Compost and Fertilizer Mineralization Effects on Soil and Harvest in Parkland Agroforestry Systems in the South-Sudanese Zone of Burkina Faso

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Cover picture: Maize plants at the begining of rainy season in a parkland dominated by young *Faidherbia albida* and *Vitellaria paradoxa* in Burkina Faso. (picture: Z. Gnankambary)

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Abstract

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Decomposition of, and the subsequent nutrient release from tree leaf litter as well as external inputs of nutrients are important in the traditional agroforestry parklands of West Africa. The management of nutrient resources is essential to optimize crop performance and soil fertility. To explore temporal and spatial nutrient release in such management options has been the overall objective of this study. Specifically, this thesis investigated: (i) decomposition patterns and nutrient release from litters of *Faidherbia albida* and *Vitellaria paradoxa*; (ii) limitation of microbial respiration, as a result of low nitrogen (N) and phosphorus (P) in the *F. albida* and *V. paradoxa* parklands; and (iii) the effects of applications of combined compost and urea on maize yield in the *F. albida* and *V. paradoxa* parklands. The litter of *F. albida* lost more mass and nutrients than litter of *V. paradoxa*. However, the decomposition rate of *V. paradoxa* increased in the presence of *F. albida* litter or following the application of inorganic fertilizers. Soil microbial respiration was mainly limited by P-fixation, but N was also limiting. Two microbial growth peaks were observed when excess carbon and P were present, suggesting that either two pools of N are sequentially available to microbes or that two microbial communities do exist. Respiration tests also indicated that P and N availability to microorganisms were higher under the canopy than outside it. Maize yield was similar with the addition of urea, compost, or a combination of compost and urea, if applied at an equivalent N-content. However, in the driest year, the combination of compost and urea had the greatest effect in the increase of maize yield as compared with control treatments. The maize yield under the canopies of *F. albida* was up to 2.3 times the yield outside the canopies, while under the canopies of *V. paradoxa* it was 0.6 to 0.8 times the yield outside the canopies. The yield under the canopy was relatively better in dry year. Compost-N and inorganic fertilizer-N recoveries in maize shoot biomass were low, indicating that a large proportion of maize shoot-N is derived from the soil. Also, under the canopy of *F. albida*, the proportion of N derived from fertilizer in maize shoot was lower compared with that outside the canopy, implying that the soil N-pool was more readily available to plants under trees. In conclusion, there is a potential to improve the decomposition rate of *V. paradoxa* litter by inorganic fertilizer application or by mixing it with *F. albida* litter. Thus, the litter of *V. paradoxa* can be a useful to improve soil quality, rather than being burnt as is nowadays practiced by the farmers. Application of combined compost and inorganic fertilizer offers a management option that is cheaper than only inorganic fertilizers and more manageable than only compost applications.

Keywords: Burkina Faso, Canopy, *Faidherbia albida*, Litter decomposition, Maize, Microbial respiration, N recovery, Nutrient limitation, *Vitellaria paradoxa*

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Dedication

To my wife Géraldine Ida, my daughter Fawzia Sakina Karen, my son Abdel Raouf Yohann and my parents.

Contents

Appendix

Paper I-III

This thesis is based on the following papers, which will be referred to in the text by their respective Roman numerals:

I. Gnankambary Z., Bayala J., Malmer A., Nyberg G. and Hien V. (2007). Decomposition and nutrient release from mixed plant litters of contrasting quality in an agroforestry parkland in the south-Sudanese zone of West Africa. *Nutrient Cycling in Agroecosystems (conditional acceptance)*

II. Gnankambary Z., Ilstedt U., Nyberg G., Hien V. and Malmer A. (2008). Nitrogen and phosphorus limitation of soil microbial respiration in two tropical agroforestry parklands in the south-Sudanese zone of Burkina Faso: The effects of tree canopy and fertilization. *Soil Biology and Biochemistry 40, 350-359*

III. Gnankambary Z., Zomboudré G., Nyberg G., Ilstedt U., Bado B.V., Hien V. and Malmer A. (2007). Short-term effects of compost and N-fertilizer inputs on maize performance and nutrient uptake in agroforestry parklands of Burkina Faso, West Africa *(Manuscript)*

Paper **II** is reproduced with the kind permission of the journal concerned

Introduction

Background

Soil constraints in Sub-saharan Africa

Soil degradation is widely recognized as a global problem associated with desertification in the drylands (Gisladottir & Stocking, 2005). In Sub-Saharan Africa it is also associated with soil fertility depletion (mainly the nitrogen, phosphorus and carbon content) which is a major threats to food security (Sanchez & Jama, 2002; Bationo *et al.*, 2004). This problem is exacerbated by wind and water surface soil erosion (Zougmoré, 2003), poor rainfall distribution (Sivakumar & Wallace, 1991), restricted fallow periods in which to restore soil fertility (Floret & Pontanier, 2001) and low rates of fertilizer application (Camara & Heinemann, 2006). The region is also characterized by climatic conditions that accelerate the degradation of soil organic matter (Andrén *et al.*, 2007) which, in turn, reduces the water holding capacity of the soils. It also leads to soil deficiency in N and P.

Sustaining soil fertility has, therefore, become a major issue in agricultural research and crop production. Since Sub-Saharan Africa is the home of the world's poorest people, of whom 90% live in villages and rely on subsistence agriculture (Bationo & Buerkert, 2001), sustaining soil fertility must be based around affordable practices, which result in higher crop production at low cost. One example of such a system is agroforestry.

Agroforestry

Agroforestry parklands are a common feature of Sub-Saharan Africa (Pullan, 1974; Nair, 1993; Depommier, 1996). Some major advantages of this system are that trees enhance soil fertility in terms of plant-available nitrogen and phosphorus (Sanchez & Palm, 1996; Rao, Nair & Ong, 1997), there is improved water use efficiency as a result of reduced run-off, soil evaporation and drainage (Ong *et al.*, 2002) and valuable tree products, including fruit, fodder and wood, can be produced.

Trees can acquire nutrients from atmospheric deposition, nitrogen fixation and deep and lateral roots access areas where crop roots cannot reach. Trees can be efficient in P uptake through mycorrhizal infection. These nutrients are then immobilized in the tree's biomass. They are redistributed to the soil system via litter and root decomposition and mineralization (Rao, Nair & Ong, 1997). Thus, tree may contribute to the nutrient supply to the soil reducing the need for external inputs and increase the soil organic matter. The improvement in soil physical properties under trees is widely established. Tree root systems have been reported to reduce bulk density, increase porosity and improve aggregate stability. These changes lead to higher rain water infiltration and, thus, higher water availability (Sanchez, Buresh & Leakey, 1997; Ilstedt *et al.*, 2007). However, animal trampling can cause drastic reduction in the infiltration rate. In a study carried out in Burkina Faso, Savadogo, Sawadogo & Tiveau, (2007) reported a steady state infiltration rate of 110 mm h^{-1}, 80 mm h^{-1} and 16 mm h^{-1} when animal grazed at the rate of 0, 6 and 8 animals ha^{-1} day^{-1}, respectively.

Shade under the tree canopy affects the microclimate by reducing temperature maxima and evapotranspiration and increasing relative humidity. This changed microclimate favours soil biological activity.

As a result of litterfall and root decomposition, trees in parklands have a strong influence on soil organic matter; this, in turn, influences soil physical properties and nutrient availability in semi-arid tropical regions (Rhoades, 1997; Bayala *et al.*, 2006). Many reports confirm that there is higher soil organic matter and more nutrients under a canopy than outside it (Nyberg & Högberg, 1995; Breman & Kessler, 1997; Boffa, Taonda & Dickey, 2000; Bayala, Teklehaimanot & Ouedraogo, 2002) and may enable reduced use of inorganic fertilizer under trees. Furthermore, many studies have reported that inorganic fertilizers interact positively with organic fertilizers to increase crop production (Vanlauwe *et al.*, 2002; Teklay, Nyberg & Malmer, 2006; Mucheru-Muna *et al.*, 2007; Ouédraogo *et al.*, 2007).

Burkina Faso

Burkina Faso (10°-15°N and 2°E-5°30W, Fig. 1) covers an area of 274 000 km^2 and has a population of ca. 13.7 million, of which 82% lives in rural areas. The population growth rate is 2.9% per annum and 27.2% of the population lives below the poverty line of 1 US$ per day (UNDP, 2006). The agricultural sector accounts for 40% of the Gross Domestic Product (GDP) and employs around 92% of the active population (FAO, 2007). Agricultural practices are extensive and rarely mechanized; agriculture is dominated by smallholders contending with low productivity mainly due to poor climatic conditions, soil nitrogen, phosphorus and carbon deficiencies (Bationo, Lompo & Koala, 1998; Bationo *et al.*, 2004), limited labor and few external inputs (Breman, Groot & van Keulen, 2001).

In rural areas, the average farm size varies considerably, but is mainly determined by the 'household wealth'. The wealthiest households are large with many wives and children and are often, as a consequence, associated with larger farms. In the southwest, for example, Gray (2005) reported that the number of workers (>16 years old) in a typical household ranged from 3.7 to 10.7 and the associated cultivated area ranged from 2.7 to 13 ha. In this area, over 60% of households own more than two oxen and 65% own ploughs. Depommier (1996) reported as much as 125 kg ha^{-1} of inorganic fertilizers applied to land at the village of Dossi. On the farms closest to the village, the rate of compost application varied between 700 and 11,700 kg ha^{-1}.

