Nutrient and water dynamics in rotational woodlots. A case study in western Tanzania

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Nutrient and water dynamics in rotational woodlots. A case study in western Tanzania

Gerson Isaac Nyadzi

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Propositions (Stellingen)

1. Sustainability of rotational woodlots is jeopardized more by depletion of nutrients than by depletion of water.

   This thesis

2. In the short term, *Acacia crassicarpa* is a good choice for rotational woodlots, but in the long term *Leucaena pallida* is preferred.

   This thesis

3. Technology development makes missions possible.

   Mars Exploration Rover Mission, January 2004.

4. Participatory research is more beneficial for the scientist who has no experience in farming than for the farmer who has no experience in science.

5. People may doubt what you say, but they will believe what you do.

6. The easiest way to grow as a person, is to surround yourself with people smarter than you.

Propositions belonging to the Ph.D. thesis of Gerson Isaac Nyadzi entitled: "Nutrient and water dynamics in rotational woodlots. A case study in western Tanzania".
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ABSTRACT

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Rotations of trees and crops on farms are considered as a potential technology to overcome the shortage of wood, reverse deforestation of natural forests and improve soil fertility for food security enhancement in western Tanzania, sub-Saharan Africa. However, over-exploitation of soil water resources and depletion of soil nutrients have been suggested as possible negative effects of growing trees on farms in the semi-arid tropics. Such possible pitfalls undermine and even threaten a successful implementation of the woodlot technology at larger scale. Evidently, without proper understanding of the interactions and possible competition between trees and crops, the potential benefits of this agroforestry technology will not be realized. Therefore, this study was focused on improving the understanding of tree-soil-crop interactions by examining water and nutrient dynamics of various trees planted in rotational woodlots with a 5-year cycle.

Field trials were established with five-year rotational woodlots. Five tree species were compared with natural fallow and continuous maize. Inter-cropping of maize between trees was possible for the first two years of tree establishment without sacrificing maize yield. There was no evidence that trees were over-exploiting the water reserves after three years. Transpiration was greatest in *A. crassicarpa* and was related to stem diameter, size of the tree canopy and soil water availability. Trees depleted relatively more water than continuous maize and natural fallow, but were able to store more water after rains. Acacia trees had high litter fall but the leaves were low in P and N, which led to N and P immobilization during decomposition. Trees retrieved leached inorganic N and made better use of it than natural fallow and continuous maize. Wood production at the end of the five-year growing period ranged from 30 to 90 Mg ha^{-1} while C sequestered in the aboveground biomass during the same period ranged between 13 to 30 Mg ha^{-1}. The rate of biomass production was highest for *Acacia* species while the foliage nutrient accumulation was highest for *Leucaena* species. The wood component varied greatly among species, ranging from 32 to 85% of the total tree biomass.

Maize yields were higher after growing trees than after natural fallow and continuous maize when no fertilizers were applied. The benefits of tree fallows compared to natural fallows were modest, in terms of maize yield increases. The increase in crop yields after woodlots was attributed in part to higher soil inorganic N. Maize responded to fertiliser N and P. The agronomic efficiency was about 30 kg grain per kg N applied at a rate of 50 kg fertilizer N, and 15 kg kg^{-1} between 50 and 100 kg N applied. Application of more than 20 kg ha^{-1} of P or K did not significantly increase maize yields. The benefit of woodlots expressed in terms of maize yield was more pronounced at mid and lower slope positions than at upper slopes. The significance of rotational woodlots in improving soil fertility is limited by substantial accumulation of nutrients in wood. Nutrient mining by wood exportation is therefore a major threat for the sustainability of woodlots, when the exported nutrients are not supplemented via external sources. Medium-term rotational woodlots have the potential to meet the domestic and industrial wood needs and at the same time to reduce deforestation in Sub-Saharan Africa.

Key words: Acacia, aboveground biomass, agronomic efficiency of fertilizers, C sequestration, decomposition, deforestation, fuel-wood, harvest index, immobilization, internal nutrient utilization efficiency, land degradation, Leucaena, nutrient content, recovery efficiency of fertilizers, Senna, soil fertility, transpiration, woody fallows, wood production.

