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Optimizing the productivity of agroforestry parkland systems in West Africa using shade-tolerant annual crops

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**OPTIMIZING THE PRODUCTIVITY OF AGROFORESTRY
PARKLAND SYSTEMS IN WEST AFRICA USING SHADE-TOLERANT
ANNUAL CROPS**

By

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ABSTRACT

An experiment was conducted in Nobéré, Burkina Faso, West Africa to assess the effect of shade of two indigenous fruit trees, *Adansonia digitata* (Baobab) and *Parkia biglobosa* (Néré) on a shade-tolerant crop called taro (*Colocasia esculenta*) in comparison with millet (*Pennisetum glaucum*), a shade-intolerant crop, with the aim of optimising the productivity of agroforestry parkland systems. Eight trees of each of néré and baobab were randomly selected on farmers lands for the study. To assess the effect of tree shade on associated crops, the area under each tree was subdivided into three tree influence concentric zones: zone A= from tree trunk to half radius of the crown; zone B=from half radius to the edge of the crown and zone C=from the edge to 3 m away. A control plot was established for each tree in an open area. The performance of crops in terms of growth, yield, dry matter production and nutritional composition was assessed during three cropping seasons between 2006 and 2008 according to concentric zones around trees and the control plot. In addition, biophysical factors including photosynthetically active radiation (PAR), transpiration, photosynthesis, soil physical and chemical properties and root length density were measured under the trees and the control. Finally, the socio-economic implications of optimizing crop production under trees using taro was evaluated using cost-benefit analysis.

Millet performed better under baobab ($806.1 \pm 121.48 \text{ kg ha}^{-1}$) than under néré ($320.2 \pm 59.91 \text{ kg ha}^{-1}$) which was less than the yield in the control plot ($595.8 \pm 83.43 \text{ kg ha}^{-1}$). In contrast, the yield of taro was better under néré ($4124.0 \pm 469.05 \text{ kg ha}^{-1}$) than under baobab ($2738.3 \pm 595.61 \text{ kg ha}^{-1}$) which was almost similar to the yield in the control plot ($2336.9 \pm 617.04 \text{ kg ha}^{-1}$). The higher yield of taro under néré, which had dense and wide crown, confirms its shade tolerance, which was further ascertained by the significantly negative correlation found between PAR availability and the yield and dry matter production of taro. In contrast, the performance of millet increased when PAR availability increased. Results of the nutritional composition showed that tree shade had no effect on the quality of either millet or taro. In terms of yield and nutritional composition, using taro immediately under tree crowns seems to be appropriate strategy for optimising crop production in agroforestry parkland systems. According to the results of the cost-benefit analysis, taking into account the traditional cropping practice in agroforestry parkland systems where the average tree density is 14 trees ha^{-1} and the common crops grown included maize, millet, sorghum, cowpea and peanut, the net present value was estimated at 24317.2 FCFA per hectare (655.957 FCFA is equivalent to 1 €). This was increased to 84696.1 FCFA per hectare if taro is grown under trees at the average tree density of 14 trees ha^{-1} . The net present value increased further with an increase in tree density. Therefore, it was concluded that by using shade-tolerant crops such as taro beneath tree crowns farmers would be able to maintain high density of trees on parklands and improve the systems productivity.

Key words: *Adansonia digitata*, *Colocasia esculenta*, Parkland, *Parkia biglobosa*, *Pennisetum glaucum*, shade tolerance

DEDICATION

To the memory of my parents

Pierre Sanou, my father

And

Roda Djima, my mother

Who valued my education above all.

*To my wife, Marie-Madeleine, my son, Yannick and my daughter, Yolande who
shared the pains of loneliness while away for studies.*

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LIST OF ABBREVIATIONS

ANOVA :	Analysis Of Variance
ASECNA:	Agence pour la Sécurité de la Navigation aérienne en Afrique et à Madagascar
BCR :	Benefit-Cost Ratio
BUNASOL:	Bureau National des Sols
CNRST :	Centre National de Recherche Scientifique et Technologique
DAS:	Days After Sowing
FAO :	Food and Agriculture Organisation of United Nations
FCFA :	Franc de la Communauté Financière Africaine
GLM:	General Linear Model
GPS :	Global Positioning System
INERA :	INstitut de l'Environnement et de Recherches Agricoles
LAI:	Leaf Index Area
MAHRH:	Ministère de l'Agriculture, de l'Hydraulique et des Ressources Halieutiques
NPV :	Net Present Value
OM:	Organic Matter
PAR:	Photosynthetically Active Radiation
PN:	Net photosynthesis
RLD:	Root Length Density
RUE:	Radiation Use Efficiency
RWD:	Root Weight Density
SAFRUIT :	Sahelian Fruit Trees
SE:	Standard Error
TDP :	Thermal Dissipation Probe
WUE:	Water Use Efficiency

CHAPTER 1: INTRODUCTION

1.1. Aims of the project

Food security is a major problem in countries of the Sahel region such as Burkina Faso because the agriculture of these countries depends greatly on climate conditions that are characterised by low and highly unpredictable rainfall patterns (400-1200 mm year⁻¹) with nine months of dry season, frequent periods of drought, and high temperatures throughout the year (FAO, 2004). In this context, natural resources play a key role in food supply and income generation for rural people (Teklehaimanot, 2004; Nikiéma, 2005). Since natural woodlands are degrading and woodland resources are diminishing in many parts of West Africa due to population pressure, agroforestry parkland systems are increasingly becoming the only resource base for many farmers (Bayala, 2002).

In parkland agroforestry systems, trees and crops have been grown together since ancient times (Brookfield and Padoch, 1994) as an option to minimise risks. Nevertheless, the trees and crops may compete for light, water, and nutrients or have complementary needs (Sanchez, 1995). Because this competition is often unfavourable for the crops, farmers tend to reduce the density of the trees in their fields (Gijbers *et al.*, 1994; Boffa, 1999; Kelly *et al.*, 2004; Nikiéma, 2005). However, in dry areas, the ecological role of trees in maintaining favourable conditions for crop production is a reason to encourage farmers to maintain higher density of trees (Boffa, 1999; Bayala *et al.*, 2006).

The decision of farmers to maintain trees in their crop fields was also related to the products and services that they provide (Boffa *et al.*, 2000; Bayala, 2002). The main crops grown in parklands are traditional cereals (millet and sorghum) which are sensitive to the effect of tree shade (Boffa *et al.*, 2000; Teklehaimanot, 2004). Many studies dealing with the subject have shown that yields of these cereals (millet and sorghum) are significantly reduced by 30-60% under tree crowns compared to their production in open area (Maiga, 1987; Kater *et al.*, 1992; Kessler, 1992; Boffa, 1999; Boffa *et al.*, 2000; Bayala *et al.*, 2002). The major factor responsible for the yield decrease was found to be light interception by tree crowns (Kater *et al.*, 1992; Kessler, 1992). One approach to solve the problem of light interception by tree crowns was pruning of branches (Bayala, 2002). Bayala (2002) tested this solution on karité

(*Vitellaria paradoxa* C. F. Gaertn) and néré (*Parkia biglobosa* (Jacq.) R. Br. ex G. Don) and it gave good results with an increase in cereal crop yields and an improvement of soil fertility by the mulching of leaves resulting from the pruning (Bayala *et al.*, 2002; 2003). However, total pruning of trees resulted in reduced tree fruit production for at least five years before the trees recovered to their original production level (Bayala *et al.* 2008). Of course, the loss of tree fruit production was compensated by increased crop production under pruned trees. If, however, farmers decide not to prune trees for various reasons, an alternative would be to plant shade-tolerant crops beneath tree crowns and shade-intolerant crops in areas outside the influence of tree crowns.

There are several traditional crops that have been reported to be shade-tolerant such as yam (*Dioscorea sp.*), sweet potato (*Ipomea batatas* (L.) Lamb), taro (*Colocasia esculenta* (L.) Schott), cocoyam (*Xanthosoma sagittifolium* (L.) Schott) and cassava (*Manihot esculenta* Crantz) (Teklehaimanot, 2004). The use of such shade-tolerant crops beneath tree crowns where traditional cereals do not perform well, would optimise crop production in these agroforestry parkland systems.

1.2. Background

1.2.1. Woody component of agroforestry parkland systems

In the parklands of Sub-Saharan Africa, trees found scattered in farmlands are those preserved by farmers from the original forest vegetation (Bonkougou *al.*, 1993). These trees are multifunctional providing various products and services (Gijbers *et al.*, 1994). Some of the products that farmers obtain from trees on farmlands are fruits, wood and leaves and some of the services that the trees provide include shade, soil fertility improvement and local medicinal uses (Smektala *et al.*, 2005; Bayala *et al.*, 2006). Yaméogo *et al.* (2005) reported that 80.5% of trees that are preserved by farmers in farmlands in Sahelian zone of Burkina Faso are due to their edible fruits, 14.8% due to their use in traditional medicine, 4% for shade and 2.7% for other reasons. The density of trees and their species composition in parklands was determined by the value that farmers give to these products and services (Boffa *et al.*, 2000).

Tree density varies from farm to farm and was usually between 15 and 30 trees per hectare in

Burkina Faso according to Kessler and Boni (1991). Gijbers *et al.* (1994) found that the density of trees was lower (11 trees per hectare) in the Sahel. Many studies indicated that parkland tree diversity and density are degrading (Gijbers *et al.*, 1994; Boffa, 1999; Kelly *et al.*, 2004; Nikiéma, 2005). Nikiéma (2005) has shown in a Sudan savannah zone of Burkina Faso that parkland degradation was mainly due to the reduction of fallow period.

Three tree species are dominant in parklands of West Africa: *Vitellaria paradoxa*, *Parkia biglobosa* and *Faidherbia albida* (Delile) A. Chev. (Gijbers *et al.*, 1994; Bayala, 2002). According to Nikiéma (2005), *Vitellaria paradoxa* was the most common parkland tree species, accounting for more than 20% of the total number of tree species in the parklands in Sudanian and South-Sahelian ecozones of Burkina Faso. Other common tree species cited by the author are *Adansonia digitata*, *Lannea microcarpa* Engl. & K.Krause, *Sterculia setigera* Delile, *Bombax costatum* Pellegr. & Vuill., *Diospyros mespiliformis* Hochst. ex A. DC., *Acacia seyal* Delile, *Parkia biglobosa* and *Pterocarpus erinaceus* Poir.. Nikiéma (2005) has ranked fruit trees of Burkina Faso parklands, based on published rankings with regard to social and economical value assigned to the species by farmers from different regions of the country. This overall ranking has shown that the three most important species in order of rank are *Vitellaria paradoxa*, *Parkia biglobosa* and *Adansonia digitata*.

Vitellaria paradoxa belongs to the family of Sapotaceae and is encountered within a belt 500-750 km wide and of 500 km length from west to east Africa (Hall *et al.* 1996). The species is commonly called karite in French and shea nut tree in English. The fruit's pulp is eaten fresh and butter is extracted from its kernel which is the main economic product of the tree (Hall *et al.* 1996, Maranz *et al.*, 2003). The butter is used for cooking, cosmetics, medicine and also as a substitute of cocoa butter which is traded on international markets (Boffa *et al.*, 2000).

Parkia biglobosa is commonly called néré in French and locust bean in English (Plate 1.1 b). The species is from the family of Fabaceae, under sub-family of Mimosoidea but its trees do not fix nitrogen (Tomlinson *et al.*, 1998). Néré is large, up to 20 m high, with a wide-spreading crown. It is an important agroforestry tree species in the Sudanian zone and is found from Senegal in the West to Uganda in the East (Sina, 2006).

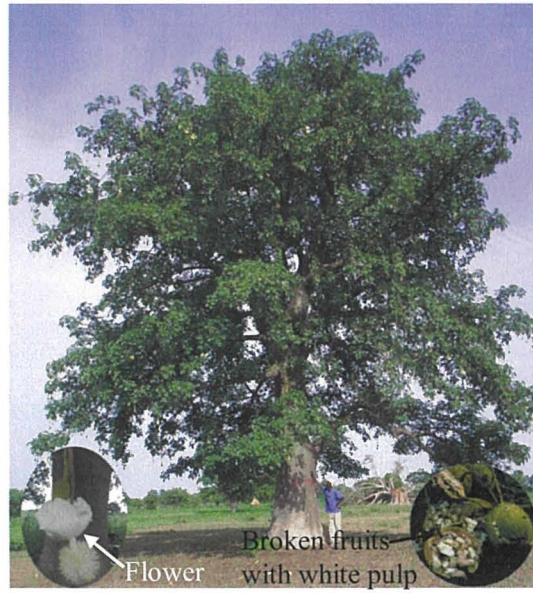
The wood of néré is used as fuelwood and for other purposes such as light constructions. Its bark, branches, leaves, seeds, pulp are used in traditional medicine (Tomlinson *et al.*, 1995;

Hall *et al.*, 1997). The pulp of the fruit is consumed in various culinary forms, as an auxiliary food. The seeds are locally processed as soumbala which is used for seasoning sauces (Hall *et al.*, 1997). The seeds and their processed form (soumbala) are the major commercialised products of *néré* that gives to the species its socio-economical importance in parklands (Teklehaimanot, 2004). The density of the tree varies from 0.8 to 25 ha⁻¹ in parklands of Burkina Faso (Kessler, 1992; Yélémou, 1993, Hall *et al.*, 1997; Sina, 2006).

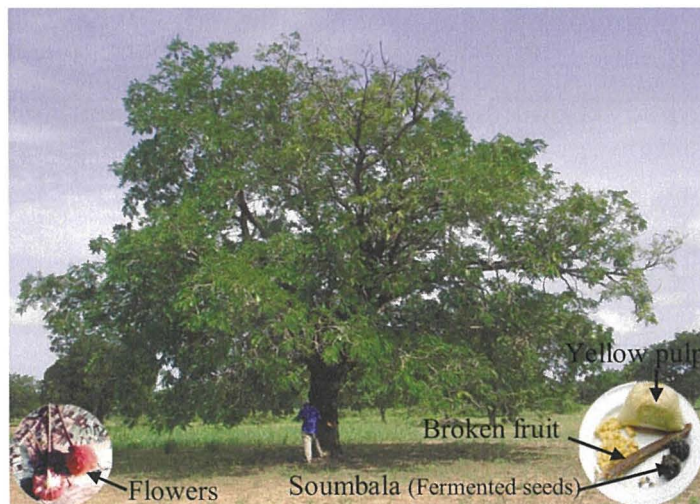
Adansonia digitata, commonly called baobab, is a species that belongs to the family of Bombacaceae (Sidibé and Williams, 2002; Diop *et al.*, 2005). Baobab is a large deciduous tree, which can grow up to 25 m tall (Gebauer *et al.*, 2002), with a large trunk of up to 10 m in diameter, pendular flowers and a rounded crown (Plate 1.1 a) (Diop *et al.*, 2005). The fresh or dried leaves of the tree are sold all year round in markets and used for cooking sauces (Bonkougou *et al.*, 1999). The pulp of the fruits have high content of vitamins B1, B2, B6 and C (Diop *et al.*, 2005), and are consumed as drinks and in various food recipes. The bark is used for rope and basketry and the wood which is of poor burning quality is used as mulch (Boffa, 1999; Sidibé and Williams, 2002). Fruits and leaves were used in local medicines. The tree density is generally very low on parklands due to its big size. For example, in Mali a mean density of 0.43 tree ha⁻¹ was reported by Dhillion and Gustad (2004) while Kyndt *et al.* (2009) estimated to 0.06 tree of baobab per hectare in the sudano-sahelian zone of Burkina Faso.

The present study was based on the later two indigenous trees: *Parkia biglobosa* and *Adansonia digitata* (Plate 1.1 a and b). *Vitellaria paradoxa* was not included in the present study because there were several previous studies and a few ongoing researches on this tree. In addition, *néré* was in particular was included in the present study because there has been reports that showed significant negative impacts of *néré* on associated cereal crops, but no study has so far been conducted on its effect on shade-tolerant crops.

Plate 1.1. Baobab (*Adansonia digitata*) and néré (*Parkia biglobosa*): the two fruit-trees of the study



a. Baobab (*Adansonia digitata*)



b. Néré (*Parkia biglobosa*)

Photographs: SANOU Josias

1.2.2. Traditional cereal crops in parkland agroforestry systems

The major crops associated with trees in agroforestry parklands of semi-arid areas are cereals usually millet and sorghum (Boffa *et al.*, 2000). In addition, maize, cotton, peanut and cowpea are grown on small areas or intercropped with millet and sorghum. In the Sahel zone, millet was the most commonly grown cereal crop.

Millet (*Pennisetum glaucum*) is an annual plant of the Poaceae family taking between 45 to 180 days from sowing to harvest (Plate 1.2 a) (Tostain and Marchais, 1992). The species is an essential cereal crop of dry zones where it is used for preparing various recipes such as Tô (porridge), couscous, cakes, mush and drinks (Clément *et al.*, 1993; Devos *et al.*, 2006). Millet stems are used as building material, fuel and as fodder for livestock (Clément *et al.*, 1993).

Many studies have reported a reduction of cereal crops yields under trees such as *nééré* and *karité* in parklands (Maïga, 1987; Kessler, 1992; Boffa *et al.*, 2000; Bayala *et al.*, 2002; Teklehaimanot, 2004). Compared to an open area, millet yield under *karité* trees were reduced by 35%, 50% and 44% according to Maïga (1987) in Burkina Faso, Kapp (1987) and Kater *et al.* (1992) in Mali, respectively. A reduction of millet yield of 60% under *nééré* trees was reported by Kater *et al.*, (1992). Kessler (1992) found that sorghum yield was reduced by 50% and under the crowns of *karité* and 70% under *nééré* trees. Kater *et al.* (1992) reported a reduction of sorghum yield of 44% and 66%, respectively under *karité* and *nééré* trees. A lower yield reduction (16%) for sorghum under *karité* trees was recorded by Boffa *et al.* (2000). Maize (*Zea mays* L.) production was reduced by 35% and 54% under brush canopies and ball canopies of *karité*, respectively in Burkina Faso (Zomboudré *et al.*, 2005). Not only cereal crops yields are reduced under parkland trees, cotton yield also decreased under *nééré* trees by 65% as reported by Kater *et al.* (1992). Contrary to all the findings above, a study on the influence of *nééré* and *karité* on millet yield conducted during a good rainfall season has shown no difference between the yields under tree crowns and in open areas (Jonsson *et al.*, 1999). The authors concluded that the shade effect on millet was compensated by an improvement in soil fertility and plant temperature under trees.

These contradictory results show that parkland trees can have either negative, positive or neutral effects on associated crops as reported by Sanchez (1995) and Bayala *et al.* (2002).

The main cause of the negative effect of trees on crop growth is light reduction under tree crowns (Rao *et al.*, 1998; Noordwijk *et al.*, 2004). The others factors that negatively affect crop yields in association with trees are competition for soil nutrients and moisture, weeds development, fungal attacks due to high humidity and crop destruction by insects and birds (Kessler, 1992; Soumaré, 1996; Ong *et al.*, 1996; Rao *et al.*, 1998; Boffa, 1999; Bayala *et al.*, 2004). On the other hand, trees can increase soil fertility (Breman and Kessler, 1995; Tomlinson *et al.*, 1995; Young, 1997; Garcia-Barrios and Ong, 2004; Bayala *et al.*, 2006), water availability (Ong *et al.*, 1996; Garcias-Barrios and Ong, 2004; Ong and Swallow, 2003) and plant temperature (Rao *et al.*, 1998; Jonsson *et al.*, 1999).

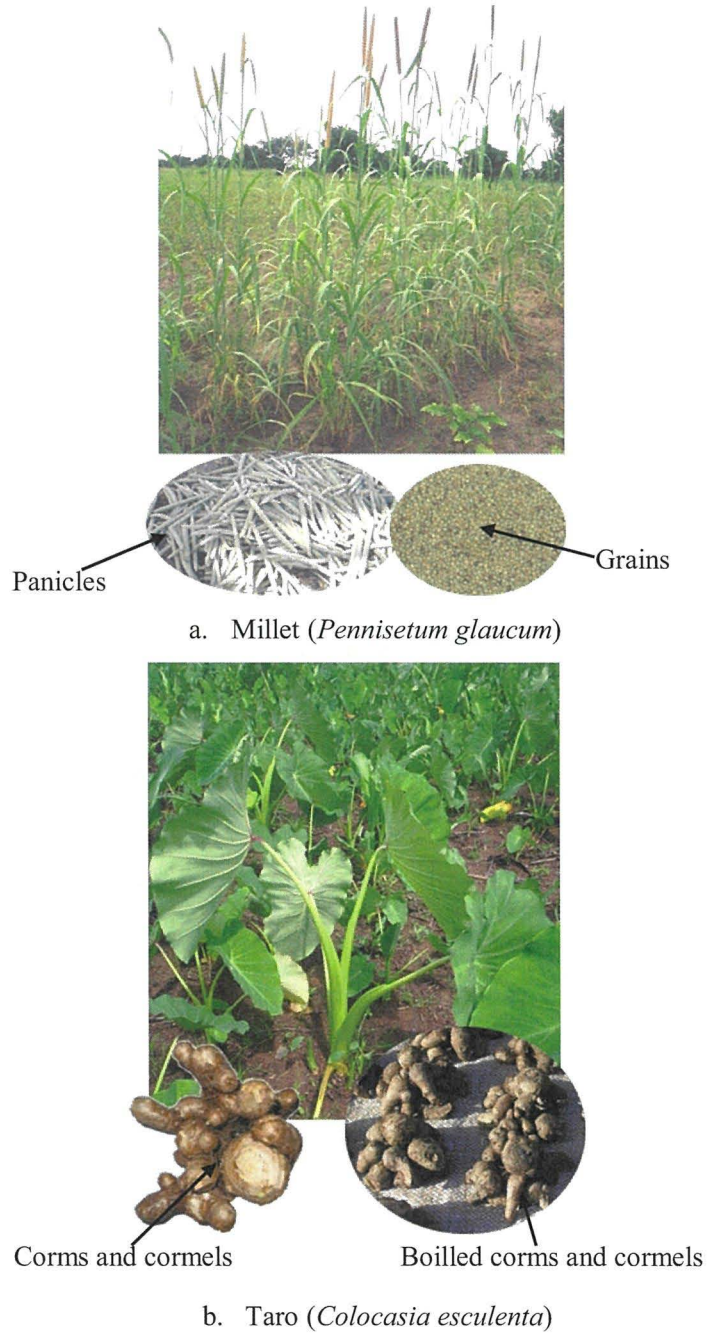
1.2.3. Traditional shade tolerant annual crops in parkland agroforestry systems in Burkina Faso

The major vegetable, root and tuber crops that are commonly grown in the parklands of Burkina Faso include chilli peppers (*Capsicum sp.*), yam (*Dioscorea sp.*), sweet potato (*Ipomoea batatas*), fabirama (*Solenostemon rotundifolius* (Poir.) J. K. Morton), cassava (*Manihot esculenta*), cocoyam (*Xanthosoma sagittifolia*), and taro (*Colocasia esculenta*) (Kessler, 1992).

Colocasia esculenta (L.) Schott (taro) is one of the most common edible species of the Araceae family commonly cultivated by farmers in Burkina Faso (Plate 1.2 b). Taro is a herbaceous plant which grows between 1-2 m height and has a subterranean edible corm surrounded by secondary corms called cormels and four to five peltate leaves (20-50 cm) with long petioles above ground (Onwueme, 1999). The species has a fibrous root system located generally in the top one meter of soil (Onwueme, 1999). It is grown for its corms which are used as an important staple food for people of many tropical countries including Burkina Faso. Various recipes are prepared using taro corms: boiled, roasted, fried or pounded in fufu (Onwueme, 1994). The young leaves are also eaten as potherbs (O'Hair, 1990).

Some findings have shown that taro grows better under shade due to its good physiological functioning in shade condition. For example, Schaffer and O'Hair (1987) reported that CO₂ assimilation rate, transpiration rate and stomatal conductances (for CO₂ and water) were higher for leaves of taro grown in 40% shaded area compared to leaves in full sun.

Plate 1.2. Millet (*Pennisetum glaucum*) and taro (*Colocasia esculenta*): the two crops of the study



The high photosynthesis efficiency of taro in shade condition was due to anatomical and physiological changes that took place in its leaves in response to shade. According to Johnston and Onwueme (1998) taro responded to shading by increasing leaf size and chlorophyll content per unit area of leaf while other root crop species such as yam, cassava and sweet potato did not. Onwueme and Johnston (2000) also reported that taro grown under shade increased its leaf stomatal density in both the upper and lower epidermis. All the above quoted studies were, however, conducted in treeless plots under artificial shade, which is different from field trials in parklands where trees and crops would also compete for growth resources.

1.2.4. Trees effect on the nutritive quality of crops in parkland agroforestry systems

Despite much research examining shade effects on crop growth and yield, the nutritive content of crops in response to shade has not yet investigated in semi-arid areas. Studies exploring shade effect on forage quality in parkland pastures revealed a general increase of protein content in forage grown under shade (see Smith *et al.*, 1984; Lin *et al.*, 2001; Ladyman *et al.*, 2003; Peri *et al.*, 2007). Some studies have demonstrated that the macronutrient contents (such as P, K, Mg, Ca and S) and digestible fibre were not influenced by shade (Ladyman *et al.*, 2003; Norton *et al.*, 1990) while another study reported increases to macronutrients due to shade in forage crops (Peri *et al.*, 2007). Ajithkumar & Jayachandran (2003) reported that shade increased volatile oil and starch content in the rhizome of ginger (*Zingiber officinale* R.) but it decreased fibre content in the plant rhizome.

Because of the reported increase in nutritive contents of forage and ginger in shade condition as a result of the high nutrient content of soils under trees, it is expected that an improvement of nutrient content may also occur in root and vegetative crops under tree shade in parkland systems.

1.3. Summary and objectives

Previous findings on tree-crop interactions in parklands have shown that the presence of trees causes reduction in yield of traditional cereal crops such as millet and sorghum (Kessler, 1992; Boffa, 2000; Bayala *et al.*, 2004). Many authors have mentioned that tree shade is the

major factor responsible for yield reduction in understory crops (Boffa, 1999; Bayala *et al.*, 2002). Some attempts to solve the shading problem by pruning tree crown have given better yield of millet compared to open areas (Bayala *et al.*, 2008). However, total pruning of trees resulted in reduced tree fruit production for at least five years before the trees recovered to their original production level (Bayala *et al.* 2008). Of course, the loss of tree fruit production may be compensated by increased crop production under pruned trees. If, however, farmers decide not to prune trees for various reasons such as the benefit of fruit production, an alternative would be to plant shade tolerant crops beneath tree crowns and shade intolerant crops in areas outside the influence of tree crowns.

Therefore, there is a need for further studies to investigate how shade-tolerant crops such as taro perform in terms of both yield and nutritive value under tree shade in comparison with shade intolerant crops such as millet. Despite its shade tolerance, taro, like most shade tolerant crops, has high demand for water and nutrients (Caesar, 1980; Bussel and Bonin, 1998). Because there are several evidences of higher fertility and water content of soil under trees it is believed that taro could perform better under tree crowns than millet.

The broader aim of the study reported in this thesis was to generate knowledge, which might contribute to the maintenance of relative high tree densities agroforestry parkland systems of Sahel region. The general objective was to determine the suitability of taro (*Colocasia esculenta* (L.) Schott), a shade-tolerant root crop, as an alternative crop to millet (*Penisetum glaucum* (L.) R. Br.), a traditional cereal crop, under tree crown shade in parkland agroforestry systems in Burkina Faso using two fruit tree as models (Baobab (*Adansonia digitata* L.) and néré (*Parkia biglobosa* (Jacq.) R. Br. ex G. Don)). The suitability of millet replacement by taro was assessed through the agronomic performances of both crops and the socio-economic benefits that arise from this management of agroforestry parkland systems.

To contribute to the broader aim, the present study was carried out with the following specific objectives:

1. To assess the effects of Néré (*P. biglobosa*) and Baobab (*A. digitata*) on the growth and yield of associated taro (*C. esculenta*), a shade-tolerant crop and millet (*P. glaucum*), a shade-intolerant crop based on biophysical, agronomic and physiological measurements.
2. To assess the effects of Néré and Baobab on the nutritional quality of associated millet and taro crops based on chemical analyses.
3. To assess the socio-economic significance of combining the production of millet and taro in agroforestry parkland systems.

CHAPTER 2: LITERATURE REVIEW

2.1. Description of parkland agroforestry systems

Parklands are landscapes of cultivated or recently fallowed fields with scattered mature trees (Raison, 1988). The plate 2.1. shows an example of parkland at Nobéré in Burkina Faso. Parkland agroforestry systems are the practices of growing crops and these scattered trees together on the same area and at the same time (Sanchez, 1995). This practice has been used since ancient times by farmers to obtain both products from trees and crops in order to enhance their food security (Brookfield and Padoch, 1994).

The scattered trees in fields were selectively preserved by farmers from the original woodland vegetation (Bonkougou *et al.*, 1993; Rao *et al.*, 1998). Remnant trees within parklands were retained for their various products (fruits, wood and leaves) and services (soil fertility, shade and medicines) but were rarely planted (Gijbers *et al.*, 1994; Rao *et al.*, 1998; Smektala *et al.*, 2005; Yaméogo *et al.*, 2005; Bayala *et al.*, 2006).

Parklands are often dominated by one tree species and this dominant species gives its name to the corresponding parkland (Boffa, 1999). So, the major parklands in the sub-humid zone of West Africa are *Vitellaria paradoxa*, *Parkia biglobosa* and *Faidherbia albida* parklands (Boffa, 1999). In semi-arid areas, parkland names are different due to the different dominant trees such as *Acacia raddiana*, *Acacia senegal*, *Adansonia digitata* and *Balanites aegyptica* parklands (Boffa, 1999). Parklands where trees are retained rather than planted are called selected parklands as opposed to constructed parklands (Bayala, 2002). Trees of constructed parklands are dominated by exotic species such as mango (*Mangifera indica*) and citrus (*Citrus sp*) in sub-humid zones and in dry zones by eucalyptus (*Eucalyptus sp*) and neem (*Azadirachta indica*).

A dominant tree species does not mean that parklands are mono-specific. There is always diversity in the composition of species and in the density of trees (Boffa, 1999). Species composition and tree density of parklands depend on ecological conditions and the preferences of local farmers based on the effects of the trees on associated crops. For example, it has been reported that the shade of *V. paradoxa* and *P. biglobosa* depends mainly on their crown size. *P. biglobosa* trees, due to their larger crown, are less associated with

crops than *V. paradoxa* trees (Kater *et al.*, 1992; Kessler, 1992). So, in Burkina Faso, *V. paradoxa*, due to its high economic value and relatively small crown diameter (mean diameter 10.56 m (Bayala *et al.* 2002)) has a high tree density (9.1 trees ha⁻¹ (Bayala *et al.* (2008))) whereas *P. biglobosa* with equivalent economic value but having large crown size (20.98 m (Bayala *et al.* 2002)) has lower density (1.22 trees ha⁻¹ (Bayala *et al.* 2008)). Densities of *F. albida*, which has positive effect on under-storey crops, are also high (3-45 trees ha⁻¹, Boffa, (1999)) in parklands. *A. digitata*, which is the biggest tree in the region (large trunk (5.92 m circ at breast) and large crown (16.52 m)), has very low densities: 0.8 trees ha⁻¹ (Bayala, 2000) and 0.25 trees ha⁻¹ (Personal observation).

Generally, species composition and tree density of parklands are declining (Gijbers *et al.*, 1994; Boffa, 1999; Kelly *et al.*, 2004; Nikiéma, 2005) due to high population pressure and decline in the length of fallow period. Natural regeneration ordinarily occurs in fallows which are becoming either very short or absent. (Nikiéma, 2005). Over mature parkland trees were often removed by farmers when they become old and non-productive and were increasingly being replaced by cereal crops (millet and sorghum). Dead and felled trees were not being replaced through planting and natural regeneration was limited on farmlands.

Plate 2.1. Panoramic view of a parkland with baobab (*Adansonia digitata*), néré (*Parkia biglobosa*) and karité (*Vitellaria paradoxa*) at Nobéré in Burkina Faso (2007)



Photograph: SANOU Josias

2.2. Tree crop interactions in parkland agroforestry systems

Both trees and crops in parkland agroforestry systems, interact both under-ground and above-ground (Ong, 1996; Ong and Leakey, 1999; Bayala *et al.*, 2002). This interaction influences the performance of each component of the tree-crop association (Nair, 1993). Tree-crop interactions can be positive (complementary), negative or neutral (Sanchez, 1995; Bayala *et al.*, 2002). Tree-crop interactions are a result of all biophysical changes caused by the presence of trees that impact on the performance of the associated crops. The dominant biophysical changes are light reduction, rainwater redistribution and physical and chemical changes of the soil under tree crowns (Ong, 1996; Rao *et al.*, 1998; Noordwijk *et al.*, 2004; Bayala *et al.*, 2006).

2.2.1. The effect of tree crown on light transmission

The main effect of trees on crops is due to light extinction under tree crowns (Rao *et al.*, 1998; Noordwijk *et al.*, 2004). Light that reaches the leaves of crops grown under the crown of an isolated tree is a sum of three components: diffuse radiation, direct lateral radiation and direct vertical radiation transmitted by the leaves of the tree (Knevel, 1993). Out of this total radiation, only 40% is effectively usable for the photosynthesis process by crops (Breman and Kessler, 1995). This fraction is called Photosynthetically Active Radiation (PAR) and involves wavelengths between 400 nm and 700 nm. PAR is generally measured as energy flux density and expressed as incident photon flux density (mol or μmol) on a unit area of plant (m^{-2}) per unit time (s).

PAR availability in the area under tree crown depends on the characteristics of tree species such as phenology, height, crown diameter and leaf density (Breman and Kessler, 1995; Bellow and Nair, 2003). In general PAR transmission increased with an increase in tree height and decreased with an enlargement of crown diameter (Bellow and Nair, 2003). In addition, the shape and structure of the tree crown affected PAR transmission. For example, brush shaped crowns and crowns with many gaps have higher PAR transmission than ball shaped crowns and relatively compact crowns (Bellow and Nair, 2003; Zomboudré *et al.*, 2005).

Many studies have reported light reduction under parkland tree crowns. Belsky *et al.* (1989) found a solar irradiance reduction of 45 to 65% under leafy baobab trees and a reduction by 30 to 40% under leafless baobab trees. Various light reduction measurements for *P. biglobosa* have been reported according to tree mean height and crown diameter. For example, a minimum of 80% PAR reduction for trees of 14 m height was reported by Kessler, (1992), an average PAR reduction of 75% for large trees with crown diameter ranging from 9.5 to 17.1 m by Jonsson (1995) and 62% of PAR reduction for trees of an average height of 15.38 m and an average crown diameter of 20.98 m by Bayala *et al.* (2002). PAR reductions reported in literature for *V. paradoxa* trees were also variable according to tree characteristics such as crown shape and dimensions (Kessler, 1992; Boffa *et al.*, 1999; Jonsson, 1995; Boffa *et al.*, 2000; Bayala *et al.*, 2002).

Light reduction under tree crown has a consequence on the temperature of soil and leaves of understorey crops. According to Rao *et al.* (1998) the temperature of topsoil was lower throughout the cropping season under *P. biglobosa* and *V. paradoxa* trees compared with open areas of a parkland system in Burkina Faso. Such temperature reduction in semi-arid parklands has a positive consequence for many plants grown beneath tree crowns because high temperature was identified as a limiting factor for seedling establishment and plant photosynthesis (Jonsson, 1995; Rao *et al.*, 1998; Boffa, 1999; Bayala, 2002). Another consequence of light extinction under tree crown was the reduction of evapo-transpiration due to temperature decrease in this area below the tree crown (Belsky *et al.*, 1989; Boffa, 1999). This reduction of evapo-transpiration contributes to maintain higher water content in soil under tree compared to the open field.

2.2.2. The effect of tree crown on soil water balance

Water balance in an agroforestry system is the difference between water received and water lost in the rooting zone of both the tree and the crop where the uptake of water and nutrients takes place. Water inputs to the soil are rainfall and hydraulic lift from groundwater whereas the losses are rainfall interception by the tree crown, drainage, run-off, soil evaporation and transpiration by tree and crop (Ong *et al.*, 1996; Ong and Swallow, 2003; Kurz-Besson *et al.*, 2006).

As with light interception, rainfall was also intercepted by tree crowns causing water loss through evaporation before reaching the soil, thus reducing water availability for crops growing under the tree crown compared to those grown in open area (Ong *et al.*, 1996). According to Ong and Swallow (2003), the loss of the annual rainfall due to tree crown interception was between 3 and 10% in semi-arid agroforestry systems. Rainfall interception by tree crowns depends on rainfall intensity. It increases as rainfall intensity decreases (Breman and Kessler, 1995; Boffa, 1999). Breman and Kessler (1995) estimated that for rainfall < 15 mm with low intensity interception loss was higher (up to 50%) than for rainfall > 15 mm with high intensity (between 10-20%). The amount of rainfall intercepted and evaporated also varies according to tree crown structure and environmental factors such as wind speed and temperature (Breman and Kessler, 1995).

Rainfall that is not intercepted reaches the soil under the tree crown by two processes: throughfall and stemflow. The water that reaches the soil surface first infiltrates until the soil becomes saturated and then runoff starts causing water loss for the area under tree. Water infiltration depends on soil properties, the slope of the land and rainfall intensity. Soil properties that affect water infiltration in the soil are surface crusting, surface storage, saturated hydraulic conductivity and presence of vegetation and residual vegetal elements (Ong and Swallow, 2003). It is generally accepted that water infiltration is increased by the presence of trees (Rao *et al.*, 1998; Boffa, 1999). According to Breman and Kessler (1995) the factors by which tree improves soil water infiltration are the presence of old root channels which act as macropores and litter which favour soil fauna activities resulting in soil high porosity. Therefore, for equivalent amount of rainfall received on soil, the rate of water stored under tree crown was higher than the rate in open area (Breman and Kessler, 1995).

In addition, part of the stemflow contributes to the deep soil water stock (Ong and Leakey, 1999; Ong and Swallow, 2003). A part of water stocked in the deep soil could be available to crops when drained into the topsoil. Indeed, Ong and Leakey (1999) report that subsoil water reserves could be returned to the topsoil through hydraulic lift created by tree roots. Howard *et al.* 1997 after excavating 60cm of topsoil around *Grevillea robusta* trees obtained up to 85% of the initial stem flow, proving by trees were able to uptake water from deeper soil horizons. In addition, Kizito *et al.* (2007) found that 45% of shrubs water demand in Senegalese peanut basin was extracted from deep soil and some of this was distributed to crops root layer causing an increase by 20% of the water storage in the topsoil. In summary,

the water stock in topsoil may be greater under tree crown than in the topsoil of the treeless area, if the losses due to soil evaporation under tree crown and tree and crop transpiration do not exceed those in open area.

It has been shown in many publications that there is lower plant transpiration and lower soil evaporation in crops grown under tree crowns compared to those grown in treeless zone (Belsky *et al.*, 1989; Rao *et al.*, 1998; Boffa, 1999; Ong and Swallow, 2003). This reduction of evapotranspiration in the area beneath tree results from a decrease in wind speed and temperature due to tree crown shade (Boffa, 1999; Ong and Swallow, 2003). According to Ong and Swallow (2003) soil evaporation could be reduced up to 30% due to the presence of tree crown compared to a treeless area. In Burkina Faso, Jonsson (1995) found that evaporation was 22% lower under *P. biglobosa* and *V. paradoxa* trees compared to the open. The reduction of water lost through evaporation compensated rainfall interception by the tree crown for low annual rainfalls less than 700 mm but the compensation was dependent on rainfall intensity and soil physical properties.

Like soil evaporation, the transpiration of crops grown under tree crowns was lower compared to the same crop transpiration in open area (Rao *et al.*, 1998; Ong and Swallow, 2003). The low transpiration rates of crops underneath trees were due to decreases in temperature and decreases in solar radiation which are a result of increased tree shade (Boffa, 1999). In the Sahel region, the low transpiration rates underneath trees could be advantageous to crop growth especially C3 plants which generally become light saturated in treeless areas (Ong and Swallow, 2003).

The decrease in crop water use contributes to increased soil moisture content under the tree crown, but if tree transpiration is taken into account, the water loss due to transpiration could be higher compared to an area without trees (Radersma and Ong, 2003). The values of transpired water varied from one year to another depending on the amount of rainfall and PAR received (Bayala, 2002). The author showed that in a high rainfall year with lower PAR, transpiration was low (146 l h^{-1} and 18 l h^{-1} for *P. biglobosa* and *V. paradoxa* trees, respectively) compared to a low rainfall year and higher amount of PAR received (79 l h^{-1} and 9 l h^{-1} for *P. biglobosa* and *V. paradoxa* trees, respectively). In the Sahel region, such amounts of water loss could be expected to drastically reduce crop growth under trees if all the water transpired is taken from topsoil where crop and trees interact. However, many

studies reported that water use efficiency (i.e. biomass of crop produced per unit of water used) beneath trees was higher than that observed in an open area (Ong and Swallow, 2003).

This higher productivity was due to the fact that trees meet part of their water demand from subsoil and also due to the higher soil moisture content under tree crown. Kizito *et al.* (2006) found in Senegal that the water volumetric content of soil decreased from the base of shrub trunk to 2 m distance and that the roots of pearl millet were found in topsoil (0.2 to 0.5 m) whereas shrubs roots were found deeper (0.9 to 1.2 m). Therefore, water balance of soil in tree and crop association depends greatly on whether there was an overlap in the fundamental niches of the component species. In an optimal association where trees and crops do not compete for water niche differentiation occurs resulting in higher crop production (Ong *et al.*).

2.2.3. The effect of tree shade on weeds composition and biomass

The microclimate created under tree crowns could be favourable for some weeds. According to Libert and Eyog-Matig (1996) the effect of *Faidherbia albida* tree shade is associated with lower weeds diversity and a significantly lower density of the plant parasite *Striga hermontica* compared to open areas. Similar observation was made by Gworgwor (2007) in Nigeria where the author found none emergence of *S. hermontica* under *F. albida* trees whereas the parasite was causing up to 17.13% reduction of millet panicle yield in open area. Boffa (1999) suggested that the lack of radiation under trees selectively suppresses plants, which have high demand for light for their development. As an example the author described a study by Sabiiti and Cobbina (1992) which showed that more palatable and shade tolerant weeds (*Panicum maximum* and *Brachiaria* spp) were found under *P. biglobosa* crown than in open areas where the weeds species consisted of mainly *Andropogon* and *Imperata* spp.. Breman and Kessler (1995) reported that in the Sahel region, C3 grass species are more frequent under the shade of individual trees than in open area even though C4 grass species are dominant in the region. The authors explained this dominance of C3 grasses under tree by the low temperature and shade unfavourable to C4 plants growth under trees crown.

In addition to its effects on weeds composition, tree crowns also influence the phenology of weeds as reported in the literature (Boffa, 1999). Libert and Eyog-Matig (1996) reported an early growth of weeds under *F. albida* tree crown compared to open areas in accordance with

the general observation made by Breman and Kessler (1995) on grass species in African savannahs. This early growth of weeds under tree crowns may be a disadvantage to farmers because of the high labour demand of weeding.

Rao *et al.* (1998) have summarized the effects of tree crowns on weeds as a reduction in density, a change in species composition and a decrease in both perennial rhizomes and the annual seed bank. These effects are favourable for crop growth under trees. Many workers have also reported a higher biomass production of weeds underneath of trees compared to open areas (Breman and Kessler, 1995; Boffa, 1999). In the sahelian zone of Ferlo (Senegal), Grouzis and Akpo (1997) noted a higher amount of above ground and root biomass of grasses (1.5 to 4 times and 2 times, respectively) than under full sunlight. Higher growth of weeds under *P. biglobosa* and *V. paradoxa* tree crowns compared to open areas was also noted by Kessler (1992) in a farmed parkland of Burkina Faso. According to Kessler (1992), the effects of parkland trees on weeds ecology may be one of the major limitations to the cultivation of shade tolerant plants at large scales by farmers farming in parklands.

2.2.4. The effect of tree shade on soil characteristics

The major positive biophysical effect of trees in parklands was soil fertility improvement. This was well understood by local farmers (Bayala *et al.*, 2006). The improvement of soil physical and chemical properties was the result of litterfall from trees in addition to animal and bird excreta (associated with the tree cover) which increased soil organic matter under tree crowns and reduced erosion due to soil stabilisation by tree roots and litter cover of soil (Breman and Kessler, 1995; Soumaré, 1996; Young, 1997; Garcia-Barrios and Ong, 2004).

It has been proven that due to both the higher organic matter and moisture content of soil, the population of both macro-fauna and micro-fauna was higher under trees compared to the open (Rhoades, 1997; Buresh and Tian, 1998; Boffa, 1999). Munoz *et al.* (2007) found in a semiarid zone that microbial biomass carbon was higher under trees (357-1105 mg kg⁻¹) compared to the outside (277-366 mg kg⁻¹) and that soil respiration was higher under trees than outside due to greater microbial activities. As a result of macro-fauna and micro-organism activities, more macroporosity and lower bulk density were found in soils under trees (Rhoades, 1997; Munoz *et al.*, 2007). This allowed better aeration and water infiltration compared to open areas. Soil texture was also affected by the presence of trees. Increased

activities of termites and deposition of windborne soil particles under trees result in finer soil texture under tree crowns than in the open (Mando and Miedema, 1997; Boffa, 1999).

The decomposition of organic matter by soil macro- and micro-fauna contributes to increased nutrient contents under trees (Buresh and Tian, 1998; Boffa, 1999; Brussaard *et al.*, 2007). In addition, trees also capture airborne nutrients which are deposited on leaves and released under trees (Tomlinson *et al.*, 1995; Rhoades, 1997; Boffa, 1999). Trees are also capable of taking up nutrients from deeper soils and releasing them on surface soils through fine root and leaf litter decomposition (Rao *et al.* 1998). In conclusion, the concentration of nutrients derived from various sources was higher under trees crown compared to open areas in the Sahel region (Kater *et al.*, 1992; Kessler, 1992; Tomlinson *et al.*, 1998; Bayala 2002).

2.2.5. The effect of tree shade on associated crop production

As reported above, tree shade reduces PAR and temperature which have an impact on the morphology, anatomy and physiology of crops grown beneath tree crowns. The morphological changes attributed to shade effect on crops were mainly observed in leaf size and stem height which vary from one species to another depending to its capacity to tolerate light reduction (Wong, 1991). Accordingly, Wilson *et al.* (1998) observed that the leaf area ratio and the specific leaf area of sorghum were higher under *nééré* trees than those in full sunlight. In addition, Caesar (1980) showed that *Xanthosoma sagittifolium* responded to shade in well-watered condition by increasing its petiole length and leaf blade size. In Peru, Midmore *et al.* (1988) noted an increase in potato (*Solanum spp*) plant height and a decrease in branching in shade condition compared to its performance in full sunlight. Lin *et al.* (2001) showed that leaf area and internodes length were increased while specific leaf dry weight was decreased under shade compared to the area in full sunlight for fifteen legume and grass species. According to Wong (1991) shade reduced tiller production but improved specific leaf area and leaf:stem ratio in shade tolerant forage grasses. These morphological changes in leaf are related to anatomical adaptation to shade condition in some shade tolerant plants. Leaves in shaded areas have thinner palisade and spongy mesophyll that result in a thinner total lamina (Wong, 1991). In addition, an increase in chlorophyll content per unit area and stomatal density of leaf was observed in shade tolerant plants such as *Colocassia esculenta* (Johnston and Onwueme, 1998; Onwueme and Johnston, 2000).

Physiological responses of crops in shade condition also vary from one species to another. Reduced light and temperature and increased air humidity under tree crowns affect plant photosynthetic parameters. Schaffer and O'Hair (1987) reported that CO₂ assimilation rate (5.3 $\mu\text{mol CO}_2 \text{s}^{-1}\text{m}^{-2}$), transpiration rate (7.8 $\text{mmol CO}_2 \text{s}^{-1}\text{m}^{-2}$) and stomatal conductances for CO₂ (339.0 $\text{mmol CO}_2 \text{s}^{-1}\text{m}^{-2}$) and water (491.0 $\text{mmol CO}_2 \text{s}^{-1}\text{m}^{-2}$) were higher for taro plants in 40% shaded area compared to the figures recorded in full sunlight (4.1 $\mu\text{mol CO}_2 \text{s}^{-1}\text{m}^{-2}$, 5.3 $\text{mmol CO}_2 \text{s}^{-1}\text{m}^{-2}$, 197.0 $\text{mmol CO}_2 \text{s}^{-1}\text{m}^{-2}$ and (286.0 $\text{mmol CO}_2 \text{s}^{-1}\text{m}^{-2}$, respectively). In contrast, Zomboubré *et al.* (2005) found that maize photosynthetic rate was lower on 40, 50 and 60 days after sowing (DAS) under karité tree shade (16.71, 6.81 and 3.34 $\mu\text{mol m}^{-2} \text{s}^{-1}$, respectively) compared to open areas (28.06, 14.44 and 8.70 $\mu\text{mol m}^{-2} \text{s}^{-1}$, respectively).