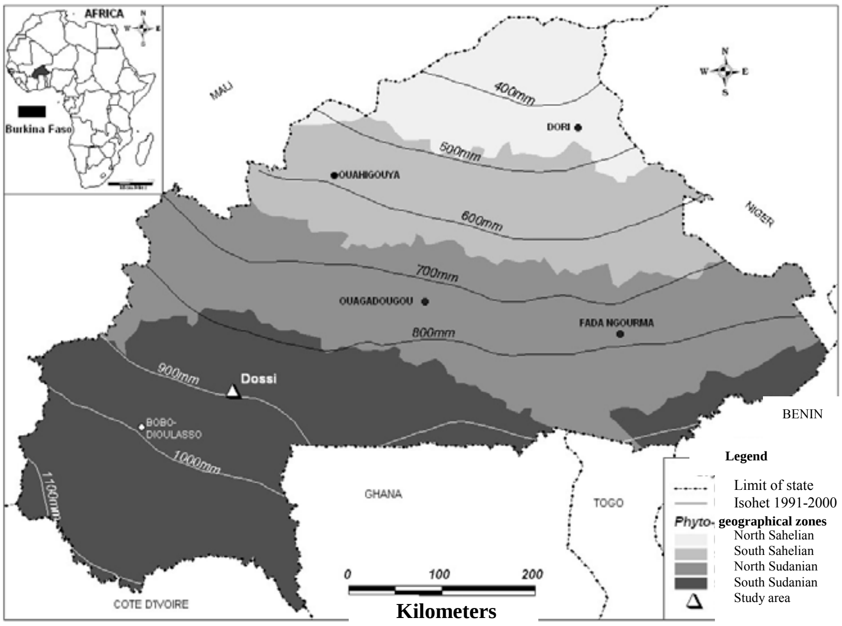

Fig. 1. Vegetation map of Burkina Faso, showing the location of the study site (INERA, adapted from Fontès & Guinko, 1995 and Direction of the National Meteorology).

In Burkina Faso, cereal cropping (millet, sorghum and maize) accounts for 80% of the country's cultivated area. Maize crops cover a total area of 435 500 ha and the total production in 2004 was 665 000 Mg (DGPSA, 2005), making it the third most common crop in the country. Both area and production of maize increased by about 73% between 1989 and 2004.

The Sudanese zone has an annual rainfall ranging from 600 to 1200 mm and about 70% of Burkina Faso's cropland is located in this zone. Maize in this zone is the main cereal crop because of the suitability of the climatic conditions for highly productive maize varieties. Cash crops (cotton, groundnut and sesame) receive more fertilizer inputs and are more productive. This is particularly true for cotton, which represents the primary source of income in the rural areas. Burkina Faso is the largest exporter of cotton fiber in Africa.

Conceptual framework

In agroforestry systems nutrient cycling involves soil–plant–water–livestock relationships, linked by processes that can be managed. Improving our understanding of these processes would enable better nutrient management in the parklands. The conceptual model (Fig. 2) represents a simplified nutrient cycling for parkland and highlights the roles of a number of components and processes in relation to my study; these are discussed below.

Inputs of inorganic and organic fertilizers

Soil productivity in Africa is declining as a result of soil nutrient and organic matter depletion, soil erosion and water scarcity; in addition, about 65% of the croplands in Africa have been affected by soil degradation during the last 40 years (Scherr, 1999; Katyal & Vlek, 2000; Bationo *et al.*, 2007). In sub-Saharan Africa, croplands have a negative nutrient balance, with annual losses ranging from 15 to 71 kg^{-1} ha^{-1} of N, P and K mainly due to nutrient exports by harvest and losses by erosion, combined with low inputs (Stoorvogel & Smaling, 1990; Henao & Baanante, 2006).

Inorganicl fertilizers are the major method of replenishing soil fertility and boosting crop performance. However, their use remains very limited in Burkina Faso with only 0.38 kg ha^{-1} applied to cropland in 2002 compared with averages of 9 kg ha^{-1} for sub-Saharan Africa, 22 kg ha^{-1} for Africa and 100 kg ha^{-1} worldwide (FAO, 2004; Camara & Heinemann, 2006). The trend is towards an increase in fertilizer consumption in Burkina Faso, but this is correlated with an expansion in the area of cultivated land and the development of cotton cropping. It is also important to stress that the application of inorganic fertilizers alone on weakly buffered West African soils may lead to soil degradation through a rapid decrease in soil organic matter, exchangeable bases and pH, and, cannot hence sustain crop productivity in the long-term (Piéri, 1989; Sédego, 1993; Bationo & Buerkert, 2001).

Organic inputs, including compost, animal manure, crop residues and green manure, are a good method of enhancing both soil physical, chemical and biological properties and crop performance (Dakora & Keya, 1997; Buerkert, Bationo & Dossa, 2000; Jama *et al.*, 2000; Ouédraogo, Mando & Zombre, 2001; Harris, 2002). Organic inputs contribute to improving soil structure and aggregation and decrease soil bulk density and thus increase the percentage of pore space (Sylvia *et al.*, 1999). As consequence, soil water infiltration and water holding capacity increase, (Tilander & Bonzi, 1997; Weber *et al.*, 2007) but the strength with which water is held may also increase. It also increases the capacity of the soil to buffer changes in pH and cation exchange capacity, and serves as a reservoir of nutrient such as N, S, P and many minor elements (Crecchio *et al.*, 2001; Schlecht *et al.*, 2006). Organic inputs are also source of energy and slowly available carbon to support soil organisms' activity which are the primary agent for decomposition in the soil and increase

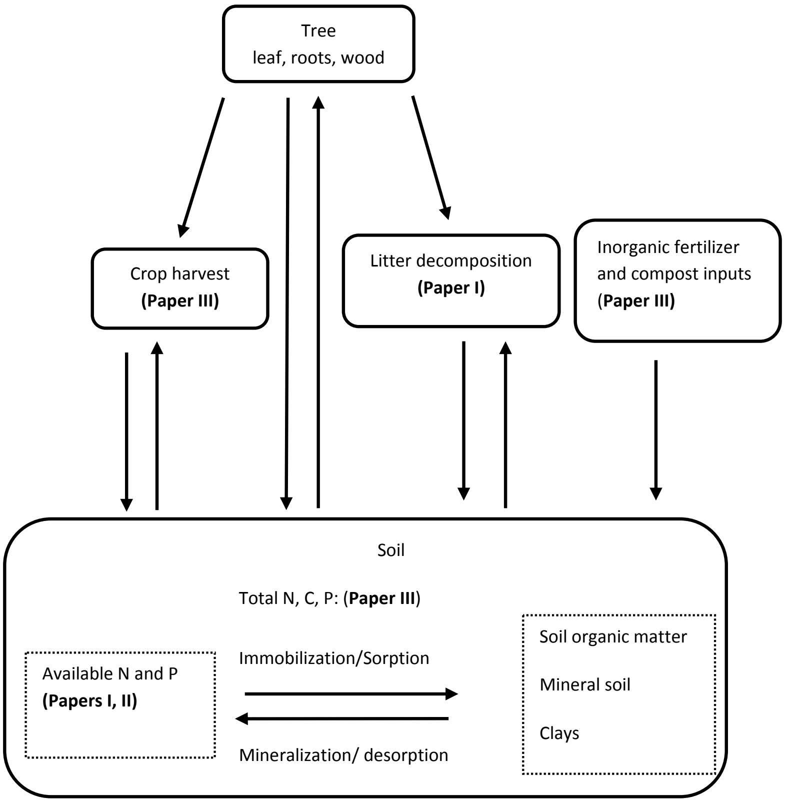

Fig. 2. Conceptual model indicating the simplified main pathways for N and P cycling in parkland systems, with the emphasis on components and processes studied in this thesis. Note that nutrient loss (e.g. leaching, run-off, volatilization) and other nutrient inputs (e.g. fixation, cow dung) are not included.

enzymatic activity (Marinari *et al.*, 2000; Crecchio *et al.*, 2001). However, continuous application of compost can increase soil heavy metal concentrations (Illera *et al.*, 2000) and may lead to increase plant uptake (Moolenaar, Lexmond & van der Zee, 1997). This leads to a deterioration of the quality of soil for sustainable crop productivity. The organic compounds can also bind strongly pesticides and thus reduce their bioavailabity.

In Burkina Faso, there is a growing interest in organic inputs to agriculture and compost manufacturing has been promoted since 1986 when the national slogan "One rural family, one compost pit" was launched (Ganry *et al.*, 2001). However, the use of compost in the field remains limited by e.g. constraints of transport between the production areas and the fields and the lack of available water for compost watering. In situations with limited access to both organic and inorganic fertilizers, a combination of inorganic fertilizers with different types of organic inputs have been widely reported to improve crop yields and soil properties (Sanchez *et al.*, 1997; Vanlauwe *et al.*, 2001a; Teklay, Nyberg & Malmer, 2006; Ouédraogo *et al.*, 2007). However, organic inputs may immobilize inorganic-N (Choi *et al.*, 2001) but can improve organic inputs -N use efficiency (Han *et al.*, 2004).

Due to a combination of low economic input and the need for high and sustained production, combining inorganic and organic inputs seems to be appropriate in West Africa and for other tropical areas. The need to efficiently use both organic and inorganic fertilizers to sustain soil fertility and crop production has been recognized due to positive interactions and complementarities between them (Vanlauwe *et al.*, 2001a). One key complementarity is that organic inputs enhance soil organic matter and the associated aspect of soil fertility, while inorganic fertilizers provide key limiting nutrients. The combination of organic and inorganic fertilizers is in fact the technical support of the wider concept of Integrated Soil Fertility Management (ISFM) (Vanlauwe, Ramisch & Sanginga, 2006) promoted by the Tropical Soil Biology Fertility Institute (TSBF) and the International Institute for Soil Fertility Management (IFDC). ISFM takes also into account the social, economic and political aspects of organic inputs management. As trees are source of organic matter (green leaves, litter), agroforestry is therefore one of the technical options for ISFM (Breman, 2002).

Low levels of external inputs in agriculture due, for example, to economic and lifestyle factors, increase the need for techniques that integrate natural processes such as nutrient cycling, biological nitrogen fixation, and natural pest control, into the food production system, since these are more appropriate and sustainable (Graves, Matthews & Waldie, 2004).