PREFACE

The aim of the project was to improve the understanding of tree-soil-crop interactions in an agroforestry system by examining water and nutrient dynamics in rotational woodlots technology. This thesis has been possible through a sandwich PhD programme sponsored by Wageningen University and Research Centre (WUR) of the Netherlands and the Carolina MacGillavry PhD fellowships of the International Foundation for Science (IFS), Sweden. The research was also partly funded by the Ministry of Agriculture through the Tanzania Agricultural Research Project phase two (TARP II) and the African Network for Agroforestry Education (ANAFE) of the World Agroforestry Centre (WAC). To them all I extend my acknowledgement.

Many people have helped me in one way or the other but it would be difficult to mention them all. I am particularly grateful to Professor Dr. Oene Oenema for accepting to promote my study. His critical comments and suggestions on the structure and contents of the thesis have considerably improved its quality and readability. I am also grateful to my supervisors and co-promoters, Dr. Bert Janssen and Dr. Harry Booltink for their tireless encouragement, criticisms and support that helped me to accomplish my work successfully. I learned a lot from all of them and would like to thank particularly Dr. Janssen for his excellent guidance and availability all the time. I also really benefited from his knowledge and long experience in problems related to tropical soil fertility. Bert, I am very proud to be your last Ph.D. student before your retirement!

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Gerson Nyadzi
Wageningen, November 2003

Dedicated to my mother and to the memory of my brother Zavery

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CHAPTER 1

1.1 General introduction

1.1.1 Food insecurity in Africa

Food production in developing countries has tripled in the last 30 years, keeping up with population growth, except in sub-Saharan Africa (Sanchez 2000). The area under cultivation in sub-Saharan Africa has expanded notably, and there is large-scale conversion from fallow-based cropping systems to continuous cultivation (Franzel and Scherr 2002). Nonetheless, per capita food production has declined by about 2% per year since 1960 (World Bank 1996), and constraints on growth of agricultural sectors have remained prominent in most African economies (Cleaver and Schreiber 1994). In fact, sub-Saharan Africa is the only remaining region of the world where per capita food production has remained stagnant over the past 40 years (Sanchez 2002). Absolute poverty, characterised by incomes of less than U.S. $1 per person per day, is coupled with an increasingly damaged natural resource base (Pinstrup-Andersen et al. 2000). Africa's food insecurity is directly related to insufficient total food production and political instability in some countries. According to Sanchez et al. (1997) soil fertility depletion is the root cause of food insecurity in Africa.

1.1.2 Depletion of soil nutrient stocks

Depletion of soil fertility, along with the concomitant problems of weeds, pests, and diseases, is a major biophysical cause of low per capita food production in Africa. This is the result of the breakdown of traditional practices, such as shifting cultivation, and the low priority given by the governments to the rural sector (Buresh et al. 1997; Smaling et al. 1998). Over decades, farmers have removed large quantities of nutrients from their soils without using sufficient quantities of manure or fertilizer to replenish the soil (World Bank-FAO 1996).

Proper nitrogen (N) management requires a supply of N that matches the demand of N by crop. This supply can be achieved through N fertilizer application, green manuring, legume rotations or leguminous tree-shrub fallows. Rotations usually require a fallow period foregoing one or more staple crop harvests, which is not feasible for smallholder farmers in land-limited areas. In such areas there are few options for farmers except mineral N fertilizers. But fertilizers cost is two to six times as much in Africa as in Europe, North America, or Asia (Sanchez 2002), so other approaches to N management are important, particularly those based on N_2-fixing legumes.

The regeneration of natural vegetation (fallowing) for three to 15 years after two to three years of cropping was a traditional practice for restoring fertility of agricultural land in many parts in the tropics (Nye and Greenland 1960; Sanchez 1976). However, fallow periods throughout the tropics have increasingly shortened as a result of land pressure arising from human population growth. This shortening of traditional fallows, combined with little or no use of fertilizers has had negative consequences on agricultural productivity and agroecosystem integrity in the tropics.

With the rapid increase in population and the marked expansion and intensification of farming, total forested area in the tropics is declining (Makundi 2001), reducing the availability of wood products for fuel and construction, degrading range resources, and exposing vulnerable soils to erosion. Improved water and soil quality management is crucial for sustainable intensification of agriculture (i.e. more yield per unit time and per unit area).