These two different results illustrate the difference in photosynthetic behaviour between a C3 shade tolerant plant (taro) and a C4 plant (maize) sensitive to light reduction. The efficient CO₂ assimilation rate in plants with C3 photosynthetic pathway in shaded environment could be explained by three major factors. Firstly, in order to perform additional carboxylation steps in photosynthesis and intercellular transport of intermediate metabolites, C4 plants require more light energy than C3 plants. Secondly, since C3 plants have light saturation under high radiation, the photosynthetic process improved when radiation was reduced. Finally, the quantum efficiency of C3 plants is higher at low temperatures (under 15-16°C) compared to C4 plants (Hay & Porter, 2006; Osborne *et al.*, 2008).

Kater *et al.* (1992) observed that the stalk of millet and sorghum plants was longer in the open area than those in the shaded area under karité trees, but under néré trees millet plants showed a reverse trend (i.e. longer stalk under trees). Similar result was observed by Wilson *et al.* (1998) on sorghum grown under néré trees; sorghum plants were shorter under trees compared to plants in open area. Zomboubré *et al.* (2005) found that height and number of leaves of maize were lower under karité trees compared to open areas. They also observed that number of leaves of maize was reduced by heavy shade under karité trees with ball shaped crown compared to trees with brush shaped crown. Boffa *et al.* (2000) noted that sorghum plants in a zone of 2 m around trees were shorter than plants in zones further than 2 m from the trunk. Bakhom *et al.* (2001) observed a similar growth trend of millet and sorghum under *Sterculia setigera* trees where plant height increased with distance from the trunk.

Because of the difference in growth rate between plants in shaded area and in full sunlight,

crop yield was also affected depending how tolerant the species was to shade. Many studies reported a decrease in cereal crop yield under tree crowns compared with crops in the open (Maiga, 1987; Kessler, 1992; Boffa *et al.*, 2000; Bayala *et al.*, 2002). However, a study of the influence of *néré* and *karité* trees on millet yield conducted during a good rainfall season has shown no difference of yield under tree crowns compared to open areas (Jonsson *et al.*, 1999). These contradictory results suggest that shading was not the only limiting factor for millet growth under tree crowns. Root competition between trees and crop for water and nutrients was also implied as shown by Bayala *et al.* (2002).

Caesar (1980) showed that taro corm yield was reduced by 20% under shade and water stress condition compared to the yield in an area under full sunlight where water supply was optimal. The author concluded that light and water availability was probably of equal importance for taro corm development and yield. In contrast, Rogers and Iosepha (1993) reported that the best quality of taro corms was obtained in shade condition without mulch. Miyasaka *et al.* (2003) also found that low temperature combined with low solar radiation did not affect taro corm yield. It appears that these contradictory results of taro performance under shade could be due to other environmental factors such as nutrient availability and also probably due to different varieties of taro used in these experiments.

In summary, shade has a negative effect on plant growth but this impact seems to be less on C3 crops than in C4 crops. Shade effect was also accentuated by adverse environmental conditions such as the lack of water and nutrients. Water and nutrients availability combined with root competition between trees and crops should determine the choice between common cereal crops and shade tolerant crops in areas influenced by parklands trees.

2.2.6. The effect of tree shade on the nutritive composition of associated crops

Although several studies have been carried out on the effect of shade on crop growth and yield, there was a lack of information on crops' nutritional content in relation to shade. Although there are few studies, they are mostly related to forage species quality of parkland pastures. These previous studies have shown a general increase in protein content in forage species grown under shade (Smith *et al.*, 1984; Lin *et al.*, 2001; Ladyman *et al.*, 2003; Peri *et al.*, 2007). According to Smith *et al.* (1984), nitrogen content in the cells of pearl millet was greater (1.53%) for 75% shaded condition than the value found in plants in full sunlight

(0.60%). The positive effect of shade on protein content in forage species varies with species as shown by Lin *et al.* (2001) in their study of fifteen grass and legume species. They found that shade effect was less important in legumes than grasses grown under 50% and 80% artificial shades.

Shade effect on the content of other macro-nutrients in forage species reported in literature was contradictory. According to Ladyman *et al.* (2003), there was no change in the content of neutral and acid detergent fibres in grasses grown under shade compared to those in full sunlight. Ajithkumar & Jayachandran (2003) studied the influence of shade on growth and yield of ginger. The authors noted an increase of volatile oil and starch content in the rhizomes of ginger with an increase of shade while in contrast, an increase in shade resulted in a decrease of fibre content in the crop.

In a temperate pasture, Peri *et al.* (2007) found that when photosynthetic photon flux density (PPFD) level decreased from 100% to 24%, the contents of macro-nutrients (P, K, Mg Ca and S) in *Dactylis glomerata* leaves increased but organic matter digestibility was little affected. Accordingly, Norton *et al.* (1990) showed that shade had no significant effect on the chemical composition of leaf and cell walls. In contrast of the results above, Johnson *et al.* (2002) found that the nutritive values of *Arachis glabrata* (leaf and stem) decreased by shading compared to open areas.

The major reason for high nutrient content of plants under shade was attributed to the high nutrient content of soil under trees (Lin *et al.* 2001, Peri *et al.*, 2007). The higher nitrogen content of grasses grown in shade condition could also be due to a decrease in photosynthesis that increases nitrogen concentration in plants cells (Peri *et al.*, 2007). These results of shade effect on nutrient content observed in forage species could also apply to crop species. Thus, it was expected that the protein content of the vegetative parts of crop plants may be higher under parkland trees than those grown in full sunlight although an increase in nutrient content in vegetative parts does not necessary imply a similar increase in reproductive organs such as grains or tubers.

2.3. Differential responses of C3 and C4 plants to shade and to water and nutrients availability

The number of CO₂ molecules attached to the first organic molecule generated by the primary carbon fixation process determines the type of photosynthesis pathway. Plants with a single chloroplast type that converts light energy into chemical energy used to fix CO₂ on ribulose-1, 5-bisphosphate (RuBP) to generate a three carbon compound 3-phosphoglycerate are called plants of C3 pathway of photosynthesis. The enzyme ribulose-1, 5-bisphosphate carboxylase-oxygenase (rubisco) that catalyzes this primary carbon fixation also catalyze another process called photorespiration. Photorespiration is where O₂ competes with CO₂ in reactions with rubisco, resulting in the wasteful fixation of O₂ to produce 3-phosphoglycolate and 3-phosphoglycerate. 3-phosphoglycolate must be recycled to phosphoglycerate to be used in the photosynthetic carbon reduction cycle (PCR). Therefore, the photorespiration process requires more energy to convert 3-phosphoglycolate to phosphoglycerate, so reduces the efficiency of the C3 pathway of photosynthesis. Photorespiration occurs at a higher rate at high levels of solar radiation and at higher air temperatures, such as are prevalent in savannah climates.

This photorespiration process is mostly suppressed in plants with the C4 pathway of photosynthesis. These plants have two types of chloroplast and their leaves possess the Kranz anatomy: an outer ring of mesophyll cells surrounding a ring of bundle sheath cells around a vein. Mesophyll cells without Rubisco fix CO₂ using phosphoenolpyruvate carboxylase enzyme to produce the four-carbon dicarboxylic acid oxaloacetate compound. This acid compound is converted into malate or aspartate with regard to plant species. When these acids diffuse into inner ring cells, they are decarboxylated to increase CO₂ concentration at this site of Rubisco. Then, CO₂ is fixed by Rubisco. By this complex adaptation, plants of C4 pathway reduce or avoid the photorespiration process by excluding O₂ from the inner ring of bundle sheath cells.

2.3.1. Differential responses of C3 and C4 plants to shade

The competition between CO₂ and O₂ fixation in the C3 pathway of photosynthesis combined with the energy cost to convert 3-phosphoglycolate to phosphoglycerate result in a lower rate of net photosynthesis compared to C4 pathway of photosynthesis. Consequently, C4 plants are expected to have higher quantum yield compared to C3 plant in similar conditions. Then,

C4 plants may have higher light use efficiency under shade condition compared to C3 pathway plants. However, under shade condition C3 plants adapt their leaves morphology and anatomy as describe in section 2.2.5 to harvest more light energy compared to C4 plants. Therefore, the net photosynthesis of C3 plants is less reduced under shade condition compared to C4 plants. In addition, light saturation point (point at which increase in light does not result in increase in photosynthesis) is higher for C4 plants than C3 plants and high temperatures reduce photosynthesis in C3 plants in contrast of C4 plants (Hay & Porter, 2006; Osborne *et al.*, 2008). Consequently, photosynthesis in C3 plants may perform better under tree shade where temperature is reduced compared to the open field of Sahel region with temperatures up to 30-40°C. Yang *et al.* (2004) in arid and semi-arid area in China using *Phaseolus radiatus* L. and *Setaria italica* (L.) Beauv. demonstrated these differential response in light saturation and high temperature between C3 and C4 plants. Indeed, the authors showed that *S. italica*, a C4 plant, had high capacity to control or regulate the reduction state of the primary electron acceptor of PSII in contrast of *P. radiatus*, a C3 plant. Hence, the C4 plant dissipates the excessive energy due to intense irradiance and high ambient temperature and maintains a high net photosynthesis rate.

In summary, because of high irradiance and high temperature in Sahel region, C3 pathway plants should have better photosynthesis performance under tree shade compared to the open field. In contrast, a better photosynthesis performance of C4 pathway plants should be expected in the open field.

2.3.2. Differential responses of C3 and C4 plants to water stress

According to Pearcy & Ehleringer (1984) the carbon concentrating mechanism of C4 pathway plants allows maximal rates of net photosynthesis at lower stomatal conductance than C3 pathway plants. By this mechanism C4 plants reduce their evapotranspiration and conserve water in hot conditions such as in Sahel region. Accordingly, Feldhake & Boyer (1986) observed that grasses of C4 pathway had a higher resistance to water loss compared to C3 type grasses. In addition, Feldhake & Boyer (1986) noted that forages with the C4 pathway had 30% lower evapotranspiration at 13°C soil temperature compared to those of C3 pathway and the difference of evapotranspiration between the two photosynthesis pathway decreased to 10% at 29°C soil temperature. Consequently, C4 pathway plants have higher generally a

higher Water Use Efficiency (WUE) compared to C3 plants when placed in the same environmental conditions (Ripley *et al.*, 2007). However, C4 plants lose the advantage of their higher photosynthesis rate over C3 plants under severe drought condition because of a higher metabolism limitation of C4 plants under such conditions (Ripley *et al.*, 2007). According to Ghannoum (2009) the decline of photosynthesis of plants under water is due to stomatal and non-stomatal factors. The reduction of stomatal conductance with the decline in leaf water status results in a decrease of photosynthesis rate. Essentially, the non-stomatal factors are a reduction of photosynthetic enzyme activity, an inhibition of nitrate assimilation, an induction of early senescence and changes to the leaf anatomy and ultrastructure. Ghannoum (2009) suggested after a review of the subject that the limited capacity for photorespiration or the Mehler reaction to act as significant alternative electron sinks under drought condition in C4 pathway plants could explain why C4 plants are similarly or more sensitive to water stress compared to C3 pathway plants despite their higher WUE.

2.3.3. Differential responses of C3 and C4 plants to nutrients stress

Previous work showed that the response of plants to nutrients stress differs according to the pathway of photosynthesis (Smith *et al.*, 1984; Sage & Pearcy, 1987; Halsted & Lynch, 1996; Abraham *et al.*, 2007; Ripley *et al.*, 2008). Halsted & Lynch (1996) observed a greater reduced total biomass production of C3 plants than C4 plants under phosphorus (P) stress. However, the authors showed that plants of the two pathways photosynthesis (C3 and C4) had similar photosynthetic P use efficiency.

In contrast, several workers observed a higher photosynthetic N use efficiency (PNUE) of C4 plant compared to C3 plants (Sage & Pearcy, 1987; Abraham *et al.*, 2007; Ripley *et al.*, 2008). Ripley *et al.* (2008) showed that the higher PNUE in the C4 than C3 subspecies was linked with greater investment in sexual reproduction and storage that gives to C4 plants an advantage over C3 plants in disturbed and infertile ecosystems. The last authors explained the lower N demand of C4 plants by their CO₂ concentrating mechanism that reduce or avoid photorespiration. Therefore, C3 plants must invest more in Rubisco because of the photorespiration and then increase their demand of N. The difference between the C3 and C4 photosynthetic N-use efficiency (PNUE) increase at high temperatures due to the decrease of Rubisco specificity for CO₂ with increasing temperature (Ripley *et al.*, 2008).

According to Smith *et al.* (1984), a higher concentration of iron in nutrient solution is necessary for the maximum growth of C4 plants compared to C3 plants because of a different ability of root of the two plant types to absorb iron. However, the authors noted a higher concentration in the leaves of C3 plants compared to the counterpart in leaves of C4 plants. Then, C4 plants are likely more sensitive to iron stress than C3 plants.

Apart from these general differential responses of C3 and C4 plants to nutrient stresses, millet and taro have different nutrients demand. Generally, the nutrients demand of taro plants as given in previous works is rather higher than millet, and even between cultivars. Goenaga & Chardon (1995) demonstrated differential nutrients uptake of two cultivars of taro (“Blanca” and “Lila”). The maximum nutrients uptake were 208 kg ha⁻¹ N, 70 kg ha⁻¹ P, 376 kg ha⁻¹ K, 106 kg ha⁻¹ Ca, 24 kg ha⁻¹ Mg and 0.88 kg ha⁻¹ Zn for the cultivar “Blanca”. Except for Mg, the values recorded for the cultivar “Lila” were lower compared to the cultivar “Blanca”: 154 kg ha⁻¹ N, 48 kg ha⁻¹ P, 254 kg ha⁻¹ K, 62 kg ha⁻¹ Ca, 25 kg ha⁻¹ Mg and 0.71 kg ha⁻¹ Zn.

Kay (1987) also noted a high demand for potassium (K) and for calcium (Ca) in taro plants. The author recommended a complete formulation such as 12:6:20 NPK when taro is grown on poor soils. However, Onwueme (1999) observed a widely variation of inorganic fertiliser type and quantities applied according to countries such as 13:13:21 at 400 kg ha⁻¹ in Fiji and only 200 kg N ha⁻¹ in the form of urea in Papua New Guinea.

In contrast, millet is known as a crop with low nutrients requirement that grows well on poor soils and in low rainfall conditions (Maman *et al.*, 1999; Payne, 2000). Indeed, Roy *et al.* (1980) estimated the nutrients removal from soil to be 26.6 kg N ha⁻¹, 9.4 kg P ha⁻¹ and 32.6 kg K ha⁻¹ for a millet grain yield of 1000 kg ha⁻¹, nearly the average yield in Burkina Faso. For millet grain production between 100-500 kg ha⁻¹, Krogh (1997) estimated demand for nitrogen, phosphorus in sandy soil was 3-23 kg N ha⁻¹ and 0.11-1.04 kg P ha⁻¹, and in loamy/clayey soil, it was 6-36 kg N ha⁻¹ and 0.30-1.23 kg P ha⁻¹ in the northern zone of Burkina Faso.

With regard to the two crops nutrients demand and the general low soil fertility in Sahel region, the production taro in the open field may be more limited than millet. However, taro could perform better under trees where higher soil fertility is expected compared to the open field.

CHAPTER 3: THE EFFECT OF *PARKIA BIGLOBOSA* (NÉRÉ) AND *ADANSONIA DIGITATA* (BAOBAB) ON THE PERFORMANCE OF AN ASSOCIATED SHADE- TOLERANT AND SHADE-INTOLERANT CROP

3.1. Introduction

In parkland agroforestry systems, trees and crops interact with one another in the process of capturing resources from the environment that are required for growth and development (Sanchez, 1995; Ong, 1996; Ong and Leakey, 1999; Bayala *et al.*, 2002). The interaction between trees and crops can be complementary, neutral or competitive for both underground and aboveground resources (Sanchez, 1995; Bayala 2002). Trees have been reported to affect light and rainwater distribution as well as soil physical and chemical properties under their crowns (Ong, 1996; Rao *et al.*, 1998; Bayala, 2006). Several previous studies demonstrated that tree shade was the major factor causing a decrease in the yield of associated crops such as millet (Maiga, 1987; Kessler, 1992; Boffa *et al.*, 2000; Bayala *et al.*, 2002). However, Jonsson *et al.* (1999) also reported a positive effect of tree shade on millet yield due to the increase in soil water availability and the reduction in temperature under shade.

Light reduction by trees in parkland systems as reported by Belsky (1989), Kessler (1992), Boffa *et al.* (2000) and Bayala *et al.* (2002) have been reported to result in a reduction in temperature under tree crowns (Rao *et al.*, 1998; Boffa, 1999 and Garcias-Barríos and Ong, 2004). Because of the temperature reduction, evapo-transpiration under tree crowns was reduced compared to the open field (Belsky *et al.* ,1989; and Boffa, 1999). Despite higher rainwater interception under trees (Breman and Kessler,1995); Boffa, 1999 and Ong and Swallow 2004), several workers reported higher soil water availability under tree crowns due to the reduced evapo-transpiration rate (Ong *et al.*, 1996; Garcias-Barríos and Ong, 2004; Ong and Swallow, 2003). However, trees and crops compete for this available soil water if their rooting systems occupy the same niche.

Trees and crops also compete for soil nutrients although higher soil nutrient content under tree crowns compared to the open field have been reported (Breman and Kessler, 1995; Young, 1997; Boffa, 1999; Bayala *et al.* 2006). The high soil nutrient and water availability underneath trees provides a favourable condition for crop growth. However, the performance of any crop under tree crowns depends on its ability to compete with trees for soil water and nutrients and its photosynthetic efficiency under reduced light condition beneath tree crowns.

Thus, the favourable microclimate and the edaphic conditions created under tree shade may favour shade-tolerant crops such as taro more than shade intolerant crops such as millet. However, different results of shade effect on taro performance were reported in previous studies. Caesar (1980) found a reduction of taro corm yield as a result of a combination of shade and water stress effects. In contrast, Miyasaka *et al.* (2003) observed that low temperature and low light availability did not significantly affect taro corm yield. In addition, Rogers and Iosepha (1993) obtained best quality of corms (corm percentage dry matter) and highest total plant biomass (dry weight) of taro under shade condition. However, no studies comparing the effect of parkland trees on shade tolerant crops such as taro and shade intolerant crops such as millet have been carried out.

Therefore, the present research was conducted to assess the effects of *néré* (*Parkia biglobosa*) and baobab (*Adansonia digitata*) on the performance of associated millet (*Pennisetum glaucum*), a shade intolerant crop, and taro (*Colocasia esculenta*), a shade tolerant crop, in a parkland agroforestry system based on agronomic and physiological measurements. The two tree species were chosen because they are the dominant and highly valued trees of parklands in West Africa.

The hypotheses tested were:

- 1) Trees have no effect on the performance of taro and millet.
- 2) There is no relationship between the photosynthetic performance of the two crops and their growth performance under trees

3.2. Materials and methods

3.2.1. The study area

The study was carried out in parklands located 6 km from Nobéré village, a village located at 11°30' North and 00°58' West in the South-Central region of Burkina Faso (fig 3.1). Nobéré is about 100 km south of Ouagadougou and 40 km north of Pô. The village, with 4000 inhabitants, is in the department of Zoundwéogo province. The local climate is a soudanian type with a rainy season of 4-5 months (Nikiéma, 2005). The 30 year average rainfall calculated from data for 1971 to 2000 is between 800-900 mm (Ouedraogo *et al.*, 2006). The rainy season runs from May to September with a mean annual temperature of around 30°C. According to official report by the Ministère de l'économie et du Développement du Burkina Faso (2005), the highest temperatures are from March to April (38°C) and the lowest from December to February (20°C).

The rainfall in 2006 was 843.4 mm (from 38 rainy days) which was within the normal range of the region's rainfall (800-900 mm, Ouedraogo *et al.*, 2006) (fig. 3.2). In 2007 and 2008, however, the annual rainfall was 46.1 mm and 223.3 mm higher than the normal maximum for the region, respectively. There were 56 and 59 rainy days on 2007 and 2008, respectively. The high rainfall of 2007 was not evenly distributed compared to the rainfall of 2006. About half of the annual rainfall was recorded only in august (412 mm). Therefore, there was water shortage just before the crop harvests in October 2007. In contrast to 2007, the rainfall of 2008 was high and well distributed on the cropping season.

The main activities of the inhabitants are crop production and rearing of livestock. The major crops grown in parklands around the village are millet, sorghum, maize, cotton, peanut and cowpea. In addition farmers produced taro, sweet potato and vegetables such as eggplants, chilli pepper, tomato and okra as cash crops. Cash crop production was located around a dam and also during the beginning of rainy season in fields close to their homesteads. Livestock in the area consisted of cattle, sheep, goats and donkeys. The autochthones (Mossi) have a small number of livestock while the large herds belong to Fulani. In both cases, the animals graze in the parklands.

The area of the site was around 100 ha and the most frequent tree species were fruit trees:

Adansonia digitata, *Lannea microcarpa*, *Parkia biglobosa* and *Vitellaria paradoxa*. Trees densities per species on the parkland were 0.25 trees ha⁻¹ for *A. digitata* (Baobab), 1.18 ha⁻¹ for *L. microcarpa*, 1.81 ha⁻¹ for *P. biglobosa* (Néré) and 9.76 ha⁻¹ for *V. paradoxa* (Karité). The collective tree density for all species was 13.58 ha⁻¹.

The landscape of the site is characterised by a flat plateau with a slight slope oriented from the south to the north. The soil is a luvisol with a sandy loam texture (clay = 11.5%, silt = 20.1% and sand = 68.4%) with low nutrient content (N = 0.69 g/kg, P = 0.14 g/kg and K = 0.50 g/kg) and low organic matter content (1.32%) in the uppermost 10 cm of soil. The National Park named Kaboré Tambi borders the study area on its south size. The site consists of fields and fallows of 2 to 5 years old used as pastureland on the cropping season (Nikiéma, 2005). Animal husbandry (cattle, sheep and goats) relies on field crop residues during the dry season. In addition to farmers' livestock estimated to be an average of four cattle, five goats, four sheep and one donkey per household (Osman, 2008), large herds owned by Fulani use the site as a pastureland after harvests until the next sowings.

3.2.2. Tree phenology

Trees phenology mainly determines their effect on light interception because trees that lose their leaves during cropping season such as *Faidherbia albida* have low or no shade effect on under grown crops. The two studied species (baobab and néré) have different phenology especially with regard to their leafy period.

On the studied parkland, new leaves appear on baobab and néré by the end of April and all trees of both species are leafy by the end of May at the beginning of the rainy season. Leaf fall starts at the end of August for baobab and on November for néré. Therefore, néré remains leafy from May to December while baobab is leafy from May to September. Diop *et al.* (2005) noted in Senegal that baobab trees are leafy from June to October which gives a delay of one month compared to the leafy period in the present study (May to September). The leafy period of néré on the parkland is in accordance with the findings of other workers on tree phenology in Sahel region (Hall *et al.*, 1997; Bayala, 2002).

The reproduction of baobab happens during the rainy season (June to November) while for

néré, it takes place on the dry season (January to April). The flowers of baobab appear from May to June in Western Africa and fruits develop 5-6 months later (Sidibe & Williams, 2002). According to Sina (2006), the flowering of néré start on January and fruits development last for 4 months from mid-February to mid-June in Burkina Faso.

3.2.3. Tree selection

Before establishing the trials, an inventory of all trees within the 100 ha of the parkland at Nobéré was conducted and the co-ordinates of néré and baobab trees were recorded using a Global Positioning System (GPS) unit. Trees were selected for the study based on the following criteria: the tree was in good health, the tree was not shaded by neighbouring trees and the willingness of the owner of the tree to participate in the trial. A total of 25 and 181 trees was found for baobab and néré, respectively. Four baobab trees and 26 néré trees were discarded in the tree selection process because of their health or because they were pruned. The rest of trees were numbered and random numbers were generated in Microsoft Excel 2003 to select trees for the trials. When a selected tree was too close to another tree (distance less than 40m), it was rejected and a new random number was generated to select a new tree. Using this procedure, eight (8) trees were randomly chosen within the area for each tree species (néré and baobab). Tree characteristics such as height, circumference at 1.30 m and average of crown N/S and E/W diameters of all the selected trees were measured (Table 3.1). The crown diameter measurement was used to layout the experimental design as described in Chapter 3 of this thesis.

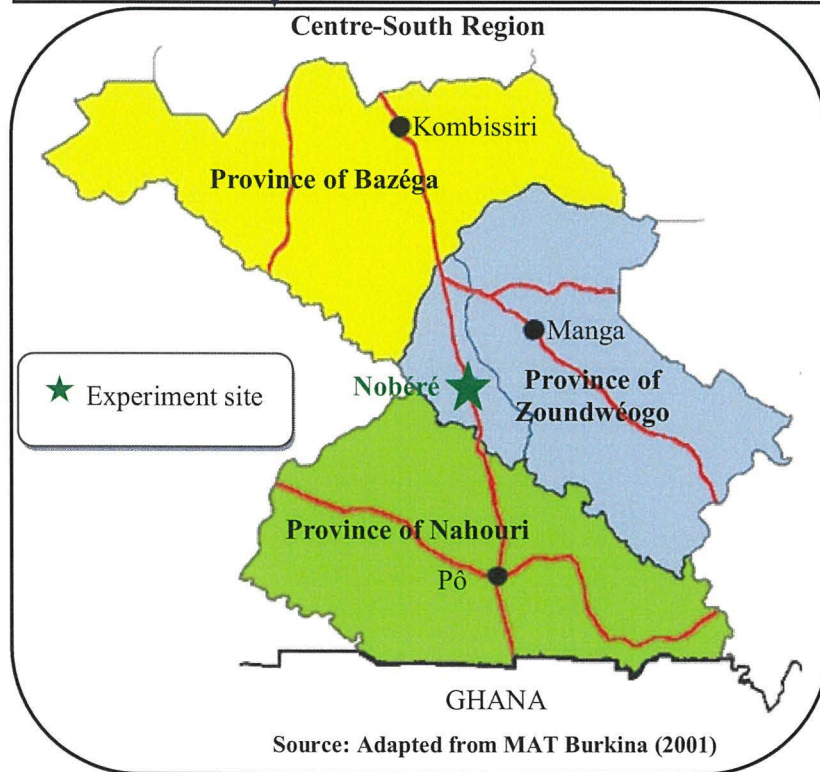
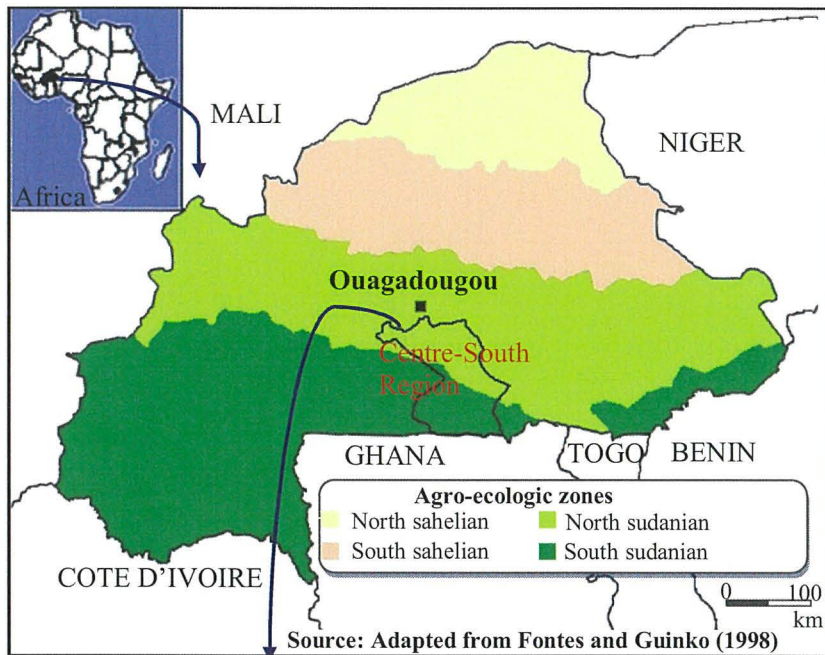
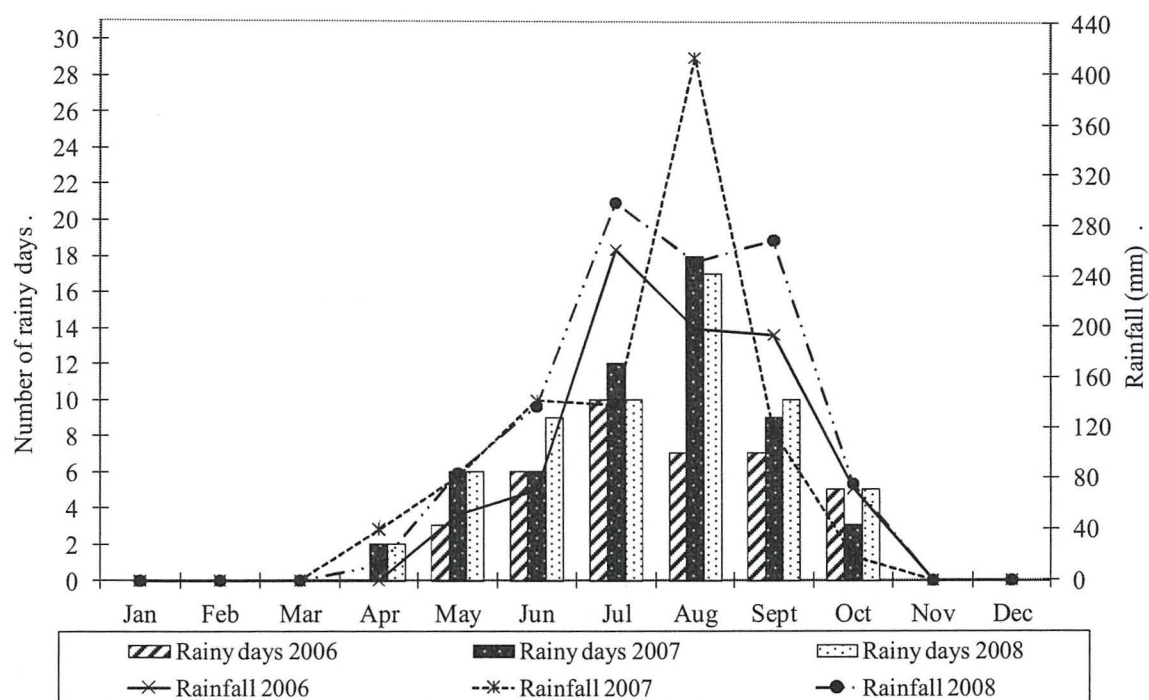


Fig. 3.1 : Location of the study site at Nobéré in Burkina Faso, West Africa



(Source: ASECNA, Nobéré, 2006-2007-2008)

Fig. 3.2 : Rainfall and number of rainy days during 2006, 2007 and 2008

Table 3.1 : Characteristics of studied trees in a parkland at Nobéré, Burkina Faso (2006)

Species	Tree N°	Crown diameter (m)	Circumference at 1.30m (m)	Height (m)
Baobab	1	13.16	7.48	15.61
	2	13.30	4.85	22.00
	3	19.88	4.88	14.63
	4	17.22	4.25	14.00
	5	17.50	9.20	17.00
	6	18.00	5.90	11.10
	7	17.28	4.67	15.00
	8	15.82	6.10	14.65
	Average		16.52±0.82	5.92±0.59
Néré	1	20.44	2.71	12.21
	2	18.72	2.09	10.56
	3	19.44	2.13	11.41
	4	16.46	2.15	11.83
	5	16.92	2.60	11.90
	6	17.09	2.08	10.90
	7	13.86	1.88	9.64
	8	14.2	1.85	10.10
	Average		17.14±0.83	2.19±0.11

3.2.4. Experimental design and layout

Figure 3.3 describes the experimental set up for each of the eight mature trees of *Parkia biglobosa* and *Adansonia digitata*. The area around each selected tree was subdivided into three concentric zones according to its crown size as follows:

Zone A - from the trunk of each tree up to half of the radius of the tree crown;

Zone B - from half of the radius of the tree crown up to the edge of the crown;

Zone C – from the edge of the tree crown to 3 m away from the tree crown.

A control plot of an area of 8 x 8 m was delimited for each sample tree to assess crop performance in the open area. The control plot was situated at least 40 m away from the edge of the crown of the sample tree and not shaded by any of the surrounding trees at any time of the day throughout the cropping season (Fig. 3.3). Dividing the area under tree into concentric zones was chosen over directional transects to reduce directional biases related to leaf and rainfall, and micro-variability of soil fertility and to separate the different influence zones of tree as defined by Rao *et al.* (1998).

Taro was grown under four of the eight selected trees of each tree species and millet under the remaining four trees of each species. The association of the crops to the selected trees was again done randomly using random numbers generated by Microsoft Excel.

Before sowing, all the areas under trees and the control plots were ploughed using oxen and plots limits were marked out. Crops were sown on 7 and 8 June 2007 on the first cropping season. In the second cropping season, the sowing of crops was later on 19 and 20 June 2007 due to delays in the start of rains. In the last season, the sowings occurred on 8 and 9 June 2008. Crops were managed as farmers traditionally do on the parkland. On the three cropping seasons, crops were planted at a density of 12 plants per m² for millet and 16 plants per m² for taro. Millet plots were weeded twice each cropping season and at the reproductive stage plots were ridged. Taro plots were weeded four times per cropping season. As is the normal practice with farmers, fertiliser NPK (15-15-15) was applied during the first weeding (around 30 days after sowing) at a dose of 100 kg ha⁻¹ and 200 kg ha⁻¹ for millet and taro, respectively. Urea (46-0-0) was applied during ridging in millet plots and on the third weeding in taro plots (around 80 days after sowing) at a dose of 100kg ha⁻¹ for both crops.

In the three cropping years, crops were harvested on November: taro was harvested on 6 November 2006, 12 November 2007 and 10 November 2008 for the three cropping years, respectively while the harvest of millet occurred on 19 November 2006, 27 November 2007 and 24 November 2008.

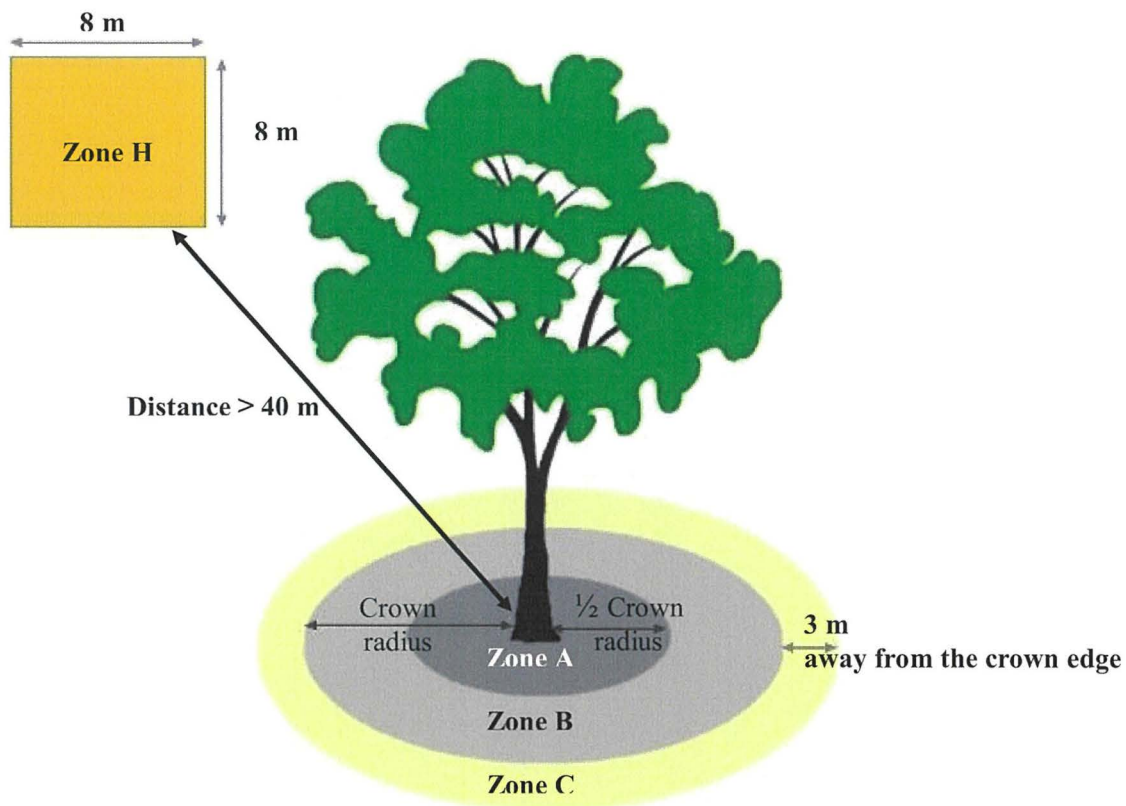


Fig. 3.3 : **Experimental design with concentric zones around a tree trunk.**

3.2.5. Agronomic assessment of crop performance

3.2.5.1. Crop yield and total dry matter production

Crop yield was assessed in each concentric zone and in the control plot by weighing all the grains or corms harvested. In addition, total dry matter was also assessed. All straws of each zone, grains of 30 panicles and 30 corms per zone and in the control plot were collected, weighed and dried in an oven at 80°C for 48 hours and weighed again.

The 30 panicles and 30 corms were selected randomly before harvesting in each zone. To select plants on which the panicles and corms were harvested, each concentric zone was subdivided into 48 sub-sections and the control plot was subdivided into 64 sub-sections (Fig. 3.4). These sub-sections were numbered for each concentric zone and for the control plot. Then, 30 random numbers were generated between one and 48 for the concentric zones and between one and 64 for the control plot using Microsoft Excel. Finally, the plant situated roughly closest to the middle of the small section numbered as the random number generated was harvested.

The dry matter weight of grains or corms in each zone was calculated using the ratio of dry matter obtained from grains of 30 panicles or 30 corms. The total dry matter (kg ha^{-1}) in a given zone was the sum of the dry matter of straw weight and the dry matter weight of grains or corms in that zone.

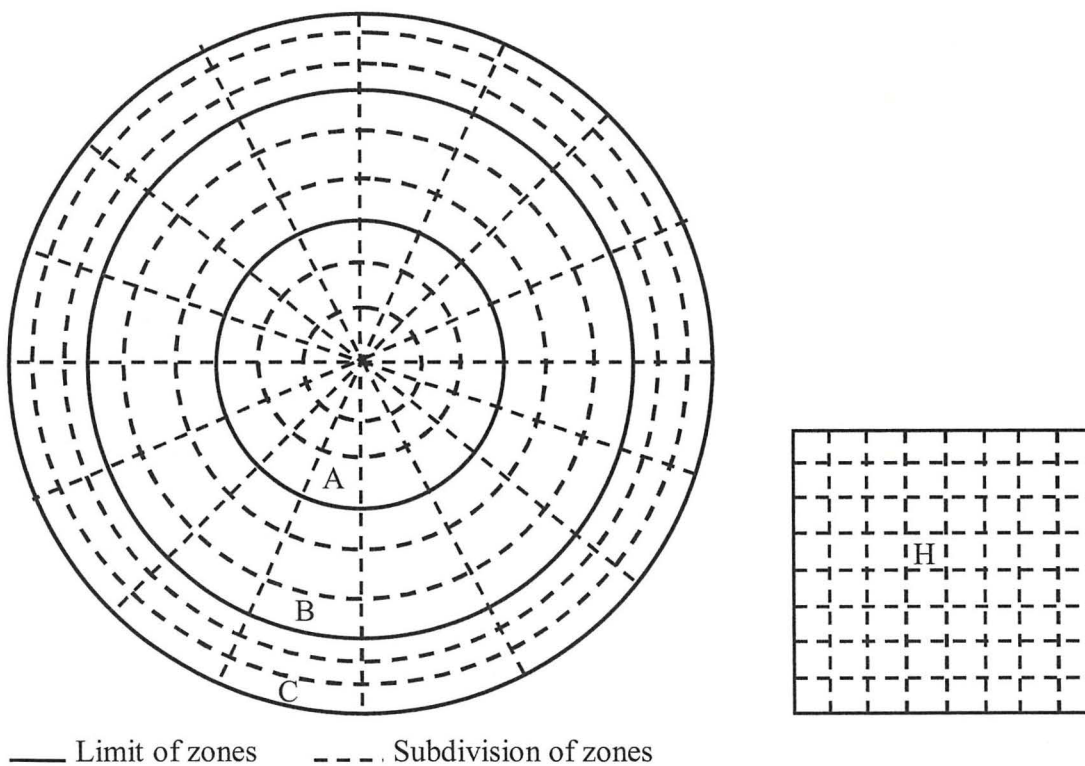


Fig. 3.4 : Subdivision of concentric zones and the control plot for random sampling.

3.2.5.2. *Assessment of crop growth*

The high fertility of soil under tree crowns may be favourable to crop growth as reported in the literature, but light attenuation could inhibit this effect if the crops were not able to photosynthesize efficiently in shaded conditions. Plant adaptation to shade was achieved by changing of growth habits especially in leaf size and plant height. Thus, observations were made to assess if these changes occurred in the two crop species during their growth period.

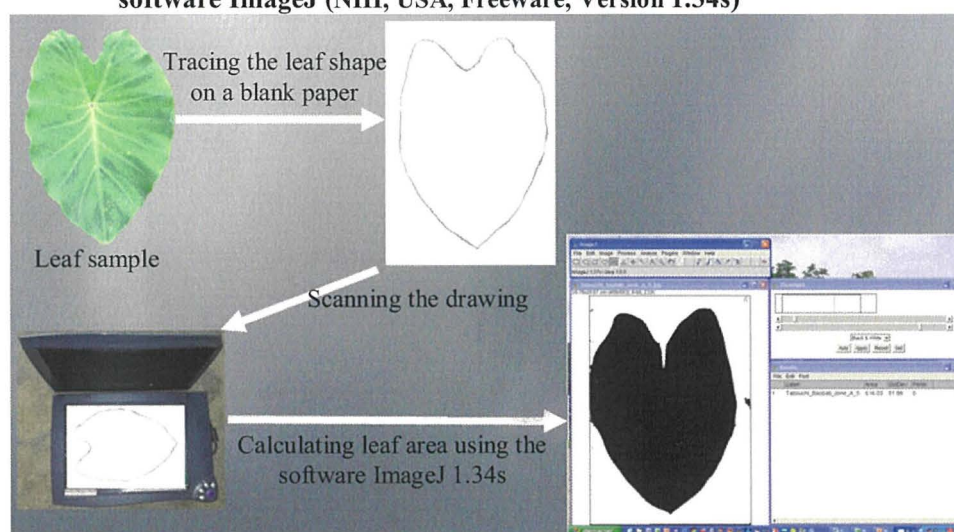
Because of the low number of plants (four) per concentric zone, it was possible to take in account for the measurement and a possible existence of variation of shade effect according to cardinal directions, one plant was selected on the each cardinal direction. All plant on a cardinal direction (East-West-North-South) in good health were numbered and a random number was generated to select one of them. These four crop plants per concentric zone and per control plot were labelled and their height measured at weekly intervals.

Leaf area was also determined digitally using a planimetric method. Thirty (30) leaves were randomly collected per concentric zone and in the control plot for each crop under each studied tree. The outline of each collected leaf was traced on a sheet of paper (Plate 3.1). Long and large leaves were cut into 2 or 3 parts to fit on a sheet. The drawings were scanned and each leaf area was computed using the software ImageJ (NIH, USA, Freeware, Version 1.34s). An average leaf area was calculated per concentric zone and in the control plot for each crop. The average value was used to calculate the total leaf area per plant. To determine the ground area occupied by a single plant, the number of plants per concentric zones and control plot were counted at harvest to estimate the final density of each crop (Table 3.2). Then, plants density was calculated dividing the area (m^2) of concentric zones or control plot by the number of plants in the given plot. Finally, leaf area index (LAI) was calculated by dividing the total leaf area (m^2) per plant by the ground area (m^2) occupied by a single plant.

Table 3.2 : The planting density and the average plants densities (number of plants m⁻²) at harvest of millet and taro according to tree species and concentric zones during cropping years 2006, 2007 and 2008 at Nobéré.

Tree species	Crops	Planting density	Density at harvest in zones			
			A	B	C	H
Baobab	Millet	12	9	9	10	10
	Taro	16	15	12	11	13
Néré	Millet	12	9	10	11	11
	Taro	16	16	14	13	12

Plate 3.1. Process of a leaf area measurement using a scanner and the software ImageJ (NIH, USA, Freeware, Version 1.34s)



3.2.6. Assessment of photosynthesis in crops

3.2.6.1. *Photosynthetic maximum quantum yield*

Photosynthetic maximum quantum yield is a measure of photosynthetic efficiency in plants. Its value for non-stressed plants of all species was 0.83 but decreased for plants under stress conditions such as drought, high or low temperature and lack of nutrients (Bjorkman and Demming, 1987). The maximum quantum conversion yield was determined in the present experiment by assessing the chlorophyll fluorescence in the leaves of both crop species.

Chlorophyll fluorescence measurements were made using a modulated fluorometer (Mini-PAM, Photosynthesis Yield Analyzer, Waltz, Effeltrich, Germany), see plate 3.2.a. Measurements were made on one leaf per plant and on four different plants per concentric

zone under four trees (2 trees associated with the taro and 2 trees with millet) and the control plot. Measurements were taken over two days during the 2008 cropping season (14/09/2008 and 21/09/2008) and each day of measurement was run for 12 hours from 6 am to 6 pm at intervals of two hours. The maximal (F_m) and the minimal (F_0) chlorophyll fluorescence were measured and stored in the Mini-PAM's memory. The maximum quantum conversion yield (Y) was calculated as follows:

$$Y = \frac{(F_m - F_0)}{F_m}$$

3.2.6.2. *Photosynthetic rate*

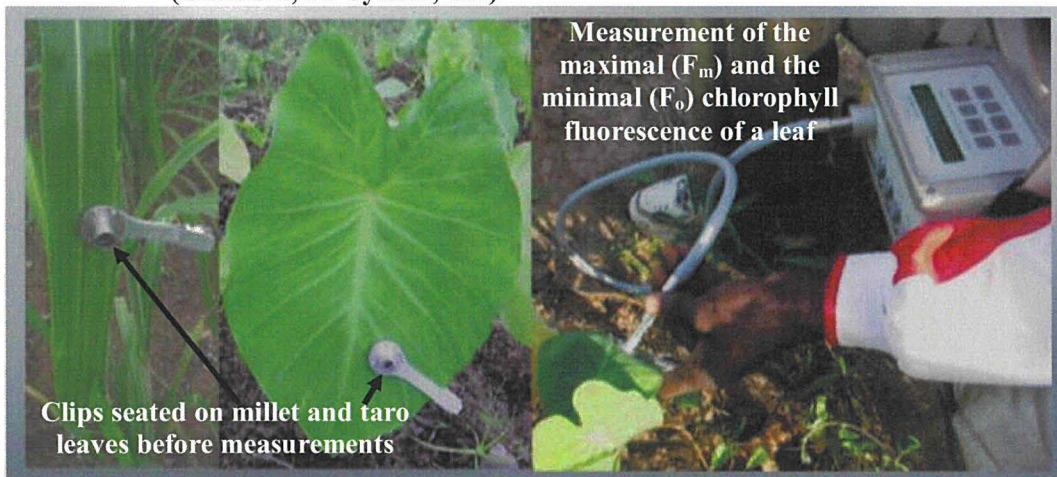
Photosynthetic rate in plants depends on environmental factors such as temperature and light and nutrient availability. The process was also regulated by physiological mechanisms such as stomatal aperture, and the amount of substances in leaf such as water, carbon dioxide and carbohydrates.

Measurements of photosynthetic rate were made using a CIRAS-1 infra-red gas analyser (PP-Systems, UK). Four plants not shade by other plants were selected in each concentric zone under four trees (two trees associated with taro and two trees with millet) and in the control plot using the process described in section 3.2.2.2. The second completely expanded leaf (7 to 14 days old) from the top of each selected plant was labelled for the measurements of the day. Measurements were made at one-hour intervals, from 7 am to 5 pm for four days during the vegetative growth phase of crops in the 2008 growing season: two days at the beginning and two days at the end of the vegetative growth phase. As shown on plate 3.2.b, each leaf was enclosed and placed perpendicular to the sun in the leaf chamber PLC-B (CIRAS-1, PP-Systems, UK). Then, net photosynthesis (P_N), stomatal conductance (g_s), photosynthetic active radiation (PAR) and transpiration (E_t) were recorded by the instrument (CIRAS-1).

The daily average net photosynthesis rate was calculated as the sum of the net assimilation per hour of daytime. The net assimilation per hour was the instantaneous P_N ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) measured at the given hour multiplied by 3600 s. The mean daily net assimilation was calculated estimated as the daily average of net photosynthesis multiplied by the LAI of each crop in a zone. The instantaneous Radiation Use Efficiency (RUE_i) and instantaneous Water

Use Efficiency (WUE_i) were calculated as the ratios between P_N and PAR, and between P_N and E_t , respectively. In some experiments RUE_i was labelled as LUE (Light Use Efficiency) see Grace *et al.* (2007). It was expressed as mmol of CO_2 captured per mol of PAR absorbed. WUE_i was defined as mmol of CO_2 captured per mol of water lost.