Trees in croplands

Croplands with scattered trees are often referred to as 'parkland systems' or 'farmed parkland' (Pullan, 1974). They constitute one of the main agroforestry systems in sub-Saharan Africa (Nair, 1993). Trees in such parklands are rarely planted but are the result of natural regeneration and anthropogenic management (Lovett & Haq, 2000), as well as choosing to retain woody species during field preparation. Major benefits of scattered trees include improvement of soil fertility and crop performance (Rhoades, 1997; Bayala, Teklehaimanot & Ouedraogo, 2002; Bayala *et al.*, 2006) and the supply of wood, fodder, medicines, fruits etc. Species such as *Vitellaria paradoxa*, *Parkia biglobosa* and *Acacia senegal* depress crop yield but are a reliable source of income for farmers (Ouédraogo, 1995; Seif El Din & Zarroug, 1996; Elias & Carney, 2007).

In West Africa, including Burkina Faso, parklands are dominated by *Faidherbia albida*, *Parkia biglobosa*, *Vitellaria paradoxa* and *Azadirachta indica* (Vandenbeldt, 1992; Tilander, Ouedraogo & Yougma, 1995). Previous studies have reported beneficial effects of the tree *F. albida* (Rhoades, 1997; Payne *et al.*, 1998; Kho *et al.*, 2001) and negative effects of *V. paradoxa* on cereal yields (Boffa, Taonda & Dickey, 2000; Bayala, Teklehaimanot & Ouedraogo, 2002; Zomboudré *et al.*, 2005), but studies on the effects of fertilizer inputs, litter decomposition and microbial activities were rarely undertaken.

Faidherbia albida

Faidherbia albida is a leguminous nitrogen-fixing tree, widely distributed in Africa. The tree occurs throughout the Sahelian and Sudanese zone of West Africa, where annual rainfall ranges between 500 and 1500 mm; it is also found in eastern and southern Africa (Boffa, 1999). The tree produces wood, medicine, animal fodder and edible fruits. It sheds its leaves during the rainy season but retains them in the dry season (Wickens, 1969). This phenology is ideal for agroforestry because it minimizes competition with associated crops for light, nutrients and water (Payne *et al.*, 1998).

Many studies have reported greater crop yields under *F. albida* compared with open fields; this has been variously explained by improved water availability, soil physical and chemical properties, reduced soil and air temperatures, symbiosis with rhizobium and arbuscular endomycorrhizae, previous termite activity and improved nutrient cycling (Brouwer, Geiger & Vandenbeldt, 1992; Depommier, 1996; Rhoades, 1997; Kho *et al.*, 2001).

Vitellaria paradoxa

Vitellaria paradoxa (also known as the shea butter tree in English and karité in French) is a non nitrogen-fixing tree. It grows naturally from West to East Africa along the 5000 km expanse of the semi-arid Sahel and Guinean savanna woodlands, where annual rainfall ranges between 500 and 1400 mm (Hall *et al.*, 1996; Elias & Carney, 2007). The tree provides a number of valuable products. The nuts are an important local and export product, which are used to produce butter for cooking, cosmetics, medicines and more recently as a substitute to cocoa butter (Masters, Yidana & Lovett, 2004). Other products of the tree include fruit, fuelwood and medicine. In Burkina Faso, the species occupies around 6.5 million ha with a density ranging from 6 trees ha^{-1} to 19 trees ha^{-1} in the farm fields (Maranz & Wiesman, 2003).

In contrast to *F. albida*, *V. paradoxa* has a dense canopy during the rainy season and, has been widely reported to reduce production of the associated crop, mainly due to a competition for nutrients and water and a reduction in light intensity and photosynthetic activity (Kater, Kante & Budelman, 1992; Kessler, 1992; Jonsson, Ong & Odongo, 1999; Boffa, Taonda & Dickey, 2000; Bayala, Teklehaimanot & Ouedraogo, 2002; Zomboudré *et al.*, 2005). However, reduced crop yield was compensated for by the income generated by the sale of the tree fruit.

Decomposition and mineralization processes

Decomposition of organic material

The overall process of decomposition generally involves complementary soil organisms that act together on a substrate (Wagner & Wolf, 1999). These soil organisms are microflora (bacteria and fungi), and the soil fauna (protozoa and invertebrate groups such as nematodes, mites, and earthworms). The soil fauna are crucial for fragmenting and comminuting (i.e. reduction in the size of organic material as result of feeding, e.g. shredding) the initial organic material (litter, straw, etc.); this increases the surface area available to be attacked by the microflora, known to play critical roles in the cycling of several key inorganic nutrients in soils (Alexander, 1999).

The decomposition of plant litter is governed mostly by its quality, which has been variously defined on the basis of its chemical composition and the relative proportions of organic compounds. Indicators of the chemical composition includes total-C, total-N, soluble carbohydrates, polyphenols, hemicellulose, cellulose and lignin (Swift, Heal & Anderson, 1979; Palm & Rowland, 1997; Thuriès *et al.*, 2002). Nutrient ratios have been correlated with N mineralization and include the C-to-N ratio. This is one of the most frequently used criteria to evaluate the quality of organic material, but sometimes seems to be inadequate for predicting decomposition kinetics (Thuriès *et al.*, 2002). To evaluate the quality of organic material, other ratios have been used, including lignin/N, polyphenol/N and (polyphenol+lignin)/N (Fox, Myers & Vallis, 1990; Palm & Sanchez, 1991; Constantinides & Fownes, 1994; Handayanto, Cadisch & Giller, 1994). High quality litter has a high nutrient content and low lignin and polyphenol contents. High quality litter is expected to decompose and release nutrients more rapidly than low quality litter (Constantinides & Fownes, 1994; Young, 1997).

The age (litter vs. green leaves) of the organic material also affects the decomposition rate. Litter differs from green leaves in that it has a lower nutrient content due to the translocation of nutrients (e.g. N, P and soluble C) prior to leaf-fall. Consequently, for the same species, litter has a lower decomposition rate than green leaves (Constantinides & Fownes, 1994; Vanlauwe *et al.*, 2001b). Organic resource inputs into agroforestry systems include both fresh leaves and litter from different species. Thus, increasing our knowledge of the decomposition rate of mixed litter can help to develop strategies for the management of tree residues and other inorganic fertilizer inputs.

In Sub-Saharan Africa, numerous works on decomposition do exist; most studies have dealt with green leaves (green manure). In Burkina Faso, there is a paucity of information related to decomposition in agroforestry. A few studies have been carried out in the North-Sudanese zone: Tilander (1996) reported a decomposition constant, in the form of mass of organic matter lost, of 0.0204 day^{-1} and 0.0146 day^{-1} for fresh leaves of *Azadirachta indica* and *Acacia holocericea* respectively. Bayala *et al.* (2005) found a decomposition constant of 0.23 month^{-1} for fresh leaves of both *V. paradoxa* and *Parkia biglobosa*. There is currently no information on the decomposition rates of senescent leaf litter from *F. albida* and *V. paradoxa*, two of the main agroforestry tree species in Burkina Faso and other countries in West Africa. This vindicates our interest in investigating how litter decomposes in agroforestry systems. In addition to the quality of organic matter, decomposition is controlled by climatic conditions such as temperature and moisture (Sylvia *et al.*, 1999), soil chemical and physical characteristics and the decomposer community (Griffiths *et al.*, 1998; Brussaard *et al.*, 2007).

Factors determining soil N and P availability

There are three aspects to N and P availability: intensity factor (the concentration in soil solution i.e. immediately available), quantity factor (storage in the soil) and the buffer capacity (the change in quantity resulting from a given change in intensity). Although agricultural soil may contain large amounts of total nutrients (especially P), only a small proportion (<0.1%) is immediately available for plants and microbes. Estimates of the pools of available nutrients can be made either by chemical extraction, which usually includes a fraction of unavailable soil nutrients, or by microbial respiration methods (see Paper **II**). The flux of nutrients between the unavailable and available forms is mediated mainly by microbial activity. Soil microbes secrete enzymes and organic acids that mineralize or release nutrients previously in organic form or bound to soil particles. The released nutrients are assimilated primarily into plant and soil microbial biomass and soil organic matter, or fixed to soil particles. Therefore, mineralization and immobilization processes occur simultaneously in the soil. Their relative magnitudes determine whether the overall process is of net mineralization or net immobilization. However, in Sub-Saharan Africa, the high turn-over rate of soil organic matter and soil microbial biomass (Andrén *et al.*, 2007) leads to rapid recycling of immobilized nutrients.

From the literature, it appears that many studies have been conducted examining the effects of trees on soil properties and associated crop performance. Some data also exist on the use of organic inputs to replenish soil fertility and combat soil erosion. However, little is known about the effects of the combination of inorganic fertilizers with different types of organic inputs on crop yield and soil properties in parkland systems (Palm, Myers & Nanda, 1997; Teklay, Nyberg & Malmer, 2006). Only few investigations on senescent leaf litter, decomposition rates or microbial activities in agroforestry parklands have been undertaken. Therefore, there is a need to gather information on how to make better use of tree leaves (green and litter) and external inputs to replenish soil fertility, and enhance the sustainability of the parkland system.

Objectives

Decomposition of, and the subsequent nutrient release from tree leaf litter as well as external inputs of nutrients are important in the traditional agroforestry parklands. The management of nutrient resources is essential to optimize crop performance and soil fertility in the traditional agroforestry parklands. The overall objective of this study was to explore temporal and spatial nutrient release in such management options. The specific objectives were:

- To determine the decomposition rate and nutrient release from litter with different nutrient contents (*F. albida* and *V. paradoxa*) (**Paper I**)

- To assess the nitrogen and phosphorus limitation of soil microbial activities, and examine the availability of these elements to microbes (**Paper II**).

