	132.53
74	132.88
75	133.23
76	133.59
77	133.59
78	133.94
79	134.28
80	134.63
81	134.97
82	135.27
83	135.57
84	135.87
85	136.16
86	136.46
87	136.73
88	137
89	137.26
90	137.5
91	137.73
92	137.95
93	138.15
94	138.35
95	138.54
96	138.73
97	138.91

98	139.08

99	139.25
100	139.41
101	139.57
102	139.73
103	139.88
104	140.03
105	140.17
106	140.31
107	140.45
108	140.58
109	140.7
110	140.83
111	140.94
112	141.05
113	141.14
114	141.21
115	141.25
116	141.28
117	141.31
118	141.35
119	141.39
120	141.42
121	141.45
122	141.48
123	141.51
124	141.54
125	141.57
126	141.6
127	141.62
128	141.64
129	141.66
130	141.68
131	141.69
132	141.7

133	141.72
134	141.73
135	141.74

136	141.75
137	141.75
138	141.76
139	141.77
140	141.77
141	141.78
142	141.78
143	141.78
144	141.79
145	141.79
146	141.79
147	141.79
148	142.08
149	142.4

150	142.73
151	143.05
152	143.38
153	143.71

154	144.04
155	144.37
156	144.7
157	145.03
158	145.37
159	145.7
160	146.04

161	146.37
162	146.71
163	147.05
164	147.39
165	147.73
166	148.07

167	148.41
168	148.75
169	149.1
170	149.44
171	149.79
172	150.13
173	150.48
174	150.83
175	151.18
176	151.53
177	151.88
178	152.23
179	152.58
180	152.94
181	153.29
182	153.65
183	154.01

184	154.36
185	154.72
186	155.08
187	155.44

188	155.8
189	156.17
190	156.53
191	156.89
192	157.26
193	157.63
194	157.99
195	158.36
196	158.73
197	159.1
198	159.47
199	159.84
200	160.21
201	160.59
202	160.96
203	161.34
204	161.71
205	162.09
206	162.47
207	162.85
208	163.23
209	163.61
210	163.99
211	164.38
212	164.76
213	165.15
214	165.53
215	165.92
216	166.31
217	166.7

218	167.09
219	167.48
220	167.87
221	168.26

222	168.66
223	169.05
224	169.45
225	169.85
226	170.24
227	170.64
228	171.04
229	171.44
230	171.85
231	172.25
232	172.65
233	173.06
234	173.46
235	173.87
236	174.28
237	174.69
238	175.1
239	175.51
240	175.92
241	176.34
242	176.75
243	177.17
244	177.58
245	178
246	178.41
247	178.83
248	179.25
249	179.67
250	180.09
251	180.51

252	180.94
253	181.36
254	181.79
255	182.21

256	182.64
257	183.07
258	183.5
259	183.93
260	184.36
261	184.79
262	185.22
263	185.66
264	186.1
265	186.53
266	186.97
267	187.41
268	187.85
269	188.29

270	188.73
271	189.18
272	189.62
273	190.07
274	190.51
275	190.96
276	191.41
277	191.86
278	192.31
279	192.77
280	193.22
281	193.68
282	194.13
283	194.59
284	195.05
285	195.51
286	195.97
287	196.43
288	196.89
289	197.36
290	197.82
291	198.29
292	198.76
293	199.22
294	199.69
295	200.17
296	200.64
297	201.11
298	201.59
299	202.06
300	202.54
301	203.02
302	203.5

303	203.98

304	204.46
305	204.94
306	205.43
307	205.91
308	206.4
309	206.89
310	207.38
311	207.87
312	208.36
313	208.86
314	209.35
315	209.85
316	210.34
317	210.84
318	211.34
319	211.84
320	212.34
321	212.85
322	213.35
323	213.86
324	214.36
325	214.87
326	215.38
327	215.89
328	216.41
329	216.92
330	217.43
331	217.95
332	218.47
333	218.99
334	219.51
335	220.03
336	220.55
337	221.08

338	221.6
339	222.13
340	222.66

341	223.19
342	223.72
343	224.25
344	224.78
345	225.32
346	225.85
347	226.39
348	226.93
349	227.47
350	228.01
351	228.55
352	229.1
353	229.64
354	230.19

355	230.74
356	231.29
357	231.84
358	232.39

359	232.95
360	233.5
361	234.06
362	234.62
363	235.18
364	235.74
365	236.3
366	236.86
367	237.43
368	238
369	238.56
370	239.13
371	239.7
372	240.28
373	240.85
374	241.43
375	242
376	242.58
377	243.16
378	243.74
379	244.33
380	244.91
381	245.5
382	246.08
383	246.67
384	247.26
385	247.85
386	248.45
387	249.04
388	249.64

389	250.24
390	250.84
391	250.84
392	250.86

393	250.93
394	251.15
395	251.76
396	252.36
397	252.97
398	253.57
399	254.18
400	254.79
401	255.4
402	256.01
403	256.62
404	257.24
405	257.85
406	258.47
407	259.09
408	259.11
409	259.15
410	259.19
411	259.25
412	259.33
413	259.42
414	259.53
415	259.69
416	259.69
417	260.32
418	260.94
419	260.94
420	261.56
421	262.19
422	262.82

423	263.45
424	264.07
425	264.7
426	265.34

427	265.97
428	266.61
429	267.24
430	267.88
431	268.52
432	269.17
433	269.81
434	270.46
435	271.1
436	271.75
437	272.41
438	273.06
439	273.72
440	274.37
441	275.03
442	275.69
443	276.36
444	277.02
445	277.69
446	278.35
447	279.02
448	279.7
449	280.37
450	281.05
451	281.72
452	282.4
453	283.08
454	283.77
455	284.04
456	284.32

457	284.57
458	284.81
459	285.05
460	285.28

461	285.49
462	285.72
463	285.92
464	286.12
465	286.31
466	286.5
467	286.68
468	286.87
469	287.04
470	287.22
471	287.39
472	287.56
473	287.72
474	287.87
475	288.02
476	288.17
477	288.3
478	288.43
479	288.54
480	288.63
481	288.67
482	288.72
483	288.77
484	288.82
485	288.87
486	288.92
487	288.96
488	288.99
489	289.03
490	289.07
491	289.11

492	289.15
493	289.19
494	289.22
495	289.26

496	289.29
497	289.33
498	289.37
499	289.41
500	289.44
501	289.48
502	289.51
503	289.53
504	289.56
505	289.59
506	289.61
507	289.63
508	289.66
509	289.68
510	289.7
511	289.73