Plate 3.2. Apparatus for the measurement of photosynthetic maximum quantum yield (Mini-PAM, Waltz, Germany) and photosynthesis rate (CIRAS-1, PP System, UK)



a. Measurement of photosynthetic maximum quantum yield using Mini-PAM



b. Measurement of photosynthesis rate using

Photographs: SANOU Josias

3.2.7. Rooting systems of trees, crops and weeds

The rooting system of trees, crops and weeds was studied by assessing their root length density (RLD) and root weight density (RWD). RLD and RWD are defined as the length (cm) and weight (mg), respectively, of fine roots in a volume of soil (cm^3). The two parameters are used to describe niche differentiation by plant roots and then, to estimate the competition between different species of plants for soil water and nutrients.

Soil core sampling was made at the end of the crop vegetative growth phase, at 10 cm intervals up to 60 cm soil depth in each concentric zone under trees and in the control plot (Plate 3.3). Two sampling positions were randomly chosen within each concentric zone. So, there were 12 samples that were bulked for each soil layer to obtain 6 composite samples for each concentric zone and a total of 30 samples for each tree species. Roots were washed using a Root Washer (Delta T Ltd, UK) in order to separate soil from roots (Plate 3.3). Cleaned roots were sorted into three categories: trees, crops and weeds (roots of other plants). For both annual (crops and weeds) and tree roots only fine roots ($d \leq 2$ mm) were collected to assess root length density. Roots length (L) was estimated using the line intercept method described by Tennant (1975) using the equation 4.8.

$$L = \pi ND/4 \quad (\text{Equation 4.8})$$

where N = number of counts; D (cm) = grid size.

After root length measurement, collected roots were dried in an oven at 70°C for 48 hours and weighed to determine root weight density (RWD).

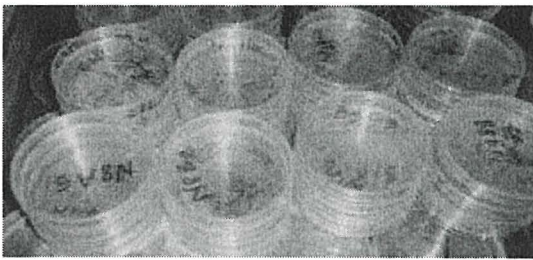
Plate 3.3. Fine roots processing for root length density and root weight density estimation



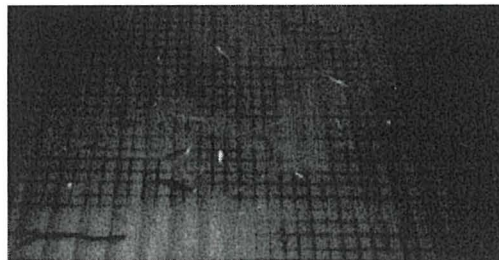
a. Soil sampling



b. Soil washing



c. Separated fine roots in Petri dishes



d. 1 cm grid for line intercept counting

Photographs: SANOU Josias

3.2.8. Data analysis

In the experimental design used for the study, it was not possible to randomise the concentric zones that are a representation of the gradient of tree effect. The variation between zones can not be analysed by ANOVA because it is not possible to calculate a valid estimation of error as residuals of zones are correlated (see Wilson *et al.*, 1998). Therefore, the variation of data according to cropping years, tree species and crops were analysed using the ANOVA General Linear Model (GLM) while the variation between concentric zones and the control plot was tested using a pairwise t-tests. All these analyses were performed using modules of the software Minitab 15 (Minitab Inc., USA). After a GLM analysis, means were compared using Tukey's test at a confidence level of 95%. The t-tests were performed assuming that the difference between the two zones compared was equal to zero and this hypothesis was rejected in case of a significant result of the test.

As crop performance is determined by many factors including physiological parameters and biophysical parameters, a Pearson's correlation test was run for each parameter to estimate a possible influence on crop performance. Then, a multiple regression was used to estimate the best-fitted relationship between crop performance and the physiological and biophysical parameters in the chapter 4.

3.3. Results

3.3.1. Crop growth

3.3.1.1. Leaf area index (LAI)

The average leaf area index (LAI) varied significantly between the three cropping years ($P < 0.01$), the two crop species ($P < 0.001$), the two tree species ($P < 0.001$) and the three concentric zones under trees ($P < 0.001$). There were also significant interactive effects of crops and tree species ($P < 0.05$) on LAI. LAI of millet was higher in 2007 ($P < 0.01$) than in 2006 and 2008 (1.2 ± 0.06 , 0.9 ± 0.08 and 1.0 ± 0.05 , respectively) while no significant difference in LAI was found for taro between the cropping years. Taro had a significantly higher LAI over the three cropping years ($P < 0.001$) compared to millet (1.7 ± 0.14 and 1.0 ± 0.04 ,

respectively). LAI of millet was almost the same under both baobab and néré while LAI of taro was significantly higher ($P < 0.001$) under néré than baobab (2.6 ± 0.35 and 1.3 ± 0.22 , respectively) (Fig. 3.5).

As shown in figure 3.5, LAI of millet was significantly higher (Table 3.3) in zone C (1.4 ± 0.13) under baobab when compared to the values in zones A, B and the control plot (0.8 ± 0.12 , 1.0 ± 0.09 and 0.9 ± 0.12 , respectively). Excepted LAI of millet in zone C that was higher compared to the control plot (1.1 ± 0.08 and 0.9 ± 0.06 , respectively), no difference in the LAI was noted between the other zones under néré. LAI of taro decreased significantly (Table 3.3) from the tree trunk to the open area under both tree species. However, LAI of taro in zone C under baobab was lower than the value in the control plot (0.5 ± 0.09 and 0.9 ± 0.09 , respectively).

Table 3.3 : Pairwise T-tests on differences of millet and taro Leaf Area Index (LAI) between zones under baobab and néré

Crops	Tree species	Compared zones	N	T-value	Significance	
Millet	Baobab	A-B	12	-1.94	ns	
		A-C	12	-5.93	***	
		A-H	12	-0.38	ns	
		B-C	12	-5.39	***	
		B-H	12	1.10	ns	
		C-H	12	4.00	**	
		Néré	A-B	12	-0.79	ns
	A-C		12	-1.42	ns	
	A-H		12	-0.03	ns	
	B-C		12	-0.86	ns	
	B-H		12	1.10	ns	
	C-H		12	3.86	**	
	Taro		Baobab	A-B	12	3.46
		A-C		12	4.24	**
A-H		12		3.04	*	
B-C		12		5.72	***	
B-H		12		0.87	ns	
C-H		12		-2.85	*	
Néré		A-B		12	-0.67	ns
		A-C	12	6.66	***	
		A-H	12	9.30	***	
		B-C	12	8.57	***	
		B-H	12	6.24	***	
		C-H	12	1.94	ns	

* = $P < 0.05$ ** = $P < 0.01$ and *** = $P < 0.001$

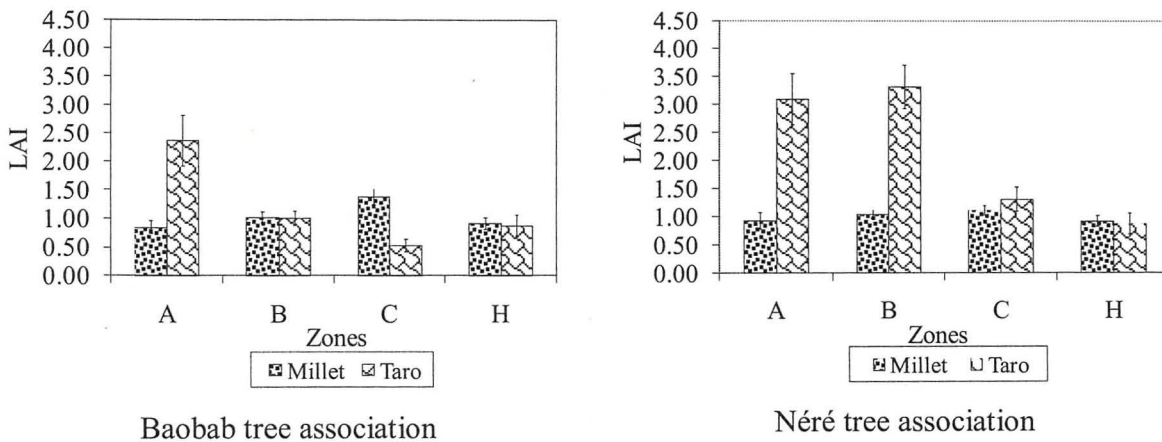


Fig. 3.5 : Average Leaf area Index (LAI) of millet and taro according to zones under baobab and néré (A, B and C) and the control plot (H) (Nobéré, 2006, 2007 and 2008)

3.3.1.2. Plant height

Height of millet varied significantly ($P < 0.001$) between the three cropping years except on 76 and 97 days after sowing (DAS) (Table 3.4). Significant differences in height of millet were also found between tree species. Millet was taller in 2008 (192.9 ± 5.16 cm) compared to 2006 and 2007 (158.3 ± 6.24 cm and 143.5 ± 6.00 cm, respectively). At the end each season, taller plants of millet were found under baobab (180.3 ± 5.24 cm) compared to those under néré (151.1 ± 4.38 cm). On 48 and 55 DAS, millet was taller in zone C and in the control plot compared to zones A and B under baobab (Table 3.5 and Fig. 3.6). Under néré, however, height of millet in zone A was lower compared to the height in the other zones during the same DAS (Fig. 3.6).

Height of taro also varied between cropping years and tree species on all dates of measurement except on 34 and 41 DAS where no significant differences were found between tree species (Table 3.5). The height of taro increased from the cropping year 2006 (27.1 ± 1.11 cm) to 2008 (31.9 ± 1.25 cm and 38.6 ± 1.11 cm). In contrast to millet, taro was taller under néré (35.5 ± 1.06 cm) than under baobab (29.5 ± 0.89 cm). As shown in figure 3.6, taro plants in zone A of baobab were significantly taller (Table 3.5) compared to plants in other zones. In contrast of baobab, taro plants in zones A and B was similar and taller compared to plants in zone C and the control plot.

Table 3.4 : Results of ANOVA on height of millet and taro according to cropping years and tree species

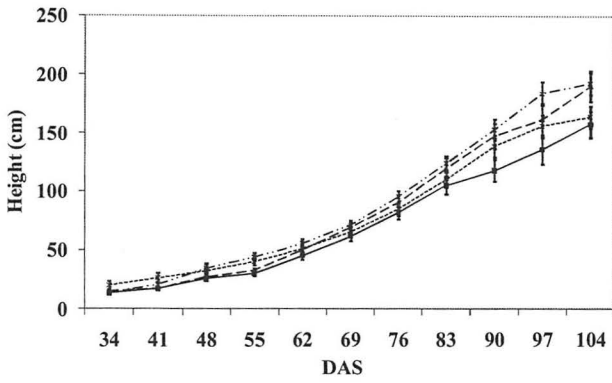
Crop	DAS	Year	Species	Year*Species
Millet	34	*	ns	ns
	41	**	ns	ns
	48	***	**	ns
	55	***	ns	**
	62	***	ns	**
	69	***	ns	**
	76	ns	ns	*
	83	*	ns	*
	90	***	ns	ns
	97	ns	**	ns
	104	***	***	ns
	Taro	34	**	ns
41		***	ns	ns
48		***	***	ns
55		***	***	ns
62		***	***	ns
69		***	**	ns
76		***	**	ns
83		***	***	ns
90		***	***	*
97		***	***	*
104		***	***	*

* = P < 0.05 ** = P < 0.01 and *** = P < 0.001

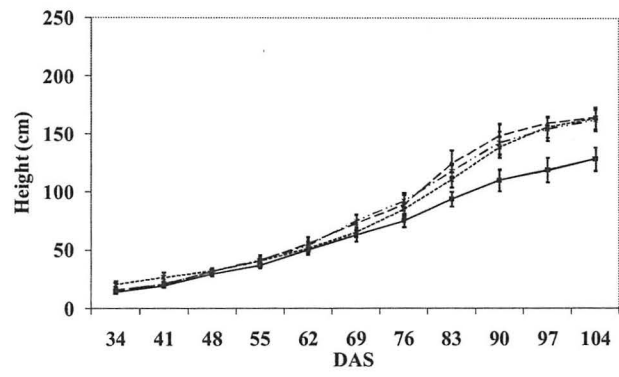
Table 3.5 : Pairwise T-tests on differences of millet and taro height according to the number of days after sowing between zones under baobab and néré

Crops	DAS	Compared zones of baobab						Compared zones of néré					
		A-B	A-C	A-H	B-C	B-H	C-H	A-B	A-C	A-H	B-C	B-H	C-H
Millet	34	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	41	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	48	ns	**	**	**	*	ns	ns	ns	ns	ns	ns	ns
	55	ns	**	**	**	*	ns	ns	ns	ns	ns	ns	ns
	62	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	69	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	76	ns	**	ns	ns	ns	**	ns	**	ns	ns	ns	ns
	83	ns	**	ns	ns	ns	ns	***	***	**	ns	ns	ns
	90	**	**	*	ns	ns	ns	***	***	***	ns	ns	ns
	97	ns	***	ns	ns	ns	**	***	***	***	ns	ns	ns
104	**	***	ns	ns	*	**	***	***	***	ns	ns	ns	
Taro	34	ns	**	ns	*	ns	ns	**	ns	ns	*	ns	ns
	41	ns	***	ns	***	ns	***	ns	**	ns	*	ns	ns
	48	**	***	***	**	**	ns	ns	***	***	***	***	ns
	55	**	***	***	**	**	ns	ns	***	***	***	***	ns
	62	***	***	***	**	**	ns	ns	***	***	***	***	ns
	69	**	***	***	**	ns	ns	ns	***	***	***	***	ns
	76	***	***	***	**	ns	ns	ns	***	***	***	***	ns
	83	***	***	***	***	**	ns	ns	***	***	***	***	ns
	90	***	***	***	***	***	ns	ns	***	***	***	***	ns
	97	***	***	***	***	**	ns	ns	***	***	***	***	ns
104	***	***	***	***	**	ns	ns	***	***	***	***	ns	

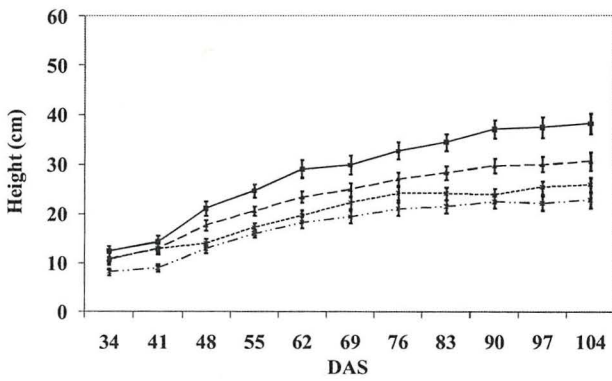
DAS=Days After Sowing, * = $P < 0.05$ ** = $P < 0.01$ and *** = $P < 0.001$



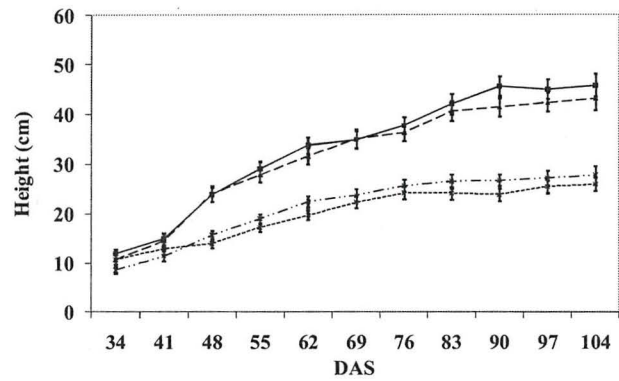
Millet associated with baobab



Millet associated with néré



Taro associated with baobab



Taro associated with néré

Legend : — Zone A - - Zone B ··· Zone C - · - Zone H

Fig. 3.6 : Height (cm) of millet and taro grown in association with baobab and néré according to the number of days after sowing (DAS) and the the concentric zones compared to the open field at Nobéré (2006, 2007 and 2008)

3.3.2. Crop yield

There was no significant difference in millet yield between cropping years. However, millet yield varied significantly between trees species ($P < 0.001$). Millet yield under baobab ($806.1 \pm 121.48 \text{ kg ha}^{-1}$) was higher than the value in the control plot ($595.9 \pm 72.79 \text{ kg ha}^{-1}$) while the yield under néré ($320.2 \pm 59.91 \text{ kg ha}^{-1}$) was lower than the yield in the control plot (Fig. 3.7).

Taro yield varied significantly between cropping years and tree species ($P < 0.001$, and $P < 0.001$, respectively). Yield of taro under néré ($4124.0 \pm 469.05 \text{ kg ha}^{-1}$) was higher than the yield in the control plot ($2336.9 \pm 662.21 \text{ kg ha}^{-1}$) and under baobab ($2738.3 \pm 595.61 \text{ kg ha}^{-1}$) (Fig 3.7).

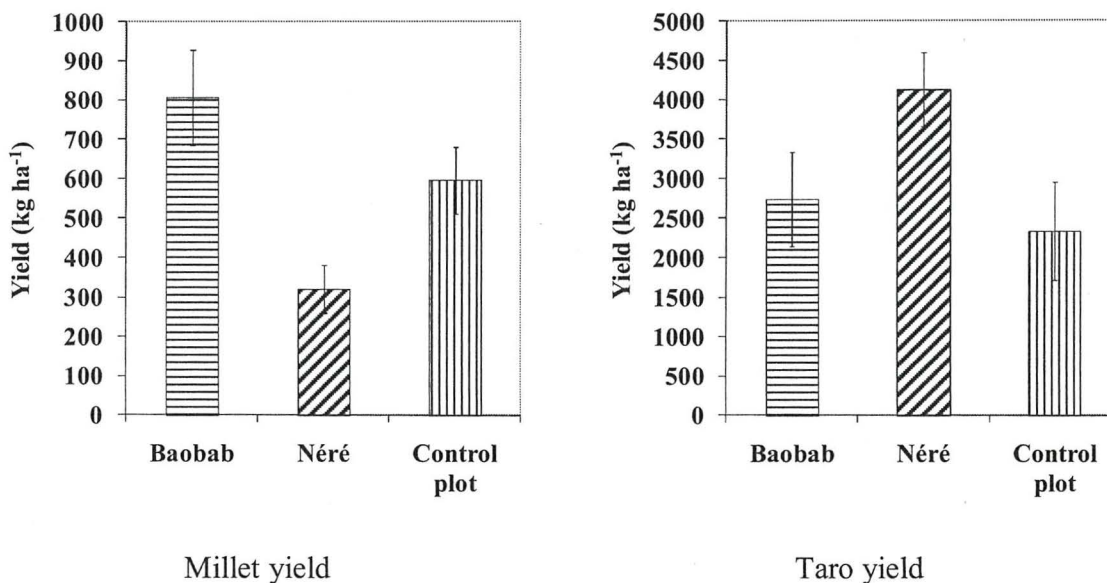


Fig. 3.7 : Millet and taro yield under baobab and néré and in the control plot (Nobéré, 2006, 2007 and 2008)

Yield of millet under baobab was significantly higher in zones B ($908.8 \pm 162.19 \text{ kg ha}^{-1}$) and C ($860.7 \pm 89.25 \text{ kg ha}^{-1}$) compared to the values in zone A ($648.9 \pm 113.00 \text{ kg ha}^{-1}$) and the control plot ($595.8 \pm 62.15 \text{ kg ha}^{-1}$) (Table 3.6 and Fig. 3.8). Under néré, however, it increased from the tree trunk to the control plot (Fig. 3.8).

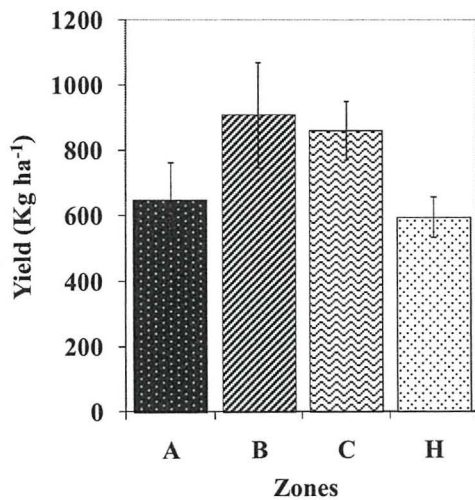
Yield of taro under baobab was significantly higher only in zone A ($4200.2 \pm 764.18 \text{ kg ha}^{-1}$) compared to the value in the control plot ($2336.9 \pm 662.21 \text{ kg ha}^{-1}$) (Table 3.5 and Fig. 3.8).

Under néré, however, taro yields in zones A and B ($4455.6 \pm 462.38 \text{ kg ha}^{-1}$ and $5088.0 \pm 536.47 \text{ kg ha}^{-1}$, respectively) were higher compared to the values in zone C and the control plot ($2828.5 \pm 408.30 \text{ kg ha}^{-1}$ and $2336.9 \pm 662.21 \text{ kg ha}^{-1}$, respectively) (Fig. 3.8).

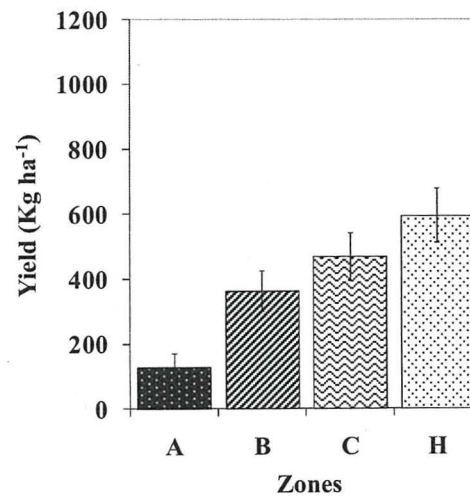
Table 3.6 : Pairwise T-tests on differences of millet and taro yield between zones under baobab and néré

Crops	Tree species	Compared zones	N	T-value	Significance	
Millet	Baobab	A-B	12	-2.48	*	
		A-C	12	-2.23	*	
		A-H	12	-1.85	ns	
		B-C	12	0.38	ns	
		B-H	12	2.47	*	
		C-H	12	2.22	*	
		Néré	Néré	A-B	12	-6.85
A-C	12			-5.14	***	
A-H	12			-2.23	*	
B-C	12			-1.86	ns	
B-H	12			0.10	ns	
C-H	12			1.62	ns	
Taro	Baobab			A-B	12	3.36
		A-C	12	6.55	***	
		A-H	12	2.38	*	
		B-C	12	2.32	*	
		B-H	12	-0.36	ns	
		C-H	12	-1.60	ns	
		Néré	Néré	A-B	12	-1.49
	A-C			12	3.54	**
	A-H			12	3.31	**
	B-C			12	5.88	***
	B-H			12	4.53	**
	C-H			12	1.12	ns

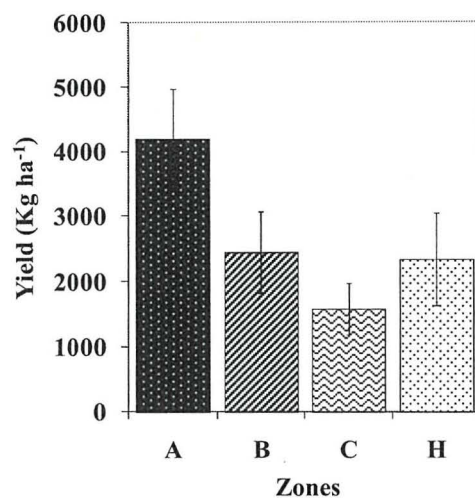
* = $P < 0.05$ ** = $P < 0.01$ and *** = $P < 0.001$



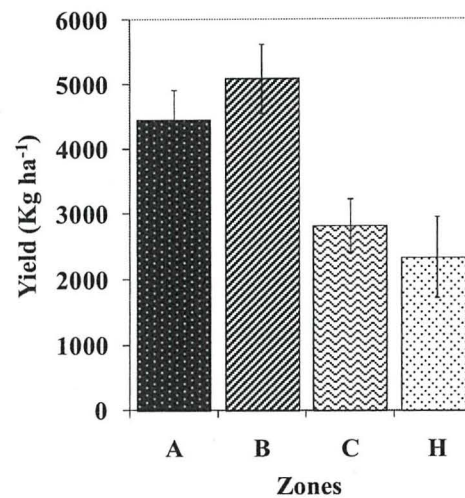
Millet associated with baobab tree



Millet associated with néré tree



Taro associated with baobab tree



Taro associated with néré tree

Fig. 3.8 : The yield of millet and taro according to zones under baobab and néré and the control plot (Nobéré, 2006, 2007 and 2008)

3.3.3. Dry matter production

Aboveground dry biomass varied significantly between crops, cropping years and tree species ($P < 0.001$, $P < 0.001$ and $P < 0.01$, respectively). Dry matter production of millet under baobab ($2220.9 \pm 188.46 \text{ kg ha}^{-1}$) was equal to the value in the control plot ($1820.4 \pm 241.70 \text{ kg ha}^{-1}$) but higher to the value under néré ($1303.9 \pm 111.05 \text{ kg ha}^{-1}$). In contrast, dry matter production of taro was higher under néré compared to the value in the control plot ($1025.3 \pm 80.14 \text{ kg ha}^{-1}$).

and $752.2 \pm 122.50 \text{ kg ha}^{-1}$, respectively). But no difference was found between the values in the control plot and under baobab ($875.4 \pm 105.78 \text{ kg ha}^{-1}$) (Fig. 3.9)

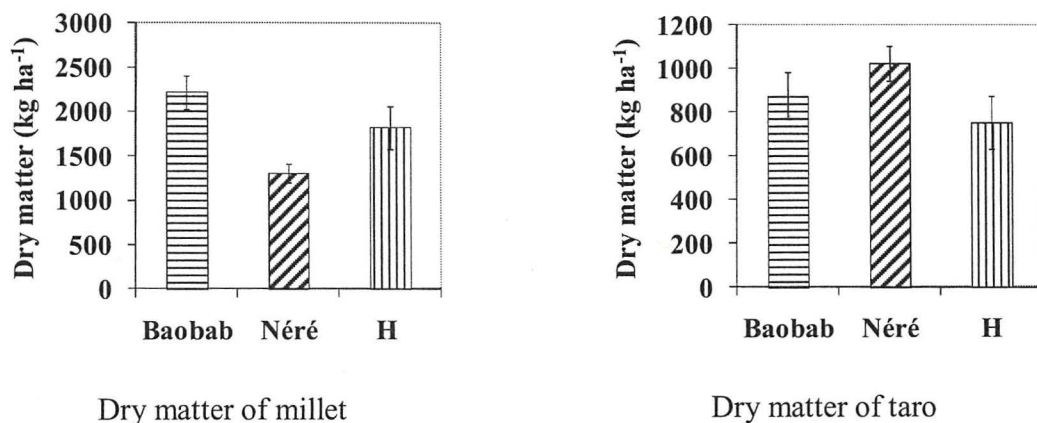


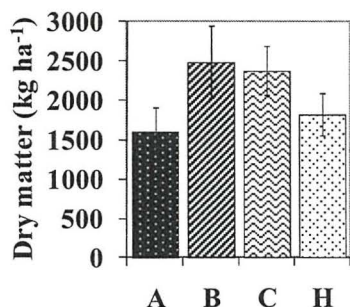
Fig. 3.9 : **Dry matter production of millet and taro under baobab and néré and in the control plot (H) (Nobéré, 2006, 2007 and 2008)**

The table 3.7 gives the results of pairwise t-test on differences of crops dry matter production between zones. As shown in figure 3.10, dry matter production of millet was lower in zone A under both tree species compared to the values in zones B and C and the control plot. In contrast, the dry matter of taro was higher in zone A under baobab compared to the values in zones B, C and the control plot. Dry matter production of taro under néré decreased from the tree crown to the open area (Fig. 3.10).

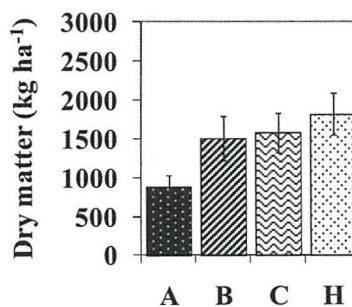
Table 3.7 : Pairwise T-tests on differences of millet and taro dry matter production between zones under baobab and néré

Crops	Tree species	Compared zones	N	T-value	Significance	
Millet	Baobab	A-B	12	-2.64	*	
		A-C	12	-3.27	**	
		A-H	12	-2.10	ns	
		B-C	12	0.17	ns	
		B-H	12	-0.07	ns	
		C-H	12	-0.15	ns	
		Néré	Néré	A-B	12	-3.61
A-C	12			-3.90	**	
A-H	12			-1.68	ns	
B-C	12			-0.05	ns	
B-H	12			0.94	ns	
C-H	12			1.24	ns	
Taro	Baobab			A-B	12	2.38
		A-C	12	3.22	**	
		A-H	12	1.75	ns	
		B-C	12	1.39	ns	
		B-H	12	0.47	ns	
		C-H	12	-0.27	ns	
		Néré	Néré	A-B	12	-0.55
	A-C			12	5.05	***
	A-H			12	4.62	**
	B-C			12	4.82	**
	B-H			12	4.79	**
	C-H			12	1.46	ns

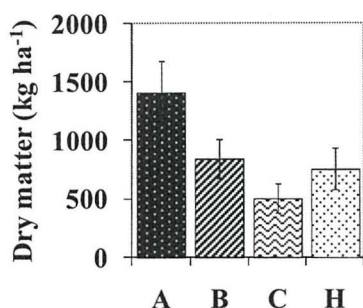
* = $P < 0.05$ ** = $P < 0.01$ and *** = $P < 0.001$



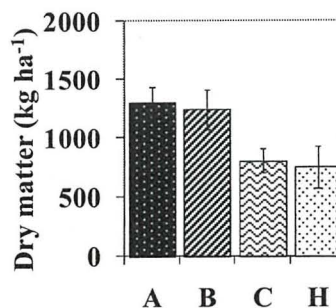
Millet associated with baobab tree



Millet associated with néré tree



Taro associated with baobab tree



Taro associated with néré tree

Fig. 3.10 : The dry matter production of millet and taro according to zones under the baobab and néré and the control plot (Nobéré, 2006, 2007 and 2008)

3.3.4. Photosynthesis

3.3.4.1. Photosynthetic maximum quantum conversion yield (Y)

All the values of the maximum quantum conversion yield (Y) recorded for millet and taro during the two assessment dates were lower than the reference value for a non-stressed plant (0.83). On 14/09/2008, Y ranged from 0.19 to 0.81 and its values were between 0.02 and 0.68 on 21/09/2008.

Y recorded on the first measurement date (0.5 ± 0.01) was significantly higher ($P < 0.001$) than the value recorded on the second measurement date (0.4 ± 0.01). On both measurement dates, Y was significantly different between the two crops ($P < 0.001$ and $P < 0.001$). On the first measurement date, Y of taro (0.6 ± 0.01) was higher than the value of millet (0.5 ± 0.01), whereas the reverse was observed on the second measurement date when Y of millet (0.5 ± 0.01) was higher than the value of taro (0.4 ± 0.01).

Y of millet varied significantly ($P < 0.05$) between tree species on the first date but not on the second date of measurement. In contrast, Y of taro did not vary between tree species on the first date but it was significantly different between tree species on the second date of measurement ($P < 0.001$). Y was higher under *néré* (0.5 ± 0.01 and 0.42 ± 0.02 for millet and taro, respectively) compared to the values under *baobab* on the second date for millet (0.5 ± 0.01) and for taro (0.3 ± 0.02).

The significant variations between zones under both tree species of Y of millet and taro on the two dates of measurement are given in tables 3.8 and 3.9. On the first date of measurement, Y of millet was higher in zone A under both tree species compared to the value in the control plot (Table 3.10). Y of taro recorded in zones A and B under both tree species was higher than the value in the control plot.

On the second date of measurement, Y of millet decreased from the tree trunk to the control plot under both tree species. The same trend was observed for taro. As shown in table 3.11, Y of millet recorded at 7h and 9h were the highest values of the day in zone C and the control plot while Y in zones A and B were similar during the day. The highest value of Y of taro was recorded at 9h under *baobab* while under *néré* the highest values were recorded at 7h and 9h in zone C and the control plot (Table 3.11).

Table 3.8 : Pairwise T-tests on differences of millet and taro maximum quantum conversion yield (Y) according to daytimes between zones under baobab and néré on 14/09/2008 at Nobéré

Crops	Hours	Compared zones of baobab						Compared zones of néré					
		A-B	A-C	A-H	B-C	B-H	C-H	A-B	A-C	A-H	B-C	B-H	C-H
Millet	7	ns	**	***	ns	**	ns	**	***	***	ns	ns	ns
	9	ns	ns	***	ns	**	ns	ns	ns	**	ns	ns	**
	11	*	**	***	ns	ns	ns	ns	ns	**	ns	ns	*
	13	ns	***	***	ns	ns	ns	***	***	***	***	ns	***
	15	*	ns	ns	**	**	ns	**	ns	**	ns	ns	ns
	17	ns	ns	ns	ns	ns	ns	ns	ns	***	ns	**	***
Taro	7	ns	ns	**	ns	***	***	ns	ns	ns	ns	ns	ns
	9	ns	ns	**	ns	***	***	ns	ns	ns	ns	**	ns
	11	ns	ns	ns	ns	*	**	*	**	**	ns	ns	ns
	13	ns	ns	ns	ns	**	ns	ns	ns	ns	ns	*	ns
	15	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	17	ns	ns	ns	ns	ns	ns	ns	ns	ns	**	**	ns

* = $P < 0.05$ ** = $P < 0.01$ and *** = $P < 0.001$

Table 3.9 : Pairwise T-tests on differences of millet and taro maximum quantum conversion yield (Y) according to daytimes between zones under baobab and néré on 21/09/2008 at Nobéré

Crops	Hours	Compared zones of baobab						Compared zones of néré						
		A-B	A-C	A-H	B-C	B-H	C-H	A-B	A-C	A-H	B-C	B-H	C-H	
Millet	7	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	*	*	
	9	ns	**	**	ns	*	ns	***	***	***	ns	*	ns	
	11	ns	***	***	ns	ns	ns	***	***	***	*	ns	ns	
	13	ns	***	ns	ns	ns	ns	ns	**	ns	**	*	ns	
	15	*	ns	**	ns	ns	ns	**	***	***	***	**	**	ns
	17	***	**	***	ns	ns	ns	*	***	***	*	ns	ns	
Taro	7	ns	***	***	*	ns	ns	ns	ns	ns	ns	ns	ns	
	9	ns	ns	**	ns	*	ns	ns	***	ns	*	ns	***	
	11	ns	ns	ns	ns	ns	ns	ns	*	ns	*	ns	***	
	13	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	ns	ns	
	15	ns	ns	ns	ns	ns	ns	ns	**	***	ns	**	**	
	17	ns	ns	ns	ns	ns	ns	ns	***	***	ns	*	*	

* = $P < 0.05$ ** = $P < 0.01$ and *** = $P < 0.001$

Table 3.10 :The maximum quantum conversion yield recorded for millet and taro every two hours from 07h to 17h under baobab and néré and the control plot on 14/09/2008 at Nobéré

Tree species	Hour	Millet				Taro			
		A	B	C	H	A	B	C	H
Baobab	07h	0.5±0.02	0.5±0.05	0.4±0.06	0.4±0.02	0.5±0.10	0.5±0.06	0.5±0.03	0.4±0.05
	09h	0.6±0.01	0.5±0.03	0.5±0.05	0.4±0.01	0.6±0.08	0.6±0.07	0.6±0.02	0.5±0.14
	11h	0.6±0.00	0.6±0.05	0.5±0.04	0.5±0.02	0.6±0.04	0.6±0.03	0.6±0.00	0.5±0.06
	13h	0.7±0.01	0.5±0.14	0.4±0.02	0.4±0.02	0.6±0.07	0.6±0.01	0.6±0.06	0.5±0.07
	15h	0.5±0.05	0.6±0.02	0.5±0.03	0.4±0.03	0.6±0.06	0.6±0.05	0.5±0.09	0.5±0.08
	17h	0.6±0.03	0.6±0.03	0.5±0.05	0.6±0.04	0.6±0.03	0.7±0.07	0.5±0.09	0.6±0.07
Néré	07h	0.6±0.05	0.5±0.02	0.5±0.04	0.5±0.03	0.5±0.07	0.5±0.09	0.5±0.07	0.5±0.05
	09h	0.6±0.03	0.5±0.06	0.6±0.02	0.5±0.07	0.6±0.05	0.7±0.03	0.6±0.07	0.6±0.02
	11h	0.6±0.03	0.5±0.06	0.6±0.02	0.5±0.07	0.5±0.11	0.6±0.02	0.6±0.03	0.6±0.03
	13h	0.6±0.02	0.6±0.05	0.6±0.02	0.4±0.01	0.6±0.05	0.6±0.00	0.6±0.04	0.5±0.06
	15h	0.6±0.02	0.5±0.04	0.5±0.06	0.5±0.05	0.5±0.08	0.6±0.01	0.5±0.06	0.6±0.02
	17h	0.6±0.02	0.6±0.03	0.6±0.05	0.5±0.04	0.6±0.05	0.6±0.02	0.5±0.04	0.5±0.04

Table 3.11 :The maximum quantum conversion yield recorded for millet and taro every two hours from 07h to 17h under baobab and néré and the control plot on 21/09/2008 at Nobéré

Tree species	Hour	Millet				Taro			
		A	B	C	H	A	B	C	H
Baobab	7.00	0.5±0.07	0.5±0.05	0.5±0.03	0.5±0.02	0.4±0.05	0.3±0.06	0.2±0.05	0.3±0.01
	9.00	0.6±0.04	0.6±0.04	0.5±0.03	0.5±0.01	0.56±0.10	0.4±0.07	0.5±0.07	0.5±0.02
	11.00	0.6±0.01	0.5±0.09	0.4±0.04	0.4±0.04	0.4±0.11	0.3±0.15	0.49±0.03	0.5±0.05
	13.00	0.6±0.03	0.5±0.08	0.5±0.04	0.5±0.05	0.4±0.12	0.2±0.11	0.2±0.08	0.5±0.07
	15.00	0.5±0.03	0.4±0.10	0.4±0.06	0.5±0.03	0.3±0.12	0.3±0.10	0.2±0.03	0.3±0.08
	17.00	0.5±0.03	0.4±0.10	0.4±0.06	0.4±0.03	0.4±0.13	0.3±0.12	0.3±0.06	0.3±0.03
Néré	7.00	0.6±0.03	0.6±0.02	0.6±0.02	0.5±0.05	0.5±0.04	0.5±0.07	0.5±0.07	0.5±0.027
	9.00	0.6±0.03	0.5±0.04	0.5±0.04	0.6±0.00	0.5±0.03	0.5±0.04	0.6±0.02	0.4±0.02
	11.00	0.6±0.02	0.5±0.04	0.4±0.04	0.4±0.03	0.4±0.03	0.4±0.04	0.5±0.03	0.3±0.12
	13.00	0.5±0.06	0.5±0.04	0.4±0.08	0.4±0.07	0.4±0.03	0.4±0.07	0.4±0.07	0.3±0.12
	15.00	0.5±0.03	0.5±0.01	0.3±0.10	0.4±0.05	0.5±0.07	0.3±0.10	0.3±0.07	0.2±0.09
	17.00	0.6±0.03	0.5±0.02	0.4±0.11	0.4±0.04	0.5±0.04	0.4±0.12	0.4±0.03	0.2±0.09

3.3.4.2. Net photosynthesis (P_N)

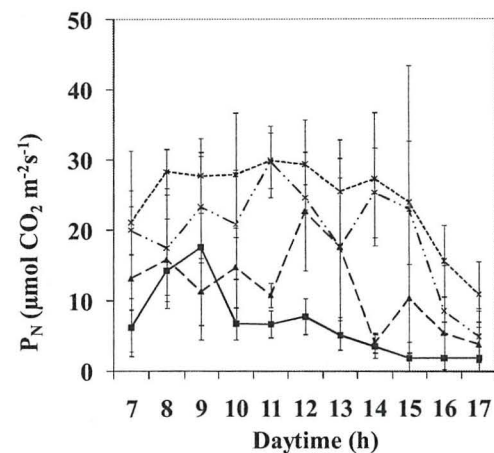
The mean net photosynthesis (P_N) recorded in the control plot was higher for millet plants ($24.79 \pm 1.621 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) compared to taro plants ($14.3 \pm 0.71 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$). The highest P_N values for both crops under both trees species were recorded between 10h and 15h in zone C and the control plot (Fig. 3.11). In the association of millet with baobab tree, the highest values of P_N were observed between 8h and 9h in zone A and between 12h and 13h in zone B. P_N values did not vary diurnally in zones A and B under néré for both crops and under baobab for taro only. The main difference of P_N between zones was noted between 9h and 15h. During this period, the P_N of the two crops was reduced under the tree crown (A and B) compared to the values in zone C and the control and the reduction was more noticeable in zones under néré than under baobab (Fig. 3.11).

Cumulative P_N per day or daily assimilation rate was significantly different between the two crops ($P < 0.01$) but there was no difference according to tree species. P_N of millet ($669.1 \pm 99.35 \text{ mmol CO}_2 \text{ m}^{-2} \text{ day}^{-1}$) was higher compared to the value of taro ($428.5 \pm 42.05 \text{ mmol CO}_2 \text{ m}^{-2} \text{ day}^{-1}$). The significant differences of daily values of P_N between zones for both crops are shown in table 3.12. The average daily P_N of the two crops increased from the trunk of both species to the open area (Fig 3.12). The reduction of daily P_N values in zones influenced by trees (zones A, B and C) compared to the open field was more accentuated for millet plants (72%, 60% and 22%, respectively) compared to taro plants (53%, 44% and 11%, respectively). Therefore, the two crops had comparable daily P_N values in zone under trees (A and B) while the values of daily P_N of millet were higher in zone C and the control plot when compared to the values of taro.

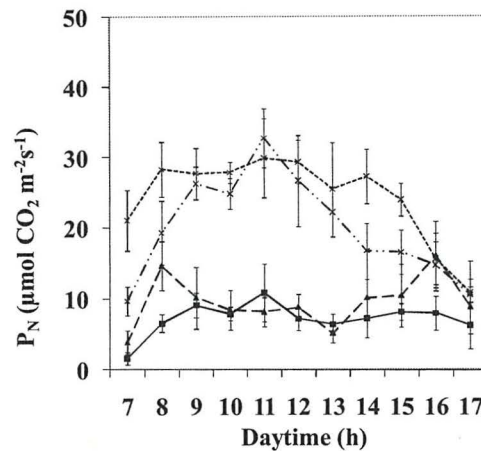
Table 3.12 :Pairwise T-tests on differences of millet and taro daily net photosynthesis rate between zones under baobab and néré

Crops	Compared zones	N	T-value	Significance
Millet	A-B	8	-3.44	*
	A-C	8	-9.32	***
	A-H	8	-7.64	***
	B-C	8	-9.18	***
	B-H	8	-7.22	***
	C-H	8	-4.56	**
Taro	A-B	8	-2.48	ns
	A-C	8	-7.42	***
	A-H	8	-4.84	**
	B-C	8	-4.42	**
	B-H	8	-3.73	**
	C-H	8	-1.88	ns

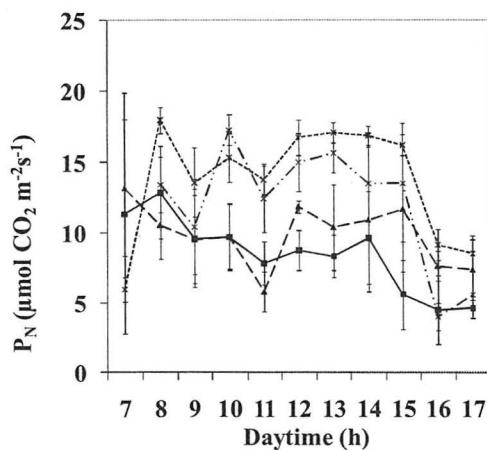
* = $P < 0.05$ ** = $P < 0.01$ and *** = $P < 0.001$



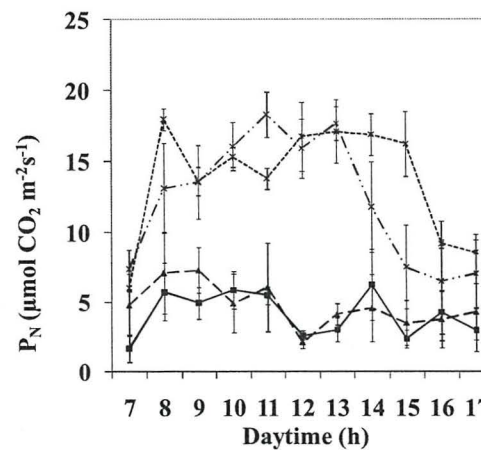
A- Millet associated with baobab



B- Millet associated with néré



C- Taro associated with baobab tree



D- Taro associated with néré tree

Legend : — Zone A — Zone B - - - Zone C - - - Zone H

Fig. 3.11 : Diurnal course of the net photosynthesis (P_N) of millet and taro associated with baobab and néré trees according to the zones at Nobéré (2008)

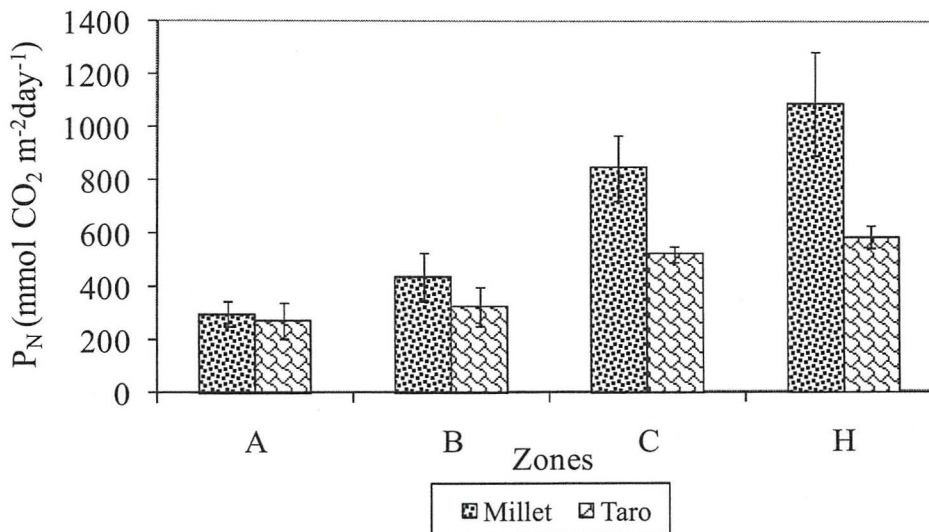


Fig. 3.12 : Daily average of net photosynthesis (P_N) rate of millet and taro according to zones under the influence of baobab and néré trees and the control plot

For both crops, the mean daily net assimilation varied between trees species ($P < 0.01$ and $P < 0.05$ for millet and taro, respectively). Table 3.13 shows the significant differences of the daily net assimilation of millet and taro between zones of both tree species.

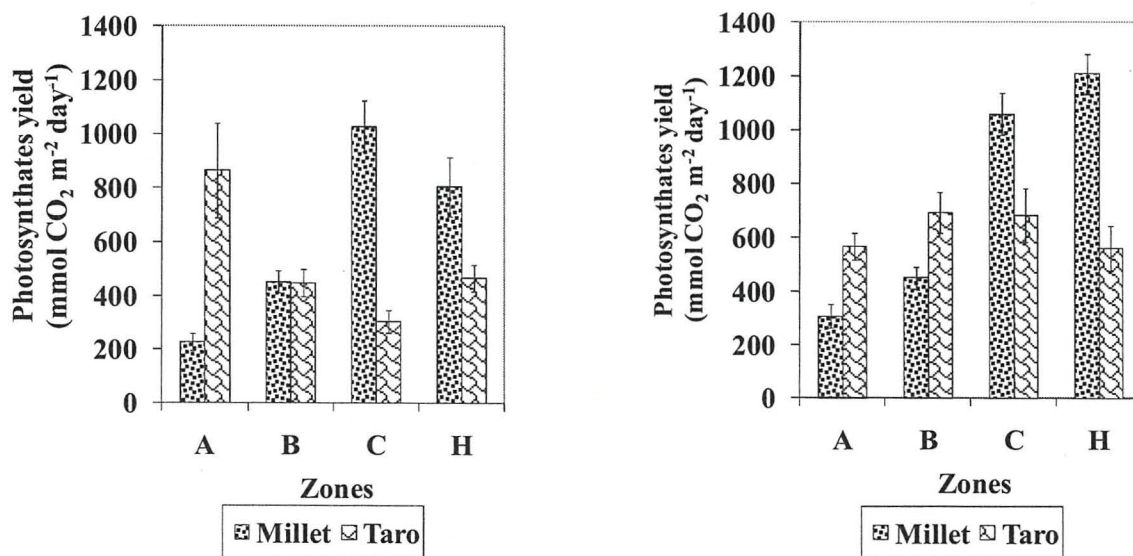
As shown in figure 3.13, the mean daily net assimilation in zone A under baobab was higher for taro compared to millet (864.7 ± 174.94 mmol CO₂ m⁻² day⁻¹ and 227.7 ± 31.42 mmol CO₂ m⁻² day⁻¹, respectively). In zones A and B under néré, daily P_N of taro was higher (566.5 ± 49.16 mmol CO₂ m⁻² day⁻¹ and 692.3 ± 76.19 mmol CO₂ m⁻² day⁻¹, respectively) compared to the values of millet (307.1 ± 44.6 mmol CO₂ m⁻² day⁻¹ and 450.4 ± 39.9 mmol CO₂ m⁻² day⁻¹, respectively).