- To study the effects of combined compost and inorganic fertilizer inputs on maize performance (grain yield and nutrient uptake) and soil chemical properties in both the field and controlled greenhouse conditions (**Paper III**).

Hypotheses

The study was based on the following hypotheses:

Paper I: (i) *F. albida* leaf litter decomposes faster than *V. paradoxa* litter; (ii) mixing litter of the two will enhance the decomposition rate of the lower quality litter (*V. paradoxa*); and (iii) applications of inorganic fertilizer will stimulate the litter decomposition process.

Paper II: (i) When microbes are not energy limited, respiration will be limited by N and P, but P-limitation will be lower under the tree canopies and, (ii) the maximum respiration rates after adding C will be higher with than without applications of inorganic fertilizer in the field.

Paper III: (i) The combination of compost and urea will be more beneficial for maize yields than applications of compost or urea alone; (ii) the proportion of N uptake in maize biomass from inorganic fertilizer would be lower on soil from under canopies than that from outside canopies.

Material and Methods

Study sites

Study **I** was conducted at Boni (11°35’N, 3°26’W, 340 m a.s.l) while the field experiment for study **III** was carried out at Dossi (11° 26’N, 3° 24’ W, 350 m a.s.l), which is located at 7 km from Boni. Both sites are located in western Burkina Faso, West Africa and have a south-Sudanese climate (Fig. 1) (Fontès & Guinko, 1995). The rainfall pattern is unimodal and generally irregularly distributed from May to October. Monthly rainfall during the experiment (from 2004 to 2006) is shown in Fig. 3. During this period, the study sites received a mean annual rainfall of 860 mm and the mean monthly minimum and maximum temperatures were 19 °C and 37 °C, respectively. Study **II** was performed in the laboratory of the Department of Forest Ecology and Management (SLU) at Umeå, Sweden, using soil samples collected from the experimental plots used in study **III**.

At Dossi village, the vegetation is woody and shrub savannah, dominated by *Faidherbia albida* with a relative frequency of 57%; also present are *Lannea microcarpa* 17% frequency and *Vitellaria paradoxa* 8% (Depommier, 1996). *Accacia sieberiana*, *Azadirachta indica*, *Ficus gnaphalocarpa*, *Parkia biglobosa*, *Combretum* spp. and *Mangifera indica* occur at low frequencies. The main grass species are *Loudetia togonesis* and *Andropogon* spp. The region is characterized by monospecific stands of *F. albida* and *V. paradoxa* (Depommier, 1996) and the main crops grown are cotton, maize, pearl millet and sorghum.

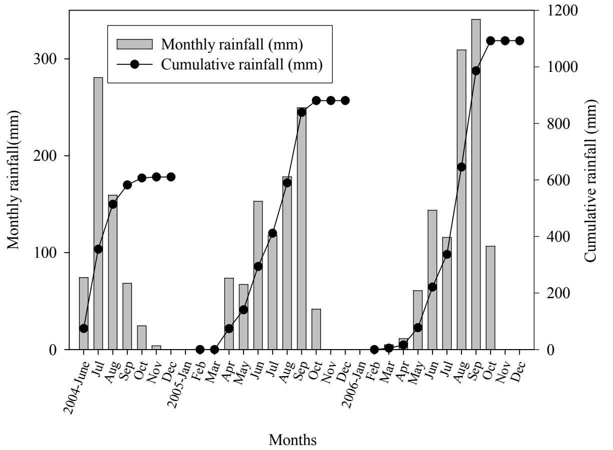

Fig. 3. Monthly and cumulative rainfall distribution from June 2004 to December 2006 at Dossi in Burkina Faso, West Africa. The amount of rainfall from June to October (corresponding to the maize cropping period) was 606 mm, 740 mm and 1016 mm in 2004, 2005 and 2006, respectively.

The study sites have a substratum of Birimian, volcano-sedimentary rocks, fissured and weathered to a depth of several meters (Hottin & Ouedraogo, 1975). The *F. albida* and *V. paradoxa* parklands are mainly found on Regosols and Cambisols (FAO, 1988). The first horizon (0-15 cm) has a silty-clay texture; its properties are presented in Table 1.

Table 1. *Physical and chemical characteristics of the top soil horizon in the Faidherbia albida and Vitellaria paradoxa parklands at Dossi in Burkina Faso, West Africa. Samples were collected from the soil description pits, which were excavated between trees*

Soil properties	*F. albida* parkland 0-15 cm	*V. Pardaoxa* parkland 0-12 cm
Clay (%)	29.4	37.3
Silt (%)	39.2	25.5
Sand (%)	31.4	37.2
CEC* (cmol kg^{-1})	18.3	18.9
pH (in water)	6.1	5.7
Total C (g kg^{-1})	15.0	14.2
Total N (g kg^{-1})	0.7	0.7
Total P (mg kg^{-1})	487	443

*CEC: cation exchange capacity

Methods

*Decomposition of mixed plant litter (Paper **I**)*

This study was conducted in the field and laboratory, in the latter case using a respirometer. In the field, the effect of inorganic fertilizers on decomposition rates and nutrient release from mixed leaf litter of *F. albida* (higher nutrient content) and *V. paradoxa* (lower nutrient content) were investigated over nine months from mid-August 2005 until mid-April 2006. Initial litter characteristics are presented in Table 2. Litterbags of 10 × 10 cm, with a 1 × 1 mm mesh and containing leaf litter of *F. albida* and *V. paradoxa* in varying proportions were buried at 10 cm depth in the experimental plots. The following treatments were applied: no fertilizer (control); inorganic nitrogen; phosphorus in the form of Triple superphosphate (TSP, 46% P_2O_5), and phosphorus in the form of rock phosphate from Burkina Faso (BP, 27% P_2O_5). Litterbags were collected 2, 4, 6, 8, 16 and 36 weeks after the commencement of the experiment. On each collection date, the undecomposed litter from each species was separated, and its remaining mass, N, P and K contents were determined. A single exponential model (Olson, 1963) was used to describe the decomposition pattern and to calculate the decomposition rate constants.

The decomposition of leaf litter was also investigated under laboratory conditions. Leaf litter from *F. albida* and *V. paradoxa* were ground and added to 10 g of soil adjusted to *ca.* -25 kPa (Ilstedt, Nordgren & Malmer, 2000); to investigate the species separately 0.5 g of the litter was used and for the mixed litter 0.25 g from each was used. The experiment, thus, had three leaf litter quality treatments (*F. albida*; *V. paradoxa* and a mixture of *F. albida* and *V. paradoxa*) and each was replicated six times. Decomposition rates were assessed on the basis of CO_2 evolution, measured hourly using a computerized respirometer (Respicond III, Nordgren Innovations, Umeå, Sweden). The specific microbial growth rate was determined as described by Nordgren (1988) (see also Paper **II**).

Table 2. *Initial total nutrient concentrations (± SE) in litter used in the decomposition experiment at Boni in Burkina Faso, West Africa. n=4*

	C ($g\ kg^{-1}$)	N ($g\ kg^{-1}$)	P ($mg\ kg^{-1}$)	K ($mg\ kg^{-1}$)	C/N
F. albida litter	494±16	18.1±3.6	1225±207	4715±587	27
V. paradoxa litter	534±32	8.4±0.7	839±198	1616±666	64

*Nitrogen and phosphorus limitation of soil microbial respiration (Paper **II**)*

In study **II**, the nutrient limitations to microbial respiration in soil supplemented with various nutrient sources were assessed in the laboratory. Hourly measurements of soil respiration were made using a computerized respirometer (Respicond III). Soils were collected from the top 0-5 cm of plots receiving no additional nutrients (control) and N, P, and K fertilizer applications in study **III**. Soil samples were passed through a 4 mm sieve, mixed with perlite (Ilstedt, Singh & Nordgren, 2007), adjusted to a water potential of ca -25 kPa (Ilstedt, Nordgren & Malmer, 2000) and finally incubated at 20°C in the respirometer. Respiration rates were measured before and after additions of a substrate containing glucose (C) in combination with N and P. A model of soil microbial respiration derived from previous studies (Nordgren, 1992; Ilstedt, Nordgren & Malmer, 2006; Teklay, Nordgren & Malmer, 2006), was used to determine the microbial respiration parameters (Fig. 4).

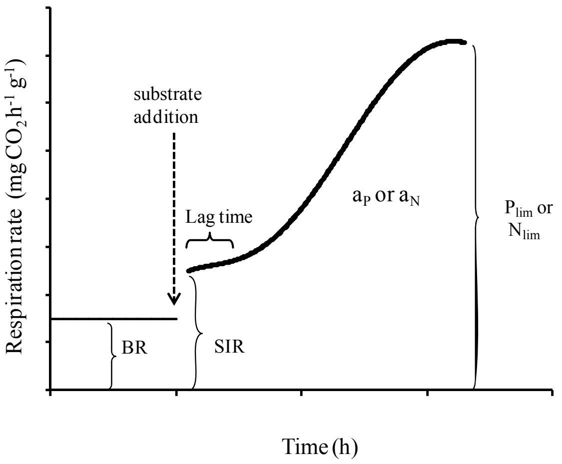

Fig. 4. A model of soil microbial respiration kinetics before and after substrate addition. The addition of "glucose + N" or "glucose + P" leads to a slope in increase in respiration rate a_P and a_N, respectively and in a maximum respiration indicated as P_{lim} and N_{lim}, respectively. BR is the Basal Respiration and SIR the substrate induced respiration.

Prior to any additions, a stable respiration rate, referred to as the basal respiration (BR), was calculated as the average values of the 40 hourly measurements. A few hours after substrate additions, respiration rates increased rapidly (substrate induced respiration, SIR); this was related to microbial biomass (Anderson & Domsch, 1978) and suggests that microorganisms were using C for energy production (Alden, Demoling & Bååth, 2001). After SIR, the respiration rate stayed constant for varying lengths of time (the lag time), depending on the substrate added and the nutrient content of the soil. Then, respiration increased exponentially as a result of microbial growth (specific microbial growth). In this study (Paper **II**), we did not measure the specific microbial growth using the method described by Nordgren (1988) and Marstorp & Witter (1999) because, in general, the microbial growth during P-limitation was not exponential. Instead, we used the slopes a_N and a_P (Fig. 4), obtained from linear regressions of the growth phase data in the N-limited (C and P addition) and P-limited (C and N addition) experiments, respectively. The slopes a_N and a_P were used as measures of N- and P-limitation, with the increase in respiration rate assumed to be related to the rate at which microbes extract and use N and P, respectively. The greater the slope of the regression, the more readily available the nutrients are to the microbes.

The respiration rate reached a peak when N or P (hereafter abbreviated as N_{lim} and P_{lim}, respectively) became limiting to further increases in the respiration rate (Fig. 4). This is assumed to reflect the limiting amounts of N and P for microbial growth when C is added in excess (Ilstedt *et al.*, 2003). Thus, additions of small doses of N and P to the N- and P- limited curves resulted in an increase in the maximum respiration rate (ΔN_{lim} or ΔP_{lim}) and were used as an internal standard to calculate the amounts of N and P available to the microbes in the samples (Nordgren, 1992; Demetz & Insam, 1999).

*Study of combined inorganic fertilizer and compost inputs on maize performance (Paper **III**)*

This study (**III**) was conducted both in the field and under greenhouse conditions. The on-farm experiment was carried out in typical monospecific *F. albida* and *V. paradoxa* agroforestry parklands over three consecutive cropping seasons. This study investigated the effect of urea (46% N) and compost (0.7% N, 0.3% P, and 15% C) applications (applied individually or in combination) on maize yields and soil chemical properties. The compost used in this study was provided by a single farmer using selected household refuse, animal manure, crop residues, and ash as raw material. It contained a high proportion of mineral soil and ash. Urea and compost were applied separately underneath and outside the canopy of each tree species studied, at the rate of 80 kg-N ha^{-1}, or in combination each at the rate of 40 kg-N ha^{-1}. These treatments were compared with unfertilized control treatments. For each parkland type, the experimental design was a split-plot with eight treatments (two canopy positions × four fertilization combinations) and four replications. Compost was applied to the topsoil a few days before maize sowing, while urea was applied in rows in two splits; one third of the total was applied three weeks after sowing, and the remaining two-thirds was applied at the time of flowering. Maize performance was measured as grain yields. Sub-samples of grain were also taken for N and P content determinations. Soils were sampled each year before treatment applications and at harvest for chemical analysis.

The on-farm experiments were complemented with a greenhouse experiment using soil from beneath and outside the tree canopies in the field experiment. The aim was to study crop N-uptake from ammonium sulphate (inorganic fertilizer) and compost using labeled ammonium sulphate (Westerman & Kurtz, 1974; Hauck & Bremer, 1976; Zapata & Axmann, 1995). Unlike the field experiment, where light transmission beneath the tree canopy was one of the main differences between the two species, this factor was excluded in the greenhouse experiment. Treatments were the same as for the field study and were replicated four times. Maize shoot biomass was harvested at flowering, and its dry weight was determined. Sub-samples were finely ground to determine the total N and $\delta^{15}N$ content.

Chemical analysis of soil and plant samples

For studies **I**, **II** and **III**, soil samples were air-dried and passed through a 2 mm sieve. The total soil carbon (C) was determined using the Walkley and Black method (1934). To determine the total soil nitrogen (N), phosphorus (P) and potassium (K), the samples were first mineralized using H_2SO_4-Se-H_2O_2 (Houba, van der Lee & Novozamsky, 1997). The total N and total P contents in the digested solution were assessed using an automatic colorimeter (Skalar SANplus Segmented flow analyzer, Model 4000-02, Breda, Holland). Total N was determined using a modified Bethelot reaction (Krom, 1980), and total P following the Murphy & Riley method (Murphy & Riley, 1962). Total K was determined using a flame photometer (Jencons PFP 7, Jenway LTD, Felsted, England). The soil pH (in water) was measured using a pH-meter (WTW InoLab, Weilheim, Germany) in slurries formed from a ratio of 1 g soil to 2.5 ml water. Available phosphorus was extracted according to the Bray I method (Bray & Kurtz, 1945) and determined colorimetrically as for total P. The total organic matter content of the leaf litter was determined from mass loss after ignition at 550 °C for 5 h; this provided a measure of the total carbon (Nelson & Sommers, 1982). The total N, P and K contents in the plant materials were determined as for the soil. However, for the greenhouse experiment in study **III**, total N content and $\delta^{15}N$ values of maize shoot biomass samples were determined using an ratio isotope mass spectrometer (Model 20-20, Europa Scientific Ltd, Crewe, UK) interfaced with an element analyzer (ANCA NT system, solids–liquids preparation module, Europa Scientific Ltd, Crewe, UK). The recovery (%) of fertilizer N, or the fertilizer use efficiency, was calculated according to Westerman & Kurtz (1974).

Data analysis

Data from the different studies were subjected to analysis of variance (ANOVA) using either GenStat for windows (Ver. 8) general statistics package (Rothamsted Experimental Station) (study **I**) or Minitab (V. 14) statistical software for Windows (Minitab Inc.) (Studies **II** and **III**). The General Linear Model (GLM) univariate and repeated measures were both used in the three studies. Data were checked for normality prior to running the ANOVA. Means that showed differences at $p<0.05$ were compared using Tukey's pair-wise tests.

Results

Decomposition and nutrient release from mixed litters (Paper I)

The litter of *F. albida* decomposed more rapidly than *V. paradoxa*: their decomposition rates ranged from 0.031 to 0.131 week^{-1} and from 0.015 to 0.086 week^{-1}, respectively. When the two litters were mixed, the decomposition rate of *F. albida* was unchanged but that of *V. paradoxa* increased. In the plots receiving inorganic N and TSP, the decomposition rates of both litter types were faster than those receiving BP or no addition (Control). Sixteen weeks after litterbag deployment, *F. albida* released more nutrients than *V. paradoxa* litter. *F. albida* litter released 70, 80 and 91% of its initial N, P and K content respectively. *V. paradoxa* released 35, 51 and 61% of it initial N, P and K content respectively. In the laboratory experiment, the microbial specific growth rate of *F. albida* litter (0.135 h^{-1}) was higher than that of *V. paradoxa* litter (0.069 h^{-1}) and, thus, decomposed more rapidly.

Nitrogen and phosphorus limitation of soil microbial respiration (Paper II)

The respiration curve patterns following C+P and C+N additions were different, but the maximum rate was similar (Fig. 5). The slope of the increase in respiration rate obtained under N-limiting conditions (a_N) was higher than under P-limiting conditions (a_P). These slopes were steeper with soil from under the tree canopy than with samples from outside the canopy (Paper **II**). Following addition of the C+P mixture, two peaks were observed (Figs. 5a, b). The first appeared after approximately 27 (±2) h. The second peak appeared after around 80 (±4) and 131 (±21) h, in incubations of samples collected from outside and under the canopy, respectively. The addition of C+N (Figs. 5c, d) resulted in a slower initial increase in respiration rate, and the first maximum appeared ca. 46±10 h later than with the C+P addition. In the *V. paradoxa* parkland, the respiration parameters were higher with fertilized soil than with the control soil (no fertilizers added).

Canopy effects

The P- and N-limited increases in respiration rate (a_P and a_N) were significantly different for samples from underneath and outside the canopy of the control (unfertilized) plots. The a_P and a_N slopes were steeper with samples from under the canopy than with samples from outside the canopy (a_N values; 48±5 and 23±12 μg CO_2 h^{-2} g^{-1} dw, respectively). With samples from the fertilized plots under the tree canopy and outside it (a_N values were 55±30 and 44± 38 $\mu g\ CO_2\ h^{-2}\ g^{-1}$ dw, respectively).

The soil under the canopy of *F. albida* had a 19% higher BR, compared with the soil outside the canopy, although no such significant difference was found for *V. paradoxa*.

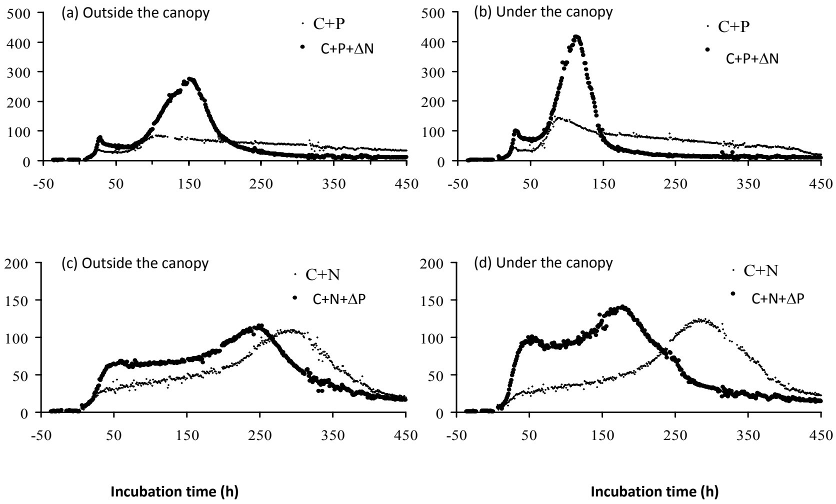

Fig. 5. Microbial respiration kinetics of soils from under and outside the *Vitellaria paradoxa* canopy from the experimental control treatments after the further addition of 'glucose and phosphorus' (C+P), 'glucose and phosphorus and small amounts of nitrogen' (C+P+ΔN), 'glucose and nitrogen' (C+N) and 'glucose and nitrogen and small amounts of phosphorus' (C+N+ΔP). Each point represents an average for the three field replicates. Note the difference in scale between C+P addition (Figs. a and b) and C+N addition (Figs. c and d).