The mean daily net assimilation of millet increased from the tree trunk to the open area under both tree species (Fig. 3.13). For taro, the highest mean daily net assimilation was recorded in zone A under baobab and the lowest was in zone C (864.7 ± 174.94 mmol CO₂ m⁻² day⁻¹ and 306.5 ± 42.78 mmol CO₂ m⁻² day⁻¹). No difference in mean daily net assimilation was recorded between zones for taro under néré (Fig. 3.13).

Table 3.13 :Pairwise T-tests on differences of millet and taro mean daily net assimilation between zones under baobab and néré

Crops	Tree species	Compared zones	N	T-value	Significance	
Millet	Baobab	A-B	12	-7.17	***	
		A-C	12	-10.64	***	
		A-H	12	-5.17	***	
		B-C	12	-9.10	***	
		B-H	12	-3.85	**	
		C-H	12	2.31	*	
		Néré	A-B	12	-2.79	*
	A-C	12	-10.31	***		
	A-H	12	-10.77	***		
	B-C	12	-9.47	***		
	B-H	12	-10.01	***		
	C-H	12	-3.42	**		
	Taro	Baobab	A-B	12	3.02	*
			A-C	12	3.80	**
A-H			12	2.19	ns	
B-C			12	3.85	**	
B-H			12	-0.27	ns	
C-H			12	-2.43	*	
Néré			A-B	12	-1.92	ns
A-C		12	-1.21	ns		
A-H		12	0.09	ns		
B-C		12	0.19	ns		
B-H		12	1.14	ns		
C-H		12	0.95	ns		

* = $P < 0.05$ ** = $P < 0.01$ and *** = $P < 0.001$



Association with baobab tree

Association with néré tree

Fig. 3.13 : Mean daily net assimilation of millet and taro according to zones under the influence of baobab and néré trees and the control plot

3.3.4.3. Radiation use efficiency (RUE_i)

The instantaneous radiation use efficiency (RUE_i) was significantly different between crop species ($P < 0.05$). Higher RUE_i was recorded for millet ($20.3 \pm 2.45 \text{ mmol CO}_2 \text{ mol}^{-1} \text{ PAR}$) compared to value of taro ($14.7 \pm 1.15 \text{ mmol CO}_2 \text{ mol}^{-1} \text{ PAR}$). There was no significant difference in RUE_i between tree species in both crops. However, RUE_i values were significantly different between zones for taro (Table 3.14) but not for millet. RUE_i values of taro decreased from the tree trunk to the control plot (Fig. 3.14).

Table 3.14 : Pairwise T-tests on differences of millet and taro RUE between zones under baobab and néré

Crops	Compared zones	N	T-value	Significance
Millet	A-B	8	1.43	ns
	A-C	8	1.16	ns
	A-H	8	1.15	ns
	B-C	8	0.71	ns
	B-H	8	0.60	ns
	C-H	8	-1.26	ns
	Taro	A-B	8	5.15
A-C		8	3.24	*
A-H		8	10.08	***
B-C		8	2.19	ns
B-H		8	12.95	***
C-H		8	3.07	*

* = $P < 0.05$ ** = $P < 0.01$ and *** = $P < 0.001$

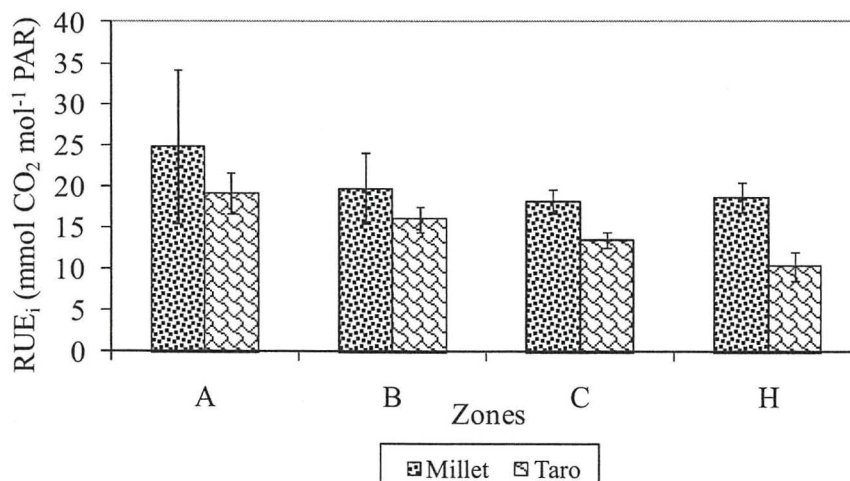


Fig. 3.14 : Average instantaneous RUE_i of millet and taro according to zones under the influence of baobab and néré trees and the control plot

3.3.4.4. Instantaneous Water Use Efficiency (WUE_i)

There was significant difference in the instantaneous water use efficiency (WUE_i) between the two crops ($P < 0.001$). WUE_i of millet was higher compared to the value of taro (4.8 ± 0.45 mmol CO_2 mol $^{-1}$ H_2O and 2.3 ± 0.17 mmol CO_2 mol $^{-1}$ H_2O , respectively). WUE_i values did not significantly differ between tree species for both crops. For both crops, WUE_i varied significantly between zones (Table 3.15). The values of WUE_i increased from the area under the tree crown (zones A and B) to zone C and the control plot for both crops (Fig. 3.15).

Table 3.15 : Pairwise T-tests on differences of millet and taro WUE between zones under baobab and néré

Crops	Compared zones	N	T-value	Significance
Millet	A-B	8	1.88	ns
	A-C	8	-5.55	**
	A-H	8	-4.88	**
	B-C	8	-5.72	**
	B-H	8	-5.84	**
	C-H	8	-1.09	ns
	Taro	A-B	8	-1.92
A-C		8	-5.72	**
A-H		8	-4.83	**
B-C		8	-3.17	*
B-H		8	-2.98	*
C-H		8	-0.58	ns

* = $P < 0.05$ ** = $P < 0.01$ and *** = $P < 0.001$

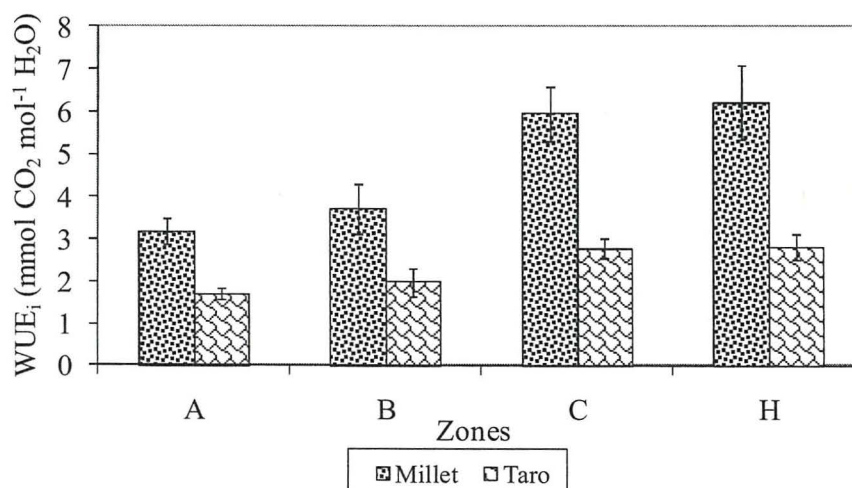


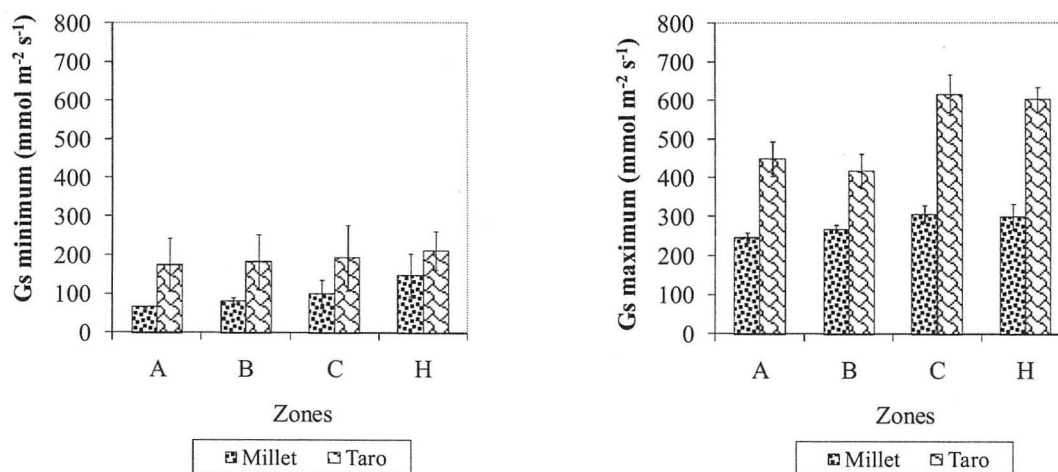
Fig. 3.15 : Daily average of WUE_i of millet and taro according to zones under the influence of baobab and néré trees and the control plot

3.3.4.5. Stomatal conductance (g_s)

The maximum and the minimum stomatal conductance (g_s) varied significantly between crops ($P < 0.01$) but not between tree species. Maximum and minimum values of g_s were higher for taro ($589.9 \pm 67.60 \mu\text{mol m}^{-2} \text{s}^{-1}$ and $150.8 \pm 22.05 \mu\text{mol m}^{-2} \text{s}^{-1}$, respectively) compared to the values for millet ($319.4 \pm 25.44 \mu\text{mol m}^{-2} \text{s}^{-1}$ and $69.6 \pm 13.13 \mu\text{mol m}^{-2} \text{s}^{-1}$, respectively). The maximum g_s of taro was higher compared to millet in all zones while the minimum g_s of taro was only higher in zones A and B compared to millet (Fig. 3.16)

3.3.5. Correlation between photosynthesis parameters (mean daily net assimilation, RUE_i and WUE_i) and crop growth

Height, yield and dry matter production of millet were negatively and significantly correlated with RUE_i (-0.30, -0.55 and -0.37, respectively). No significant relationships were found between mean daily net assimilation and WUE_i and the performances of millet except that the LAI was positively correlated to the mean daily net assimilation (Table 3.16). In contrast, height, LAI, yield and dry matter production of taro were positively and significantly correlated with RUE_i (0.63, 0.63, 0.36 and 0.32, respectively). There was also a significant negative correlation between height and dry matter of taro and WUE_i (-0.68, -0.67, -0.45 and -0.38, respectively). Daily assimilation rate was positively and significantly correlated with the LAI, yield and dry matter production of taro (0.75, 0.30 and 0.31) (Table 3.16).



Minimum stomatal conductance

Maximum stomatal conductance

Fig. 3.16 : **Maximum and minimum values of stomatal conductance (G_s) of millet and taro according to zones under the influence of baobab and néré trees and the control plot**

Table 3.16 :Pearson’s correlations between daily gross assimilation, RUE_i, WUE_i and growth (plants height and dry matter) of millet and taro

		Height	LAI	Yield	Dry matter
Millet	Daily assimilation rate	0.03 ns	0.61***	0.08 ns	0.11 ns
	RUE _i	-0.30**	-0.06 ns	-0.55 ***	-0.37***
	WUE _i	0.32 ns	0.09 ns	-0.04 ns	0.15ns
Taro	Daily assimilation rate	0.16 ns	0.75 ***	0.30 **	0.31 **
	RUE _i	0.63***	0.63 ***	0.36 ***	0.32**
	WUE _i	-0.67***	-0.67 ***	-0.45 ***	-0.38***

n=32 * = P < 0.05 ** = P < 0.01 and ***= P < 0.001

3.3.6. The distribution of trees, crops and weeds roots

3.3.6.1. Root Length Density and Root Weight Density

Root length density (RLD) and root weight density (RWD) were significantly different between tree species, millet, taro and weeds ($P < 0.001$ and $P < 0.001$, respectively). RLD and RWD of both tree species were higher compared to millet, taro and weeds in all soil layers under tree crown.

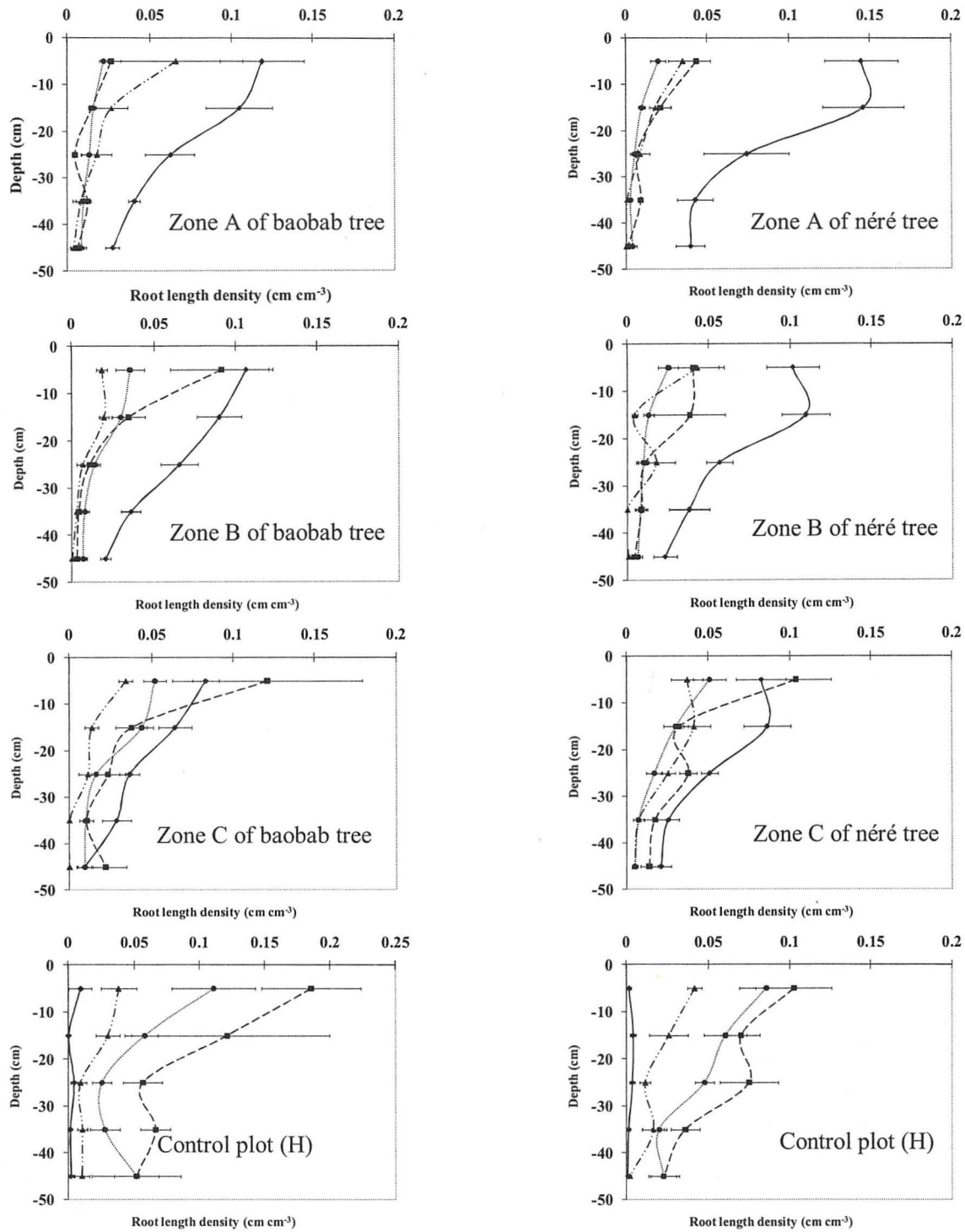
According to the pairwise T-tests on the differences between soil layers, RLD and RWD of both crops, weeds and both tree species decreased from the soil top layer to 50 cm depth. Pairwise T-tests on the differences between zones showed that RLD of both tree species were similar in zones A, B and C but lower in the control plot compared to the values in the three zones under trees (Fig. 3.17). However, RWD of both tree species decreased from the tree trunk to the open area (Fig. 3.18). Few roots of baobab and néré were found in three and 5 control plots, respectively. Therefore, tree roots are extended more than 40 m as assumed in this study.

Millet in association with baobab had a similar RLD in soil top layer (0-10 cm) of zones B and C compared to baobab trees. In the same layer, millet RLD was only statistically equal to néré tree RLD in the zone C. RLD of taro from the top layer to 50 cm depth was lower compared to either of the two tree species in zones A, B and C except in the top layer of zone A of the baobab tree. In the control plot, few roots of the two tree species were found and at 30 cm depth, the RLD of millet and weeds were higher compared to taro (Fig. 3.17).

The RWD of both tree species was higher compared to both crops and weeds in zones under the tree crown. In zone C of both tree species, tree RWD was higher only in the 10-20 cm layer compared to crops and weeds (Fig. 3.18). The RLD and RWD of millet increased from the tree trunk to the control plot while these parameters were similar in zones for taro. However, there was a trend for RLD and RWD of taro plants to decrease from the tree trunk to the open area. Weeds RLD and RWD followed the same trend of millet: increase with distance from tree trunk (Fig. 3.17 and 3.18).

There was no significant correlation between the performances of millet and taro and the root length density of baobab (Table 3.17). The RLD of *nééré* at the 10-20 cm soil-depth was negatively and significantly correlated with the total dry matter of millet (Table 3.18). Taro performance was positively correlated with the RLD of *nééré* at the 0-10cm soil-depth. At 10-20cm soil-depth, the RLD of *nééré* was also positively correlated with the yield and total dry matter of taro. A positive correlation was also found between the RLD of *nééré* and taro yield at the soil-depth of 40-50cm (Table 3.18).

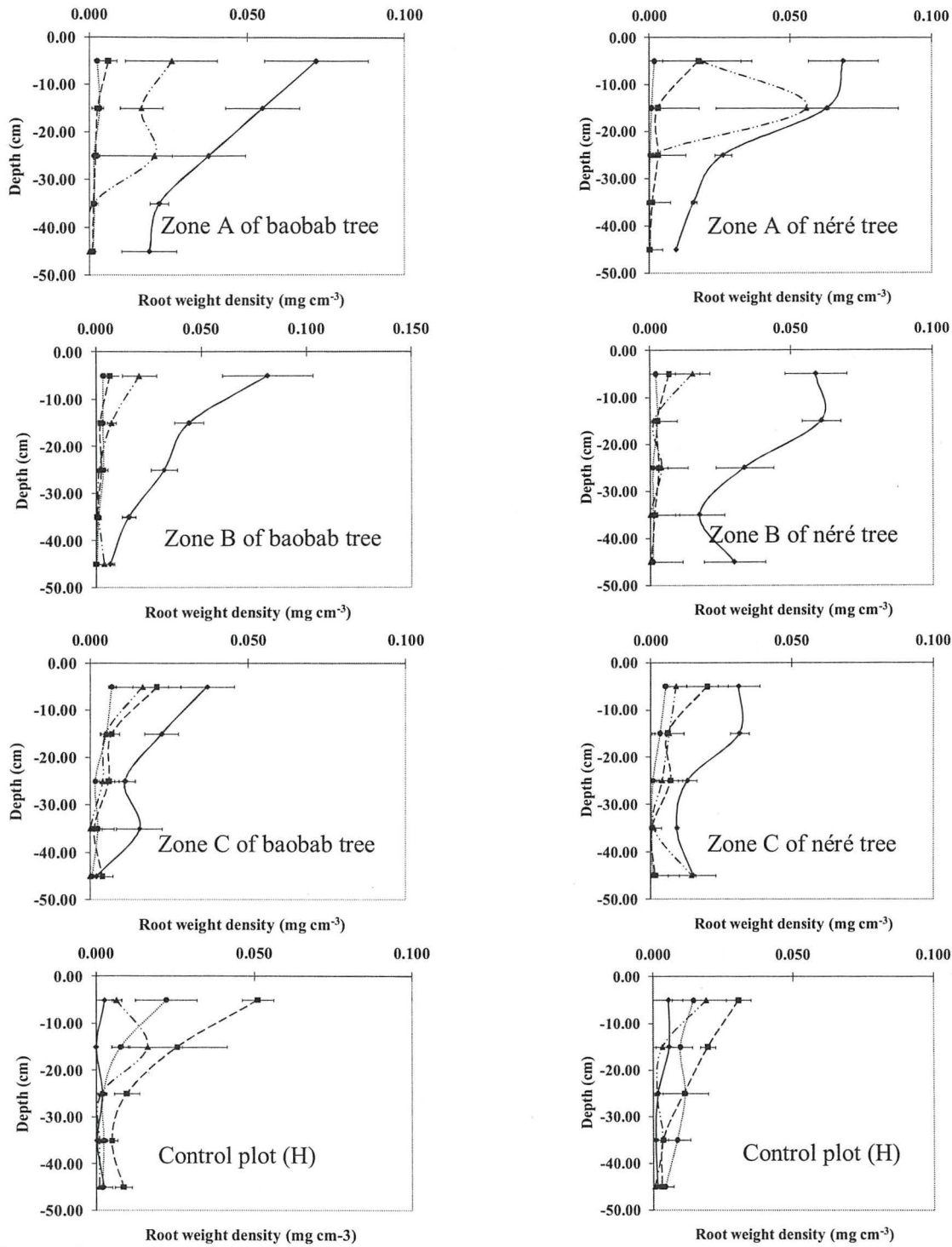
No significant correlation was found between the performance of both crops and the RLD of weeds (Table 3.19). The RLD of millet was not correlated with its performance in association with baobab and *nééré* (Table 3.20). In contrast, positive correlation was found between the RLD of taro at the 30-40 cm soil-depth and the performance of the crop in association with baobab while in the top soil (0-10cm), only the LAI of taro was positively correlated with the RLD of the crop (Table 3.21). In the association with *nééré*, the RLD of taro at the 10-20cm soil-depth was only negatively correlated with the LAI of the crop. The coefficient of correlation was positive in the topsoil but was negative in the soil-depth lower than 0-10 cm (Table 3.21).



Legend : —●— Baobab —■— Millet —▲— Taro —◆— Weeds

—●— Néré —■— Millet —▲— Taro —◆— Weeds

Fig. 3.17 : Root length density (RLD) of millet, taro, weeds and the associated trees (baobab and néré) according to the zones at Nobéré (2007)



Legend :
 —●— Baobab -■- Mil -▲- Taro -◆- Weeds —●— Baobab -■- Mil -▲- Taro -◆- Weeds

Fig. 3.18 : Root weight density (RWD) of millet, taro, weeds and the associated trees (baobab and néré) according to the zones at Nobéré (2007)

Table 3.17 :Pearson's correlation between RLD of baobab and the performance of millet and taro

		RLD of baobab				
Depth		0-10 cm	10-20 cm	20-30 cm	30-40 cm	40-50 cm
Millet	LAI	0.37 ns	0.14 ns	-0.08 ns	-0.11 ns	-0.20 ns
	Yield	0.35 ns	-0.18 ns	-0.21 ns	-0.30 ns	-0.28 ns
	Dry matter	0.13 ns	-0.23 ns	-0.30 ns	-0.10 ns	-0.23 ns
Taro	LAI	-0.13 ns	-0.20 ns	-0.26 ns	0.07 ns	0.18 ns
	Yield	-0.06 ns	-0.28 ns	-0.28 ns	0.02 ns	0.33 ns
	Dry matter	0.07 ns	-0.06 ns	-0.06 ns	0.15 ns	0.37 ns

n=32

Table 3.18 :Pearson's correlation between RLD of néré and the performance of millet and taro

		RLD of néré				
Depth		0-10 cm	10-20 cm	20-30 cm	30-40 cm	40-50 cm
Millet	LAI	0.34 ns	0.01 ns	-0.07 ns	0.10 ns	-0.12 ns
	Yield	-0.31 ns	-0.40 ns	-0.30 ns	-0.36 ns	-0.06 ns
	Dry matter	-0.40 ns	-0.51*	-0.480 ns	-0.43 ns	-0.21 ns
Taro	LAI	0.60**	0.36 ns	0.12 ns	0.17 ns	0.48 ns
	Yield	0.54*	0.54*	0.34 ns	0.46 ns	0.56*
	Dry matter	0.60*	0.53*	0.26 ns	0.31 ns	0.49 ns

n=32 * = P < 0.05 ** = P < 0.01 and ***= P < 0.001

Table 3.19 :Pearson's correlation between RLD of weeds and the performance of millet and taro

		RLD of weeds				
Depth		0-10 cm	10-20 cm	20-30 cm	30-40 cm	40-50 cm
Millet	LAI	-0.25 ns	0.24 ns	-0.24 ns	-0.08 ns	-0.10 ns
	Yield	0.27 ns	0.25 ns	0.23 ns	-0.03 ns	-0.08 ns
	Dry matter	0.11 ns	0.08 ns	0.00 ns	-0.15 ns	-0.08 ns
Taro	LAI	-0.02 ns	0.01 ns	-0.11 ns	-0.12 ns	-0.26 ns
	Yield	0.28 ns	0.36 ns	0.40 ns	0.06 ns	-0.16 ns
	Dry matter	0.35 ns	0.21 ns	0.44 ns	0.20 ns	-0.34 ns

n=32

Table 3.20 :Pearson's correlation between RLD of millet and the performance of the crop

		RLD of millet				
	Depth	0-10 cm	10-20 cm	20-30 cm	30-40 cm	40-50 cm
Baobab	LAI	0.36 ns	0.17 ns	0.15 ns	-0.33 ns	-0.25 ns
	Yield	0.29 ns	0.14 ns	0.06 ns	0.01 ns	0.07 ns
	Dry matter	0.11 ns	0.01 ns	-0.06 ns	-0.14 ns	-0.08 ns
Néré	LAI	-0.23 ns	0.04 ns	-0.23 ns	-0.11 ns	-0.06 ns
	Yield	0.35 ns	-0.03 ns	0.24 ns	-0.07 ns	0.17 ns
	Dry matter	0.41 ns	0.08 ns	0.44 ns	0.16 ns	0.24 ns

n=32

Table 3.21 :Pearson's correlation between RLD of taro and the performance of the crop

		RLD of taro				
	Depth	0-10 cm	10-20 cm	20-30 cm	30-40 cm	40-50 cm
Baobab	LAI	0.59 *	0.07 ns	0.12 ns	0.55*	0.43 ns
	Yield	0.41 ns	0.01 ns	0.32 ns	0.69 **	0.51 ns
	Dry matter	0.37 ns	0.13 ns	0.38 ns	0.56 *	0.34 ns
Néré	LAI	0.16 ns	-0.51*	-0.40 ns	-0.40 ns	-0.44 ns
	Yield	0.17 ns	-0.35 ns	-0.11 ns	-0.36 ns	0.01 ns
	Dry matter	0.08 ns	-0.27 ns	-0.13 ns	-0.19 ns	0.09 ns

n=32 * = P < 0.05 ** = P < 0.01

3.4. Discussion

3.4.1. Crop LAI and plant height

As reported in previous studies, plants usually adapt to shade by increasing their total leaf area and number of leaves (Caesar, 1980; Wong, 1991; Wilson *et al.*, 1998 and Lin *et al.*, 2001). In the present study, an increase in leaf area index (LAI) of both crops was observed under tree crowns compared to the control. The highest LAI of taro was found in the areas with most shade: within zones A and B of *nééré* trees and zone A of the baobab trees. Johnston and Onwueme (1998) observed a similar result of the effect of shade on leaf area of taro. In contrast, the highest LAI of millet was recorded in zone C of the baobab trees while LAI of millet in all zones under *nééré* was similar to the control plot.

A positive linear relationship between LAI and light interception, which was directly related to crop performance, was reported by Ewert (2004) and Monteith (1977). LAI of taro was increased under shade as part of the plant's strategy to enable it to intercept more light and consequently it was able to grow better under shade. In contrast, millet did not show clear differences in LAI under shaded and open areas, suggesting the absence of an adaptation strategy of the crop to shade condition.

The main difference between zones in height of millet was observed at the end of each growing season. Millet plants in zones B and C were the tallest under baobab while plants in zone A were the shortest under *nééré*. Therefore, millet's growth performance was negatively affected by the heavy shade in zone A around tree trunk, as it was a shade-intolerant crop. In contrast to millet, the shade of both tree species had a positive effect on the height of taro plants. In addition, the difference in height between shaded plants and plants in open area was more noticeable under *nééré*.

3.4.2. Crop yield and dry matter production

Yield of millet recorded in the open area of the present study ($595 \pm 83.43 \text{ kg ha}^{-1}$) was within the range of values recorded in Saponé (Burkina Faso) by Bayala *et al.* (2002) but lower than the average national yield of 934 kg ha^{-1} in 2007 reported by MAHRH (2007). The higher

national average of millet yield is mainly due to the better performance of millet in the Southwest, Haut-Bassins and Cascades regions of the country (1151 kg ha⁻¹, 1353 kg ha⁻¹ and 1909 kg ha⁻¹, respectively) where soils are more fertile and rainfall is higher compared to the rest of the country (MAHRH, 2007).

The yield of taro in the open area (2337 ± 617.04 kg ha⁻¹) was low compared to the worldwide average yield of 6000 kg ha⁻¹ cited by previous workers (Onwueme, 1991; Goenaga, 1995; Goenaga and Chardon, 1995). The low performance of taro in the present study could be attributed to unfavourable site conditions in the parkland of the present study area, such as low soil fertility and water availability (Caesar, 1980; Bussel and Bonin, 1998). In addition, taro has a variable growing period, up to 18 months in the wet lands and less than 6 months in the dry lands (Kay, 1987) that result in a highly variation of its corms yield from less than 1000 kg ha⁻¹ to 75 000 kg ha⁻¹ (Kay, 1987; O'Hair, 1990; Onwueme, 1999; Tumuhimbise *et al.*, 2009).

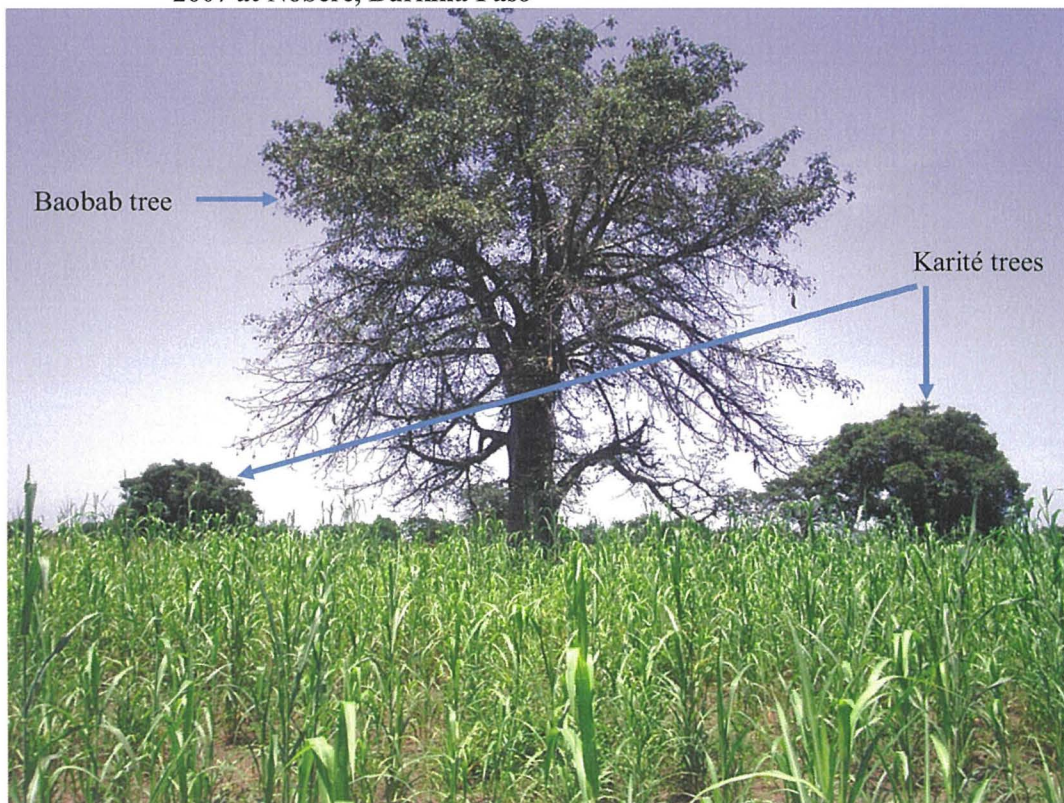
Millet performed better in terms of yield and total dry matter production under baobab compared to its performances under néré and in the open field. Similar observations were made by Kater *et al.* (1992) and Bayala *et al.* (2002) who reported that millet yield decreased from the open area to the trunk of néré trees because of the effect of shade. Millet yield in zone C of baobab was nearly twice as high as the yield recorded in zone C of néré (860.7 ± 89.25 kg ha⁻¹ and 469.6 ± 74.22 kg ha⁻¹, respectively). The high yield of millet under baobab may be due to the early leaf fall (August) in baobab which increased light availability under the tree crowns between September and October (see plate 3.3). This period corresponds to the millet reproductive stage during which, according to Bieler (1992) cumulative assimilation rate increases which leads to high crop yield. Therefore, the improvement of light availability combined to improved soil fertility in zones B and C of baobab resulted in better millet yield. However, total dry matter production of millet was similar under both tree species; only the total dry matter in zone A was lower compared to the control plot.

In contrast, the best performance (yield and total dry matter) of taro was obtained under néré. Yield and total dry matter production of taro under baobab was higher only in zone A compared to the control plot while under néré, taro performed better in zones A and B compared to the control plot. Therefore, the performance of taro, being a shade tolerant plant,

was enhanced due to the favourable microclimate created by heavy shade while its weak performance in the open field could be related to its C3 photosynthesis pathway. Indeed, the performance of the C3 plant (taro) was decreased by the additional energy loss through the increase of photorespiration because of the high temperature and light saturation in the open field as previously reported in C3 plants (Yang *et al.*, 2004; Hay & Porter, 2006; Osborne *et al.*, 2008).

The performance of taro in the present study was similar to the results obtained by Rogers & Iosepha (1993) while Caesar (1980) reported 20% reduction of corm yield due to shade and water stress. These contradictory results could be due to the difference in study site conditions. In the study site of Caesar (1980), temperature and light at noon were 29.2°C and 160000 lux ($\approx 2500 \mu\text{mol m}^{-2}\text{s}^{-1}$) in the open while in the present study the maximum values of these parameters were 38.2°C and $1619.4 \mu\text{mol m}^{-2}\text{s}^{-1}$ reported in Chapter 4.

Plate 3.1. View of a parkland showing baobab leaf fall on 16 September 2007 at Nobéré, Burkina Faso



Photograph: SANOU Josias

3.4.3. Crop photosynthesis

3.4.3.1. *Photosynthetic maximum quantum conversion yield*

The values of the maximum quantum conversion yield (Y) of both crops were lower than the reference value of 0.83 reported for non-stressed plants (Bjorkman and Demming, 1987). The result shows that both crops were stressed under both tree species. The stress may be due to unfavourable environmental conditions such as drought (Yordanov *et al.* 2000; Winkel *et al.*, 2002), high temperature (Yu and Ong, 2002; Wang *et al.*, 2003) and low level of light (Jiang and Zhu 2001, Peng and Gilmore 2003) (see Chapter 4 for details).

The values of Y recorded on the first date of measurement were higher compared to the values of the second date of measurement for both crops. The first date of measurement occurred when rain was still regular, while on the second date, rain was scattered and of low intensity. So, the lower values of Y on the second date could be mainly due to lack of soil water on the second date compared to the first date. The higher Y values of both crops in the shaded zones under trees could be explained by relatively lower temperature under shade. High temperatures are known to cause stress to plants (Yu and Ong, 2002 and Wang *et al.*, 2003). On the second date, the combination of temperature and water stresses may be the cause of the decrease of Y values from the tree trunk, where temperatures are low and soil moisture was high, to the open area with high temperature and low soil moisture content (see details in Chapter 4). Plate 3.4 shows the stress gradient of taro plants from the open field to the trunk of tree.

3.4.3.2. *Net photosynthesis*

The diurnal trend of net photosynthesis (P_N) of both crops in the control plot showed no peak as also noted in a previous study by Boegh *et al.* (1999). As shown above by the results of the maximum quantum conversion yields, both crops were stressed in all zones. Stressors of plants in parklands that could limit photosynthesis are mainly high temperature, water deficit and lack of nutrients, all of which were high in the control plot in the present study area. The peak of P_N was expected around noon when daylight intensity was optimum, but at this time, temperature was also high and top soil moisture was reduced compared to the morning. So,

these two unfavourable factors could explain for the lack of a peak in the diurnal course of P_N in the control plot.

The average P_N of millet ($24.3 \pm 5.01 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) recorded in the control plot in the present study was within the range of values of 4.4 to $62.94 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ reported by previous studies (Mac Pherson, 1973; Warner and Edwards, 1988; Masojidek *et al.*, 1991; Tewolde *et al.*, 1993; Boegh *et al.*, 1999). The average P_N of taro in the control plot ($13.8 \pm 1.18 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) was also within the range of values reported by Sugimoto *et al.* (1997), Sato *et al.* (1978) and Schaffer and O'Hair (1987), (4.1, 12.62 and $30.93 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, respectively).

The daily net photosynthesis rate of both crops increased away from the tree trunk to the open area, showing that the photosynthesis of both crops was limited by PAR availability under tree crowns. However, the daily rate of net photosynthesis in taro was less affected in the shaded area than millet. Therefore, in contrast with zones of the open field, the daily net photosynthesis of taro in the shaded zones (A and B) was comparable to the value recorded for millet. The maintenance of such net photosynthesis levels requires adaptation of the photosynthesis system of taro plant to shade as reported by Onwueme (1998) and Onwueme and Johnston (2000).

An increase in chlorophyll content per unit area as observed by Johnston and Onwueme (1998) and an increase in stomatal density as observed by Onwueme and Johnston (2000) may have also occurred in taro under shade. In the present study, it was observed that minimum stomatal conductance of taro was the same in shaded zones and in the open field while the minimum stomatal conductance of millet decreased with an increase in shade. It may be concluded that taro, through such an adaptation, increased its efficiency of PAR capture in the shaded area. Indeed, the results of the analysis of the radiation use efficiency (RUE_i) of taro showed a decrease from the tree trunk to the open area while no variation was observed in millet between zones. The increase in RUE_i of taro may have helped it to avoid a drastic reduction of net assimilation production in shade conditions.

The mean daily net assimilation increased for millet from tree trunk to the open field while higher value of mean daily net assimilation was found for taro associated with baobab in zone A and no difference was noted between zones under *néré*. This high net assimilation per unit

land area by taro plant was also made possible by the increase in the crop leaf area index in the shaded zones. Therefore, the increase in leaf area in the shaded area may have allowed taro to accumulate more daily assimilate per plant than millet. These results confirm that taro was better adapted to the conditions under tree shade than millet.

The WUE_i values of both crops were lower in shaded areas (zone A and B) compared to zone C and control plot and WUE_i value of taro was lower than that of millet. The low WUE_i values in shaded zones indicate that both crops lost more water per unit PAR captured perhaps due to more open stomata. The result of the stomatal conductance indicates that taro had more open stomata than millet in all zones because higher stomatal conductance indicates higher number of open stomata. The number of open stomata in millet leaves increased from the tree trunk to the control plot while the number did not vary between zones in taro. These results indicate that taro in shaded zones maintained a high number of open stomata to harvest more CO_2 , but at the same time also lost more water as a result of the open stomata. The similar open stomata number of taro leaves in the open area and under shade could be an expression of the stresses due to high irradiance, high temperature and low soil moisture in the open field. In contrast, millet had fewer open stomata and less transpiration in shaded areas and captured less amount of PAR. The increase in WUE_i of millet from the tree trunk to the open indicates that WUE_i in millet increased with an increase in environmental stress and this was in accordance with the findings of Singh and Singh (1995) who showed that WUE_i of millet increased with an increase in water stress.

Accordingly with the behaviour of taro under shade condition reported by Johnston and Onwueme (1998) and Onwueme and Johnston (2000), the morphological and anatomical adaptations of the crop to shade resulted in a better performance of taro than millet in the shaded area under tree crowns. Indeed, the strong and positive correlation between taro performances (plant height, LAI, yield and dry matter production) and RUE_i and mean daily net assimilation shows a strong adaptation of taro to shade. In contrast, the negative correlation observed between RUE_i and millet performances may also indicates that millet was indeed shade-intolerant. Contrary to RUE_i , WUE_i of taro was negatively correlated with its growth parameters. Therefore, taro production in open area seems to be limited by water availability as also observed by Caesar (1980) who noted the importance of light and water in taro production (see plate 3.4).

3.4.4. Root distribution of tree species, crops and weeds

Root length density (RLD) and root weight density (RWD) of baobab and néré decreased with soil depth. A similar observation was made by Bayala (2002) on karité and néré. RLD and RWD of crops and weeds showed the same trend. Therefore, the fine roots of tree species, crops and weeds were concentrated in the top soil (0-20 cm). RLD of both tree species was the same in zones under tree crowns but their RWD decreased with distance from the tree trunk. RLD of trees was not significantly different in zones A, B and C, although a trend of decrease from A to C was noticeable. Such results were reported in previous works by Odhiambo *et al.* (2001) and Bayala (2002). RLD and RWD of millet, however, increased from the tree trunk to the open area and this observation was in close agreement with the findings by Odhiambo *et al.* (2001).

The absence of significant correlation of the RLD of baobab with the performance of both crops suggests an absence of competition between the tree species and the crops. In contrast, the RLD of néré was negatively correlated with millet total dry matter production and a positive correlation with the performance of taro in the topsoil. This result suggests a possible competition between néré and millet and an absence of competition between and taro néré for water and nutrients. The positive correlation between taro performance and the RLD of néré could be due to the niche differentiation that occurred between fines roots of néré and taro.

Weeds roots were found in all zones despite the weedings in all plots of the trial. This result is due to the manual weeding used traditionally by farmers that consists of removing the above ground part of weeds using a hoe. Therefore, some weeds species grow again from the remaining roots. This ability of some weeds species to grow from roots could explain why RLD and RWD of weeds increased from the area under tree crown to the open field. Indeed, Boffa (1999) stated that there is a selective effect of tree shade on weeds species, which according to Breman and Kessler (1995) results in more C4 species in the open area and more C3 in the area under tree. In addition, Rao *et al.* (1998) observed that the effect of tree crown results in a reduction of weeds density and in both perennial rhizomes and seed bank under tree.

In sum, the manual weeding used in the plots did not eliminate the possibility of competition between crops and weeds roots. In addition, there was potentially more competition between crops and weeds roots in the open area and the competition may be more drastic for taro plants as the RLD and RWD of the crop were lower compared to weeds.

Plate 3.1. The gradient of the stress due to temperature and soil water content on taro plants from the open field to the trunk of néré tree at Nobéré, Burkina Faso (2008)



Photograph: SANOU Josias

CHAPTER 4: BIOPHYSICAL FACTORS UNDER TREES AND THEIR RELATIONSHIPS WITH THE PERFORMANCE OF ASSOCIATED CROPS

4.1. Introduction

Several previous workers reported changes in microclimate parameters under trees compared to the conditions in the open field (Ong *et al.*, 1996; Rao *et al.*, 1998; Boffa, 1999; Bayala, 2002; Ong and Swallow, 2003; Noordwijk *et al.*, 2004). The microclimate due to tree presence was characterised by lower solar radiation reaching the soil, lower air and soil temperature, higher air and soil moisture compared to conditions in the open field (Boffa, 1999). The reduction of sunlight under tree crowns, which varied with tree architecture according to Breman and Kessler (1995) and Bellow and Nair (2003), resulted in a decrease of temperature that reduced evaporation under tree crowns.

In semi-arid agroforestry parkland systems, the reduced temperature and increased soil moisture under trees was favourable to plants growing under tree crowns (Boffa, 1999). In contrast, light reduction under tree can result in slower development of plants growing under trees unless they are shade-tolerant. The presence of trees in agroforestry parklands induced a change in plant community structure in the system where only shade-tolerant species thrived under tree crowns. For example, Breman and Kessler (1995), Rao *et al.* (1998) and Boffa (1999) observed differences in weeds floristic composition between areas under tree crowns and in the open field in their studies.

A number of studies have identified an increase in soil organic matter content under tree crowns (Breman and Kessler, 1995; Soumaré, 1996; Young, 1997; Garcia-Barrios and Ong, 2004). The combination of high organic matter and increased moisture content of soil under trees resulted in an increase in soil fauna populations (Rhoades 1997; Buresh and Tian, 1998 and Boffa, 1999). An increase in soil fauna resulted in increased macro-porosity of soil under trees which improved soil aeration and water infiltration. Plants growing under tree crowns may benefit by having a better roots development than those growing in the open field.

In the present study, biophysical factors under baobab and néré were assessed to determine their impacts on the performance of millet and taro. Therefore, the following four null hypotheses were tested in this study:

- 1- Light interception by baobab and néré is similar and has no effect on the performance of millet and taro
- 2- Transpiration rate by baobab and néré is similar and has no effect on the performance of millet and taro
- 3- The physical and chemical properties of soil under the crowns of baobab and néré and in the open field are similar and have no effect on the performance of millet and taro
- 4- The root systems of taro and millet under trees are similar and compete more efficiently for water and nutrient with the roots of trees and weeds.

4.2. Materials and methods

4.2.1. Light interception by tree

Photosynthetically active radiation (PAR) was measured during three cropping seasons (2006 - 2008) using Delta T quantum sensors (Delta T Ltd, UK) (see Plate 4.1). Data from these sensors were continuously logged at 10 minutes intervals using a Delta T data logger (DL2e, Delta T Ltd, UK). The measurements of PAR under each tree were made at three positions corresponding to the three concentric zones described in the experimental design in Chapter 3, and at one location in the open area as a reference measurement. To select the measurement points, each concentric zone was subdivided into 16 smaller grids and the location of sensors in these grids was determined by means of random numbers. The measurement under each tree lasted for 96 hours. After four days of monitoring, the equipment was moved to another tree of the other species. This continued until all the sample trees were measured for the both tree species. Then, the equipment was shifted to the first tree where the measurement started for a new cycle. These measurement cycles were repeated for all the 16-studied baobab and néré trees during each cropping season from May to November. To measure the amount of light incident on the associated crop layer accurately, the light sensors were raised from the ground progressively with the growth of crop plants.

4.2.2. Tree transpiration

Trees transpiration was estimated through their sapflow (SF) using Thermal Dissipation

Probes (TDP) (Delta T Ltd, UK) (see Plate 4.1). TDP is an improved heat dissipation sensor, which measures the temperature difference (dT) between a heated needle implanted in the sapwood of a tree and a second needle at the sapwood temperature located below (Granier, 1985). The temperature difference is used to calculate sap flux density (SFD, $\text{cm}^3 \text{cm}^{-2} \text{s}^{-1}$) using the equation 4.1 proposed by Granier (1987). Finally, the sapflow ($\text{cm}^3 \text{s}^{-1}$) is computed multiplying the sap flux density by the sapwood cross-sectional area (cm^2) of the tree trunk at the height of heated probe see equation 4.2 (Granier, 1987).

Three installation points were prepared at 60° intervals around the stem of each tree and at 1.5 m above the ground. The TDP needles of 8 cm length were inserted in the trunk and each TDP set up was insulated against solar radiation, wind and rain by covering it with aluminium foil. The readings were taken at a minute intervals and a 30-minute average was stored in the data logger. The measurement on each tree lasted for 96 hours and these were taken simultaneously with the measurement of PAR described above. To estimate the natural thermal flux occurring in the morning and at sunrise, measurement on the first day of the four days was made without heat supply. During the next three days, energy supply was provided. The data for those three days were corrected by subtracting from them the value of the first day measurement that was due to natural thermal flux (Bayala, 2002). The measurements were made during the whole cropping season from May to November from 2006 to 2008.

$$\text{SFD} = 119 \times 10^{-6} \left(\frac{dT_{\text{max}} - dT}{dT} \right)^{1.231} \quad (\text{Equation 4.1})$$

where SFD = sap flux density, dT_{max} = temperature difference when there is no flow (SFD=0), dT = temperature difference

$$\text{SF} = \text{SFD} \times S_A \quad (\text{Equation 4.2})$$

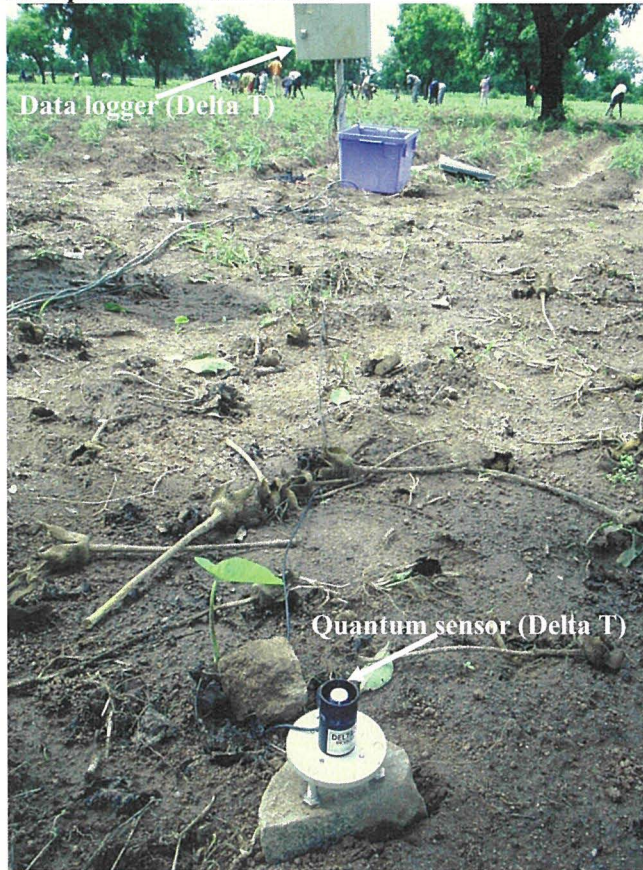
where SF = sapflow and S_A = sapwood cross-sectional area.

The sapwood cross-sectional area (cm^2) of each trunk of the eight baobabs and eight néré was estimated to calculate the sapflow as shown in equation 4.2. A core was extracted from each trunk using a drill at the same level where TDP probes were installed. From this the depth of the sapwood (L_{sw} , cm) was measured and the sapwood cross-sectional area was estimated using equation 4.3.

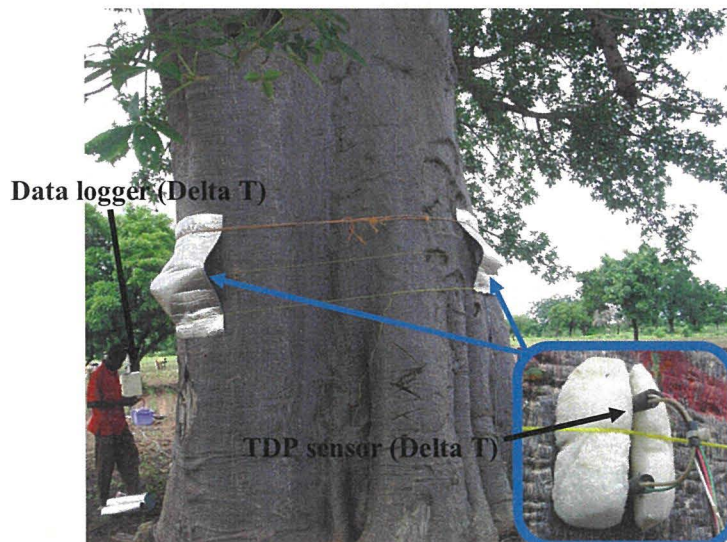
$$S_A = \pi L_{\text{sw}} (R - L_{\text{sw}})$$

where S_A = sapwood cross-sectional area, R = radius of the trunk at 1.5 m above ground and L_{sw} = length of the sapwood

Plate 4.1. Apparatus for photosynthetically active radiation (PAR) and transpiration measurement



a. Measurement of PAR using delta T quantum sensors



b. Measurement of transpiration using Thermal Dissipation Probes (TDP)

Photographs: SANOU Josias

4.2.3. Soil physical and chemical properties

4.2.3.1. Soil texture and chemical properties

Soil samples were randomly taken at two points in each concentric zone and in the control plot at depths of 0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm and >60 cm. Two samples were taken at each depth and in the same zone were mixed, so there was a total of 20 composite samples per tree for analyses of soil physical and chemical properties. The samples were air dried and sent to the laboratory of the Bureau National des Sols (BUNASOL), Burkina Faso, for analysis of the following soil properties. The percentage content of clay, sand and silt were assessed for each sample using the Robinson pipette method on sieved soil (<2mm) dried at 105°C (as described in Mathieu and Pieltain, 1998). Total carbon and organic matter content were determined using the Walkley-Black method (as described in Allison, 1965). The Kjeldahl method was used to assess the total nitrogen content and acid mineralization was used to determine the total phosphorus content (Houba *et al.*, 1985). Silver thiourea attraction was used to assess the level of available phosphorus, total potassium, calcium ions (Ca^{++}), magnesium ions (Mg^{++}), potassium ions (K^+), sodium ions (Na^+) while the cation exchange capacity (CEC) was assessed according to the method described by Walinga *et al.* (1989).

4.2.3.2. Soil water infiltration

Infiltration measures were made during the dry season (February 2007) using two tension disc infiltrometers: model SW 080 and model SW 080 B (SDEC, Paris, France). The SW 080 infiltrometer has a disc diameter of 8.255 cm and the SW 080 B a disc diameter of 20 cm. Three tensions of water pressure, -10 cm, -5 cm and 0 cm (1, 0.5 and 0 kPa, respectively), were applied to the contact surface between the disc and the soil. The soil surface was levelled and covered with a thin layer of wetted clean sand (Plate 4.2). The measurements were made at two positions in each of the three concentric zones under trees and in the control plot for the three pressure heads, starting with the lowest. Measurements were replicated twice for each pressure and zone.

The volume of infiltrated water was recorded as a function of time from the beginning of measurement to the end; the steady infiltration rate was determined as the slope of the

regression of infiltrated water volume by time. The steady infiltration rate was used to calculate the hydraulic conductivity according to Wooding's equation:

$$Q = K \left[1 + \frac{4}{\pi r \alpha} \right] \text{ (Equation 4.3),}$$

where r (mm) is the disk radius, Q (mm h^{-1}) the steady infiltration rate, K (mm h^{-1}) the hydraulic conductivity and α is a constant dependent on soil porosity (Wooding, 1968).

According to Gardner (1958) there is an exponential relationship between hydraulic conductivity ($K(h)$) at the applied pressure head (h) and saturated hydraulic conductivity (K_{sat}):

$$K(h) = K_{sat} \exp(\alpha h) \text{ (Equation 4.4)}$$

The calculation of K_{sat} requires the measurement of infiltration for at least two pressure heads (h_1 and h_2). The following equations were derived from equations (4.3) and (4.4):

$$Q(h_1) = K_{sat} \exp(\alpha h_1) \left[1 + \frac{4}{\pi r \alpha} \right] \text{ (Equation 4.5)}$$

$$Q(h_2) = K_{sat} \exp(\alpha h_2) \left[1 + \frac{4}{\pi r \alpha} \right] \text{ (Equation 4.6)}$$

where $Q(h_1)$ is the steady-state infiltration rate at the applied pressure head h_1 .

The constant α could be calculated dividing equation 4.5 by 4.6:

$$\alpha = \frac{\ln\left(\frac{Q(h_1)}{Q(h_2)}\right)}{(h_1 - h_2)} \text{ (4.7)}$$

Two values of α were calculated: α_1 between pressure heads of -10cm and -5cm and α_2 between pressure heads of -5m and 0cm.

K_{sat} was calculated using equations (4.5) or (4.6) with the α calculated from equation (4.7), the pressure heads h_1 and h_2 fixed and the corresponding Q measured. Finally, the hydraulic conductivity K was calculated using equation (4.4) and the parameters α and K_{sat} associated with each of the applied pressure heads.

Plate 4.1. Measurement of soil infiltrability using an infiltrometer SW 080 (SDEC, France)



Photograph: Casimir GARBA

4.2.3.3. *Soil moisture content*

Soil water content was determined gravimetrically with samples immediately weighed in the field. Then samples were oven dried at 105°C for 24 hours to obtain dry weights. Soil water content was calculated as the difference between the wet and the dry weights and expressed as a percent of the wet weight.

The sampling was carried out once in the dry season and twice during the wet season of 2007. In the dry season, two samples were taken, the first when a water infiltration of 0 cm pressure head after steady infiltration was obtained. The second sampling in the dry season was done close to the infiltration measurement point where soil was not watered. The two sampling periods during the wet season were in September when rainfall was of low intensity and intermittent (116.4 mm for 9 rainy days). The first sampling was on 18/09/2007 and the second on 29/09/2007. At each sampling time, two soil samples were collected in each zone of the 16 studied baobab and néré trees giving a total of 32 samples per zone and 128 samples per sampling time.

4.2.4. Data analysis

Data were analysed as noted in section 3.2.4 with regard to the systematic arrangement of the concentric zones around tree. Therefore, the ANOVA General Linear Model (GLM) was used to analyse the variation of data according to cropping years, tree species and crops while a pairwise t-tests was used to test the variation between concentric zones and the control plot using modules of the software Minitab 15 (Minitab Inc., USA). After a GLM analysis, means were compared using Tukey's test at a confidence level of 95%. The t-tests were performed assuming that the difference between the two zones compared was equal to zero and this hypothesis was rejected in case of a significant result of the test.

As crops performance is determined by many factors including physiological parameters and biophysical parameters, multiple linear regressions were used to estimate the best-fitted relationship between crop performance and the physiological and biophysical parameters. The best subsets module of regression was run in Minitab 15 to explain the three years average total dry matter production and yields of millet and taro by the RUE_i, WUE_i and RLD of millet and taro, soil properties (contents of OM, N, P, K and water, hydraulic conductivity), the transpiration rate of baobab and néré. The best predictors, which give the highest r^2 , were used in a regression to test if their relationship with crops performance was significant. The distribution of the residuals of the model was checked. The t-test on predictors was examined and when there was no significant evidence that the coefficient of a predictor was not zero ($p < 0.05$) and if by removing the predictor, r^2 did not significantly decrease, then the predictor was removed from the model.

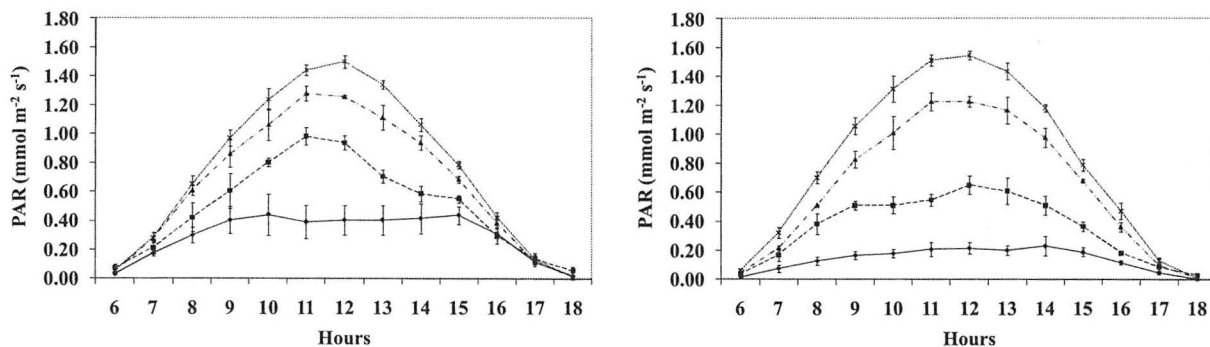
4.3. Results

4.3.1. Light interception by the crown of baobab and néré

Photosynthetically active radiation (PAR) did not vary between cropping years but was significantly different between trees species ($P < 0.01$) and the hours of the day ($P < 0.001$). The diurnal course of PAR in each zone under baobab and néré is shown in figure 4.1.

The average PAR recorded per day in the open area was 67.78 mol m^{-2} for the three cropping years (2006, 2007 and 2008). PAR was more reduced under néré (83%, 55% and 18%, in zones A, B and C, respectively) compared to the values under baobab (62%, 38% and 15%, in the zones A, B and C, respectively) (Fig. 4.1).

The highest PAR was recorded between 11 am to 12 noon under both tree species in zones B, C and H, while in zone A, PAR level remained constant from 8 am to 3 pm ($0.40 \text{ mmol m}^{-2} \text{ s}^{-1}$ and $0.19 \text{ mmol m}^{-2} \text{ s}^{-1}$) for Baobab and Néré, respectively (Fig. 4.1).



a- PAR recorded under Baobab tree

b-PAR recorded under Néré tree

Legend : \rightarrow Zone A \dashrightarrow Zone B \dots Zone C \dashrightarrow Zone H

Fig. 4.1 : Diurnal course of average PAR ($\text{mmol m}^{-2} \text{ s}^{-1}$) received under baobab and néré trees compared to the open area (Zone H) on 2006, 2007 and 2008 at Nobéré (Burkina Faso)

4.3.2. The physical and chemical properties of soil

4.3.2.1. The textural and chemical contents of soil

There was no significant difference in soil texture (% clay, % silt and % sand) between the tree species. Clay and sand content varied significantly according to soil layer ($P = 0.001$ and $P = 0.003$, respectively) but no variation was noted for silt content. Clay content increased from top layer to the layer of 40-50 cm, while sand content decreased with soil depth (Fig. 4.2.). There was no significant variation between zones according to the pairwise t-tests. The average contents were 11.52, 20.10 and 68.39%, for clay, silt and sand, respectively. The texture of the soil was sandy loam according to FAO classification.

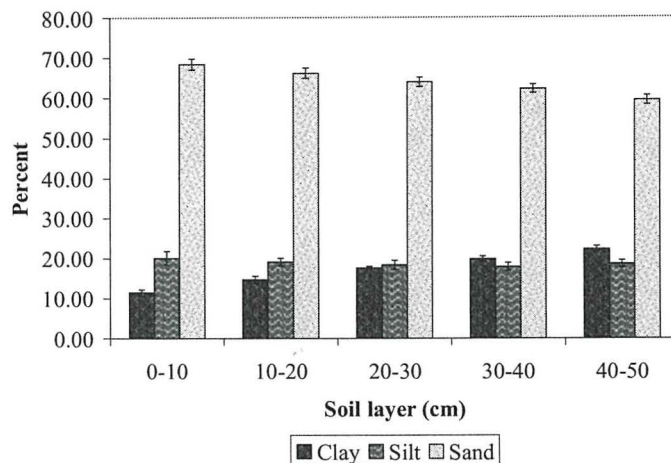


Fig. 4.2 : Clay, silt and sand contents in soil layers of 0-10, 10-20, 20-30, 30-40 and 40-50 cm in a parkland at Nobéré (2007)

The organic matter and chemical contents of soil were influenced by the two species of trees. Soil organic matter content decreased from the trunk of the both tree species to the open area (Fig. 4.3.). The contents of N, P, K and cation exchange capacity in soils under baobab trees (zones A and B) were higher compared to the soil of the control plot. Cation exchange capacity of soils decreased from néré tree trunks to the open while the contents of N and K were higher in zone A of néré trees compared to the control plot. The pH of soil was lower in the control plot compared to zone A of both tree species (Fig. 4.3.). With the exception of the top layer of zone A (10 cm for néré trees and 20 cm for baobab) where the pH was neutral, all the soils pH were acidic under both tree species and in the open area.

With regard to tree species, the total phosphorus content was higher under baobab trees (187.20 ppm) compared to néré trees (106.45 ppm) and soils under néré trees were more acidic (pH=6.26) compared to soils under baobab trees (pH=6.78).

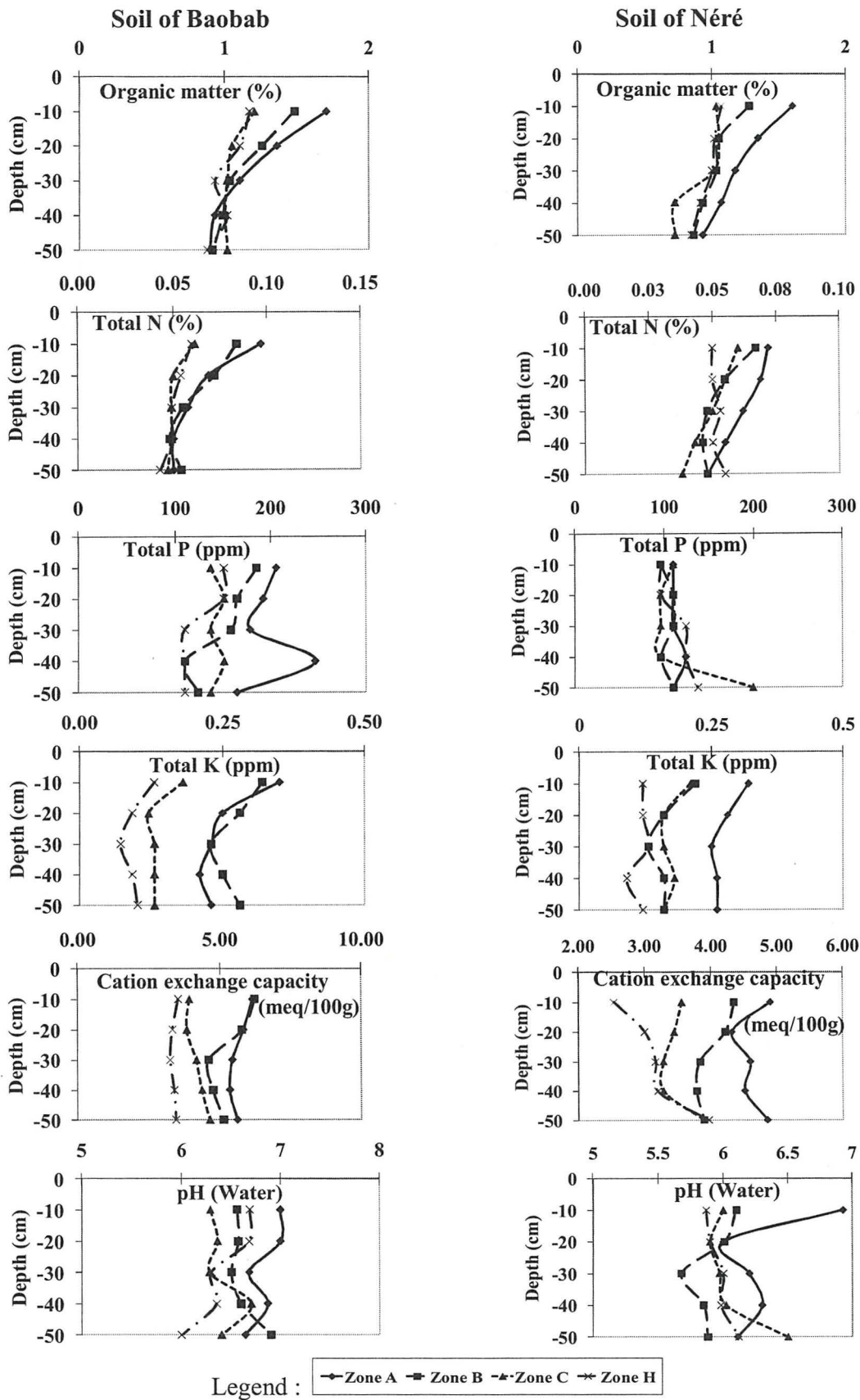


Fig. 4.3 : Organic matter and chemical content of soils as a function of the depth and zone (Nobéré, Burkina Faso: 2006)

4.3.2.2. Soil infiltrability

At the three tensions (-10, -5 and 0 cm), the steady-state infiltration rates (Q) were not significantly different between trees species. There was also no significant difference between zones at tension head 0 but at tensions -5 and -10 cm, Q values were higher in zone C compared to zones A and B under both species. The general trend in Q values was a decrease from zone C to the tree trunks (Table 4.3).

The saturated hydraulic conductivity (K_{sat}) was not significantly different between tree species. The average value for all zones of both species was $65.67 \pm 13.56 \text{ mm h}^{-1}$. K_{sat} values in zone A were lower compared to the values in zones B and C and the control plot (Table 4.3).

The hydraulic conductivity (K) value did not vary according to tree species at the three tension heads. K values decreased from zone C to zone A at the three tension heads (Fig. 4.4). As shown on figure 4.4, K values in zone C at tension - 10 cm were also significantly higher compared to the control plot ($17.12 \pm \text{mm h}^{-1}$ and $12.27 \pm 1.33 \text{ mm h}^{-1}$, respectively).

Table 4.1 : Steady-state infiltration rate (Q, mm h-1) and saturated hydraulic conductivity (Ksat, mm h-1) for the concentric zones under baobab (*Adansonia digitata*) and néré (*Parkia biglobosa*) trees and in the control plot at different tension heads (-10 cm, -5 cm and 0 cm), Nobéré, Burkina Faso (2007)

Zones	Tension heads			$K_{sat} \pm SE$
	-10 cm	-5 cm	0 cm	
	Q \pm SE	Q \pm SE	Q \pm SE	
A	26.09 \pm 4.25	43.45 \pm 5.94	163.50 \pm 23.93	39.77 \pm 8.36
B	30.97 \pm 3.49	57.41 \pm 5.07	171.58 \pm 16.48	75.88 \pm 20.86
C	36.62 \pm 3.74	70.71 \pm 5.29	178.30 \pm 17.21	74.76 \pm 10.59
H	26.06 \pm 3.33	56.59 \pm 6.03	173.57 \pm 20.41	72.28 \pm 14.42

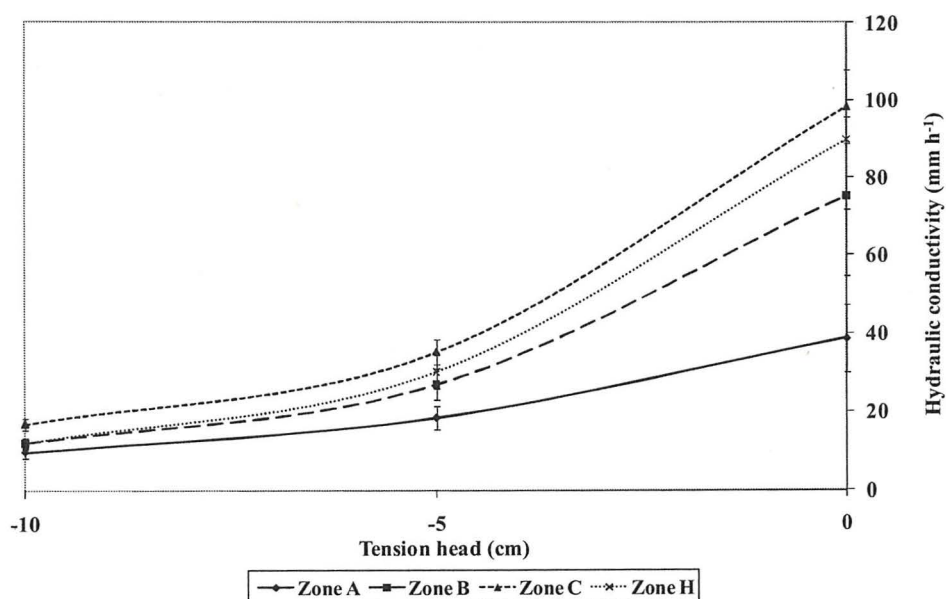


Fig. 4.4 : Hydraulic conductivity (K , mm h^{-1}) as function of tension heads in the zones under baobab (*Adansonia digitata*) and néré (*Parkia biglobosa*) trees (A, B and C) and the control plot (H) at Nobéré (Burkina Faso)

4.3.2.3. Soil moisture content

Soil moisture varied significantly between tree species for the dry season without watering ($p < 0.05$). For this period, soil moisture was higher under néré compared to the values under baobab ($2.26 \pm 0.21\%$ and $1.62 \pm 0.06\%$, respectively). Soil moisture did not vary significantly between species for the other sampling periods.

Soil water content for the dry season without watering was not significantly different between zones of baobab while the water content in zone A for néré was higher compared to the open field ($p < 0.05$). Water content for the dry season sampling after watering was also not different between zones under baobab but water content in soil of zones A and B under néré was higher compared to zone C and the control plot. For the two samplings during the wet season, the general trend in soil water was a decrease from tree trunks to the open field (Fig. 4.5).

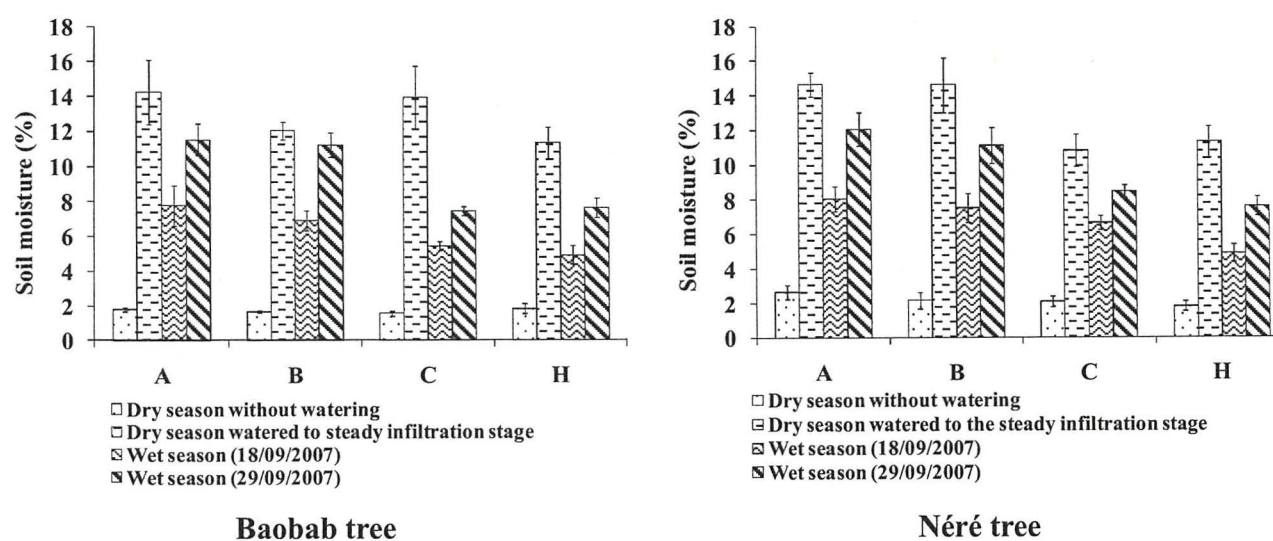


Fig. 4.5 : Soil moisture contents recorded under baobab (*Adansonia digitata*) and néré (*Parkia biglobosa*) trees according to concentric zones in a parkland at Nobéré (2007)

4.3.3. Tree transpiration

Tree transpiration significantly varied between cropping year ($P < 0.001$) and tree species ($P < 0.001$). There was also significant interactive effect of cropping year and tree species on transpiration ($P < 0.01$). Transpiration rate across the three years was higher for baobab (92.25 $l\ hr^{-1}$, 61.25 $l\ hr^{-1}$ and 99.06 $l\ hr^{-1}$ in 2006, 2007 and 2008, respectively) compared to the values for néré (12.93 $l\ hr^{-1}$, 18.55 $l\ hr^{-1}$ and 28.43 $l\ hr^{-1}$ in 2006, 2007 and 2008, respectively). Transpiration rate of baobab was higher in 2008 and 2006 compared to 2007 while the transpiration rate of néré was higher in 2008 compared to the two previous years (2006 and 2007).

As shown in figure 4.6., highest rates of transpiration by baobab (162.70, 129.97 and 191.80 $l\ hr^{-1}$ in 2006, 2007 and 2008, respectively) were observed around noon (11-12h) and by néré at 12h in 2006 (26.85 $l\ hr^{-1}$) and around 9h in 2007 and 2008 (46.84 and 58.46 $l\ hr^{-1}$, respectively).

During the three years, the mean daily (over 24h) amount of water transpired by baobab was 2214 l, 1470 l and 2378 l, in 2006, 2007 and 2008, respectively while for néré the values were

310 l, 445 l and 682 l, in 2006, 2007 and 2008, respectively (Fig. 4.6). The average transpiration rates over the three years were 2020 l day⁻¹ and 479 l day⁻¹ for baobab and néré, respectively.

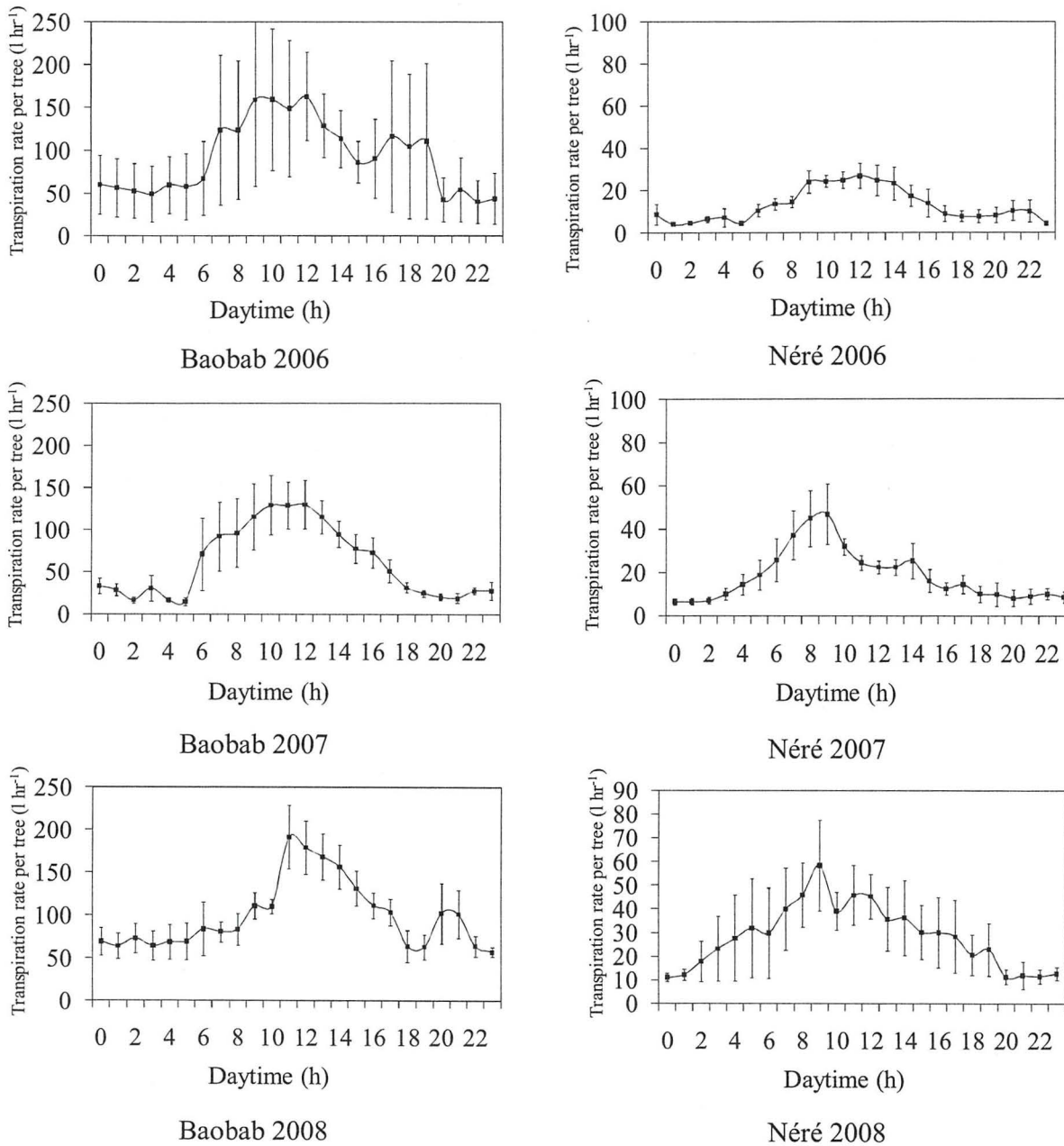


Fig. 4.6 : The mean daily course of the transpiration rate of Baobab and Néré trees on 2006, 2007 and 2008 at Nobéré (Burkina Faso)

4.3.4. Relationship between crops performances and biophysical parameters

The significant best-fitted regressions between the total dry matter and yield of millet and taro and the biophysical parameters are shown in table 4.2. The combination of PAR availability and WUEi of millet plants determined the dry matter production and grain yield of the crop by 44% and 40%, respectively. The WUEi of taro plants and the transpiration rate of the associated tree determined 50% and 61% of the variations of dry matter production and corms yield of taro.

Table 4.2 : Regressions between the total dry matter and grains and corms yield of millet and taro and the the crops WUEi and transpiration rate of baobab and nere, Nobéré, Burkina Faso (2007)

Crop	df	Regression	r ²
Millet	31	TDM = 2082 + 47.0 PAR - 508 WUEi **	0.44
	31	Grains Yield = 721 + 21.4 PAR - 232 WUEi ***	0.40
Taro	31	TDM = 2119 - 418 WUEi - 0.146 Transpiration of the tree ***	0.50
	31	Corms Yield = 7964 - 1768 WUEi - 0.524 Transpiration of the tree ***	0.61

The best-fitted regressions between WUEi of millet and taro and soils properties showed a strong relationship with soil OM content that determine soil water holding capacity (Table 4.3). Indeed, 77% and 56% variations of WUEi of millet and taro, respectively were explained by soil OM contents and the increase of soil OM content decreased WUEi of the both crops.

Table 4.3 : Regression between WUEi of millet and taro and soil organic matter content (OM), Nobéré, Burkina Faso (2007)

Crop	df	Regression	r ²
Millet	31	WUEi = 19.7 - 13.1 OM ***	0.77
Taro	31	WUEi = 6.75 - 4.15 OM ***	0.56

4.4. Discussion

4.4.1. Light reduction under baobab and néré trees and its relationship with crop performance

In the present study PAR decreased under both tree species as one moved from the open area to under the tree crowns because of shade or light interception by the trees. However, PAR reduction was higher under néré (82.73%, 55.16% and 18.42%, in zone A, B and C respectively) compared to baobab (62.49%, 37.74% and 15.48%, in zone A, B and C respectively). These results are in accordance with previous findings by other workers (Belsky *et al.*, 1989; Jonsson, 1995; Boffa *et al.*, 1999; Bayala *et al.*, 2002). Light reduction by baobab trees was estimated to be between 45 to 65% by Belsky *et al.* (1989) while higher reductions were reported under néré by Kessler (1992), Jonsson (1995) and Bayala *et al.* (2002) (80%, 75% and 62%, respectively).

As observed by several researchers, the difference between the tree species could be explained by a difference in height, crown density and shape (Breman and Kessler, 1995; Bellow and Nair, 2003; Zoumboudré *et al.*, 2005). In fact, baobab trees were taller compared to néré trees in the present study (15.50 ± 1.10 m and 11.07 ± 0.33 m, respectively), which allowed more lateral radiation to reach the ground surrounding the tree trunk. There were also more gaps in baobab tree crowns, which reduced light interception. Finally, the early leaf fall reduced the crown density of baobab trees and then increased light availability under the crown at the end of the rainy season (September to October). Both baobab and néré were leafy during the rainy season but leaf fall started for baobab trees at the end of August (Personal observation). Gebauer *et al.* (2002) also observed the short leafy period (only 4 months) for baobab while Bayala (2002) noted néré trees in leaf from May to December.

4.4.2. Effect of trees on soil nutrient and water content

Soil organic matter content in the top layer (20 cm depth) decreased from the tree trunk to the open area and remained higher in zone A down to soil depths of 30 cm under baobab and 50 cm under néré. The higher OM content of soil under the tree crown could be attributed mainly to the litter input such as leaves, flowers, fruits and small twigs from the trees. However, the drops of animals also contributed soil OM content as note by Soumaré (1996) and Garcia-

Barrios & Ong (2004). Even though all the litter that fall under trees may not completely be incorporated in the soil under trees due to dispersion by wind and runoff (Higuera & Martinez, 2006), it is expected that some of it may be incorporated. In addition, the parkland is used as a pastureland during the dry season and the dung of animals that shelter under tree highly contribute to increase the OM of the soil under the crown. The OM content of soil plays a key role in its physical properties such as water holding capacity and infiltrability (Rao *et al.*, 1998; Boffa, 1999).

Soil infiltrability under baobab and néré tree crowns in the open area were quite similar. The null hypothesis that soil infiltrability under baobab and néré tree crowns and in the open area was similar may be accepted based on the result of the present study. This result is, however, contrary to the general findings as reported in the literature by other researchers who found that trees increase water infiltration under their crowns (Belsky *et al.* 1989; Rao *et al.*, 1998; Boffa, 1999; Salako and Kirchhof, 2003). Tillage has been shown to have contrary effects on water infiltration: it can decrease water infiltration by causing the macropores created by soil fauna and root growth to become discontinuous (Eldridge and Freudenberger, 2005; Lampurlanes and Cantero-Martine, 2006; Ouattara *et al.*, 2007). However, tillage can also increase infiltration by breaking any soil crust and creating new macropores (Kribaa *et al.*, 2001; Cameira *et al.*, 2003, Abrisqueta *et al.*, 2006). The infiltration rate of a tilled soil is a result of the balance between the two above-mentioned tillage effects depending on soil properties and tillage practice (Kooistra *et al.*, 1984; Ouattara *et al.*, 2007). In the present study site, farmers usually use oxen or donkeys for ploughing in the open area but not in the area close to tree trunks (zone A). Instead, in this area they use manual hoeing or weeding. This area under trees that cannot be ploughed using oxen may be more compacted compared to the open field as farmers often use this area under trees for shelter. Therefore, the tillage effect combined with the various ploughing practices under tree crowns and in the open field could explain why similar infiltration rates were observed under trees and in the open field.

The main variations observed in the present study were in relation to concentric zones and tension heads. There was a general trend in values for infiltration and hydraulic conductivity to increase from the base of the tree trunk to the edge of the crown (Zone C). In addition, water infiltration and hydraulic conductivity at tensions – 10 cm and – 5 cm were higher in zone C compared to the control plot. K_{sat} was also lower in zone A compared to other zones. However, a relatively high standard error was found for saturated hydraulic conductivity. The

high standard error can be attributed to variation in soil properties under trees because of the effect of tillage as observed in previous studies (Coutadeur *et al.*, 2002; Abrisqueta *et al.*, 2006).

The higher infiltrability of soil in zone C compared to the control plot could be the result of tree growth. Zone C which is at the edge of the tree crown is more subject to the influence of both faunal activities under trees and tree roots compared to the control plot. Therefore, tree roots and faunal activities can increase macropores in zone C where there is less trampling since it is not under shade at midday compared to the control plot. This means higher water infiltration due to the abundance of macropores in zone C (Rao *et al.*, 1998; Boffa, 1999; Salako and Kirchhof, 2003).

The lower soil infiltrability values found in zones A and B compared to zone C could be due to a lack of deep ploughing close to tree trunks as explained above. Another factor that could explain lower infiltrability in these zones includes soil compaction under tree crowns due to trampling. Farmers use this area to take shelter themselves and animals rest in the shade from trees during the dry season. Indeed, the parkland is used as pastureland after harvests for the animals from the village and those transiting to Ghana. Therefore, large animal herds refuge under trees around noon when temperature is very high, causing high trampling effect around the base of the trees. This explanation is supported by Savadogo *et al.* (2007) who noted a decrease in soil infiltrability that was caused by trampling in a grazed area in Burkina Faso.

In contrast to soil infiltrability, the soil moisture results agreed with those reported by Ong *et al.* (1996), Boffa *et al.* (2000) and Garcias-Barrios and Ong (2004). Higher soil moisture values were found under tree crowns compared to open fields. As noted by Rao *et al.* (1998), Jonsson *et al.* (1999), and Ong and Swallow (2003), temperature reduction under trees from shading decreases evaporation and to thus cause higher soil moisture in the shaded area. In the present study, it was observed that there was a general trend in soil moisture increase from the open field to the base of trees.

Soil water content under baobab trees ($1.66 \pm 0.11\%$) and in the open field ($1.81 \pm 0.30\%$) during the dry season without watering was lower than the average permanent wilting point for sandy loam soils (2.3%) as reported by Maduakor (1991) for the Sudano-Sahelian zone. Similar low soil moisture values were also noted by Boffa *et al.* (2000) at the beginning of the

dry season (November) in the same region as the present study. Significantly greater soil moisture was found under *néré* than baobab during the dry season without watering. This difference could be due to *néré* having larger crown size compared to baobab; also, in February when the sampling was carried out baobab trees had shed their leaves while *néré* trees were still in full leaf. The results confirm the effect of temperature reduction under trees on soil water content as noted by Rao *et al.* (1998), Jonsson *et al.* (1999) and Ong and Swallow (2003).

The positive effect of trees on soil infiltrability as reported in literature was only observed at the edge of tree crowns. Closer to tree trunks, the effect on soil infiltrability is constrained by trampling. Despite the lack of increased water infiltration under tree crowns, higher soil moisture was recorded under tree crowns due to the reduction in temperature there. This increase in moisture content in the shaded area is very important for plant growth, especially in sandy loam soils that have poor water holding capacity.

Soil nutrient contents of N, P, K and cation exchange capacity were higher under both tree species compared to the open area, with the exception of P content in soil under *néré*. This finding is in agreement with the observation of Bayala (2002) in soils under *karité* and *néré* trees. The nutrient content also varied according to tree species probably due to a difference in the quality of their decomposed litter. Both tree species had an effect on soil pH that was neutral in the top soil of zone A but acidic in other zones. In summary, it may be concluded that soil nutrient content conditions were better for crop growth under tree crowns compared to the open area.

Transpiration rates of both tree species varied between years probably due to rainfall and temperature fluctuations between years. However, both trees species had high average transpiration rates (84.2 l hr⁻¹ and 19.9 l hr⁻¹ for baobab and *néré*, respectively). Transpiration by *néré* in the present study was less than the value of 146 l hr⁻¹ found by Bayala (2002) at Saponé (Burkina Faso) on *néré* trees with an average height of 15.38 m and an average crown diameter of 20.98 m. The lower transpiration in the present study could be due to the smallest average tree size (11.07 m height and 17.14 m diameter of the crown) compared to the tree studied by Bayala (2002). Indeed, lower transpiration (18 l hr⁻¹) was recorded by Bayala (2002) on *karité* trees with an average height of 11.67 m and an average crown diameter of 10.56 m.

Assuming that the water transpired by tree is removed from the area of crown projection of the ground as did Bayala (2002), the amount of water transpired by baobab and néré will give 9.43 mm day^{-1} and 2.08 mm day^{-1} . That assumption, however, is not realistic because the result of tree RLD showed that tree root were found in zone C outside the crown and even in three and five control plots situated at least 40 m of tree baobab and néré, respectively. Therefore, the water and nutrient remove by tree is more extended than the area of its crown. Therefore, the competition between tree and crop may be less critical as if the water and nutrients demand of tree was removed only in the smaller area under the crown.

4.4.3. Relationship between crops performances and biophysical parameters

The results of best-fitted regressions between millet performance and biophysical parameters showed that millet grain yield and its dry matter production were strongly dependent on PAR availability and the WUE_i of plants. An increase in PAR availability resulted in an increase of millet performance while an increase of the WUE_i of plants decreased the crop performance. As discussed in the chapter 3, WUE_i of the crop increase as water availability decrease from tree trunk surround to the open field. This variation of WUE according to water stress is supported by the findings of Singh and Singh (1995). Accordingly, 77% of the variation of millet WUE_i was determined in the study by soil OM content. Soil OM strongly determines its water holding capacity then under tree where high soil OM content and low evaporation were found, soil water content was high and that result in a high WUE_i of millet. In contrast, low soil OM content in the open and high evaporation decreased soil water content and the water stress increased millet WUE_i. Thus, the null hypothesis that millet performance is not influenced by the effect of tree shade or light interception by trees may be rejected based on the results of the present study ie millet performance is limited by PAR reduction under tree crown while it is decreased by water stress in the open field. Of course, the soils under trees are also improved in water and nutrient availability compared to the open area as described in the section on soil properties above. That is why millet yield was better in zones C and B under baobab where light availability was increased from September to October.

In contrast, PAR availability did not directly affect taro performance but the crop performance was mainly determined by water availability. Indeed, the WUE_i of plants and tree transpiration rate were the key factors that affected taro yield. As stated above, the variation

of WUE_i was strongly (56%) linked to soil OM content on which depended soil water content. Therefore, the performance of taro was limited by water stress in the open field and under tree crown where higher soil water content was found because of water removed by the roots of tree. Certainly, taro was more sensitive to competition for soil water because of its high water demand (Caesar, 1980; Bussel and Bonin, 1998). Despite this competition for soil water between the plants of taro and the tree, the better performance of taro was recorded under tree because of higher water and nutrients availability in the tree surround and because high temperature and light saturation in the open field may reduce the performance of taro as a drought sensitive C₃ photosynthesis pathway plant (Yang *et al.*, 2004; Hay & Porter, 2006; Osborne *et al.*, 2008). Indeed, the additional energy required by taro plants because of the increase of photorespiration, combined with the low soil fertility limited the performance of the crop in the open field.

In contrast, millet as a C₄ pathway photosynthesis crop was able to dissipate the excessive energy due to intense irradiance and high ambient temperature and maintained good performance in the open field. In addition, millet known to have low water demand (Masojidek *et al.*, 1991) was not affected as taro, a C₃ plant with lower WUE (Ripley *et al.*, 2007), by the low soil water content in the open field.

CHAPTER 5: THE EFFECT OF TREE SHADE ON THE NUTRITIONAL COMPOSITION OF AN ASSOCIATED SHADE TOLERANT AND NON-SHADE TOLERANT CROP

5.1. Introduction

Several previous studies have reported yield reduction of cereal crops in parkland systems due to the effect of tree shade (Maiga, 1987; Kessler, 1992; Boffa *et al.*, 2000; Bayala *et al.*, 2002). The reduction in cereal crop production under trees was mainly caused by low photosynthetic activity of crops in shaded conditions. A deficiency in the photosynthetic process would also cause a reduction in the quality of the crop products such as grains of cereals and corms of vegetable crops. Ajithkumar and Jayachandran (2003) showed that crude fibre in ginger (*Zingiber officinale* R.) decreased with light reduction. In addition, Eze (1987) observed a reduced accumulation of carbohydrate and ascorbic acid in *Amaranthus hybridus* (African spinach) under shade condition compared to the full daylight. In contrast, Koukoura *et al.* (2009) showed that artificial light reduction increased crude protein content by 25% in *Dactylis glomerata* and *Festuca ovina* while Ajithkumar and Jayachandran (2003) found an increase in volatile oil content in ginger with increased shade. Therefore, the effect of shade on crop nutritive composition may depend on the crop species, type of nutrient and nutrients content in the soil.

On the other hand, photosynthetic efficiency was also related to soil moisture and nutrient contents. Higher moisture and nutrient contents in soil under tree crowns were reported in several previous studies carried out in parkland systems (Breman and Kessler, 1995, Tomlinson *et al.*, 1995, Garcias-Barrios and Ong, 2004; Ong and Swallow, 2003, Bayala *et al.*, 2006). Such an increase in moisture and nutrient contents under tree crowns compared with open areas may result in an improvement in the nutritive quality of crops grown under trees as reported for forage by Lin *et al.* (2001), Ladyman *et al.* (2003) and Peri *et al.* (2007).

The nutritive quality of a crop grown under tree shade may depend on its ability to take advantage of increased moisture and nutrients availability in reduced light condition. Therefore, it is hypothesised that taro as a shade tolerant plant may yield corms of better nutritive quality under shade in contrast of millet that is shade-intolerant. The effect of shade on the nutritive value of millet grains and taro corms was examined in the present study.

5.2. Materials and methods

The sampling of crops was done within the concentric zones around both tree species as described in Chapter 3 of this thesis (experimental design). At the time of crop harvest, four plants per concentric zone were randomly collected in each compass direction (east-west-north-south) and per control plot associated to each tree. The samples were oven dried at 70°C for 24 h, ground, sieved at 200 µm. Sampled grains of millet and corms of taro were analyzed for protein, carbohydrate, fat, ash, total dietary fibre, calcium (Ca), iron (Fe), magnesium (Mg), phosphorus (P), potassium (K), sodium (Na) and Manganese (Mn) after the harvest of 2006, 2007 and 2008 in the laboratory of the School of the Environment, Natural Resources and Geography, Bangor University, UK. The laboratory analytical methods used are described below.

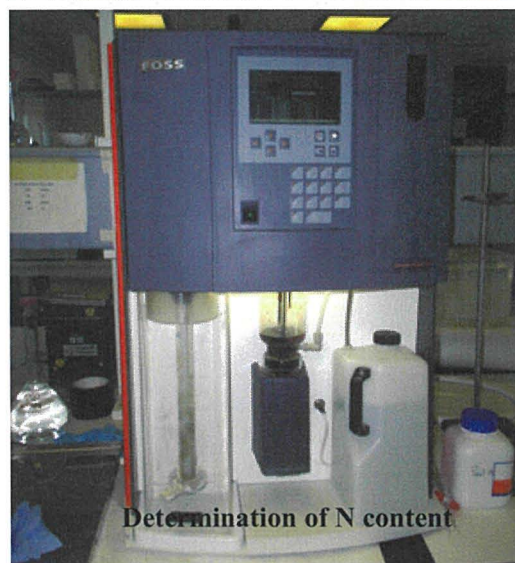
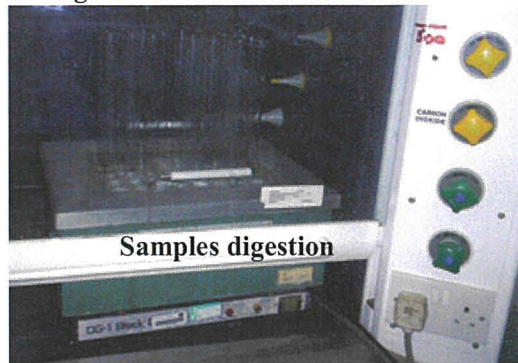
5.2.1. Assessment of protein content

The protein content of crop samples was obtained by measuring N content of the samples by the Kjeldahl method using a Kjelttec 2300 analyser unit (FOSS, Denmark). 200 mg of each sample were digested by adding 4 ml of sulphuric acid (98%) and two (2) digestive tablets and warmed at 30°C for 4 hours. During the digestion, the nitrogen in the samples was converted into ammonia in the form of ammonium ions NH_4^+ which bonded to the SO_4^{2-} ions of the acid. After the digestion, sample solutions were placed in the Kjelttec analyser unit which determined their N content. The N content was multiplied by 6.25 to obtain protein content in samples.