Fertilization effects

In the *V. paradoxa* parkland, microbially available N and P were twice and 1.6 times higher, respectively, in the fertilized plots, compared with the unfertilized (control) plots. In the *F. albida* parkland, microbially available N and P were four to five times higher in the fertilized plots compared with the controls.

The effects of inorganic fertilizer and compost inputs on maize performance (Paper III)

Both, maize yields (Figs. 6 and 7) and total rainfall (Fig. 3) increased from 2004 to 2005. Maize yield was higher under the *F. albida* canopy than outside it (Table 3, Fig. 6). Maize yields under the *F. albida* canopy were 1.0 to 2.3 times that recorded outside the canopy. In contrast, maize yield was lower under the *V. paradoxa* canopy than in the open field (Table 4, Fig. 7). The yields under the *V. paradoxa* canopy were 0.6 to 0.8 times the yield recorded outside the canopy.

In both *F. albida* and *V. paradoxa* parklands, the control treatments from under and outside the canopy had lower yields than the other treatments at the same canopy position (Figs. 6 and 7).

The urea treatment had the greatest increase on maize yield (2.2 times that of the control) in the *F. albida* parkland. In the *V. paradoxa* parkland, the combination of compost and urea produced the highest yield (2.6 times that of the control) in the driest year, while in the wettest year, the urea application produced the highest yield (2.1 times that of the control).

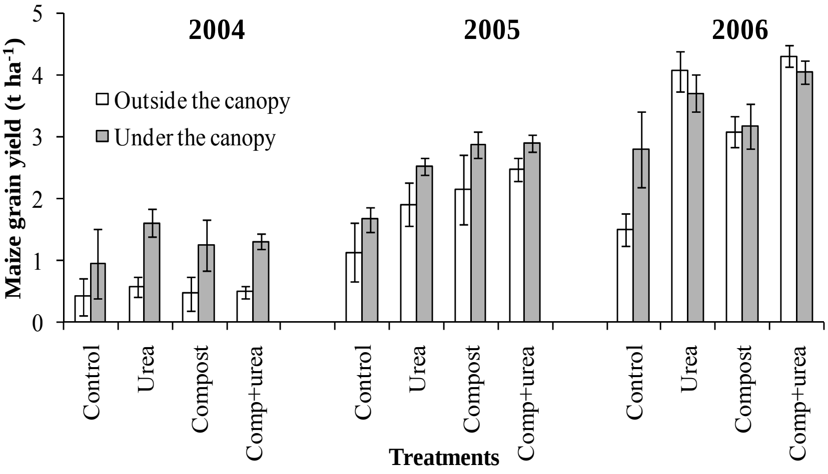

Fig. 6. Maize grain yield as affected by urea, compost or the two combined (comp+urea) applied beneath and outside the canopy of *F. albida* in 2004, 2005 and 2006 at Dossi in Burkina Faso, West Africa. Urea and compost were applied at the rate of 80 kg-N ha^{-1}. In the combined treatment, they were applied each at the rate of 40 kg-N ha^{-1}. Bars represent standard errors and n=4.

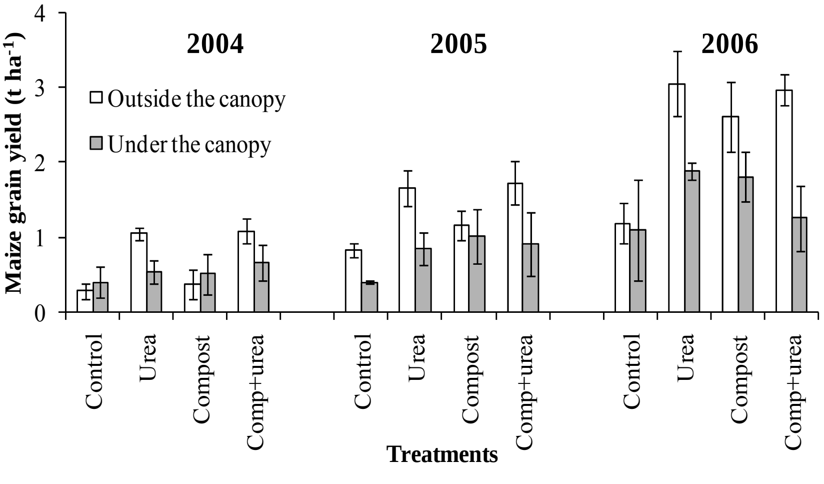

Fig. 7. Maize grain yield as affected by urea, compost or the two combined (comp+urea) applied beneath and outside the canopy of *V. paradoxa* in 2004, 2005 and 2006 at Dossi in Burkina Faso, West Africa. Urea and compost were applied at the rate of 80 kg-N ha^{-1}. In the combined treatment, they were applied each at the rate of 40 kg-N ha^{-1}. Bars represent standard errors and n=4.

Table 3. *F-values and level of significance from two-way Analysis of Variance (ANOVA) comparing maize grain yield in F. albida parkland for 2004, 2005 and 2006 at Dossi in Burkina Faso, West Africa; n = 32 and df is the degree of freedom*

Source	df	2004	2005	2006
Canopy	1	13.68^{***}	19.69^{**}	0.71^{ns}
Fertilization	3	3.41^{*}	19.51^{***}	30.53^{***}
Canopy × Fertilization	3	1.89^{ns}	0.38^{ns}	2.63^{ns}
Error	24			

ns= not significant; *p<0.05; **p<0.01; and ***p<0.001

Table 4. *F-values and level of significance from two-way Analysis of Variance (ANOVA) comparing maize grain yield in V. paradoxa parkland for 2004, 2005 and 2006 at Dossi in Burkina Faso, West Africa; n = 32 and df is the degree of freedom*

Source	df	2004	2005	2006
Canopy	1	1.62^{ns}	9.00^{**}	26.39^{***}
Fertilization	3	3.88^{*}	2.97^{*}	10.47^{***}
Canopy × Fertilization	3	0.197^{ns}	0.79^{ns}	5.07^{**}
Error	24			

ns= not significant; *p<0.05; **p<0.01; and ***p<0.001

In the greenhouse experiment, maize shoot biomass trends were consistent with the field study. Under greenhouse conditions, the recovery of ^{15}N-labeled sulphate ammonium-N, i.e. inorganic fertilizer-N, (Ndff) and compost-N (Ndfc) were 12% and 13%, respectively with soil from *F. albida* parkland. With soil from *V. paradoxa* parkland, the figures were 17% and 11%, respectively. Ndff and Ndfc were lower for soil from under the canopy of *F. albida* than for soil from outside the canopy (Fig. 8).

In the *F. albida* parkland, mean (SE) of soil total C were 13.1±0.6 g kg^{-1}and 14.1±0.6 g kg^{-1} in 2004 and 2006, respectively. For *V. paradoxa* parkland, the figures were 17.4±0.8 g kg^{-1} and 16.3±0.8 g kg^{-1}.

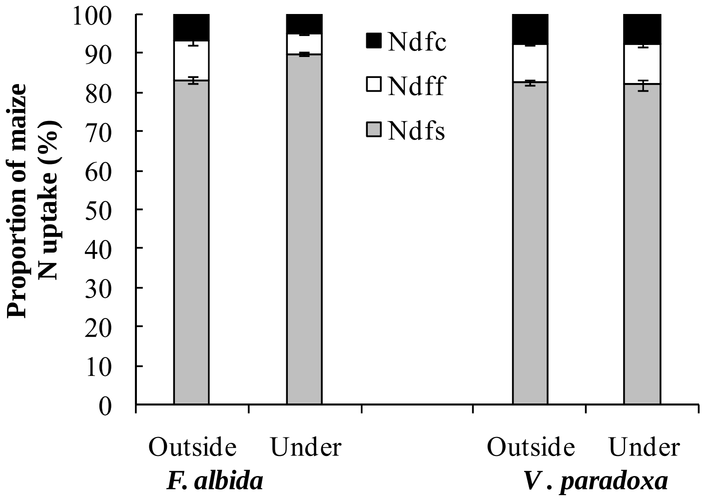

Fig. 8. Percent of N derived from soil (Ndfs), ammonium sulphate (Ndff) and compost (Ndfc) in maize shoot biomass in soil from under and outside the canopy of *F. albida* and *V. paradoxa* trees in Burkina Faso, West Africa. Bars represent the standard error of the means and n=4.

Discussion

Hypotheses

The overall influence of rainfall on maize yield

Both total rainfall during the cropping period (June to October) and maize yield increased from 2004 to 2006 (Figs. 3, 6 and 7) suggesting that more rainfall leads to higher maize yields, within the range of precipitation recorded here (Gachengo *et al.*, 1999; Ncube *et al.*, 2007). Other workers have reported that rainfall distribution rather than total rainfall determines crop success, arguing that prolonged dry spells during the critical phases of crop development are the main causes of crop failure (Lawson & Sivakumar, 1991; Fox, Rockstrom & Barron, 2005). In fact, the 2004 season had both the lowest and least favorable rainfall distribution during the cropping period (606 mm), compared with the cropping periods in 2005 (740 mm) and 2006 (1016 mm). 'Good' rainfall is difficult to predict; however, it is the key factor determining the risk of harvest loss in the semi arid zone where more than 90% of the agriculture is rain-fed. The risk can be decreased for example through tree canopy (Paper **III**) which reduced temperature maxima and evapotranspiration and increased relative humidity or by adopting some water harvesting techniques such stone rows or grass strip (Zougmoré, Mando & Stroosnijder, 2004).