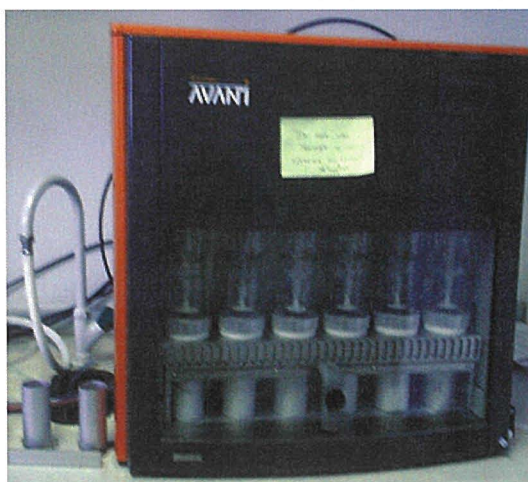
5.2.2. Assessment of fat content

Fat content was determined by the Soxhlet method using Soxtec Avanti 2050 system (Foss, Denmark). Five grams of each sample were placed in a porous thimble which was lodged into an extraction aluminium cup containing 80 ml of petroleum ether as a solvent and the fat was extracted by the Soxtec system. After the extraction, tubes were placed in an oven at 102°C to evaporate the remaining solvent and dry the sample. Extracted fat was weighed and divided by the sample weight (5g) to obtain the fat content (g g^{-1}).

Plate 5.1. Apparatus used for protein and fat contents determination in millet grains and taro corms



- a. Protein content determination using Kjeltec 2300 analyser unit (FOSS, Denmark)



- b. Fat content determination using Soxtec Avanti 2050 system (Foss, Denmark)

5.2.3. Assessment of ash content

Ash content was assessed by burning 2 grams of each crop sample in a furnace at 600°C for 12 hours. When samples were burnt, water and volatile substances were vaporized while organic substances were transformed into CO₂, H₂O and N₂ in the presence of oxygen. After samples were cooled, ash was weighed and the content (g g⁻¹) was calculated by dividing ash weight by the original weight of the sample.

5.2.4. Assessment of dietary fibre content

Dietary fibre includes some polysaccharides (cellulose, hemicellulose, pectin and hydrocolloids) and lignin, which are not digestible. Therefore, dietary fibre content determination consisted of removing all digestible substances of the samples and weighing the rest. One gram of each sample after fat extraction was used to assess dietary fibre content. Each sample was dissolved in 50 ml of phosphate (pH 6), 0.1 ml of amylase was added and the solution was incubated at 95°C for 15 minutes. After the incubation, the solution was cooled to room temperature and its pH was adjusted to 7.5 by adding NaOH (0.275 N). Then 0.1 ml of protease was added to the solution and placed in a water bath at 60°C for 30 minutes.

At the end of this second incubation, the solution was cooled at room temperature and the pH adjusted between 4 and 4.6 by adding HCl (0.325M). Then, 0.1 ml of Amyloglucosidase was added to the solution which was placed again in a water bath at 60°C during 30 minutes. By the end of this third incubation, 4 volumes of ethanol (95%) were added and the solution was left to cool overnight at room temperature. After complete precipitation overnight, the solution was filtered and rinsed with ethanol (95%) and acetone, to extract dietary fibre. Dietary fibre was dried in an oven at 70°C overnight and then weighed to obtain the content in the original sample (g g⁻¹).

5.2.5. Assessment of carbohydrates content

Digestible carbohydrates content was assessed based on the assumption that samples are constituted of ash, dietary fibre, fat, protein and digestible carbohydrate. So, when the contents of protein, fat, ash and dietary fibre are known for one gram of sample, carbohydrate content could be calculated according to the formula below:

Carbohydrate content (g g^{-1}) = 1 - (Ash content + Dietary fibre content + Fat content + Protein content).

5.2.6. Assessment of Ca, Na and K contents

Flame photometry was used to determine Ca, Na and K contents in the crop samples. The model 410 flame photometer range (Sherwood, Cambridge, UK) measured the light of a specific wavelength emitted when a solution of a particular element was burnt. The light emitted is proportional to the element concentration in the solution. To prepare aqueous solutions of samples, 2 g of each sample were burnt at 450°C in a furnace overnight to remove the carbon. The samples were then dissolved into 10 ml of hydrochloric acid (HCl) of 12M concentration. The solution obtained was diluted to 10 times for K and Na and 80 times for Ca by adding distilled water. Seven standard solutions at concentrations of 0, 5, 10, 30, 50, 70 and 100 mg l^{-1} were prepared for each element (Na, Ca and K). Then, the standards and the sample solutions were read by the flame photometer. A regression equation was derived between standard solutions and the readings of the flame photometer and the equation was used to obtain the concentration of elements in sample solutions (mg l^{-1}). Elements content (g g^{-1}) in dry samples was then calculated using the dilution rates.

5.2.7. Assessment of P content

Phosphorus content was determined using the colorimetric method (Ames, 1966). This method is based on the principle that phosphate ion reacts with ammonium molybdate to give, when reduced by ascorbic acid, a blue complex which has an intense absorption band at 820 nm. The complex absorbance is proportional to phosphate concentration in the original solution and was measured using a spectrophotometer (BioTek, model PowerWave XS).

Eighty times concentration solutions of crop samples were obtained as shown in the section above. Six standard solutions (0, 10, 30, 50, 70 and 100 mg l^{-1}) of the PO_4 ion were used to determine the relation between the spectrophotometer readings with phosphate concentrations. $80 \mu\text{l}$ of sample and standard solutions were placed in a 96 wells plate, $180 \mu\text{l}$ of Ames reagent were added at 30 second intervals and finally $30 \mu\text{l}$ of ascorbic acid (10 %) were added in each well of the plate. The absorbance of the solutions was read by the spectrophotometer after 15 minutes at an interval of 30 seconds until the last well of the plate.

The regression equation between the concentration of standard solutions and the readings of the spectrophotometer was used to obtain the phosphate concentration (mg l^{-1}) in sample solutions and then the content (g g^{-1}) in dry samples was calculated using the dilution rate.

5.2.8. Assessment of Fe, Mg and Mn contents

An atomic absorption photometer (VARIAN, model SpectrAA 220FS) was used to assess Fe, Mg and Mn contents in crop samples. The principle is that each element when burnt emits a specific wavelength light which is proportional to the content of the element in the solution. Six concentrations of each element were used as standards to calibrate the photometer. Sample solutions were prepared as described above. Ten (10) times concentration solution was used for Fe and Mn while a ninety times (90) concentration was used for Mg. Assay tubes each containing 50 ml of sample solution was placed on a 60 wells support where the first well was a tube of water and after each five (5) sample tubes, a drift solution was intercalated to control the photometer readings accuracy. The absorbance of solutions was read by the atomic absorption photometer and expressed as elements concentration (mg l^{-1}) according to the calibration done with standard solutions. The content in dry matter (g g^{-1}) was obtained by applying the dilution rates with regard to each element solution.

5.2.9. Assessment of vitamins contents

Vitamins contents were assessed by high pressure liquid chromatography (HPLC) method using VARIAN model Prostar 800. The principle is to determine for each vitamin the associated wavelength, the time of its peak apparition on the chromatogram and the area covered by this peak curve. To determine the wavelength associated to vitamins and to assess the relationship between vitamins concentration and peaks curve area, standards of all vitamin solutions at six (6) concentrations (0, 1, 2, 3, 4 and 5 mg l^{-1}) were run before samples analyses.

Samples were dissolved by adding to 1 g of each sample 10 ml of phosphate acid (90%). The samples solutions were placed on a support of the HPLC analyser with a drift solution containing standard vitamins positioned after each 10 sample solutions. Vitamins peak were located on the chromatogram after completion of the analysis and areas of peaks curve were determined by the software version 4.10 Pro of Varian Prostar 800. Vitamins concentrations

(mg l⁻¹) were then obtained using the regression equation between standards concentrations and the corresponding peak areas. These concentrations were converted in vitamins content (mg g⁻¹) using dissolution rates.

5.2.10. Data analysis

Data on crop nutritive values determined during the three cropping seasons were analysed using the ANOVA General Linear Model (GLM) for the variations according to cropping years, tree species and crops and while a pairwise t-test was used to test the variation between concentric zones and the control plot. All these analyses were performed using modules of the software Minitab 15 (Minitab Inc., USA). After a GLM analysis, means were compared using Tukey's test at a confidence level of 95%. The t-tests were performed assuming that the difference between the two zones compared was equal to zero and this hypothesis was rejected in case of a significant result of the test.

A best-fitted multiple regression was performed to find the best determinant factors of crops proximal and minerals contents among soils chemical properties and PAR availability as described in chapter 4.

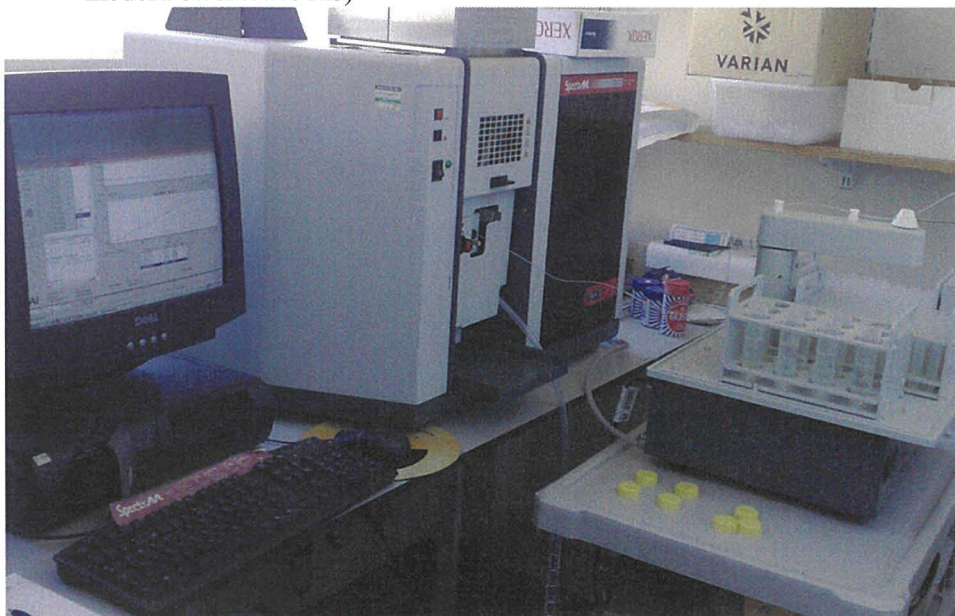
Plate 5.2. The model 410 flame photometer range (Sherwood, Cambridge, UK) used to determine calcium, sodium and potassium in millet grains and taro corms



Plate 5.3. Apparatus used for the determination of phosphorus, magnesium, iron and manganese content in millet grains and taro corms



a. Determination of phosphorus content using a spectrophotometer (BioTek, model PowerWave XS)



b. The atomic absorption photometer (VARIAN, model SpectrAA 220FS) used to assess iron, magnesium and manganese content

5.3. Results

5.3.1. Proximate composition of millet grains and taro corms

5.3.1.1. Protein content

Neither the type of tree species nor the concentric zones had any effect on the protein content of both crops. There was, however, a significant difference of protein content between the two crops ($P < 0.05$) and a significant interaction between crops and cropping years ($P < 0.05$). Protein content was higher in taro compared to millet ($0.106 \pm 0.002 \text{ g g}^{-1}$ and $0.095 \pm 0.002 \text{ g g}^{-1}$). There was also a general decreasing trend of protein content in both crops from tree trunk to the open area (Fig. 5.1). Protein content varied significantly according to cropping years in millet grains but not in taro corms. Protein content of millet recorded in 2007 was lower compared to the values in 2006 and 2008 ($0.084 \pm 0.004 \text{ g g}^{-1}$, $0.103 \pm 0.003 \text{ g g}^{-1}$ and $0.099 \pm 0.003 \text{ g g}^{-1}$, respectively).

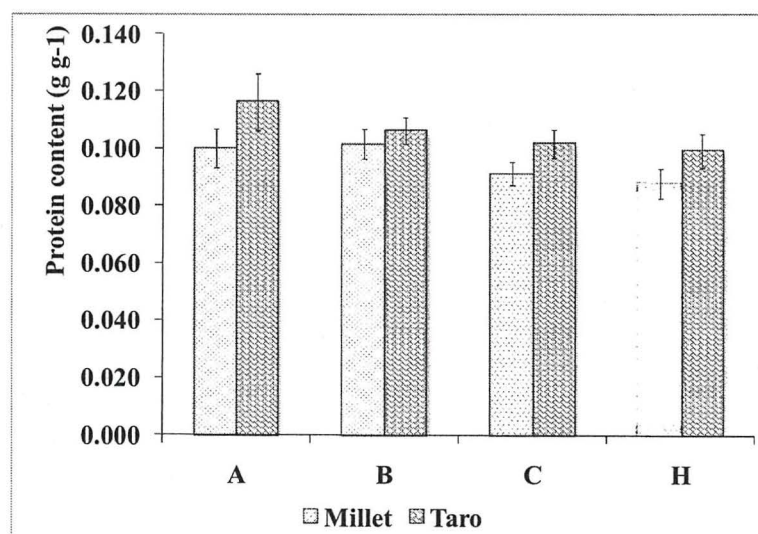


Fig. 5.1 : Protein content in millet grain and taro corm according to the concentric zones under baobab and néré trees (2006, 2007 and 2008)

5.3.1.2. Fat content

Fat content was significantly different between the two crops ($P < 0.001$). Higher fat content was recorded in millet grain compared to taro corms ($0.044 \pm 0.001 \text{ g g}^{-1}$ and

$0.007\pm 0.001 \text{ g g}^{-1}$). A significant difference was noted in fat content between tree species only for millet ($P < 0.01$). Millet grown in zones under baobab had higher fat content compared to grains harvested in zones under néré ($0.047\pm 0.002 \text{ g g}^{-1}$ and $0.040\pm 0.003 \text{ g g}^{-1}$). Fat content in taro corms increased from tree trunk to the open area under both tree species (Fig. 5.2).

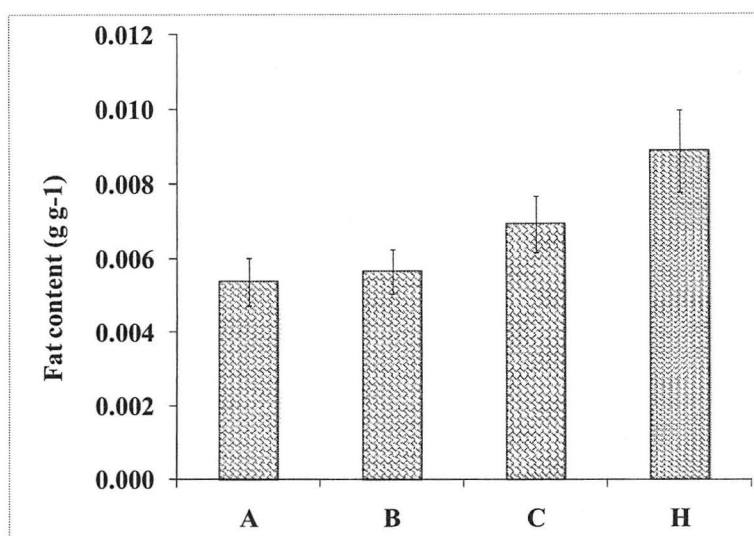


Fig. 5.2 : Fat content (g g^{-1}) in taro corm according to the concentric zones under baobab and néré trees (2006, 2007 and 2008)

5.3.1.3. Ash content

Ash content in the two crops was significantly different ($P < 0.001$). Taro corms contained higher amount of ash compared to millet grains ($0.083\pm 0.002 \text{ g g}^{-1}$ and $0.028\pm 0.002 \text{ g g}^{-1}$). According to the cropping years, ash content significantly varied in both crops ($P < 0.001$). Ash content in millet was higher in 2006 compared to the two following cropping years while its content in taro corms decreased from 2006 to 2008 (Fig. 5.3). There was no significant difference of ash content of both crops between the concentric zones.

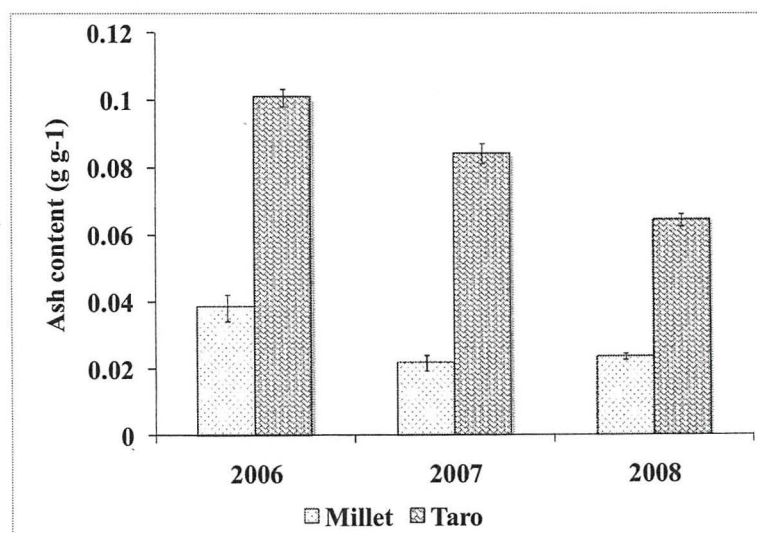


Fig. 5.3 : Ash content (g g^{-1}) in millet grains and taro corms according to the cropping years (2006, 2007 and 2008)

5.3.1.4. Dietary fibre content

There was a significant difference between the dietary fibre content in the two crops ($P < 0.001$). The dietary fibre content in taro corms was higher compared to millet grains ($0.332 \pm 0.007 \text{ g g}^{-1}$ and $0.182 \pm 0.006 \text{ g g}^{-1}$, respectively).

Both crops dietary fibre content varied significantly according to the cropping years ($P < 0.001$). Dietary fibre content in millet increased from 2006 ($0.129 \pm 0.006 \text{ g g}^{-1}$) to 2008 ($0.163 \pm 0.007 \text{ g g}^{-1}$ and $0.258 \pm 0.008 \text{ g g}^{-1}$, respectively 2007 and 2008). For taro crop, the lowest dietary fibre content was recorded in 2006 ($0.305 \pm 0.011 \text{ g g}^{-1}$) and the highest in 2007 ($0.365 \pm 0.009 \text{ g g}^{-1}$). In 2008, the dietary fibre content in taro was $0.327 \pm 0.009 \text{ g g}^{-1}$. There was no significant variation of dietary fibre in both crops according to tree species. Dietary fibre content in millet grains was also not significantly different between zones. In contrast, taro corms dietary fibre increased from the area under tree crown to the open area (Fig. 5.4).

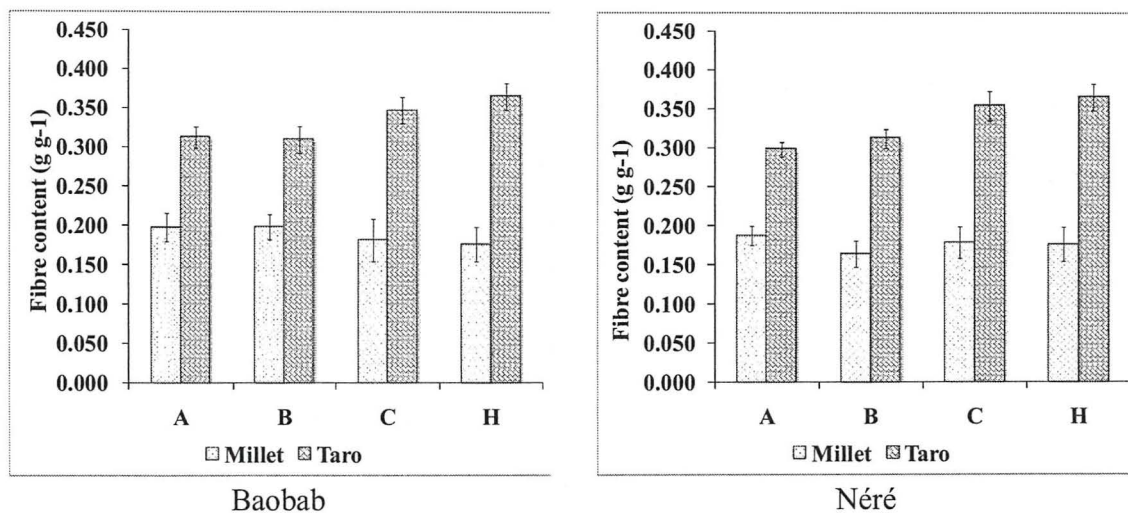


Fig. 5.4 : Dietary fibre content (g g^{-1}) in millet grains and taro corms according to the concentric zones under baobab and néré trees and the control plot

5.3.1.5. Carbohydrates content

Carbohydrates content was significantly different between millet grains and taro corms ($P < 0.001$). Higher carbohydrates content was found in millet grains compared to taro corms ($0.652 \pm 0.008 \text{ g g}^{-1}$ and $0.473 \pm 0.007 \text{ g g}^{-1}$, respectively). No significant variation of carbohydrates content in both crops was observed according to cropping years and to tree species. There was also no significant variation of carbohydrates content in millet grains between zones. However, carbohydrates content in taro corms decreased from tree beneath area to the control plot (Fig. 5.5).

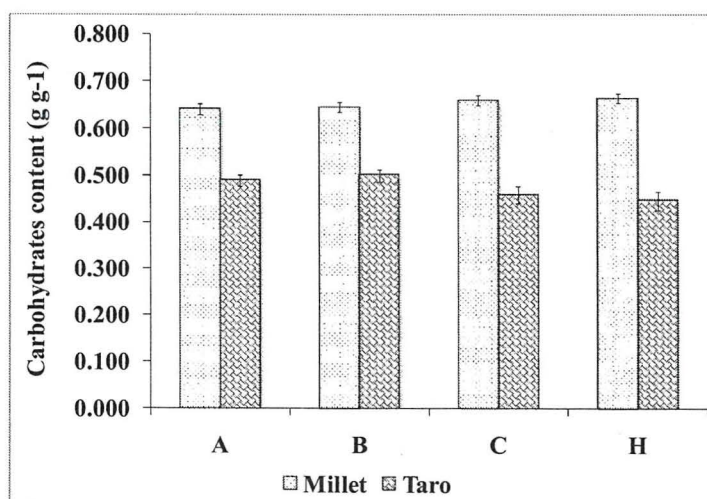


Fig. 5.5 : Available carbohydrates (g g^{-1}) in millet grains and taro corms according to the concentric zones under baobab and néré trees and the control plot

5.3.1.6. *Relationship between proximate composition of crops and PAR availability and soil nutrients and water contents*

There was no significant regression between the content of ash and dietary fibre in millet grains and the available PAR in concentric zones and soil minerals and water content (Table 5.1). There was a significant regression between protein contents in millet grains and soil cation exchange capacity where an increase in soil cation exchange capacity resulted in an increase of grains content of protein. Fat content in millet grains increased with a decrease of soil OM and an increase of soil P content. Fat and fibre contents in taro corms were only determined by PAR availability: an increase in PAR availability increased both contents in taro corms. Taro corms content of carbohydrates was increased by the increase in soil cation exchange capacity. There was no significant regression for ash and protein contents in taro corms.

Table 5.1 : Regression between the proximate contents of millet grains and taro corms and PAR availability, soil nutrients and water content, Nobéré, Burkina Faso (2006, 2007 and 2008)

Crop	Proximate composition	df	Regression	r ²
Millet	Ash	31	No significant regression	
	Fat	31	Fat = 0.0259 + 0.000131 P _{soil} *	0.14
	Protein	31	Protein = 0.142 - 0.128 OM + 0.0203 IEC*	0.22
	Fibre	31	No significant regression	
	Carbohydrates	31	Carbohydrate = 0.770 - 0.000902 P _{soil} **	0.30
Taro	Ash	31	No significant regression	
	Fat	31	Fat = 0.00333 + 0.000070 PAR***	0.37
	Protein	31	No significant regression	
	Fibre	31	Fibre = 0.283 + 0.00120 PAR***	0.39
	Carbohydrates	31	Carbohydrates = 0.398 + 0.0187 IEC*	0.14

5.3.2. Mineral contents of millet grains and taro corms

5.3.2.1. *Ca content*

Calcium content was significantly different between the two crops (P<0.001). Taro corms contained higher amount of Ca compared to millet grains (1.112±0.198 mg g⁻¹ and 0.264±0.047 mg g⁻¹). As shown in figure 5.6, there was also a significant reduction of Ca content in both crops from the first cropping year 2006 to last year 2008 (P<0.001). However, no significant difference of Ca content in both crops was noted between tree

species and between concentric zones.

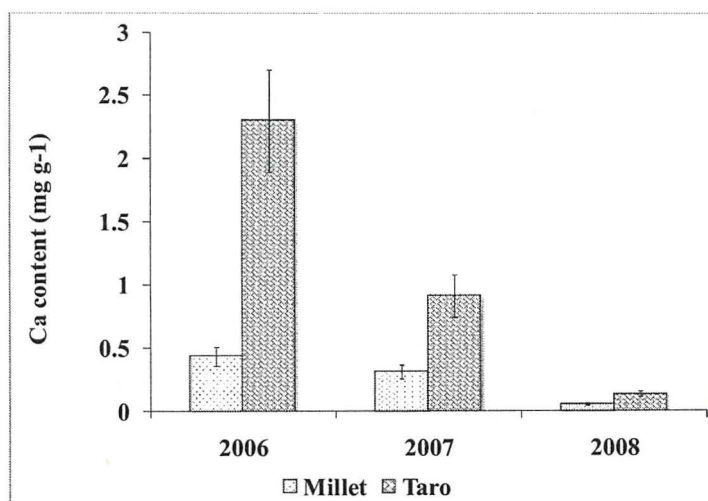


Fig. 5.6 : Calcium content (mg g⁻¹) in millet grains and taro corms according to the cropping years (2006, 2007 and 2008)

5.3.2.2. Na content

There was a significant difference of sodium content between millet grains and taro corms ($P < 0.001$). The content of Na in taro corms was higher compared to millet grains (0.342 ± 0.026 mg g⁻¹ and 0.107 ± 0.006 mg g⁻¹). Na content significantly varied according to cropping years in both crops ($P < 0.001$). Both crops content of Na decreased from 2006 to 2008 (Fig. 5.7). No significant difference of Na content in both crops was observed between tree species and between zones.

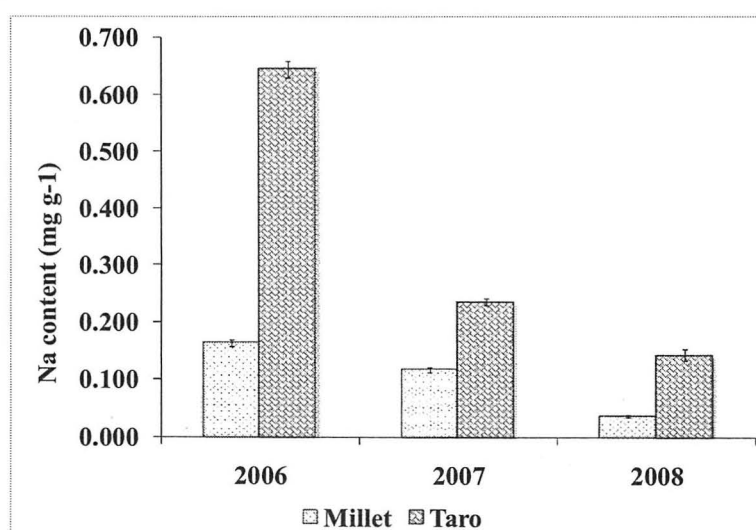


Fig. 5.7 : Sodium content (mg g⁻¹) in millet grains and taro corms according to the cropping years (2006, 2007 and 2008)

5.3.2.3. K content

Potassium content was significantly different between the two crops ($P < 0.001$). Higher content of K was found in taro corms compared to millet grains ($28.370 \pm 0.1054 \text{ mg g}^{-1}$ and $5.731 \pm 0.192 \text{ mg g}^{-1}$). A significant variation was also observed in both crops K content between the cropping years ($P < 0.01$). K content increased in both crops from 2006 to 2008 (Fig. 5.8). Tree species and concentric zones had no significant effect on K content of both crops.

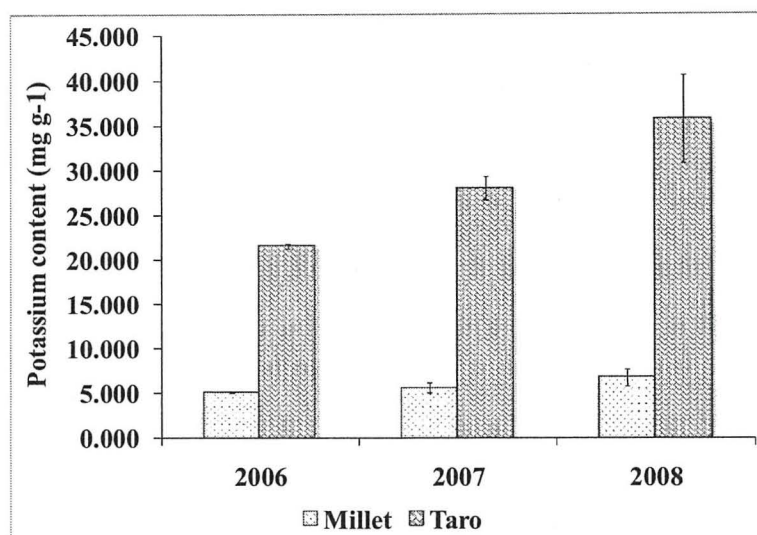


Fig. 5.8 : Potassium (K) content (mg g^{-1}) in millet grains and taro corms according to the cropping years (2006, 2007 and 2008)

5.3.2.4. P content

Phosphorus content varied significantly according to crops ($P < 0.001$) with higher content in taro corms compared to millet grains ($2.791 \pm 0.078 \text{ mg g}^{-1}$ and $2.496 \pm 0.057 \text{ mg g}^{-1}$, respectively). The P content in taro corms varied significantly according to cropping years ($P < 0.001$) but no variation was noted for millet. There was an increase of P content in taro corms from 2006 to 2008 (Fig. 5.9). A significant difference of P content was found in millet grains and taro corms according to tree species ($P < 0.01$). P content of millet and taro was higher under baobab ($2.706 \pm 0.125 \text{ mg g}^{-1}$ and $3.247 \pm 0.208 \text{ mg g}^{-1}$, respectively) compared to the area under néré ($2.403 \pm 0.190 \text{ mg g}^{-1}$ and $2.572 \pm 0.160 \text{ mg g}^{-1}$, respectively). Both crops had higher content of P in zones under baobab influence (A, B and C) compared to the control plot (Fig. 5.10).

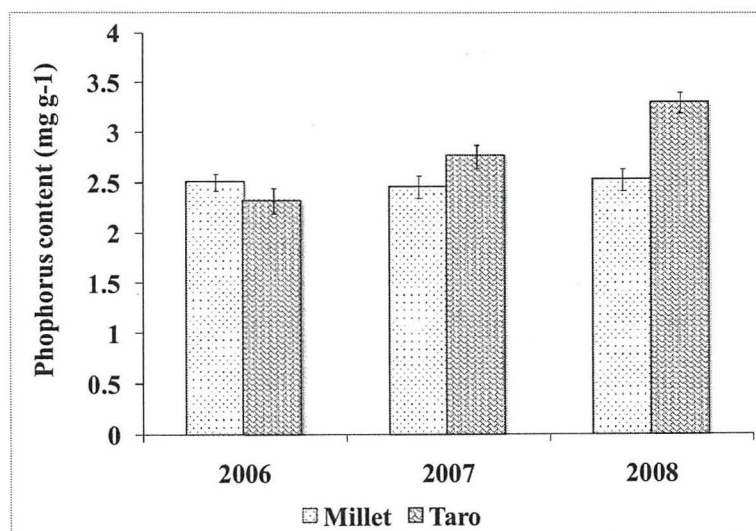


Fig. 5.9 : Phosphorus content (mg g^{-1}) in millet grains and taro corms according to the cropping years (2006, 2007 and 2008)

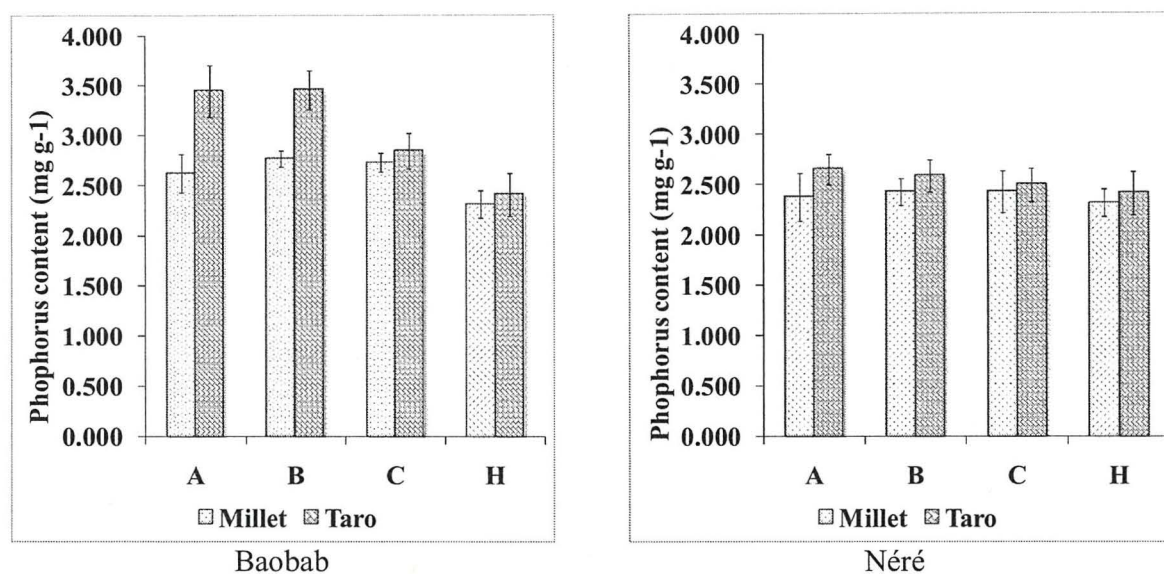


Fig. 5.10 : Phosphorus content (mg g^{-1}) in millet grains and taro corms according to concentric zones under baobab and néré trees and the control plot

5.3.2.5. Mg content

A significant difference was observed between magnesium content in millet grains and taro corms ($P < 0.001$). Mg content was higher in taro corms compared to millet grains ($2.177 \pm 0.049 \text{ mg g}^{-1}$ and $1.385 \pm 0.039 \text{ mg g}^{-1}$). There was a significant interaction between crops and cropping years ($P < 0.01$). Mg content varied significantly according to the cropping years in taro corms ($P < 0.001$) while no significant difference was noted in millet

grains between the cropping years. In taro corm, Mg content decreased from 2006 to 2008 (Fig. 5.11).

For both crops, there was no distinct trend of Mg content variation according to zones (Fig. 5.11). In 2006, Mg content in millet grains was higher in zone B compared to zone A and the control plot ($1.476 \pm 0.120 \text{ mg g}^{-1}$ and $1.120 \pm 0.073 \text{ mg g}^{-1}$, respectively). For taro corms, Mg content was lower in zone B compared to the other zones in 2007 ($1.827 \pm 0.114 \text{ mg g}^{-1}$, $2.210 \pm 0.135 \text{ mg g}^{-1}$, $2.309 \pm 0.106 \text{ mg g}^{-1}$ and $2.721 \pm 0.253 \text{ mg g}^{-1}$, B, A, C and H, respectively). In 2008, the content of Mg in taro corms was higher in zone C compared to zones A and B ($1.976 \pm 0.098 \text{ mg g}^{-1}$, $1.701 \pm 0.056 \text{ mg g}^{-1}$ and $1.715 \pm 0.056 \text{ mg g}^{-1}$, respectively).

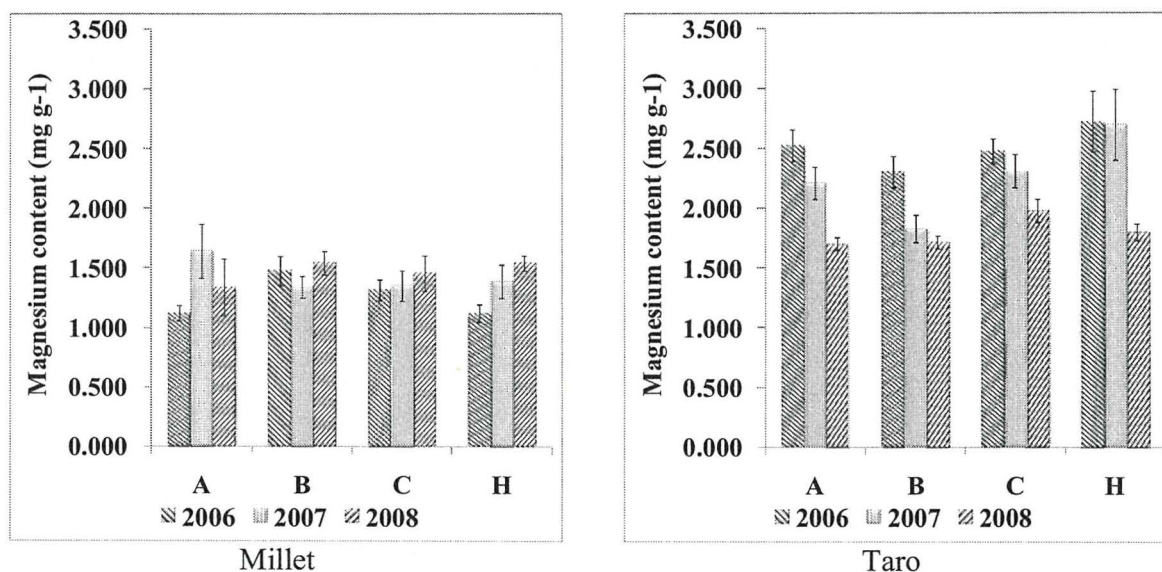


Fig. 5.11: Magnesium content (mg g^{-1}) in millet grains and taro corms according to the cropping years and concentric zones under baobab and néré trees and the control plot

5.3.2.6. Fe content

There was a significant difference of iron content between crops ($P < 0.001$). Taro corms contained more iron compared to millet grains ($0.397 \pm 0.042 \text{ mg g}^{-1}$ and $0.181 \pm 0.027 \text{ mg g}^{-1}$, respectively). Fe content also varied significantly according to the cropping years for both crops ($P < 0.001$). The general trend was a decrease of Fe content in both crops from 2006 to 2008 (Fig 5.12). No significant difference was found for Fe content in both crops according to tree species and between concentric zones.

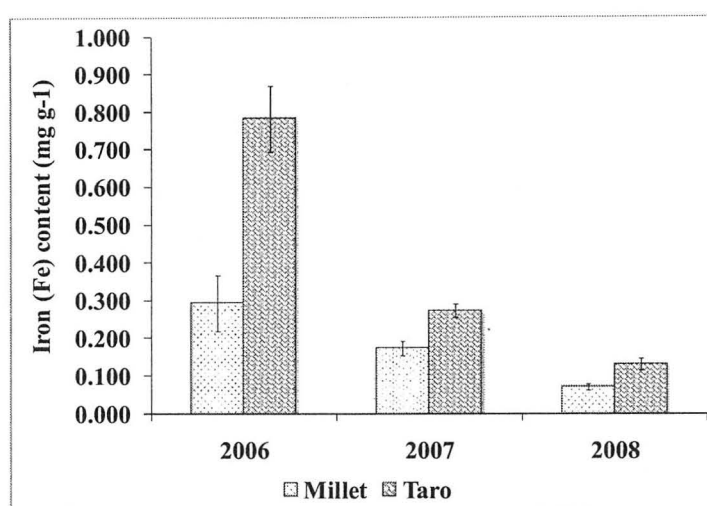


Fig. 5.12 : Iron content (mg g^{-1}) in millet grains and taro corms according to the cropping years (2006, 2007 and 2008)

5.3.2.7. Mn content

Manganese content varied significantly according to crops ($P < 0.001$) with higher content in taro corms compared to millet grains ($0.041 \pm 0.002 \text{ mg g}^{-1}$ and $0.0130 \pm 0.001 \text{ mg g}^{-1}$, respectively). No difference in Mn content was found between the cropping years for both crops. There was also no significant variation of Mn content in millet grains according to tree species and zones (Fig 5.13). In contrast, Mn content in taro corms was significantly different according to tree species and zones ($P < 0.001$ and $P < 0.01$, respectively). In taro corms, Mn content was higher under néré compared to the area under baobab ($0.050 \pm 0.003 \text{ mg g}^{-1}$ and $0.032 \pm 0.003 \text{ mg g}^{-1}$, respectively). Under both tree species, Mn content in taro corm increased from the area under tree crown to the control plot except under néré higher content was found in zone C compared to the control plot (Fig 5.13).

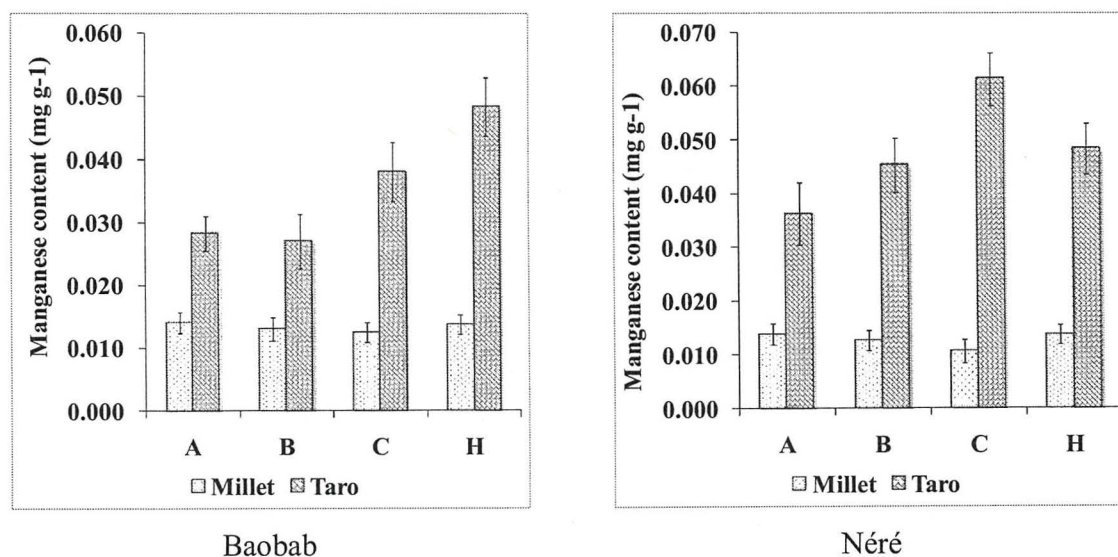


Fig. 5.13 : Manganese content (mg g^{-1}) in millet grains and taro corms according to the concentric zones under baobab and néré trees and the control plot

5.3.2.8. *Relationship between crops mineral content and PAR availability and soil nutrients and water content*

There was no significant regression between Ca, Na, Mg and Mn content in millet grains and available PAR in the concentric zones and soil minerals and water content (Table 5.2). However, P content in millet grain was fairly determined by soil cation exchange capacity while K content in grains was dependant on the availability PAR, soil OM and K. Fe content in millet grains was decreased by increase in soil P content but increased by soil OM.

As for millet, P content in taro corms was highly determined by soil cation exchange capacity. K content in taro corms was decreased by the increase in the availability of PAR and soil P content. No significant regression was found for Ca, Na, Fe Mg and Mn.

Table 5.2 : Regression between the minerals contents of millet grains and taro corms and PAR availability, soil nutrients and water content, Nobéré, Burkina Faso (2006, 2007 and 2008)

Crop	Minerals	df	Regression	r ²
Millet	Ca	31	No significant regression	
	Na	31	No significant regression	
	P	31	$P = 1.92 + 0.134 \text{ IEC}^*$	0.13
	K	31	$K = - 7.92 + 0.0393 \text{ PAR} + 8.96 \text{ OM} + 0.00332 \text{ K}_{\text{soil}}^*$	0.26
	Fe	31	$\text{Fe} = - 0.105 + 0.414 \text{ OM} - 0.00137 \text{ P}_{\text{soil}}^*$	0.20
	Mg	31	No significant regression	
	Mn	31	No significant regression	
Taro	Ca	31	No significant regression	
	Na	31	No significant regression	
	P	31	$P = 1.18 + 0.422 \text{ IEC}^{***}$	0.42
	K	31	$K = 48.2 - 0.190 \text{ PAR} - 0.0690 \text{ P}_{\text{soil}}^{**}$	0.29
	Fe	31	No significant regression	
	Mg	31	No significant regression	
	Mn	31	No significant regression	

5.4. Discussion

5.4.1. Proximate composition of millet grains and taro corms

Tree shade had no effect on the protein content of both crops. The average protein content recorded in millet grain during the three cropping years (0.095 g g^{-1}) was lower compared to the average content of 0.151 g g^{-1} for 22 sahelian landraces reported by Buerkert *et al.* (2001). However, protein content in millet grains of the present study was within the range of values reported in Burkina Faso for the landrace “Gampela” (0.087 g g^{-1}) and the improved variety “IKMP-5” (0.101 g g^{-1}) (Lestienne *et al.*, 2007).

According to Mbofung *et al.* (2006), protein content in taro flour ranged from 0.027 to 0.054 g g^{-1} in Cameroon and Tchad varieties which was lower compared to the average content recorded in the present study ($0.106 \pm 0.002 \text{ g g}^{-1}$). Ukpabi *et al.* (2007) also reported lower content of protein in taro flour of Nigeria varieties (0.059 g g^{-1}). The higher protein content in the present study could be explained by N supply through the fertiliser. Indeed, the availability of soil N determines the assimilation of N by crop through the photosynthesis process. Therefore, taro as a C3 plant has high N demand to assimilate and store protein in its corms because of the low PNUE of C4 plants (Sage & Pearcy, 1987; Abraham *et al.*, 2007; Ripley *et al.*, 2008).

Fat content in millet grains recorded in the present study ($0.044 \pm 0.001 \text{ g g}^{-1}$) was slightly lower compared to the values the landrace “Gampela” (0.056 g g^{-1}) and the variety “IKMP-5” (0.0578 g g^{-1}) reported by Lestienne *et al.* (2007). The same as for protein content, fat content in taro corms ($0.007 \pm 0.001 \text{ g g}^{-1}$) was slightly higher compared to values of 0.005 g g^{-1} reported for taro flour by Ukpabi *et al.* (2007) but was within the range of values of 0.003 g g^{-1} to 0.007 g g^{-1} found by Mbofung *et al.* (2006).

Higher ash content in millet grains ($0.028 \pm 0.002 \text{ g g}^{-1}$) was observed in the present study compared to the average content of 0.018 g g^{-1} for 22 landraces of West Africa (Buerkert *et al.*, 2001). The same as for millet grains, ash content in taro corms ($0.083 \pm 0.002 \text{ g g}^{-1}$) was slightly higher compared to the contents reported by Ukpabi *et al.* (2007) and Mbofung *et al.* (2006) (0.033 g g^{-1} and from 0.035 g g^{-1} to 0.057 g g^{-1} , respectively).

Dietary fibre content in millet grains ($0.182 \pm 0.006 \text{ g g}^{-1}$) found in the present study was higher compared to previously reported values of 0.025 g g^{-1} for the landrace Gampela and 0.042 g g^{-1} for the variety "IKMP-5" (Lestienne *et al.*, 2007). Dietary fibre content in taro corms ($0.332 \pm 0.007 \text{ g g}^{-1}$) was also higher compared to the value of 0.024 g g^{-1} reported by Ukpabi *et al.* (2007) and out of the range of values (0.004 g g^{-1} to 0.039 g g^{-1}) found by Mbofung *et al.* (2006).

Carbohydrate content in millet grains ($0.652 \pm 0.008 \text{ g g}^{-1}$) found in the present study was in accordance with the value found for the landrace "Gampela" (0.701 g g^{-1}) and for the variety "IKMP-5" (0.693 g g^{-1}) by Lestienne *et al.* (2007). Taro corms carbohydrates content ($0.473 \pm 0.007 \text{ g g}^{-1}$) was in the range of 0.333 g g^{-1} to 0.778 g g^{-1} previously observed by Mbofung *et al.* (2006) but a higher content was reported by Ukpabi *et al.* (2007) for a cultivar eddoe in Nigeria (0.885 g g^{-1}).

Differences observed between crops proximate composition in the present study and the contents reported in previous works could be attributed to difference in crop varieties and difference in ecological condition of the study sites as shown by Barikmo *et al.* (2004) and Barikmo *et al.* (2007). These authors have shown that there were significant variations in nutrient content of cereals collected in five regions of Mali according to ecological zones. However, the higher content of protein and ash in taro observed in the present study compared to the previous studies cited above may be because flour was used in the previous studies that were produced after peeling the skin of the corms. Therefore, the difference in proximate composition could be attributed to the additional content in the skin. It should be noted that the corms were not peeled in the present study because of the local cooking habit. In fact, an invariable cooking process was observed in the study area, which involved boiling the whole corm without peeling.

There was no significant variation of protein content in both crops according to concentric zones. However, there was a general decreasing trend of protein content from tree trunk (shaded area) to the open area suggesting enhanced protein content due to shade in both crops. There was no significant regression between protein content of taro and soil nutrient but protein content of millet was increased with increase in soil cation exchange capacity. Indeed, a high soil cation exchange capacity increases soil nutrients availability for crop. Therefore, N supplied through the fertiliser in the study was more incorporated by the crop

in soil with high cation exchange capacity and it resulted a high protein content. Similarly, carbohydrates content of taro corms was determined by soil cation exchange capacity that implies soil nutrient availability.

In contrast to protein content, tree shade significantly decreased fat and dietary fibre content in taro corms as attested by the significant regressions between the proximate contents of the crop and PAR availability. The increase of taro corms dietary fibre content with PAR increase is similar to the crude fibre increase in ginger (*Zingiber officinale* R.), a shade tolerant crop, with PAR increase reported by Ajithkumar and Jayachandran (2003). However, fat and carbohydrates contents in millet were mainly determined by initial soil P content: high initial soil P content increased fat content while it decreased carbohydrates content.

The determination of millet fat content by the initial soil P content implies that P provided by the fertilisation was not enough for the crop requirement. Therefore, millet plants used the initial P of soil to complete their demand of P. That is in agreement with Buerkert *et al.* (1998) who found that P application changed the nutritional quality of millet in Sahel region. Accordingly, Muehlig-Versen *et al.* (2003) showed that P was the most limiting nutrient of millet production in Sahel region.

The variations in proximate composition in crops observed between zones may be due to be a combination of many factors as the variation explained by all regressions was lower than 50% ($r^2 < 0.50$). As shown in the previous Chapter 4 of this thesis, soil moisture and soil nutrient contents were higher in shaded zones under trees crown compared to the open area. Therefore, the effect of tree shade on crops proximate composition is expressed differently depending on the crops ability to exploit the better availability of soil nutrients and moisture in reduced PAR condition under trees.

Ash content in both crops was not affected by tree shade or soil initial nutrients content. The conclusion that can be drawn from the results of the present study is that the nutritive quality of taro, a shade tolerant crop, improved under tree shade better than millet.

5.4.2. Mineral contents of millet and taro

Millet grain content of Ca and P ($0.264 \pm 0.047 \text{ mg g}^{-1}$ and $2.496 \pm 0.057 \text{ mg g}^{-1}$, respectively) were lower compared to the values of 0.46 mg g^{-1} and 3.79 mg g^{-1} , respectively reported by FAO (1995). In contrast, the content Fe (0.08 mg g^{-1}) reported by the last author was lower compared to Fe content recorded in the present study ($0.181 \pm 0.027 \text{ mg g}^{-1}$). However, millet grain content of Mg and Mn ($1.385 \pm 0.039 \text{ mg g}^{-1}$ and $0.0130 \pm 0.001 \text{ mg g}^{-1}$, respectively) were comparable to the values of 1.37 mg g^{-1} and 0.01 mg g^{-1} noted by FAO(1995). Fe content in millet was higher compared to the values given for the landrace “Gampela” (0.0187 mg g^{-1}) and the variety “IKMP-5” ($0.03.41 \text{ mg g}^{-1}$) by Lestienne *et al.* (2007). Glew *et al.* (1997) reported for millet in Burkina Faso similar values to the values of the present study for Ca, Mg and Mn (0.203 mg g^{-1} , 1.220 mg g^{-1} and 0.0148 mg g^{-1} , respectively). However, the authors reported lower content of Na and Fe (0.0141 mg g^{-1} and 0.0358 mg g^{-1} , respectively) to the results in this study ($0.107 \pm 0.006 \text{ mg g}^{-1}$ and $0.181 \pm 0.027 \text{ mg g}^{-1}$, respectively).

Mineral contents in taro corms of the present study were higher compared to the values reported in previous studies (Bradbury and Holloway, 1988; Huang *et al.*, 2000). The main reason of the higher mineral content in the present study may be due to the skins that were not peeled of the corms in the present study taking into account the local cooking practice. Therefore, the additional mineral content in the skins may have increased the whole taro content in previous studies.

PAR availability had an effect on only K content in both crops. Indeed, K content in millet was increased with PAR availability and an increase in the initial OM and K content in soil. Indeed, an increase of PAR results in an increase of photosynthesis of millet that required more incorporation of K by the crop. The relationship of K content in millet and the initial K content in soil suggests that K supplied by the fertiliser NPK (15-15-15) was not enough to meet the demand of the crop for this nutrient. In contrast of millet, K content in taro decreased with an increase of PAR and an increase of the initial P content in soil.

There was no shade effect on all the other minerals content in both crops. However, P content in both crops was determined by soil cation exchange capacity, suggesting that this mineral content was dependent on its availability in soil especially through the fertiliser supplied. Fe content in millet was positively dependent on soil OM content while decreased by increase in soil initial P content. Therefore, Fe content in millet may be determined by the nutrient content in soil where Fe and P contents were antagonist.

The contents of Ca, Na and Fe contents in both crops decreased over the three cropping years. In contrast, K content in both crops and P content in taro corms increased from the first cropping year to the last. Since K and P were supplied through the fertiliser, their availability in soil may have increased over the three years and this may have resulted in an increase in crops composition of P and K. In contrast, Ca, Na and Fe were not supplied through fertiliser, so their availability may have decreased in soil with time and consequently in crops. In addition, the application of NPK may have resulted in an acidification of soil and a decrease in cation exchange capacity as reported by Barak *et al.* (1997) and Baraud & Leleyter (2006). Therefore, the availability of Ca, Na and Fe cations for plants was decreased and consequently the incorporation of these nutrients by crops. The reduction of Na availability was more drastic for millet as a C₄ photosynthesis pathway plant that requires Na as an important micronutrient for its photosynthetic process (Grof *et al.* 1989; Orsenigo *et al.*, 1996).

The two crops have different behaviour with regard to their Mg content over the three cropping years. Mg content in taro corms decreased from the first cropping year to the third while no difference was found between years in millet grains. In both crops, there was no effect of shade on Mg content. The decrease of Mg content in taro corm through the years could be attributed to its depletion in soil with time whereas Mg content did not vary in millet grain may be due to the release in top soil through the addition millet straws. As stated above, the decrease of Mg content in taro through the years could also be attributed to the effect of NPK fertiliser application.

The main variations of mineral content in both crops between zones were found for P and Mn content. P content in both crops decreased from tree trunk to the open area under baobab while no significant variation was observed between zones under néré trees. Therefore, the highest P content noted under baobab could not be due to shade effect but it may be the result of the mineral shifting from deep soil to the top layer by roots of baobab which is known to have deeper root system than néré.

In contrast to P content, Mn content was different between zones under both tree species but the variation was noted only in taro corms. The reduced content of Mn content under trees seems to be the result of competition between roots of trees and taro plants as more reduction was noted under baobab trees compared to néré trees with the heaviest shade.

CHAPTER 6: THE SOCIO-ECONOMIC IMPLICATIONS OF INTRODUCING THE IMPROVED CROP PRODUCTION SYSTEM IN PARKLANDS

6.1. Introduction

In parkland systems, there are several reports that showed a reduction in cereal crop yield due to the effect of tree shade. For example, Kessler (1992) estimated a decrease in sorghum yield by up to 6% (30-60 kg ha⁻¹) in parkland systems. Such a reduction of yield of cereal crop grown under tree crowns surely causes a loss of household income which is estimated at 1500-3000 FCFA (€1 = 655.957 FCFA) for sorghum associated with karité (*Vitellaria paradoxa*) (Kessler, 1992). This loss in revenue could, however, be compensated by income generated from the sale of tree products. In his study, Kessler (1992) showed that income from karité and néré (*Parkia biglobosa*) compensated for the loss of income from sorghum by 5000 FCFA as net income. Boffa *et al.* (2000) also observed similar economical benefits from karité and sorghum association in the Sudanian zone of Burkina Faso. The agronomic evaluation in the chapter 3 of this study shown that it was also possible to overcome the loss of crop productivity in the parkland systems by growing shade tolerant crops such as taro under heavy shade trees.

The adoption of shade-tolerant crops by farmers depends on the productivity of the crops as well as their social acceptance by the local community. Cereal crops such as millet are widely used, socially accepted and consumed as the main food crop in the rural areas of Burkina Faso (Youl *et al.*, 2008). Millet also yields stalks used for firewood and other uses (Clement *et al.*, 1993) which otherwise will be unavailable to the households if replaced by taro. On the other hand, although taro was not consumed daily as part of the diet of the local people, it could generate cash income and contribute to diversify the diet of the households. Youl *et al.* (2008) showed the importance of such cash crops for a rural household. The income generated could help in meeting ceremonials expenses, health cost and the purchase of livestock. The best system of crop production in parkland systems, therefore, would be to maintain the production of millet but modify it by growing shade tolerant crops such as taro immediately beneath tree crowns and grow millet or sorghum in open areas up to the edge of tree crowns.

The present study was aimed at assessing the socioeconomic benefits of growing such a combination of crops in parkland systems through farmers' interviews and cost-benefit analysis. The following three (3) research questions were formulated to address the socio-economic benefits of growing crops in association with trees in parkland systems:

- 1- What is the profitability of the current traditional system of crop production in parkland system?
- 2- Can the improved crop production system of replacing millet by taro under tree crowns be more profitable than the traditional crop production system?
- 3- Are farmers willing to adopt the system of millet replacement by taro under tree crowns?

6.2. Materials and methods

A questionnaire survey was conducted to identify tree species and crops commonly grown, used and traded by the villagers in the present study area and assess their productivity. The survey targeted all the farmers, head of households using the parkland but 34 farmers effectively took part to the investigation: 14 participants involved in the present field experiment and 20 other farmers within the parkland. Four (4) farmers of the 38 households sharing the 100 hectares of the parkland were not available for the survey. Therefore, 89.47% of the households using the parkland responded to the questionnaire presented in appendix 1.

A second questionnaire survey was also carried out in the local market to assess the prices of crops and tree products sold on the local market from harvest on November 2007 to October 2008. Prices of tree and crop products were recorded twice a month on market days.

Information collected from these two surveys was used to evaluate the socio-economic benefits of tree-crop-crop combination involving both shade tolerant crops such as taro and cereal crops such as millet in parkland systems.

6.2.1. Assessment of information about tree species in the parkland of the study area

During the survey, farmers were asked to provide information on the number of tree species on their field and to identify their most preferred ones. Information on the main uses of the

preferred tree species was also collected from each respondent. The number of trees and the size of the farm of each respondent were assessed to determine tree density on the parkland. Information on tree management in relation to treatments applied to trees and tree-planting practices were also collected. Farmers were asked to estimate quantity of each product from each tree species that they obtained and to estimate the quantities and prices at which the products were sold. The quantities and prices of tree products that each respondent bought from local market were also assessed.

6.2.2. Assessment of information about crops in the parkland

Information about crops on the parkland was focused on the type of crop species commonly grown, methods of cultivation, yields, uses and income generated. Each respondent was asked to rank the three most preferred crops. The amount of labour required for crop production were identified and quantified. For each crop identified, the amount of fertiliser, manure and pesticide used was assessed. Respondents were also asked to estimate the cost of labour, fertiliser, manure and pesticide used for each crop species. The estimation of each crop yield by respondents was recorded. They were also asked to describe the distribution of their crop harvest between the different uses such as household-consumption, donation to friends and relatives, and sale. Crop selling prices and periods of sale were recorded for each crop.

6.2.3. Assessment of information about tree-crop combination in the parkland

The use of the area under tree crowns by each respondent was assessed. Farmers were asked to describe the traditional management system of the area under tree crowns. Crop species grown by the respondents under trees were identified. Respondents were also asked to estimate the yield of each crop grown under trees.

Respondents were asked if they were aware of the present experiment being conducted in the area to assess the possibility of replacing millet by taro under tree crowns and their reactions to such management system were assessed. Respondents were asked whether or not they were convinced about the possibility of replacing millet by taro under trees and whether or not they would accept or reject the idea. They were also asked to make preference between applying tree pruning to reduce shade and the use of shade tolerant crop in combination with cereal

crop to increase the system productivity. The justification of their choice and their desire to experience such systems were noted. Finally, the preference of respondents between millet and taro as food crop was noted. Apart of ordinary home consumption as food, the other uses of both crops such as in ceremonies, in local medicine preparation and for special occasions were noted.

6.2.4. Cost-benefit analysis of the traditional crop production system in the parkland

Cost-benefit analysis of each crop grown and tree products harvested from each tree species on the parkland was estimated from the information collected from respondents as described above.

The cost of crop production included the cost of all labour used in crop production plus the cost of seeds, pesticide, manure and fertiliser applied. The field activities necessary to grow crop that were used in estimating cost of labour included ploughing, sowing, weeding, ridging and harvesting. Then, an average cost per hectare was calculated for each crop.

The labour for harvesting and processing products of trees were the only cost involved in relation to tree products in the parkland. From personal observation and discussion with few farmers, labour for harvesting and processing tree products per hectare per year were estimated to be around 4 hours for collecting baobab leaves, 4 hours for collecting fruits and processing pulp powder of baobab, 4 hours for collecting fruits and extracting kernels of karité, 8 hours for collecting seeds and processing pulp powder of néré. Then, the cost for producing each tree product was calculated using the average labour cost per hour in the village (1125 FCFA h⁻¹).

Benefits generated per hectare from each crop were calculated using the yield estimated by farmers and the average price at which farmers sold the crop on the local market. Benefits generated from the products of each tree species were calculated taking in account the average tree density.

Finally, the annual costs and benefits were projected over time and discounted at 12% interest rate (average rate applied by local banks) using the crop harvest time (November) as a

baseline time. It was assumed that all crops and the products of all tree species were sold at this harvest time. In addition, it was assumed that all farmers carried out activities of growing a given crop and producing tree products at the same time. Then, the Net Present Value (NPV) of each production was calculated as follows (Baker, 2000):

$$NPV = \sum_{t=0}^n \frac{Bt - Ct}{(1+r)^t}$$

where,

Bt is benefits at time t, Ct is costs at time t, r is discount rate and n is the length of time from the beginning of first crop or tree production activity to harvest.

To estimate the productivity of the traditional crop production system on the parkland, NPV was calculated as shown above using the most common and traditional tree-crop association and the average area used for the association. The profitability of the crop production system was estimated using the Benefit-Cost Ratio (BCR) calculated as follows (Mary & Oliverio., 2007):

$$BCR = \frac{\sum_{t=0}^n Bt(1+r)^{-t}}{\sum_{t=0}^n Ct(1+r)^{-t}},$$

where,

Bt is benefits at time t, Ct is costs at time t, r is discount rate (12%) and n is the length of time from the beginning of first crop production activity to harvest.

6.2.5. Cost-benefit analysis of improved crop production systems in the parkland

Four crop production systems were evaluated for comparison with the traditional crop production system:

- 1) monocultures of millet cropped without trees,
- 2) associations of millet monocultures with trees,
- 3) associations of trees with millet alone grown in the open field (area) and taro alone grown in the tree influence zone (the crop production system tested in the present study), and
- 4) association of trees with a mixture of five traditionally grown common crops grown in the open field (area) and taro alone grown in the tree influence zone, taking into account the tradition of farmers of growing mixture of crops (improved traditional crop production

system). The traditionally grown common crops were maize, millet, sorghum, peanut and cowpea.

The three last crop production systems, where crops are grown together with trees, were evaluated at a minimum, an average and a maximum tree densities of the farmers most preferred tree species in the parkland: *Vitellaria paradoxa* (karité), *Parkia biglobosa* (nééré), *Lannea microcarpa* (Grape tree) and *Adansonia digitata* (baobab). The estimation of these tree densities was based on the information provided by farmers during the survey and personal observation as shown in Table 6.1.

Table 6.1 : Tree density ha⁻¹ of the most preferred tree species estimated by farmers in the study area

	Baobab	Néré	Karité	Grape tree	Total
Maximum	1	3	15	4	23
Minimum	0	0	4	0	4
Average	1	2	10	1	14

As karité and grape tree were not subjects of the present study, it was assumed that their shading effect on associated crops was similar to nééré. Thus, in the third and fourth crop production systems, it was assumed that taro could be grown in zones A and B under nééré, karité and grape tree but under baobab it was assumed that taro could only be grown in Zone A as millet performance was not affected in zone B of baobab (see Chapter 3 of this thesis). The yield of millet and taro under each zone was estimated using yields recorded in the present experiment as reported in Chapter 3 and taking into account the respective total area of each zone (Table 6.2). For the other four crops, that is, maize, sorghum, peanut and cowpea, the yield and the proportional area for each crop was estimated from the information elicited from farmers during the questionnaire survey.

Table 6.2 : Millet and taro yields (kg ha⁻¹) in association with baobab and néré trees and in the open field

Crop	Species	Zone*			
		A	B	C	H
Millet	Baobab	648.9±113.00	908.8±162.19	860.7±89.25	595.8±72.79
	Néré	127.8±43.11	363.2±62.39	469.6±74.22	595.8±72.79
Taro	Baobab	4200.2±764.18	2439.1±624.14	1575.5±398.5	2336.9±662.21
	Néré	4455.6±462.38	5088.0±536.47	2828.5±408.3	2336.9±662.21

* Zone A - from the trunk of each tree up to half of the radius of the tree crown

Zone B - from half of the radius of the tree crown up to the edge of the crown

Zone C - from the edge of the tree crown up to 3 m away

Zone H - the open field.

For each crop production system, crop yield were calculated as follows.

System 1: Millet as sole crop

In this crop production system, where there are no trees, the crop production area is an open field. The yield of millet ha⁻¹ = Yield (kg ha⁻¹) of millet in zone H (control plot)

System 2: Millet alone associated with trees

$$\begin{aligned} \text{Millet grains (Kg ha}^{-1}\text{)} = & D_{\text{baobab}} \times [(Y_{\text{A}_{\text{baobab}}} \times AA_{\text{baobab}}) + (Y_{\text{B}_{\text{baobab}}} \times AB_{\text{baobab}}) + (Y_{\text{C}_{\text{baobab}}} \times AC_{\text{baobab}})] + \\ & D_{\text{néré}} \times [(Y_{\text{A}_{\text{néré}}} \times AA_{\text{néré}}) + (Y_{\text{B}_{\text{néré}}} \times AB_{\text{néré}}) + (Y_{\text{C}_{\text{néré}}} \times AC_{\text{néré}})] + \\ & D_{\text{karité}} \times [(Y_{\text{A}_{\text{karité}}} \times AA_{\text{karité}}) + (Y_{\text{B}_{\text{karité}}} \times AB_{\text{karité}}) + (Y_{\text{C}_{\text{karité}}} \times AC_{\text{karité}})] + \\ & D_{\text{grapes tree}} \times [(Y_{\text{A}_{\text{grapes tree}}} \times AA_{\text{grapes tree}}) + (Y_{\text{B}_{\text{grapes tree}}} \times AB_{\text{grapes tree}}) + (Y_{\text{C}_{\text{grapes tree}}} \times AC_{\text{grapes tree}})] + \\ & Y_{\text{H}} \times \text{AH} \end{aligned}$$

where D_{baobab} = density of baobab trees (tree ha⁻¹),

$Y_{\text{A}_{\text{baobab}}}$, $Y_{\text{B}_{\text{baobab}}}$, $Y_{\text{C}_{\text{baobab}}}$ and Y_{H} are millet yields (kg ha⁻¹) in zones A, B, C under baobab and in the open area (H), respectively;

AA_{baobab} , AB_{baobab} , AC_{baobab} and AH are areas (ha) of zones A, B, C under baobab and the open field, respectively.

The open field area (AH) was calculated using the following formula:

$$\text{AH (ha)} = 1 - (D_{\text{baobab}} \times CA_{\text{baobab}} + D_{\text{néré}} \times CA_{\text{néré}} + D_{\text{karité}} \times CA_{\text{karité}} + D_{\text{grapes tree}} \times CA_{\text{grapes tree}})$$

where D_{baobab} = density of baobab trees (tree ha⁻¹) and CA_{baobab} = the average crown area of baobab trees (ha).

System 3: Millet in the open area and taro in the area under tree influence

$$\begin{aligned} \text{Millet grains (Kg ha}^{-1}\text{)} = & D_{\text{baobab}} \times [(YB_{\text{baobab}} \times AB_{\text{baobab}}) + (YC_{\text{baobab}} \times AC_{\text{baobab}})] + \\ & D_{\text{nééré}} \times (YC_{\text{nééré}} \times AC_{\text{nééré}}) + D_{\text{karité}} \times (YC_{\text{nééré}} \times AC_{\text{karité}}) + \\ & D_{\text{grapes tree}} \times (YC_{\text{nééré}} \times AC_{\text{grapes tree}}) + YH \times AH \end{aligned}$$

where D_{baobab} = density of baobab trees (tree ha⁻¹),

YA_{baobab} , YB_{baobab} , YC_{baobab} and YH are millet yields (kg ha⁻¹) in zones A, B, C under baobab and in the open area, respectively;

AA_{baobab} , AB_{baobab} , AC_{baobab} and AH are areas (ha) of zones A, B, C under baobab and the open field, respectively.

The open field area (AH) was calculated as:

$$AH(\text{ha}) = 1 - (D_{\text{baobab}} \times CA_{\text{baobab}} + D_{\text{nééré}} \times CA_{\text{nééré}} + D_{\text{karité}} \times CA_{\text{karité}} + D_{\text{grapes tree}} \times CA_{\text{grapes tree}})$$

where D_{baobab} = density of baobab trees (tree ha⁻¹) and CA_{baobab} = the average crown area of baobab trees (ha).

$$\begin{aligned} \text{Taro corms (Kg ha}^{-1}\text{)} = & D_{\text{baobab}} \times (YA_{\text{baobab}} \times AA_{\text{baobab}}) + D_{\text{nééré}} \times [(YA_{\text{nééré}} \times AA_{\text{nééré}}) + (YB_{\text{nééré}} \times AB_{\text{nééré}})] + \\ & D_{\text{karité}} \times [(YA_{\text{nééré}} \times AA_{\text{karité}}) + (YB_{\text{nééré}} \times AB_{\text{karité}})] + \\ & D_{\text{grapes tree}} \times [(YA_{\text{nééré}} \times AA_{\text{grapes tree}}) + (YB_{\text{nééré}} \times AB_{\text{grapes tree}})] \end{aligned}$$

where D_{baobab} = density of baobab trees (tree ha⁻¹),

$YA_{\text{nééré}}$ and $YB_{\text{nééré}}$ are taro yields (kg ha⁻¹) in zones A and B under nééré, respectively,

$AA_{\text{nééré}}$ and $AB_{\text{nééré}}$ are areas (ha) of zones A and B under nééré, respectively.

System 4: Taro in the area under tree crowns and a mixture of five crops in the open area

The yield of taro in zones under tree crowns was calculated using the formula below:

$$\begin{aligned} \text{Taro corms (kg ha}^{-1}\text{)} = & D_{\text{baobab}} \times (YA_{\text{baobab}} \times AA_{\text{baobab}}) + D_{\text{nééré}} \times [(YA_{\text{nééré}} \times AA_{\text{nééré}}) + (YB_{\text{nééré}} \times AB_{\text{nééré}})] + \\ & D_{\text{karité}} \times [(YA_{\text{nééré}} \times AA_{\text{karité}}) + (YB_{\text{nééré}} \times AB_{\text{karité}})] + \\ & D_{\text{grapes tree}} \times [(YA_{\text{nééré}} \times AA_{\text{grapes tree}}) + (YB_{\text{nééré}} \times AB_{\text{grapes tree}})] \end{aligned}$$

where D_{baobab} = density of baobab trees (tree ha⁻¹),

$YA_{\text{nééré}}$ and $YB_{\text{nééré}}$ are taro yields (kg ha⁻¹) in zones A and B under nééré, respectively,

$AA_{\text{nééré}}$ and $AB_{\text{nééré}}$ are areas (ha) of zones A and B under nééré, respectively.

A mixture of five crops (maize, millet, sorghum, peanut and cowpea) was used on the rest of the area (RA), which was calculated as:

$$RA \text{ (ha)} = 1 - (D_{\text{baobab}} \times AA_{\text{baobab}} + D_{\text{nééré}} \times CA_{\text{nééré}} + D_{\text{karité}} \times CA_{\text{karité}} + D_{\text{grapes tree}} \times CA_{\text{grapes tree}})$$

where D_{baobab} = density of baobab trees (tree ha^{-1}), AA_{baobab} = area (ha) of zone A under baobab and $CA_{\text{nééré}}$ = the average crown area of baobab trees (ha).

The area RA was divided between the five crops using the proportional area that farmers commonly use on the parkland: 0.32 for maize, 0.23 for millet, 0.21 for sorghum, 0.16 for peanut and 0.08 for cowpea (see results section). Then, yield of each crop was calculated using the formula as follows:

$$P_c = Y_c \times A_c$$

where P_c = the yield in kg ha^{-1} of crop c, Y_c = the yield of crop c and A_c = the area of crop c.

Benefits from crops in each crop production system were calculated using their yield per hectare and their average price on the local market. Costs in each crop production system were calculated using the same formulas as for yields.

Benefit and cost of tree products at minimum, average and maximum trees densities were calculated using yields and prices as given by farmers. The total benefit of a crop production system was obtained by adding together the benefits from crops and trees. Similarly, the total cost of a crop production system was the sum of the cost of crop and tree productions. Finally, NPV and BCR were calculated as described in the above formulas.

6.2.6. Data analysis

Data of the two surveys were computed in Microsoft Excel to derive consolidated information. Respondents generally estimated the amount of crops and tree products using a standard container called “Yoruba”. For each crop or tree product, the full container was weighed and this weight was used to convert farmers estimated quantities to kg. Crops and tree products estimated by respondents were finally converted to yield (kg ha^{-1}) using the size of respondent’s farm. Net present value (NPV) and Benefit-cost ratios (BCR) were computed for parkland crop production systems using the respective formula in Microsoft Excel spreadsheet. ANOVA was applied to the data on the NPV and the BCR using Minitab.

1.1. Results

1.1.1. Trees species in the parkland of the study area

1.1.1.1. Preferred tree species

The average tree density on the parkland calculated from information given by respondents was 11.9 ± 1.52 ha. The interviewed farmers cited six tree species as the most preferred species on their farms. These species were ranked according to the number of times they were cited by farmers. The top ranked species was *Vitellaria paradoxa* (48%), followed by *Parkia biglobosa* (37%), and the last was *Ficus gnacalocarpa* (2%) (Fig. 6.1).

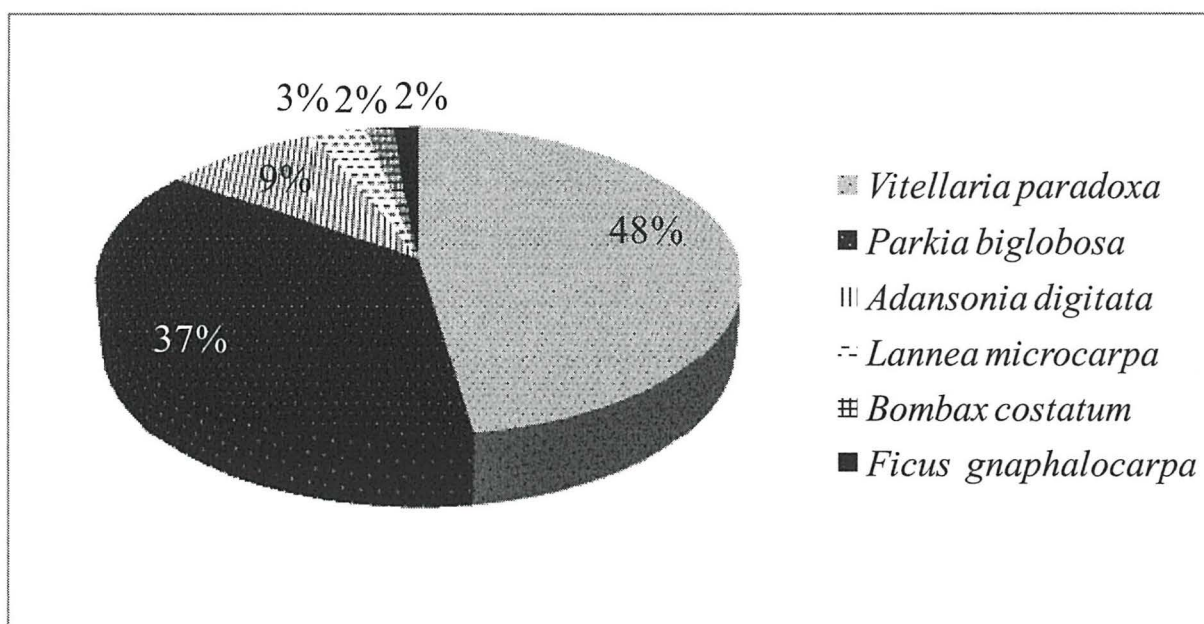


Fig. 6.1 : Ranking (% of citation) of tree species by farmers

Farmers' preferences of a tree species were mainly based on fruit and wood production (27% each). Among the other tree uses that determined the preference of trees by farmers, the highest ranked use was shade for humans and livestock (17%), flowers and windbreak were the least (1%) (Fig. 6.2).

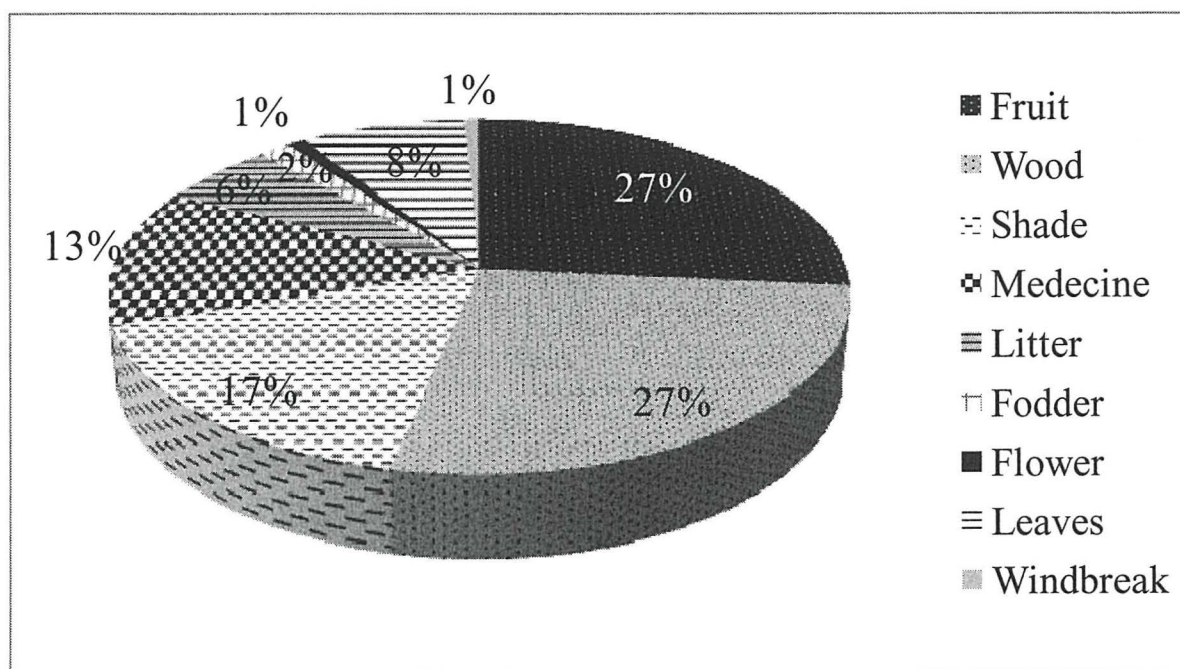


Fig. 6.2 : Ranking of products and services (% of citation) justifying farmers preferences of tree species on the parkland

Néré (*P. biglobosa*) and baobab (*A. digitata*), the two tree species of the present study were the second and third preferred species, respectively. Néré was preferred for its fruit, wood and shade while baobab was preferred because of its leaves, fruit and shade.

1.1.1.2. Tree management in the parkland

41% of the respondents planted trees on their farms. The most common planted species ranked according to farmers' citations were *Eucalyptus camaldulensis*, *Psidium guajava*, *Parkia biglobosa*, *Jatropha curcas*, *Mangifera indica* and *Senna occidentalis* (50%, 17%, 11%, 11%, 6% and 6%, respectively). Among the planted tree species, *Parkia biglobosa* was the only native tree species.

Only 29% of the respondents applied some sort of management to trees. The main practices included pruning tree branches and watering recently planted trees (86% and 14%, respectively). Among the two tree species of the present study (baobab and néré) only néré was planted and managed by pruning by farmers.

6.3.1.3. Tree products of the parkland

According to the number of citations by interviewed farmers, the most common tree products harvested from the parkland trees were fruits (*Vitellaria paradoxa*, *Parkia biglobosa* and *Adansonia digitata*), wood (*Eucalyptus camaldulensis*, *Vitellaria paradoxa*, *Parkia biglobosa* and *Senna occidentalis*), leaves of *Adansonia digitata* and flowers of *Bombax costatum* (88%, 8%, 3% and 2%, respectively).

Farmers were not able to quantify some of the tree products harvested such as wood, fresh fruit, and flowers. The difficulty of estimating the quantities was related to the occasional and individual harvest of those products. For example, only the dried branches are cut on a tree and anyone passing through the field can harvest some fresh fruits or flowers for his own consumption. Therefore, farmers were only able to quantify the amount of products they extracted from harvested fruits and leaves. The average yield of kernels produced from fruits of *Vitellaria paradoxa* was estimated at $90.8 \pm 13.31 \text{ kg ha}^{-1}$. Fruits of *Parkia biglobosa* produced an average of $73.8 \pm 2.93 \text{ kg ha}^{-1}$ of seeds and $32.2 \pm 3.18 \text{ kg ha}^{-1}$ of pulp powder. Respondents produced from *Adansonia digitata* trees an average of $15.0 \pm 7.07 \text{ kg ha}^{-1}$ of fruit pulp powder and $129.7 \pm 43.24 \text{ kg ha}^{-1}$ of fresh leaves.

The labour cost for harvesting and processing the kernels of karité was estimated to $4629 \pm 514 \text{ FCFA ha}^{-1}$. The pulp powder and seeds of néré required a total labour cost of $9525 \pm 706 \text{ FCFA ha}^{-1}$. $9216 \pm 779 \text{ FCFA ha}^{-1}$ was necessary as labour cost for harvest and processing of the leaves and pulp powder of baobab.

6.3.1.4. Tree products sold on local market

A large part of tree products harvested on the parkland was used for home consumption and the rest was sold on the local market (43%, 24% and 38%, for the products of karité, néré and baobab, respectively). The most common tree products encountered on the local market were fruits, leaves, flowers, wood, charcoal and processed products. Depending on the season, tree products were sold either fresh or dry. The fresh leaves of baobab were found on the market during the rainy season (May to October) and as dry or powder all the year round. Baobab fruit were sold on the market as capsules from November to February. Pods of néré tree were traded at harvest (March to April) while pulp powder and seeds were found throughout the

year. The most common product of néré tree that was available in the market all year round was fermented seeds called soubala which were used as a condiment in soup making. Karité butter was sold on the market all year long but the kernels of the species were more abundant from August to December.

The trading of fresh fruits of both baobab and néré trees was very low and was mainly done by children. Fresh and dry leaves of baobab, pulp powder and seeds of néré were the major products that were sold by women. The average prices of each product of karité, baobab and néré are shown in Table 6.3. Traders coming from Ouagadougou fix prices according to the product abundance on the local market. The lowest prices are recorded at harvest and the highest prices are applied when product are scarce on the market.

Table 6.3 : Minimum, maximum and average prices (FCFA kg⁻¹) of tree products at Nobéré local market

Species	Product	Minimum	Maximum	Average
<i>Vitellaria paradoxa</i>	Kernel	60	151	89±4.9
<i>Parkia biglobosa</i>	Seeds	137	343	231±26.5
	Pulp powder	75	147	110±14.1
<i>Adansonia digitata</i>	Pulp powder	556	833	694.±66.1
	Fresh Leaves	88	150	117±13.9
	Dry leaves	25	83	52±10.4

6.3.2. Crop production in the parkland of the study area

6.3.2.1. Crop species grown in the parkland

Farming area per household was relatively small in the parkland: respondents reported an average area of 2.9±0.26 ha with a minimum of 1 ha and a maximum of 6 ha per household. Each household grew several crops in association with trees on his/her field. Respondents cited eleven (11) commonly grown crops in the parkland: maize, peanut, sorghum, millet, cowpea, rice, vouandzu (*Vigna subterranea* (L.) Verdc.), taro, cotton, okra (*Abelmoschus esculentus* (L.) Moench) and eggplant ranked according to their frequency on the parkland (Table 6.4). Respondents ranked the three most preferred crops as sorghum (44%), millet (32%) and maize (28%) according to crops growing input demand and their production on the parkland.

With regard to the extent of plot size devoted to each crop, three cereal crops (maize, sorghum and millet) had the highest plot size used per household. The other crops were grown on small scale (Table 6.4). Respondents were not able to estimate the area for okra and eggplants because the area used for these crops were negligible.

Generally, farmers traditionally always grew many crops sharing the total area of their field. The minimum was two crops per farm (one cereal and peanut) and the maximum was seven (7) crops per field. The average production system in the parkland involved a combination of five (5) crops: farmers divide their field area (2.9 ± 0.26 ha at average) to grow maize (0.8 ± 0.1 ha), millet (0.6 ± 0.09 ha), sorghum (0.6 ± 0.07 ha), peanut (0.4 ± 0.05 ha) and cowpea (0.2 ± 0.05 ha).

Table 6.4 : Crops frequencies and the average area per household used to grow each crop on the parkland at Nobéré

Crops	Frequency on the parkland	Average area
Maize	19	0.8 ± 0.10
Millet	15	0.6 ± 0.09
Sorghum	17	0.6 ± 0.07
Peanut	19	0.4 ± 0.05
Cowpea	11	0.2 ± 0.05
Cotton	3	0.1 ± 0.07
Vouandzu	4	0.1 ± 0.03
Rice	8	0.1 ± 0.01
Taro	3	0.1 ± 0.02
Okra	1	-
Eggplant	1	-

6.3.2.2. *Cost of crop production in the parkland*

The labour used in crop production in the parkland was mainly for ploughing, sowing, weeding and harvesting. Ploughing and ridging were done manually or using oxen while sowing, weeding and harvest were always manual. Ridging was applied in millet fields but it was not in taro fields. The number of times weeding was done depended on the crop species: the fields of millet were weeded twice (2) while taro fields were weeded four (4) times.

Fertiliser (NPK : 15-15-15 and urea) were often used for maize production (78%) but only 9%, 3% and 3% of respondents used fertiliser for sorghum, millet and taro, respectively. NPK was applied for millet and taro at doses of 100 kg ha⁻¹ and 200 kg ha⁻¹, respectively. A dose of 100 kg ha⁻¹ urea was also applied for both crops. In addition to fertiliser, 66% of respondents supplied manure to fields, especially for maize, eggplants and rice. Doses of manure applied varied from 0.8 t ha⁻¹ to 15 t ha⁻¹, with an average dose of 5.5±0.72 t ha⁻¹.

Respondents, who grew cotton and cowpea, used pesticide for these crops. Pesticide was used in cotton fields six times at a dose of 1 l ha⁻¹ per application while two applications at a dose of 4 l ha⁻¹ per application were applied to cowpea fields. Except these crops, pesticides were not used for the other crops.

The average cost of labour, fertiliser and manure as estimated by respondents are given in table 6.5. The highest cost of labour was for ploughing (17900±1204.3 FCFA) and the least for harvesting (4780±630.2 FCFA). The average local price given by respondents for fertiliser was 409±30.4 FCFA kg⁻¹ and 208±17.9 FCFA kg⁻¹ for NPK and urea, respectively. One tonne of manure was estimated to cost on average 5021±1175.1 FCFA. The cost of pesticide for cotton was 4885 FCFA l⁻¹ and the cost of cowpea's pesticide was 1500 FCFA l⁻¹.

Table 6.5 : Minimum, maximum and average cost of labour and fertiliser as estimated by farmers at Nobéré local market

Labour cost (FCFA ha⁻¹)	Minimum	Maximum	Average
Ploughing	7000	27500	17900±1204.3
Sowing	5000	25000	8750±830.0
Weeding	5000	20000	12923±583.6
Ridging	5000	20000	10968±715.8
Harvest	1000	15000	4780±630.2
Fertiliser cost (FCFA kg⁻¹)			
NPK	200	850	409±30.4
Urea	125	425	208±17.9
Manure (FCFA tonne⁻¹)			
	3325	8500	5021±1175.1
Pesticide (FCFA l⁻¹)			
Cotton	4885	4885	4885
Cowpea	1500	1500	1500

N.B. €1 = FCFA 655.957

The total costs of crop production on the parkland are presented in figure 6.3. As shown in figure 6.3, taro production required the highest labour cost (83123 ± 4998.7 FCFA ha^{-1}) and the least labour cost was for peanut production (44354 ± 3831.6 FCFA ha^{-1}). Taro also required more seeds and fertiliser costs compared to cereals. The total cost of taro production was higher compared to millet (170280 ± 9834.3 FCFA ha^{-1} and 101150 ± 7589.2 FCFA ha^{-1} , respectively). As with taro, the production of cotton, rice and eggplants required high total input (178027 ± 10279.9 FCFA ha^{-1}), 169202 ± 15725.31 FCFA ha^{-1} and 193957 ± 15725.3 FCFA ha^{-1}).

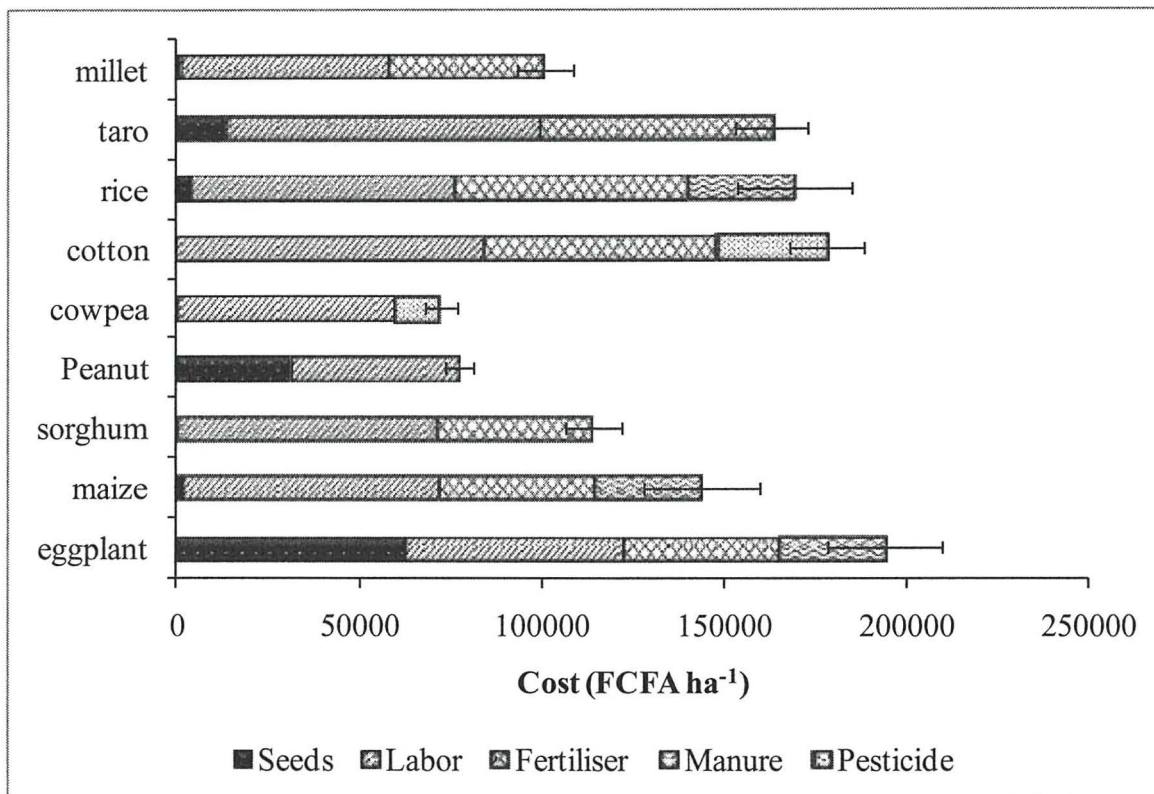


Fig. 6.3 : Input cost of crop production at Nobéré parkland as estimated by farmers (2008).

1.1.1.3. Crop yields in the parkland

Yield estimation by respondents for common crops on the parkland is given in table 6.6. Generally, farmers who applied fertilizer had higher crop yields compared to non-users. The yields of millet and taro with fertilizer application were estimated as 678.9 ± 46.83 kg ha^{-1} and 2485.4 ± 148.33 kg ha^{-1} , respectively and these were in close agreement with the yields observed in the control plots of the present experiment (595.8 kg ha^{-1} and 2336.9 kg ha^{-1} for millet and taro, respectively).

Table 6.6 : Yield (kg ha⁻¹) of common crops in a parkland at Nobéré as estimated by farmers

Crop yield (kg ha⁻¹)	Minimum	Maximum	With fertiliser	Without fertiliser
Maize	118	2200	982.4±64.22	286.0±72.46
Sorghum	118.4	1184	753.8±33.12	540.5±42.31
Millet	192.6	1284	678.9±46.83	487.7±48.73
Cowpea	125.8	2160	-	532.6±93.57
Peanut	21.6	1440	-	573.3±62.28
Rice	400	2240	982.4±132.46	612.3±165.84
Taro	1800	3000	2485.4±148.33	1684.8±152.36
Vouandzu	200	600	-	336.0±56.14
Cotton	576	585	580.5±6.42	-

6.3.2.4. *Crop sold on the local market by respondents*

All crops produced on the parkland were sold on the local market. All the respondents stated that they sold part of their crop harvest on the market. The part of harvest sold depended on the type of crops and the status of respondents. The whole quantity of cotton or a percentage of the quantity harvested for cowpea, vouandzu, maize, taro, peanut, sorghum and rice was sold on the market (Table 6.7). It must be noted that no respondent reported selling any part of his/her millet harvest.

According to respondents, they sold some of the crops at harvest and occasionally whenever they needed cash at other times. Therefore, selling prices varied depending the time of sale and the need of the respondent. The average selling price for cereals was 140±29.7 FCFA kg⁻¹, 118±2.9 FCFA kg⁻¹ and 188±6.6 FCFA kg⁻¹ for maize, sorghum and rice, respectively (Table 6.7). Taro selling price was estimated at 68±1.2 FCFA kg⁻¹ but no price was given for millet because none of the respondents sold millet.

Table 6.7 : Percentage of harvest sold and selling prices of crops as estimated by respondents

Crops	Percentage of harvest sold (%)	Price (FCFA kg ⁻¹)		
		Minimum	Maximum	Average
Millet	0	-	-	-
Maize	69	110	170	139.8±29.66
Sorghum	58	101	135	118.4±2.94
Peanut	63	113	500	252.6±13.87
Cowpea	88	60	222	153.8±19.51
Vouandzu	88	140	200	170.0±30.00
Cotton	100	165	165	165.0±0.00
Taro	67	66	70	68.2±1.23
Rice	31	182	195	188.4±6.59

The results of the market survey for millet and taro from November 2007 to October 2008 is shown on Figure 6.4. Although none of the respondents sold millet, it was found being sold on the market. Prices of both crops increased from harvest to quite double of initial price in the middle of the crop production season (July and August). The average price was 149.9±9.29 FCFA kg⁻¹ and 63.9±4.02 FCFA kg⁻¹ for millet and taro, respectively.

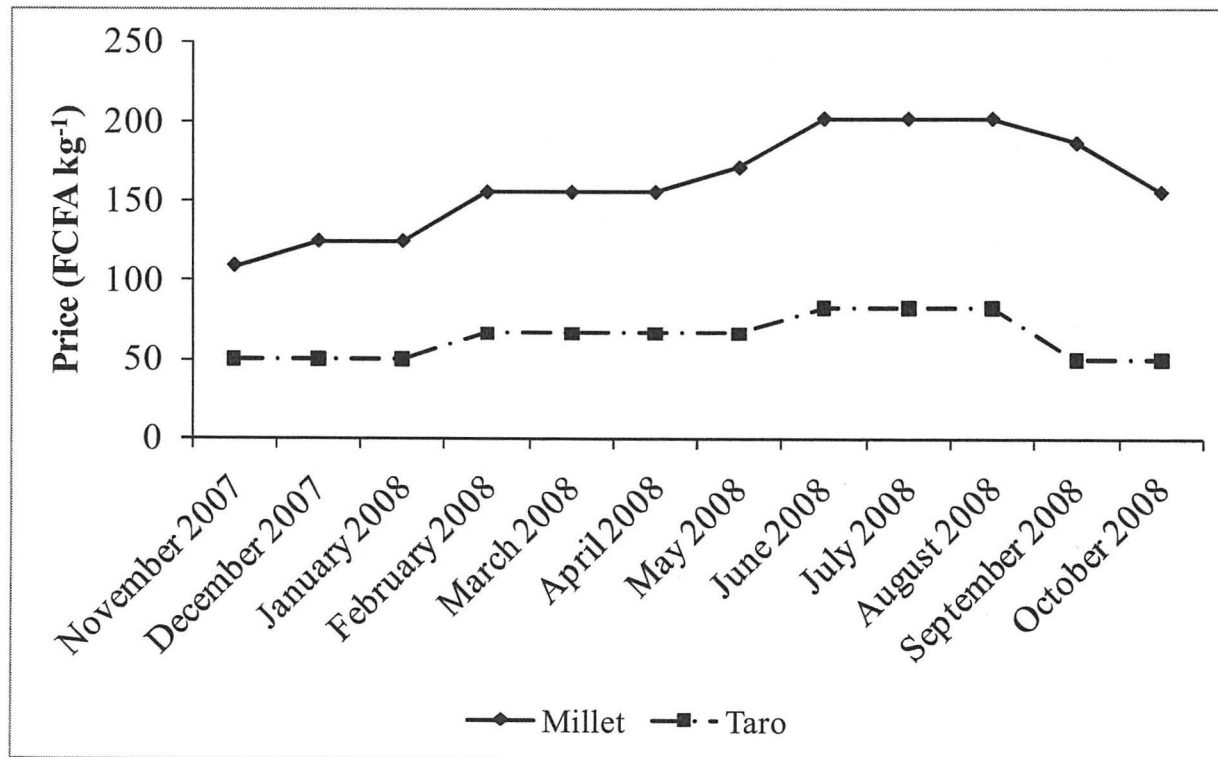


Fig. 6.4 : The monthly price trend of millet and taro on the market of Nobéré from November 2007 to October 2008.