Benefits from soil organic matter (SOM)

The treatments in this study with the highest SOM levels are under tree canopies and where compost is used, especially when the two are combined. The hypotheses that input of compost and or litter may improve the level of SOM could be accepted.

Soil organic matter directly influences, and indirectly mediates, the effects measured in these studies, i.e. microbial activity, nutrient uptake, litter decomposition and crop growth. SOM also influences other parameters not measured, e.g. water infiltration, soil water holding capacity, nutrient retention and release, cation exchange capacity, erodability, soil microbial and soil faunal activity, provide micro nutrients and improve micro climate etc. With higher SOM there are also mostly more water stable macro aggregates and thereby a better soil structure for holding water and for water infiltration into the soil (Brady & Weil, 2002; Ouattara *et al.*, 2007). Improved infiltrability reduces erosion by allowing more water into the soil (thereby reducing surface run-off). SOM also provides exchange/binding sites for soil nutrients, hence governing their availability for plants both by increasing the number of binding sites and by influencing the timing of nutrient release, i.e. temporarily immobilizing them and then releasing them at a time that might be more advantageous to crops, improved synchrony (Choi *et al.*, 2001; Han *et al.*, 2004) . Furthermore, SOM is an energy source for soil microorganisms and a substrate for soil micro and macro fauna. Polysaccharides produced by soil bacteria and humic substances produced by soil fungi increase soil aggregates and improve soil stability. These effects are often synergistic to each other and to the effects measured in this study. Reciprocally, this means that the measured effects might have other (positive) effects not measured.

Litter decomposition and nutrient availability

Effects of litter quality

As was hypothesized, the decomposition rate was higher for the *F. albida* (nutrient-rich) leaf litter than for the *V. paradoxa* (nutrient-poor) litter.

The litter of *F. albida* had a higher N-content and lower C-to-N ratio than the *V. paradoxa* litter, consequently it decomposed and released nutrients more rapidly (Constantinides & Fownes, 1994; Musvoto, Campbell & Kirchmann, 2000; Teklay & Malmer, 2004; Bayala *et al.*, 2005). These findings were supported by the laboratory experiment, in which *F. albida* litter was associated with a higher microbial specific growth rate than *V. paradoxa* litter, clearly indicating that soil microorganisms decomposed *F. albida* litter more easily. Previous laboratory studies have also reported that leaves with a high N content support higher microbial growth rates than leaves with lower levels of N (Sall *et al.*, 2003; Teklay *et al.*, 2007).

Litter that decomposes slowly favors the build-up of soil organic matter; this may explain the significantly higher total soil carbon content in the *V. paradoxa*, compared with the *F. albida*, parkland. However, the decomposition rate of this persistent litter was enhanced by mixing it with nutrient-rich litter from *F. albida*. This type of increase is attributed to N-transfer from nutrient-rich to nutrient-poor litter (Staaf, 1980; Salamanca, Kaneko & Katagiri, 1998; Schimel & Hättenschwiler, 2007).

In both *F. albida* and *V. paradoxa* parklands, the presence of a tree canopy increased total soil nutrient content, compared with the open fields. This is consistent with previous studies (Kho *et al.*, 2001; Bayala, Teklehaimanot & Ouedraogo, 2002). There is more litterfall, roots and animal faeces deposition under trees compared with open fields. The favourable climatic conditions under trees compared with open fields leads to higher rates of decomposition and nutrient release. Most likely this contributes to the difference between under and outside the trees in the two parklands.

Microbial measurements

Soil N and P were more readily available to microbes under the canopies of both *F. albida* and *V. paradoxa* than in the open fields. From the respiration measurements (Paper **II**), it was confirmed that N and P are more readily available under the canopy of both *F. albida* and *V. paradoxa* than in the open fields, based on the more rapid initial rates of respiration increase (a_N and a_P) beneath the trees. This difference may be because there is more soil organic matter, a higher microbial biomass and more soil enzymes in the dead cell or adsorbed to clay particles (Dilly & Nannipieri, 2001). This hypotheses is supported by higher microbial activity under *V. paradoxa* (Boffa, 1999) and various species of Acacia (Traoré *et al.*, 2007) compared with open field. Competition between decomposition products of organic matter and P for soil sorption sites may also increase the availability of P under the tree canopy compare to open field (Guppy *et al.*, 2005). Moreover, if nutrients in the soil solution are readily available, soil water content is one of the main determinants of soil microbial activity. Soil water content is higher under trees than in the open fields. Soil temperature also influences microbial activity; this appears to be closer to optimum under the tree canopy. These factors could support higher microbial activity under tree canopy than in the open field. Furthermore, the lower proportion of N derived from fertilizer in maize shoot biomass under the canopy of *F. albida* compared with outside the canopy (Paper **III**), provides additional evidence that the N-pool, at least, is more readily available under this tree. In fact, *F. albida* is a nitrogen-fixing which may enhance soil N availability and reduce competition for soil N with crop.

Both N and P were found to limit microbial activity in the systems studied. The maximum respiration rate was similar under conditions of N- and P-limitation, suggesting that the microbe-available pools of N and P were similar. However, microbes had more difficulty making use of soil P than N, as indicated by the fact that the slope a_P was less steep than a_N. In old tropical soils, most of the P is bound tightly to Al and Fe surfaces in the soil (on clays and soil organic matter complexes) or is present in organic forms. There is, therefore, a high C cost to microorganisms in order for them to produce organic acids or enzymes to release these forms of P. This may explain the longer time required for the respiration rate to increase and the consequently shallower slope (Ilstedt *et al.*, 2003). The double peak observed with the addition of C+P suggests that there are two N pools: the first, a small pool of readily available N and the second, a larger pool of N adsorbed by clays and organic matter which becomes available gradually (Teklay, Nordgren & Malmer, 2006). Succession in microbial communities may also help to explain the two peaks. The first peak may be related to oligotrophic organisms reproducing slowly, and the second to the dominant copiotrophic species reproducing rapidly when substrate became available and becoming dormant when the substrates becomes depleted (Blagodatsky, Heinemeyer & Richter, 2000; Cleveland *et al.*, 2007). The pattern of respiration curves following C+P addition differed from those reported from temperate studies and seems, for the time being, to be unique to two studies in tropical Africa. The only pattern similar to the reported here was presented by Teklay, Nordgren & Malmer (2006) for Andosols from Southern Ethiopia.

Effects of fertilization

Both *F. albida* and *V. paradoxa* litter decomposition constants were higher in the plots enriched with N and TSP than in the plots with no fertilizer additions (control) (Paper **I**). This implies that the availability of N and P affects positively the loss of litter mass (Alexander, 1985). Kwabiah *et al.* (1999), Ofori-Frimpong & Rowell (1999) and Liu *et al.* (2006) reported similar results. The addition of rock phosphate did not affect the decomposition constant relative to the control, probably because this slow release P-source did not increase the readily available P in the soil.

Applications of fertilizer in the field increased the amount of nutrients available to soil microorganisms, as indicated by the respiration tests (Paper **II**). It may also, therefore, have increased the decomposition rate (Paper **I**) and thus the nutrients released from the litter; this could be beneficial for crop nutrition in the parkland. Field fertilization also increased maize yields and N-uptake (Paper **III**).

Improving cultivation in parklands

Compost use

Application of compost can improve maize yields, especially in years with low rainfall. This is especially important with the threat of more erratic wet seasons as a result of changing climate (Zhang *et al.*, 2007). To survive periods of low rainfall, improved water storage through for example improved soil infiltration is needed. This can be met with compost application (Ouattara *et al.*, 2007) or higher litter and roots inputs under tree canopy (Hansson, 2005; Ilstedt *et al.*, 2007).

Maize yields obtained with applied compost was generally in this study equal to those achieved with the highest urea application rates, when the two sources contained equivalent amounts of N. Similar findings have been reported for compost and manure applications in West Africa (Vanlauwe *et al.*, 2001a; Ouédraogo *et al.*, 2007) and East Africa (Mtambanengwe, Mapfumo & Vanlauwe, 2006; Mucheru-Muna *et al.*, 2007). In this study, compost was added so that there was an equivalent total N content as in the inorganic fertilizer; this equated to a lower level of readily available N in the compost (Eghball & Power, 1999). The performance of maize following compost addition could be attributed to rapid decomposition and mineralization, resulting from its favorable C-to-N ratio (Swift, Heal & Anderson, 1979) and the adequate release of mineral-N necessary in the short term to support maize growth. The same was indicated for the uptake of N in the maize shoot biomass in the greenhouse experiment (Paper **III**). The maize yield obtained with the combined urea and compost treatment was as high as for the separate applications of compost and urea, suggesting that the effects of both urea and compost were additive (Vanlauwe *et al.*, 2001c) and that there were other positive effects from compost e.g. supply of nutrients including micro nutrient and improved soil properties. This may be the result of the interaction between decomposing compost and urea leading to improved synchrony between the supply of N and the demand for it (Vanlauwe *et al.*, 2001c). The yields obtained with these treatments indicate that compost can replace part of the inorganic fertilizer without adversely affecting yields. This is important for farmers who aim to maximize their crop output, but who cannot afford enough inorganic fertilizer.

Although total soil C in these parklands is relatively high (1.4 to 2%) compared with other soils in West Africa (<0.8%), compost is still be useful for improving maize yields. When there is little rainfall, the impact of compost on crop yield is expected to be higher in soils with low organic matter content. However, the rate of compost used alone in this study is not realistic for large-scale farming due to the high amount needed. Urea is too expensive for many farmers when used alone. As a result, a combination of the two types of fertilizer is the most economically viable option for the small-scale farmer.