6.3.3. Economic valuation of crops, trees and their association in the parkland

6.3.3.1. *Net Present Value of tree products produced in the parkland*

At an average density of 14 trees ha⁻¹ on the parkland (1 baobab tree, 10 karité trees and 2 néré trees), the average net present value (NPV) gained from the kernels of karité was estimated to be 3672.8±682.63 FCFA per hectare. Néré generated an average NPV of 11701.9±917.86 FCFA ha⁻¹ and 585.8±452.62 FCFA ha⁻¹ from seeds and pulp powder and these gave a total NPV of 12287.8±1370.47 FCFA per hectare for the species. The total NPV of baobab production was estimated at 16920.0±405.72 FCFA ha⁻¹ derived from pulp powder and fresh leaves (4458.5±528.10 FCFA ha⁻¹ and 12461.5±122.38 FCFA ha⁻¹, respectively). Finally, the total NPV generated by all trees on the parkland was 32880.6±2458.82 FCFA ha⁻¹.

The NPV generated by trees at the minimum tree density of four (4) trees ha⁻¹ in the parkland (4 karité trees) was 1469.1±273.05 FCFA. At the maximum tree density of 23 trees ha⁻¹ (1 baobab tree, 15 karité trees and 3 néré trees), the NPV of tree products was estimated at 40860.9±3442.35 FCFA.

6.3.3.2. *Net Present Values of crops produced in the parkland*

The net present values (NPV) generated by crops in the parkland, based on yield and input estimations made by farmers, are shown on figure 6.5. Except for the productions of rice, taro and millet, applying fertiliser on crops (maize, sorghum and cotton) on the parkland resulted in negative NPV. However, the application of fertiliser on millet reduced its NPV while the NPV of taro and rice was increased by fertiliser application. The highest net present revenue was given by peanut production (68,731.5±871.94 FCFA ha⁻¹) that required no fertiliser and low labour cost. The other crops that generated a positive net present values were taro, cowpea, Vouandzou, rice and cowpea (Fig. 6.5). Growing cotton, maize and sorghum on the parkland resulted in negative net present values.

Assuming that household members provide all labour as is usually the case with small farmers, the NPV of all crops was positive (Table 6.8). Peanut production yielded the highest NPV (114,744.9 FCFA ha⁻¹) while cotton production provided the smallest NPV (1431.1 F

CFA ha⁻¹). The NPV of millet produced without fertiliser application was higher (71,859.6 F CFA ha⁻¹) compared to the NPV yield by fertiliser application (58,032.5 F CFA ha⁻¹). The NPV of taro was quite similar for farmers who applied or not fertiliser (113,318.9 F CFA ha⁻¹ and 100,924.6 F CFA ha⁻¹, respectively)

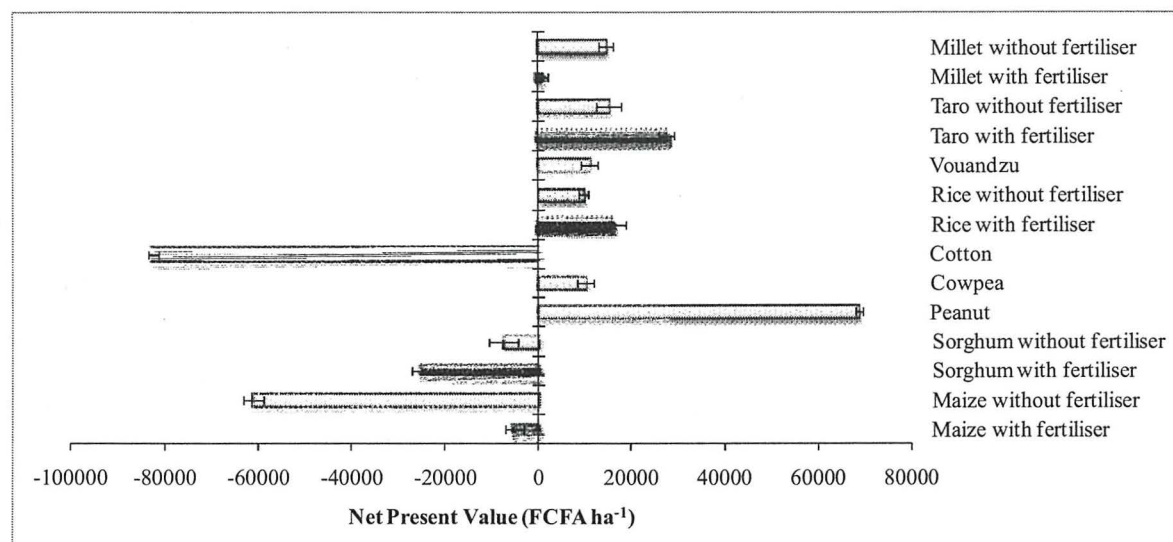


Fig. 6.5 : Net Present Values of crops produced on the parkland at Nobéré (Farmers survey, 2008).

Table 6.8 : Net revenue of crops produced on the parkland at Nobéré without labour cost

Crop	NPV (FCFA ha ⁻¹)	
	With fertiliser	Without fertiliser
Maize	65416.7	9607.3
Sorghum	45772.1	63007.5
Peanut	-	114744.9
Cowpea	-	69666.8
Cotton	1431.1	
Rice	88495.9	82427.7
Vouandzu	-	57120
Taro	113318.9	100924.6
Millet	58032.5	71859.6

6.3.3.3. Net present values of crop production systems in association with trees in the parkland

Labour demand of a crop production system can determine the decision of a farmer of whether to adopt it or not. Therefore, the NPV of each crop production system was calculated taking in account the labour cost even if the farmer does all his/her own work in the field. The traditional crop production system in the parkland, in which a combination of five common

crop species (maize, millet, sorghum, peanut, cowpea) are grown in association with trees generated a positive NPV ($24,317.2 \pm 7942.24$ FCFA ha⁻¹). In contrast, the net present value of millet sole production system (System 1) was negative (-6922.1 ± 6913.23 FCFA ha⁻¹). There was no significant difference between the NPV of millet sole production and the values of NPV generated by millet alone associated with trees (System 2) at minimum and average densities (-13161.8 ± 9164.59 FCFA ha⁻¹, -21157.5 ± 8900.28 FCFA ha⁻¹, respectively) (Fig. 6.6). However, the deficit was significantly increased, when millet is cropped alone in association with trees (System 2) at maximum density of trees (-33696.9 ± 8069.08 FCFA ha⁻¹). In contrast, the use of taro alone in the area under tree influence and millet alone in the open area (System 3) improved the net present value. Although the value remained negative at minimum tree density (-2732.8 ± 8984.64 FCFA ha⁻¹), it was positive at average and maximum trees densities (21099.7 ± 8019.02 FCFA ha⁻¹ and 42092.2 ± 7059.42 FCFA ha⁻¹, respectively). The use of taro under trees and a mixture of five crops in the open area (System 4) generated the highest NPV of all the tested systems at the three tree densities (8263.0 ± 9821.60 FCFA ha⁻¹, 84696.1 ± 8378.6 FCFA ha⁻¹ and 134908.9 ± 7032.67 FCFA ha⁻¹).

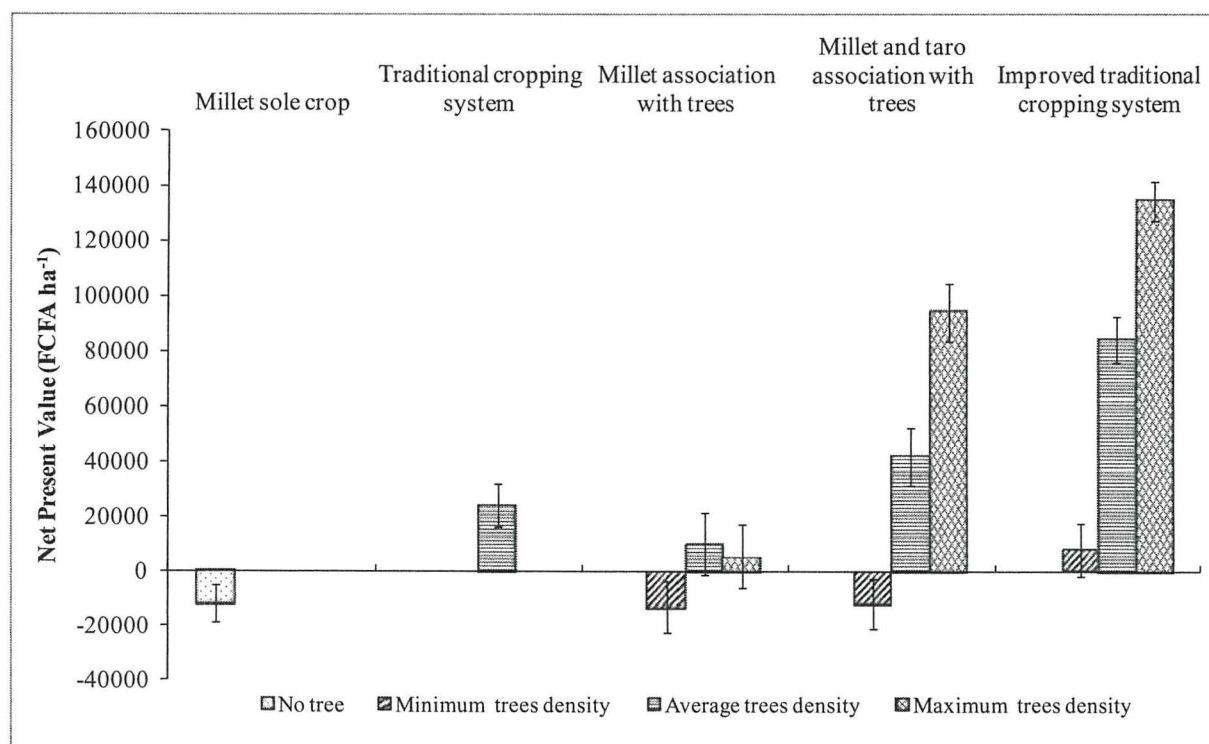


Fig. 6.1 : Net Present Value (FCFA ha⁻¹) of millet sole production system and four crop production systems using crop and trees associations at minimum, average and maximum tree densities on the parkland.

6.3.3.4. *Benefit-Cost Ratios of crop production systems in association with trees in the parkland*

BCR increased with an increase in tree density for the system of a mixture of only millet and taro associated with trees (System 3). For the system of millet alone associated with trees (System 2), the value of BCR increased from minimum tree density to average tree density and then decreased at maximum tree density (Table 6.9). The systems of millet sole production (System 1), millet alone associated with trees (System 2) at minimum tree density and a mixture of only millet and taro associated with trees (System 3) at minimum tree density gave a BCR less than 1. Out of all the five tested crop production systems, only the two systems that use taro in the area under tree influence, that is, a mixture of only millet and taro associated with trees (System 3) and the improved traditional crop production system (System 4) at average and maximum tree densities gave higher BCRs when compared to the BCR value of the traditional crop production system (1.18) (Table 6.9).

Table 6.9 : Benefit-Cost Ratio (BCR) of the traditional crop production system, millet sole cropping, millet in association with trees and the system of millet-taro association with trees at minimum, average and maximum trees densities

Crop Production Systems	No tree	Minimum trees density	Average trees density	Maximum trees density
Traditional crop production system	-	-	1.18	-
Millet sole production system	0.88	-	-	-
Millet alone associated with trees	-	0.87	1.08	1.04
A mixture of only millet and taro associated with trees	-	0.90	1.29	1.70
Improved traditional crop production system	-	1.08	1.74	2.27

6.3.4. Farmers perception of crop production in association with trees on the parkland

Crops and trees are generally associated on the parkland but crop production under tree crown varied from farmer to farmer. The majority of the respondents (63%) grew the same crop species under tree crowns and in the open area. A large number of respondents (31%) did not grow any crop under tree crowns. Two respondents used specific crops under karité and néré trees; they grew fabirama (*Solenostemon rotundifolius*) or chilli pepper (*Capsicum frutescens* and *Capsicum annum*) under both trees species.

Generally, the respondents reported low or very low crop yields under tree crowns (87.5% and 9%, respectively). However, 6% stated that yields were good under tree crowns. Only 9% of the respondents preferred tree pruning as a management to improve crop yield under tree crowns. The reason of their choice were tree rejuvenation, need of wood and better yield of millet. The majority of the respondents (91%) chose to substitute cereal crops by another food crop under tree crowns to enhance the benefit from growing crops in the association with trees without reducing the yield of tree products.

The majority of the respondents were aware of the present crop production experiment (84%) – a combination of only millet and taro in association with trees. 44% of the informants were participants in the present experiment, of the others 16% visited the experimental site at some stage and 28% were informed by other farmers. In response to the question whether or not they would adopt the improved system tested, 88% of the respondents reported that they would like to adopt the system of replacing millet by taro under trees as tested in the present experiment. The main reason given was that a good profit could be generated by the improved system (75%). 13% of the respondents wanted to test the system by themselves before adopting it to replace their traditional practice. Among the respondents who were unwilling to adopt the system, 9% claimed that growing taro in the system demanded high input because of the low fertility of their soils and 3% did not want to change their traditional practices.

Millet was the most preferred crop for household dietary needs of 97% of the respondents and the rest (3%) preferred maize. 100% of the respondents preferred the two cereals because they were consumed daily by their families. 25% of the respondents used taro, 28% rice, and 3% cowpea on special occasions in order to vary their diet. According to 72% of the respondents, millet was also used to prepare medicines while one respondent noted taro as a component of a recipe of local medicine. 9% of the respondents also reported that millet was used during social and religious ceremonies. One respondent knew this type of use of taro.

Stalks of millet were used as fodder, fuel and manure according to 88%, 28% and 6% of the respondents, respectively. No respondent reported no such use of taro stalks.

6.4. Discussion

6.4.1. Production of parkland tree products

The results of the questionnaire survey showed that the most preferred tree species in the parkland of the present study area were *Vitellaria paradoxa*, *Parkia biglobosa*, *Adansonia digitata*, *Lannea microcarpa*, *Bombax costatum* and *Ficus gnacalocarpa*. All the six tree species produce food (fruit and leafy vegetable) which is the predominant role of these trees in the parkland. Majority of the respondents preferred these species because of their fruit and wood values. When farmers convert woodland to cropland they selectively retain these trees on their farm because of their value as source of food as reported by Yaméogo *et al.* (2005) and Teklehaimanot (2004). In addition to their key role as food source, these trees also play other important roles such as providing shade for humans and livestock, source of medicine and soil fertility improvement (Yaméogo *et al.* (2005).

Despite their knowledge about the effect of the six trees on soil fertility and their values in terms food and wood, none of the respondents planted these trees on their land with the exception of *nééré*. The majority of the respondents planted exotic trees only. Sandra *et al.* (2002) made similar observation regarding farmers' preference of planting of exotic species over indigenous trees in the sudano-sahelian zone of Burkina Faso. The relative low density of *nééré* in the parkland combined with its highly valued fruit and wood may explain the reason why some farmers planted *nééré* on their farms. The very high need for wood for fuel and construction in the area may also explain why *Eucalyptus camaldulensis*, which is a fast growing tree with good quality wood for fuel and other uses, was planted by majority of the respondents.

The yields of tree products estimated by the respondents were within the range of values reported by previous workers. For example, the average yield of *nééré* seeds of 73.8 ± 2.93 kg ha⁻¹ estimated by the respondents was within the range of values of 15 to 130 kg reported by Teklehaimanot (2004) based on an average tree density of 2 trees ha⁻¹. The fruit yield per *nééré* tree of 53.0 ± 3.06 kg estimated by the respondents was also in accordance with the value of 53.4 ± 14.5 kg tree⁻¹ recorded by Bayala *et al.* (2002).

6.4.2. Crop production on the parkland

Eleven species were recorded as crops grown on the parkland. From these eleven cereal crops (i.e. sorghum, millet and maize) were the most preferred. The predominance of cereal crops reflects the subsistence nature of the crop production system, the priority of which is to ensure adequate household food supply. Secondary crops such as peanut, rice, cotton and eggplants were grown to generate income. With the exception of peanuts, crops grown to generate income received more inputs compared to cereal crops. Despite higher inputs the income associated with these plants were quite low. A typical example was cotton that yielded an average of $580.5 \pm 4.5 \text{ kg ha}^{-1}$ while the national average yield was almost threefold higher (1357 kg ha^{-1}) in 2006-2007 (Direction des Statistiques Agricoles/DGPSA/MAHRH, 2007). In contrast, millet yield ($663.5 \pm 84.63 \text{ kg ha}^{-1}$) was closer to the national average yield given by Direction des Statistiques Agricoles/DGPSA/MAHRH (2007) for 2006-2007 period (934 kg ha^{-1}). Generally, yields of all crops were lower compared to their national averages because of the very low fertility of soil in the parkland.

6.4.3. Economic valuation of crop and tree production in the parkland

Generally, crop production in the parkland yielded very low or negative net present value (NPV), except peanut with NPV worth $68731.5 \pm 871.94 \text{ FCFA ha}^{-1}$. The low NPVs or the economic inefficiency of crop production in the parkland may be due to two main factors: low soil fertility which resulted in low yields and high cost of labour and fertiliser cost. The high cost of crop production was mainly due to high demand for labour. For example, labour cost generally constituted almost 50% of cost of production for most crops and 82% for production of cotton. Indeed, assuming that farmers do themselves all labour in field, the production of all the crops resulted in a positive NPV. In addition, fertiliser cost reduced drastically the NPVs of crops that received fertilisers. The application of fertiliser on millet and sorghum resulted in a reduction of the NPV because of a weak increase of crop yield added by fertiliser supply. This bad response of millet and sorghum could be due to the fertiliser composition which indicated for cotton production. Farmers use this fertiliser because there is not a specific fertiliser for these cereals on the market in Burkina Faso.

In contrast, tree products generated positive NPVs due to the low input cost of production. The NPV of tree products increased with increase in tree density and at trees average density,

was worth 32880.6 ± 2458.82 FCFA ha⁻¹ which was higher than the NPV yielded by the best crop (peanut). The supplementary net income from tree products confirms the key role of trees in the parkland system, which is to minimise risk and increase the economic efficiency of the whole production system.

6.4.4. Profitability of parkland crop production systems

Farmers practised parkland system of crop production traditionally since ancient times to benefit from both trees and crops. A typical traditional parkland system consisted of three dominant tree species (karité, néré and baobab) intercropped mainly with five common crops (maize, millet, sorghum, peanut and cowpea). The net present value of this traditional parkland crop production system was positive (24317.2 ± 7942.24 FCFA ha⁻¹) due to the additional income from tree products.

The systems of millet monoculture and millet production in association with trees at very low tree density (4 trees ha⁻¹) yielded lower NPVs than the traditional parkland production system. However, millet production in association with trees at an average tree density of 14 trees ha⁻¹ resulted in a positive NPV comparable to the value obtained with the traditional parkland production system. The NPV decreased when the system of millet production in association with trees was considered at high tree density (23 trees ha⁻¹). This may explain why farmers reduce tree density to a level where the loss in millet yield due to the presence of trees becomes negligible.

The values of NPV and Benefit-Cost-Ratio showed that the system of crop production that was tested in the present experiment, that is, growing millet alone in the open area and taro alone in the area under tree crowns is economically more efficient and profitable than the traditional crop production system. However, this may not meet the requirements of farmers to diversify crop production. Instead, by improving the traditional crop production system whereby all the five common crops are grown in the open area and only taro is grown under tree crowns enabled very high economic efficiency and profitability to be achieved. Therefore, growing taro under tree crowns in the traditional crop production system by maintaining high tree density can increase the profitability of the whole system.

According to Yaméogo *et al.* (2005), when farmers in the central part of Burkina Faso traditionally establish new farms by converting natural woodlands, they remove most of the trees leaving behind up to 60 trees per hectare of the most valued tree species. This high tree density is progressively reduced by farmers to a density at where the equilibrium between crop and tree productions is achieved. However, if farmers adopt the system whereby common crop cultivation under tree crown was replaced by taro or other shade tolerant crops, they could avoid reducing the tree density in order to maximize the profitability of their traditional crop production system.

6.4.5. Farmers perception of replacing millet by taro under the crowns of parkland trees and the prospect for adoption

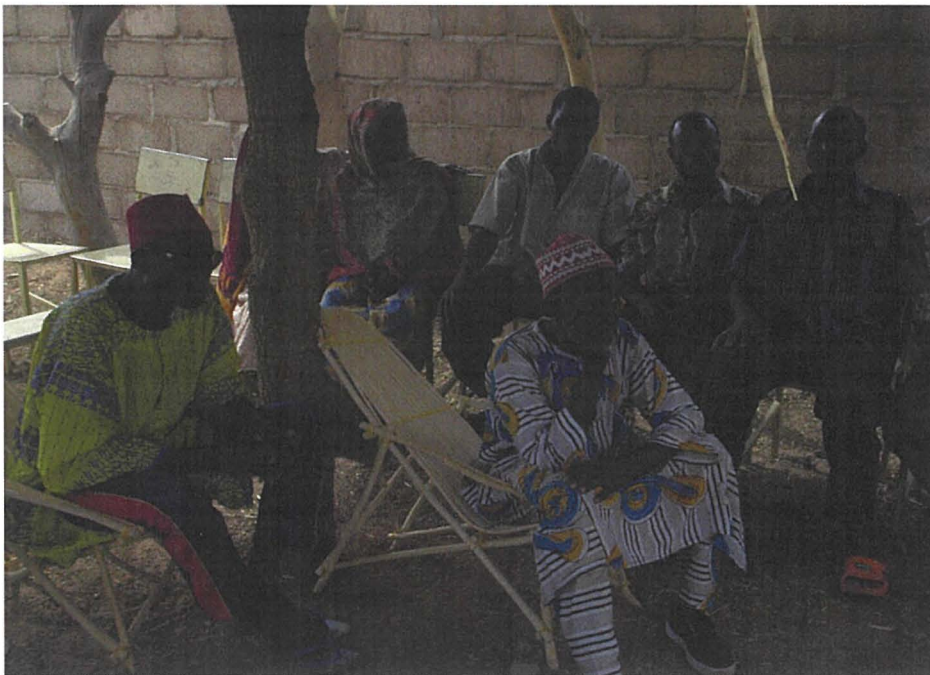
Farmers practice traditional agroforestry parkland systems to ensure that household needs for food, wood and medicine are met sustainably (Kessler, 1992). Meeting these basic needs is the priority of farmers more than generating monetary income and this may explain why millet and other cereal crops dominated the crops produced in the parkland in the study area. The fact that no respondents sold millet proves that the farming system in the parkland is subsistence farming. The basic and common diet of the local households is cereal porridge served with a sauce, which is mostly prepared from tree products such as baobab leaves, *Bombax costatum* flowers, fermented seeds of néré and karité better. Therefore, producing cereals in association with trees in the parkland system permits sustenance of household needs for this basic food. Stalks of millet and other cereal crops are also useful to farmers as they are used as fodder for animals during the dry season and a substitute for firewood. Thus, production of millet and other cereal crops is the priority for farmers more than growing cash crops such as taro.

However, once the basic food need of a household is guaranteed, the need for cash arises to meet ceremonial expenses, school fees, medical expenses, purchasing animals and buying other foods that are not produced in the parkland (Youl *et al.*, 2008). Main cash crops grown in the study for these purposes were eggplant, rice, peanut, cowpea and taro, part of the harvest was sold and the remainder used to vary household diet and given to relatives and friends as precious gifts. If, however, trees are abundant, tree products can also meet the cash needs of households as much as cash crops (Teklehaimanot, 2004).

In order to meet the needs for cash and varying household diet, growing shade-tolerant crops such as taro under crowns of trees makes sense as taro was found in the present experiment to yield better than millet under shade. In fact, most of the respondents who were willing to apply the improved system claimed that the system may be profitable because it would allow trees to be maintained on their farms. The farmers preferred the improved system over the practice of tree pruning to remove shade because fruit production from trees would be reduced due to the effect of pruning. Farmers concern about the reduction of fruit production caused by tree pruning was also reported by Kessler (1992).

Despite the demonstration of the profitability of the improved system, a few (9%) of the respondents rejected its adoption claiming that growing taro demanded high inputs. They reported that due to the low fertility of the soils in their farms, taro could not be grown unless they applied chemical fertilisers that they could not afford. Some farmers suggested that applying manure, as they already did to some cash crops such as eggplants, could be a solution. This may be the reason why some of the respondents (13%) suggested that they wanted to test the system by themselves before they adopted it. During the last year of the present experiment, two farmers were observed applying the system by growing taro under *néré* trees. Therefore, it is possible that large scale adoption of the system may occur if the two farmers who have already adopted the system became successful.

Plate 6.1. Views of a meeting held with the farmers to introduce and plan the survey



CHAPTER 7: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1. Introduction

Agroforestry parkland systems are a major land use system in the Sahel region of West Africa (Bayala, 2002). In these systems, farmers have grown crops in association with trees for thousands of years in order to ensure their food needs are met sustainably (Brookfield and Padoch, 1994). Farmers retain scattered trees on their farms after converting natural woodlands to croplands (Bonkougou al., 1993). These trees are selected and preserved on farms because farmers value them for their products and services (Gijbers *et al.*, 1994).

Indigenous fruit tree species including *Vitellaria paradoxa*, *Parkia biglobosa*, and *Adansonia digitata* dominate the tree species on West African parklands (Gijbers *et al.*, 1994; Bayala, 2002). Although they are highly valued for their fruits, several workers have reported reductions in cereal yields on parklands due to the effect of shade from these trees (Maiga, 1987; Kater *et al.*, 1992; Kessler, 1992; Boffa, 1999; Boffa *et al.*, 2000; Bayala *et al.*, 2002). In response to this unfavourable effect of tree shade on cereals, farmers mostly tend to reduce the density of trees on their farms (Boffa, 1999; Bayala *et al.*, 2006).

As an alternative solution to tree density reduction on parklands, Bayala (2002) successfully tested crown pruning of trees (*Vitellaria paradoxa* and *Parkia biglobosa*) so that cereal crop yields were not reduced due to tree shade (Bayala *et al.*, 2002; 2003). The disadvantage of pruning crowns of fruit trees is that fruit yield is reduced for at least five years after pruning as reported by Bayala *et al.* (2008). In order to avoid the loss in tree fruit production, the use of shade-tolerant crops under the shade of trees may offer an alternative solution as suggested by Teklehaimanot (2004).

The use of shade-tolerant crops was tested in the present study under the two major indigenous fruit tree species of parklands: *Parkia biglobosa* (nééré) and *Adansonia digitata* (baobab) in Nobéré, Burkina Faso over a period of three cropping seasons. The shade-tolerant crop tested was taro (*Colocasia esculenta*), a common vegetable species in the study area. Results were compared with millet (*Pennisetum glaucum*), a shade-intolerant crop also

commonly grown in the study area. It was a participatory research involving local farmers and carried out on the crop fields of local farmers. The research had three major objectives: to test the effect of tree shade on growth and yield performance of taro and millet, to test the effect of tree shade on the nutritional composition of these two crops and finally to assess the socio-economic implications of adopting taro cultivation under tree crowns in agroforestry parkland systems.

7.2. The effect of tree shade on growth and yield performance of millet and taro

In the present study, photosynthetically active radiation (PAR) was reduced from the open field to the trunk of both baobab and néré as also reported by previous workers (Jonsson, 1995; Boffa *et al.*, 1999; Bayala *et al.*, 2002). The reduction in PAR under trees was more pronounced under néré compared to baobab perhaps because of the difference in tree crown height and structure (Breman and Kessler, 1995; Bellow and Nair, 2003 and Zoumboudré *et al.*, 2005).

As consequence of PAR reduction, a microclimate different from the condition in the open field was observed under both tree species. In particular, higher soil moisture content was recorded under trees than in the open field. This may be due to temperature and evaporation reductions by tree shade as also reported by Rao *et al.* (1998); Jonsson *et al.* (1999) and Ong and Swallow (2003). In addition, differences in soil properties, perhaps not directly linked to tree shade, were also found between areas under tree crowns and the open field. Soil organic matter content decreased from tree trunks to the open field as also observed by Ong *et al.* (1996), Boffa *et al.* (2000) and Garcias-Barrios and Ong (2004). N, P and K were also higher in soil under tree crowns compared to the open field as also reported by Bayala (2002).

In summary, the properties of soil under trees (high soil nutrient and water content) were more favourable to crop growth in comparison to soil of the open field. The favourable conditions observed under trees, however, could be beneficial to plants if they are only able to photosynthesise efficiently under reduced PAR condition. This means under natural conditions only shade-tolerant plants selectively grow under tree crowns due to their high leaf photosynthetic capacity under shade. Boffa (1999) reported such selective effect of shade in weeds floristic composition that changed from the open area to the area under trees.

Although the daily cumulative net photosynthesis of both millet and taro crops increased from tree trunk to the open field, the photosynthesis rate of taro was less affected under tree shade than millet probably due to the increase in chlorophyll content in taro leaves under shade as reported by Johnston and Onwueme (1998) and an increase in stomatal density under shade as observed by Onwueme and Johnston (2000). In fact in the present study, the minimum stomatal conductance of taro in the shaded area was higher compared to the minimum value of millet. Therefore, it may be concluded that, through such adaptations, taro increased its efficiency of PAR capture in the shaded area. As a result, the radiation use of efficiency (RUE) of taro was higher than millet and decreased from the tree trunk to the control plot.

The daily CO₂ assimilation rate was positively and significantly correlated with the leaf area index (LAI) of taro. LAI of taro was higher under shade than in open field and this resulted in an increase in the mean daily net assimilation in the shaded area. However, the photosynthetic rate of taro plant increased less than in millet plants from shade area to the open field. This is due to the photosynthetic pathway of the two crops (C₄ and C₃, for millet and taro, respectively). In fact, under high irradiance such as in the open field of Sahel region, C₃ plants are limited by their low light saturation point compared to C₄ plants (Hay & Porter, 2006; Osborne *et al.*, 2008). In addition, due to the competition between CO₂ and O₂ fixation in the C₃ pathway of photosynthesis combined with the energy cost to convert 3-phosphoglycolate to phosphoglycerate, the quantum yield of C₃ plant is lower compared to C₄ pathway of photosynthesis. Therefore, taking in account this poor increase in photosynthesis rate under full sun of taro and the increase in its leaf area and chlorophyll content per unit leaf area, taro had better performance in growth and yield in shaded area while millet exhibited a reverse performance with a better growth and yield in full sun.

The higher performance of taro under shade could also be explained by the use of less growth resources for plant maintenance and/or more efficient translocation of photosynthates from leaves to other parts of the plant in shaded condition compared to the open area. Ancy and Jayachandran (2000) reported similar observation on ginger, another shade tolerant plant that had higher photosynthetic rate in the open field but had higher yield in 20% shaded area. In contrast, millet performance was reduced by heavy shade under *néré* but the light shade of baobab tree did not depreciate millet performance.

The performance of any crop under shaded conditions also depends on its capability to compete efficiently for soil nutrients and water with roots of other plants growing in the same area. The results of root length density (RLD) and root weight density (RWD) in the present study showed that taro developed more fine roots in the top soil of the shaded area than millet. This means taro was more competitive in the shaded area than in the open field.

The contrasting performance of the two crops under trees and in the open could be explained by the differential water and nutrient demand of the crops and the general low soil fertility in Sahel region. As a C3 plant, taro requires more water for its growth compared to millet as a C4 plant. Indeed, the two photosynthesis pathways differ in the carbon concentrating mechanisms which reduce evapotranspiration and conserve water for C4 plants in hot conditions such as in Sahel region (Percy & Ehleringer; 1984; Feldhake & Boyer, 1986). Therefore, the growth of taro is more limited by water availability in the open field as indicated in the present study and in agreement with previous works, soil water content decreased from tree trunk to the open field, although this is the same trend as occurs with light.

In addition, taro demand of nutrients is higher compared to millet, especially for N. Indeed, taro as a C3 plant have a lower photosynthetic N use efficiency (PNUE) compared to millet (Sage & Percy, 1987; Abraham *et al.*, 2007; Ripley *et al.*, 2008). The higher N demand of C3 plant is explained by photorespiration because the plants must invest more in rubisco which requires more N than in the C4 carboxylation pathway. This differential N demand between C3 and C4 plant is more pronounced at the high temperatures that occurs in the open field of Sahel region due to the decrease of rubisco specificity for CO₂ with increasing temperature (Ripley *et al.*, 2008). This physiological property of taro added to the higher soil fertility under tree than in the open field, result in better performance of the crop under tree compared to the open field.

Generally, the nutrient demand of taro as given in previous works is rather higher than millet (Kay, 1987; Goenaga & Chardon, 1995; Maman *et al.*, 1999; Payne, 2000). The differential in nutrients requirement of the two crops makes millet the more adapted crop to the low soil fertility in Sahel region. However, taro can be produced under tree where better soil fertility and soil water content were observed compared to the open field.

In summary, taro was more efficient than millet in exploiting the favourable conditions (reduced temperature, higher nutrient and water contents of soil) under baobab and néré trees by changing its leaf morphology and anatomy. Therefore, it could be a worthy strategy to replace millet by taro under dense tree crowns in agroforestry parkland systems.

7.3. The effect of tree shade on the nutritional composition of millet and taro

The chemical analyses carried out over three years showed that tree shade had no effect on the proximate composition of millet grains whereas it affected the proximate content of taro corms by decreasing fat and dietary fibre contents. In addition, an increase in protein and carbohydrate contents was observed in taro corms with light reduction. However, the availability of soil nutrients may play a key role in the proximate content of both crops. Indeed, protein content of millet and carbohydrates content of taro corms increased with increase in soil cation exchange capacity. The nutrients (NPK) supplied through the fertiliser were incorporated more by crops when soil cation exchange capacity was high. This suggests that the application of fertiliser affected the proximate content of crops. The rate of 100kg ha⁻¹ NPK (15-15-15) supplied to millet seemed to be less than the millet demand of P and K as the crop fat content increased with increase in the initial soil P content while its K content was dependent on soil initial K content. This result is in agreement with Buerkert *et al.* (1998) who found that P application changed the nutritional quality of millet and with Muehlig-Versen *et al.* (2003) who pointed out limiting effect of soil P content on millet production in Sahel region.

Except K content in crops, ash and minerals contents in both crops were not affected by tree shade. However, phosphorus content in both crops and manganese content in taro corms varied according to the zones. The variation of these two minerals was not directly related to PAR availability but it may mainly be attributed to the variation of their availability in soil. Even if Mg content in taro was not significantly determined by soil chemical properties, the content of P in the crop was directly linked to the soil cation exchange capacity. As for the proximate content, crops mineral content was mainly determined by their availability in soil. That is why the content of P and K, two nutrients supplied through the fertiliser, increased from the first cropping year to the last. In contrast, the content of Ca, Na and Fe that were not supplied through fertiliser, decreased throughout the cropping year due to their depletion in

soil with time and/or the acidification of the soil consequently to NPK application during the three years of the study (Barak *et al.*, 1997; Baraud & Leleyter, 2006). Indeed, soil acidification results in a decrease of the availability of cations for plants. This deficiency of cations may have limited crops performance especially the reduction of Na availability for millet as a C4 photosynthesis pathway plant. The importance of Na in the photosynthetic process of C4 plant is reported by several workers, even its role is not yet clearly established (Grof *et al.* 1989; Orsenigo *et al.*, 1996).

In summary, growing millet and taro under tree shade did not drastically alter the nutritive quality of both crops. In fact, a slight increase in protein and carbohydrate contents and a minor decrease in dietary fibre and fat contents were observed because of tree shade. The analysis of data collected over the three years showed that taro had a higher proximate composition, that is, protein, dietary fibre and ash contents than millet. The key role of these three proximate components in human nutrition especially dietary fibre is well documented. For example, Ludwig *et al.*, (1999) showed the importance of high fibre diets in the protection against obesity and cardiovascular diseases. Thus, according to the results of the present study taro provides a better and healthier diet for humans than millet. In addition to the best proximate composition, mineral contents were also higher in taro corms than in millet grains. Therefore, it may be concluded that the replacement of millet by taro in the areas under tree crowns could improve the daily dietary needs of local communities.

7.4. Socio-economic implications of replacing millet by taro under tree crowns in agroforestry parkland system

According to the results of the present research, the replacement of millet by taro under tree crowns could be in the farmers' interest as taro had good yield and nutritional quality in shaded areas. However, farmers can only adopt the replacement of millet by taro under tree crowns if it is profitable and does not require excessive additional labour.

Generally, the traditional agroforestry parkland systems have been reported to be adequate in securing the household needs for food and cash income (Youl *et al.*, 2008). However, according to the results of the economic analysis of the present study, traditional cropping system based on a mixture of maize, millet, sorghum, peanut and cowpea associated with trees generated a relatively low but positive net present value.

It must be noted that the positive value of the system was mainly due to tree products as growing crops such as cereals alone resulted in a monetary deficit if labour cost is taken in account. The net present value of the traditional cropping system was 24317.18 ± 7942.24 FCFA ha⁻¹ at a tree density of 14 trees ha⁻¹. Growing taro alone under tree crowns instead of the traditional cropping system improved the net present value of the system by almost fourfold (84696.13 ± 8378.64 FCFA ha⁻¹ at a density of 14 trees ha⁻¹).

The system of growing a C3 photosynthesis pathway crop under tree and other crops in the open field could help to solve West African soils degradation as a consequence of tree density reduction on fields. Indeed, in West African savannah (4 950 000 km², Kowal & Kassam, 1978) where agroforestry parkland is the unique traditional system, soils fertility has been depleted over the years as happened in the rest of Sub-Saharan Africa (Sanchez *et al.*, 1997, Bationo *et al.*, 2006). Stoorvogel *et al.* (1993) estimated a nutrient loss per hectare and per year in sub-Saharan Africa as 22 kg N, 2.5 kg P, and 15 kg K in 1982–84 and predicted that these values would increase to 26 kg N, 3 kg P, and 19 kg K in 2000. The enrichment of soil organic matter through litter fall of tree plays a key role in maintaining soil fertility as small-farmers can not afford mineral fertiliser input to compensate for nutrients off-take in crop harvests. Therefore, maintaining or increasing tree density of parkland fields could slow down even stop the decrease of soil fertility in West African parklands.

The use of C3 crops with relative high income under tree may stop the reduction of tree density as farmers generally cut down trees on field to take benefit of the fertile soils under their crown. The main constraint to the success of this cropping system in Sahel region is the high water demand of C3 plants. The system was successfully tested in this study carried out on very low fertility soils in a sudanian climate where the average annual rainfall ranged from 800 to 900 mm. Therefore, it could be extended to all the north area of West African savannah because the average annual rainfall decrease as one goes from south to north (Scott, 1979). In addition, the success of such cropping systems could be enhanced by the higher tree density and soil fertility encountered in this southern region of West African savannah (Ræbild *et al.*, 2007).

With regard to the high depletion of organic matter in West African soils, farmers should be encouraged to supply organic matter and mineral fertiliser to replenish soil fertility. Indeed, the increase of soil organic matter content resulted in an increase of soil cation exchange

capacity and the fertiliser use efficiency (Bationo *et al.*, 2006). The lack of soil OM could explain the lower response of crops such as cereals to fertiliser observed in the present study. In addition, the high cost of mineral fertiliser significantly reduced the net revenue of cereal crops that may prevent the majority of small farmers to apply them on these crops. Therefore, increasing the fertiliser use efficiency through the addition of soil organic matter will encourage farmers to compensate for nutrients removed by crops and avoid nutrients depletion in soil. Then the cropping system using C3 plants under tree and organic matter supply to soil could be promoted to increase West African parklands agroforestry system.

This management of parkland agroforestry system is compatible with the agriculture policy of the Economic Community of West African States (ECOWAS) that state lands and water management as one of the four fundamental sectors to solve the agricultural crisis in West Africa (NEPAD, 2005). The cropping system proposed in this study could help to exploit sustainably the 284 million hectares of potential cultivable lands in West Africa (NEPAD, 2005) and contribute to food security and poverty alleviation in the region.

7.5. Farmers perception of replacing millet by taro under the crowns of parkland trees

90% of respondents in the present study were willing to adopt the improved cropping system of replacing traditional cereal crops by taro under tree crowns due to its profitability. However, it may be possible that the importance of millet in the daily diet of local households may hinder its adoption. The daily diet of a common household is composed of cereal porridge and vegetable sauce. Crops such as taro are occasionally consumed to vary household diet or used on special events.

However, it must be noted that taro will only be only grown under tree crowns while farmers can still maintain growing millet and other cereal crops in the open field which occupies the larger proportion of farmlands. Findings from this study showed that less than 10% of farmers interviewed were not interested in adopting the improved system of cropping. The reasons given for this were that taro needed high inputs such as fertilisers as soils in parklands are very poor and taro was known to be a high nutrient demanding crop. Some farmers, however, suggested that by applying manure from domestic waste one could reduce fertiliser inputs.

The use of manure to increase cash crop production is a common practice in parklands. Therefore, the application of manure in the area under trees crown, where taro should be produce is feasible and it could help to improve soil fertility in parkland fields.

7.6. Constraints and limitations of the present study

In the present study, it was not possible to separate the effect of trees on light from other possible environmental factors that are influenced by the presence of trees such as temperature and soil moisture. In fact, it was not always possible to separate these effects on crop performance as also reported by Bayala *et al.* (2002).

The variation of soil fertility during the three cropping years of the experiment was not assessed. Annual soil sampling before planting crops would have given more precise information on the relationship between crop performance and soil fertility.

The present study was also limited in the assessment of photosynthesis parameters that could vary tremendously if the entire crop growth period was considered. A weekly recording of photosynthesis parameters all along the crop growth period would have given better and accurate values.

In addition to crop proximate and mineral compositions, analysis of vitamins would have given a better picture of the effect of trees on nutritional quality of crops. This was not possible in the present study because the laboratory work was done in Bangor and obtaining fresh samples to avoid the degradation of vitamins was not possible.

7.7. General conclusions

The performance of taro was enhanced by the effect of tree shade while millet performance was reduced under shade. The good performance of taro under tree shade was due to its shade-tolerance and due to the higher fertility and moisture of soil under tree crowns which were more efficiently utilised by taro than millet. Taro was adapted to shade by increasing its leaf area and probably its leaf chlorophyll density and as a result, it was able to yield high amount of photosynthates.

The performance of taro was better under néré trees compared to baobab because of the higher light interception by néré compared to baobab. In contrast, millet performance was more reduced under néré compared to baobab.

The proximate composition of taro revealed that it has higher contents of protein, ash, dietary fibre than millet whereas millet has higher contents of fat and carbohydrates than taro. Taro was also higher than millet in all mineral contents. Tree shade had no effect on the nutritional composition of millet. However, tree shade increased protein and carbohydrate contents and decreased fat and dietary fibre contents in taro corms.

Based on the findings of the present study it may be concluded that the replacement of cereal crops by taro under tree crowns improves the productivity of parkland agroforestry system.

7.8. Recommendations

The following recommendations are made taking into account the constraints, limitations and conclusions of the present study to improve the productivity of agroforestry parkland systems and for further investigations on the system.

7.8.1. Recommendations for the improvement of agroforestry parkland systems

Recommendations that could increase the productivity of the traditional agroforestry parkland systems are given below.

1. Owing to the fact that taro performed better than millet under tree crowns, it is recommended that shade-tolerant crops are grown under tree crowns so that farmers are able to maintain trees on their farms to be able to continue deriving benefits (products and services) from the trees.
2. Taking into account the importance of ecosystem services of trees in agroforestry parkland systems, it is recommended that farmers plant trees on their farms to replace old trees and to increase tree density so that agroforestry parkland systems become more sustainable.

3. To increase income from tree products, improved management of parkland trees and value addition to the products of the trees should be sought and implemented.

4. Taking into account the low yield of crops found in the present study due to low soil fertility, it is recommended that trees and shrubs that are known to enhance soil fertility be incorporated as green fertilisers in agroforestry parkland systems.

5. As most of the tree species planted on the parkland is exotic species, a survey should be undertaken to understand the motivation of farmers and develop a strategy to promote local species plantation to avoid the landscape degradation and to preserve the local biodiversity.

7.8.2. Recommendations for additional investigations

1. It is recommended that a screening test of shade-tolerant crops are carried out to find out crops that have lower demand for inputs and perform better than taro in order to diversify crops grown under tree crowns.

2. It is recommended that the use of compost from domestic waste, application of litter mulch from tree pruning be tested in comparison with chemical fertilisers in order to reduce the cost of commercial fertilisers for taro production.

3. Even if there is no shade effect on proximate composition and mineral contents of crops, it is recommended that further study is carried out to assess the effect tree shade on vitamins contents and antinuritive factors of crops as both are important in daily diet of humans.

4. Finally, it recommended that a further survey is carried out on the adoption of the improved cropping system by local farmers in order to assess its weakness and positive impacts and to identify areas of further investigations for its improvement.

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APPENDICES

Survey on parklands farming in Nobéré

Name:
 Gender: ...M...F Age:..... Number of household members:.....

I- The land

- 1- Are you the land owner of your field? *Yes* *No*
- 2- What is your field total area?.....
- 3- How is the soil fertility your field: *Very poor* *Poor* *Good* *Very good*

II- Trees on parklands fields

1- Trees species

How many trees do you have on your field?.....
 How many trees species do you have on your field?.....
 Which species have the highest number of trees on your field?.....
 How many trees of this species?.....
 What are the other species and their number?.....

 Which species do you prefer on your field?.....

 What are these trees utilities? *Fruits* *Wood* *Medicine* *Fodder* *Shade*
Other:.....

2- Trees management

Do you plant trees on your field? *Yes* *No*
 If yes, which species are concerned?.....

 Do you apply treatment to the trees to improve their production? *Yes* *No*
 If, yes which one?.....

III- Crops

1- Crops species

Which crops species do you grow on your field?.....
.....
.....

Could you rank the 3 preferred crops?

1:..... 2:.....3:.....

2- Crops cultivation

Do you plough before sowing? Yes No

If yes, for which crops.....

Do you use mineral fertiliser? Yes No

If yes, for which crops and which dose do you apply for each crop?.....

.....
.....
.....

Do you apply manure? Yes No

If yes, for which crops and which dose do you apply for each crop?.....

.....
.....
.....

How many times do you do weeding for each crops?.....

.....
.....
.....

Do you apply ridging? Yes No

If yes, for which crops?.....

.....
.....
.....

Do you donate or offer (as sacrifice) a part of your crops production?

<i>Crop</i>	<i>Donation/Offering</i>	<i>Quantity (kg)</i>
.....
.....
.....
.....
.....

When do you sell your crops (month)?

<i>Crop</i>	<i>Month</i>	<i>Quantity (kg)</i>
.....
.....
.....
.....
.....
.....
.....
.....

Which crops do you buy on the market?

<i>Crop</i>	<i>Quantity (kg)</i>	<i>Price (FCFA)</i>
.....
.....
.....
.....
.....
.....
.....
.....

IV- Trees and crops associations

Do you grow crops under trees? *Yes* *No*

If yes which crops and trees association?

Which crops:..... *Which tree:*.....

How are crops yields under trees?

<i>Tree- Crop association</i>	<i>Very bad</i>	<i>Bad</i>	<i>Good</i>	<i>Very good</i>
.....
.....
.....
.....
.....
.....
.....

V- Shade tolerant crops production under trees

Are you informed of the trial on millet and taro associated with baobab and néré? *Yes No*

If yes, how? *I'm a participant I visited the fields I was informed by another farmer*

Compared to trees pruning which practice do you prefer to improved crops production under trees?.....

.....

Why?.....

.....

.....

Compare the two crops for their use:

Which crop of the two do you prefer as food?.....

Why?.....

.....

Which do you use for special occasion?.....

Which crops do you use as medicine?.....

Which crops are you use for ceremonials?.....

Which is the easiest to sell?.....

Which give the best price on the market?.....

What do you do with the crops stalks?.....

Do you think that taro production under trees is profitable or not?.....

Will you experience taro production under your trees? *Yes No*

Why?.....

.....

Thanks for your answers