Tree canopy effect

Maize yields were higher under the *F. albida* canopy than outside the canopy. In contrast, the yield was lower under the canopy of *V. paradoxa* than outside the canopy. During the cropping season, the key difference between these trees is that *F. albida* is leafless, thus reducing competition with the crop for water, nutrients and light (Payne *et al.*, 1998; Kho *et al.*, 2001). In contrast, *V. paradoxa* keeps its dense canopy, thus reducing light intensity and photosynthetic activity beneath the trees (Boffa, Taonda & Dickey, 2000;

Bayala, Teklehaimanot & Ouedraogo, 2002; Zomboudré *et al.*, 2005). Pruning may be one strategy to reduce shade effect under *V. paradoxa* tree. This management practice enhanced the production of associate crop by increasing light transmission and reducing water and nutrients use by the pruned tree (Kessler, 1992; Bayala, Teklehaimanot & Ouedraogo, 2002; Bayala *et al.*, 2003). In support to this, Zomboudré *et al.* (2005) recorded higher maize yield under *V. paradoxa* with brush canopy (pruned tees) than under tree with ball canopy (unpruned trees). Bayala *et al.* (2003) reported other advantage of tree pruning in Burkina Faso; the application of the leave from pruned *V. paradoxa* as mulch increased millet production as consequence of improved soil physical and chemical properties. However, for both species, soil nutrient availability (Paper **II**) and total nutrients were higher under the canopies than in the open fields.

In this study, the shade effect was removed in the greenhouse study, but the differences in maize shoot biomass continued to mirror those in the field (Paper **III**). In the case of the soil from beneath *F. albida*, this confirms the higher soil fertility under the canopy, compared with that outside it. In addition, since this tree species is leafless during the cropping season, the maize was growing under almost similar light conditions irrespective of the presence of trees. However, in the greenhouse without canopy shade, maize shoot biomass was still lower when grown in soil taken from under the canopy of *V. paradoxa* trees. This result was consistent with the field experiment, and implies that factors other than shade and soil microclimate must affect maize performance under this species. These factors could include e.g. allelopathic effects of *V. paradoxa* leaves (Bayala *et al.*, 2003) or higher incidences of pathogens in the soil under *V. paradoxa* trees (Kater *et al.*1992) or immobilization by low quality organic matter.

The improved performance of maize under *F. albida* compared with that in open fields was higher in the dry year than in the wet year. The maize yield under *V. paradoxa* compared with the open fields was not significantly reduced in the driest year as it was in the wetter years. These results suggest that in years with low rainfall, the presence of a tree canopy can reduce the risk of maize failure. Higher water infiltration under both *F. albida* and *V. paradoxa* trees compared with that in open fields (Hansson, 2005), combined with the higher organic matter under trees, leads to better water storage under the tree canopy. This may explain the beneficial effect of the tree canopy, especially in dry seasons.

Interaction effect of treatment and canopy on maize yield

Maize yield was consistently higher under the canopy of *F. albida* than outside, regardless of the treatment (Fig. 6). However these differences were significant only for the urea and the combination urea with compost treatments in the season 2004 and for the control treatment in 2006. In the *V. paradoxa* parkland, maize yields tended to be higher (but not significantly so) under the canopy than outside for the control and compost treatments in 2004. This may indicate that the presence of the *V. paradoxa* canopy could be beneficial in the year with unfavorable rainfall, by reducing soil water evaporation and improving soil water infiltrability (cf. paragraph above). Moreover, maize yield reduction under the canopy of *V. paradoxa* was less even non-existent (in 2004) in the treatment without urea (i.e. control and compost) while the addition of urea resulted in higher difference between outside and under the tree canopy (Fig. 7). This negative effect is most likely due to the competition for urea-N between *V. paradoxa* and maize plants.

Maize yields in the *F. albida* parkland were generally higher than in the *V. paradoxa* parkland, implying that the soil is more fertile in the former. This is the reason why the village was established around the parklands of *F. albida* and why the growth of the species was promoted by the farmers (villagers' communication).

These studies showed that the application of both compost and inorganic fertilizer under and outside the tree canopies resulted in increase of maize yield. However, the absolute maize yield loss as consequence of shading effect of *V. paradoxa* tree will increase as canopy cover increase. The reduced crop yield, in some extent, could be compensated for by the income generated by the sale of the tree fruits. Thus, in the small scale farming, the benefit of the tree has to be balanced against the loss in crop yield. In the perspective of intensification with the use of adequate rate of fertilizer and mechanized ploughing, the tree density may decrease as consequence of better yield (i.e., higher income from the maize yield than the loss from the sale of the fruits), ease of ploughing and decrease of natural regeneration.

Conclusions and Recommendations

Improving soil quality and crop production on farms is a major issue for agricultural research. This thesis has contributed additional knowledge about some of the processes governing nutrient cycling in farmland. Understanding these processes helps when making recommendations for future management.

In this thesis, it was shown that there is a potential to improve the decomposition rate of *V. paradoxa* litter by inorganic fertilizer application or by mixing it with *F. albida* litter. Thus, the slowly-decomposing litter of *V. paradoxa* can be useful contribution to improve soil fertility, rather than being burnt as nowadays practiced by the farmers. Further investigations into the effects (i.e. crop yield and nutrient uptake) of this litter, either applied directly or used to produce compost, is required before recommendations can be made about its use as a source of organic fertilizer. As the decomposition rate is controlled by climatic and soil conditions, similar decomposition studies are required in different climatic zones and including litter from other common tree species.

In the parklands studied, respiration tests clearly indicated that soil microbial respiration is limited by P-fixation at low levels of available carbon, and by N when carbon is more readily available. Canopy cover increases the availability of carbon and nutrients that can be used by microbes. The respiration curve indicated unusual fast-slow-fast pattern when N was limiting. More detailed studies should elucidate whether different microbial communities are involved in the utilization of nutrients and how the communities are related to the presence of tree canopies.

Application of combined compost and inorganic fertilizer resulted in yields comparable to those achieved with the application of inorganic fertilizer alone. This nutrient resource management option is cheaper than only inorganic fertilizers and more manageable than only compost applications; this may enable farmers to apply combined fertilizers over larger areas. Hence, the combined addition of organic and inorganic fertilizer should be recommended. However, studies investigating the residual effects and longevity of compost, different rates of fertilizer application and different organic sources (*e.g.* green leaves, composting litter) should be considered in a wide range of parklands.

This study has shown that the presence of *F. albida* increased maize yield while the canopy of *V. paradoxa* is associated with maize yield reduction. In typical parkland, trees are rarely planted which have resulted in an uneven distribution of the trees and consequently an inappropriate canopy cover. Crop production in these parklands could be improved through management of the tree distribution to optimize the effect of the canopies on associated crop. Further study should lead to recommend an optimum canopy cover (tree density). Obviously, the canopy cover should be higher in the *F. albida* parkland than in the *V. paradoxa* parkland.

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Résumé en Français (French summary)

Les nutriments issus de la décomposition de la litière et des amendements organiques et minéraux sont importants dans la gestion des parcs agroforestiers traditionnels. La bonne gestion de ces nutriments est essentielle pour optimiser les rendements des cultures et la fertilité de sol. L'Objectif général de cette étude était d'étudier la libération temporelle et spatiale des nutriments dans ces parcs agroforestiers. Spécifiquement, cette thèse a étudié : (i) la vitesse de la décomposition et la libération des éléments nutritifs des litières de *Faidherbia albida* et de *Vitellaria paradoxa*; (ii) la limitation par l'azote (N) et le phosphore (P) de la respiration microbienne du sol des parcs à *F. albida* et à *V. paradoxa*; et (iii) les effets de l'application du compost et /ou de l'urée sur les rendements du maïs dans les parcs à *F. albida* et à *V. paradoxa*.

La litière de *F. l'albida* s'est décomposée plus rapidement et a perdu plus de nutriments que celle de *V. paradoxa*. Cependant, la vitesse de décomposition de la litière de *V. paradoxa* a augmenté en présence de celle de *F. albida* ou après l'application d'engrais minéraux. La respiration microbienne du sol a été limitée principalement par la fixation du P, mais également par N. Deux pics de croissance microbienne on été observées après l'addition du carbone et de P, suggérant que deux pools de N soient séquentiellement disponibles aux microbes ou que deux communautés microbiennes existent. Les mesures de la respiration du sol ont également indiqué que sous le houppier des arbres, le P et N étaient plus aisément accessibles aux microorganismes que hors du houppier. Le rendement du maïs était semblable après l'application de l'urée, du compost, ou de leur combinaison. Cependant, en année de sècheresse, la combinaison du compost et de l'urée a eu la plus grande augmentation du rendement de maïs. Le rendement de maïs sous le houppier de *F. albida* atteignait 2.3 fois le rendement obtenu en dehors du houppier, tandis que sous le houppier de *V. paradoxa,* il était de 0.6 à 0.8 fois le rendement obtenu en dehors du houppier. Le rendement du maïs sous le houppier était relativement meilleur en année de sécheresse. Le faible recouvrement de N de l'engrais minéral et du compost dans la biomasse du maïs indique qu'une grande proportion du prélèvement de N par le maïs provenait du sol. En outre, la proportion de N dans la biomasse du maïs dérivée de l'engrais minéral était inférieure sous le houppier de *F. albida* comparée à celle hors du houppier, impliquant que le pool de N de sol sous le houppier des arbres était plus aisément disponible aux plantes.

En conclusion, la vitesse de décomposition de litière de *V. paradoxa* peut être améliorée par l'application d'engrais minéraux ou en la mélangeant à la litière de *F. albida*. Ainsi, litière de *V. paradoxa* peut contribuer à améliorer la qualité de sol, plutôt que d'être brûlée tel que pratiquée par les paysans. L'application combinée offre surtout un mode de gestion de la fertilité du sol à moindre coût et plus facilement gérable que l'application séparée des engrais minéraux et du compost.

Mots-clés : Burkina Faso, Houppier, *Faidherbia albida*, Décomposition de la litière, Maïs, Respiration microbienne, Recouvrement de N, Limitation des nutriments, *Vitellaria paradoxa*