1.1.3 Agroforestry as a possible solution

Agroforestry has been widely promoted as a more sustainable agricultural production system. It is particularly attractive for developing countries where the use of external inputs is not feasible (Breman and Kessler 1997; Sanchez 1995; Winterbottom and Hazelwood 1987). Leakey (1996), defined agroforestry as "a dynamic, ecologically based, natural resources management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels". By providing a supply of fuel wood from the farm, agroforestry can help to reduce pressure on forests and communal woodlands (Ramadhani et al. 2002). Other services that trees provide, such as boundary markers, windbreaks, soil erosion barriers, beauty and shade, are difficult to quantify but are nonetheless of substantial importance to families and natural resource protection.

To date several agroforestry technologies and options have been developed, tested or improved in Southern Africa. The World Agroforestry Centre (WAC, formerly ICRAF) through its Southern Africa regional programme working in five countries (Malawi, Mozambique, Tanzania, Zambia and Zimbabwe) has a vision to contribute to the attainment of food security and poverty eradication through agroforestry research and development based on environmentally sound management of natural resources. It is expected that by 2010, at least 2.0 million small-scale farm families in Southern Africa will have been reached with agroforestry innovations (F. Kwesiga 2002, pers. comm.).

1.1.4 Rotational woodlots

In Tabora and Shinyanga, north-western Tanzania, leguminous trees of genera *Acacia, Gliricidia, Leucaena* and *Senna*, are inter-planted between a young maize crop and allowed to grow as fallows for a couple of seasons. Farmers are now establishing rotations of two years of trees inter-planted with maize followed by three years of trees fallow and then followed by two to three maize crops. The agroforestry technology practised is known as 'rotational woodlots'. These woodlots have been found to be economically (Ramadhani et al. 2002), and possibly ecologically and socially sound. They fit well with farmer customs and work calendar, which comes as no surprise since the technology is based on the current farmers' practise in the area. The on-farm production of firewood reduces encroachment onto nearby forests and woodlands, helping preserve their remaining biodiversity. However, the benefits of agroforestry practices and technologies should not be over-generalised.

So far, research on improved crop-fallow systems has been on short duration fallows with short-lived tree shrubs (Rao et al. 1997; Buresh and Tian 1997). Prior studies addressed the effects of fallows on soil fertility (e.g Drechsel et al. 1991; Buresh and Tian 1997) and the nutrient accumulation in fallow vegetation (Van Reuler and Janssen 1993). However, our understanding of nutrient and water dynamics in tree fallows is limited. Scientific understanding and quantification of water and nutrient dynamics in the semi-arid tropical climate are needed because there are many interacting factors and possible competition between trees and crops that require adequate management. For example, a long dry season may limit the growth and nitrogen fixation potential of the trees. The insufficient knowledge of these components may jeopardise the dissemination and extension of the technology to other areas.

In this chapter a brief description of the study area, the concept of rotational woodlots and its possible potential in alleviating land degradation is given. Research aims and contexts are explained. The hypotheses and the objectives of the study are given. The selection criteria for the crop and tree species used in the study are discussed. The outline of the thesis is also briefly explained.

1.2 The research area and description of the problem

1.2.1 The Western Tanzania miombo woodlands

1.2.1.1 Location and population

The research described in this thesis was conducted in the semi-arid tropical miombo woodlands of Tabora region (Figure 1.1) which is located in mid-western part of Tanzania on the central plateau between latitude 4–7° South and longitude 31–34° East. The region has an area of 76,151 km^2, the largest region of the 21 regions in the country and represents 9% of the land area of mainland of Tanzania. Forty six percent of the total area in Tabora region is allocated to forest reserves and 22% are game reserves (TRDD 1989). The annually cultivated/planted area is estimated less than 14% of the area and 18% of the land is pasture or grass/bush lands. The population of the Tabora region was 1,717,908 in 2002 with an annual growth rate of 3.6% (PHC 2003). About 12% of the rural households were female-headed (Otsyina et al. 1997).

1.2.1.2 Climate

Temperatures range from a minimum of 13.6° C in June–July to a mean maximum of 32.5° C in September-October, just before the onset of rainy season. The average annual temperature is 23° C. During the wet season temperatures are fairly constant with mean maximum temperatures of 28 to 32°C and mean minimum of 14 to 18°C. The sunshine hours range from 6.7 to 10.3 while relative humidity is at a range of 31 to 85%.

Rainfall is seasonal, distributed in one cropping season per year (mono-modal), which falls between November and April with an annual mean of 928 mm (Figure 1.2). In the west, total rainfall exceeds 1000 mm, while in the east it drops to 700 mm and less.

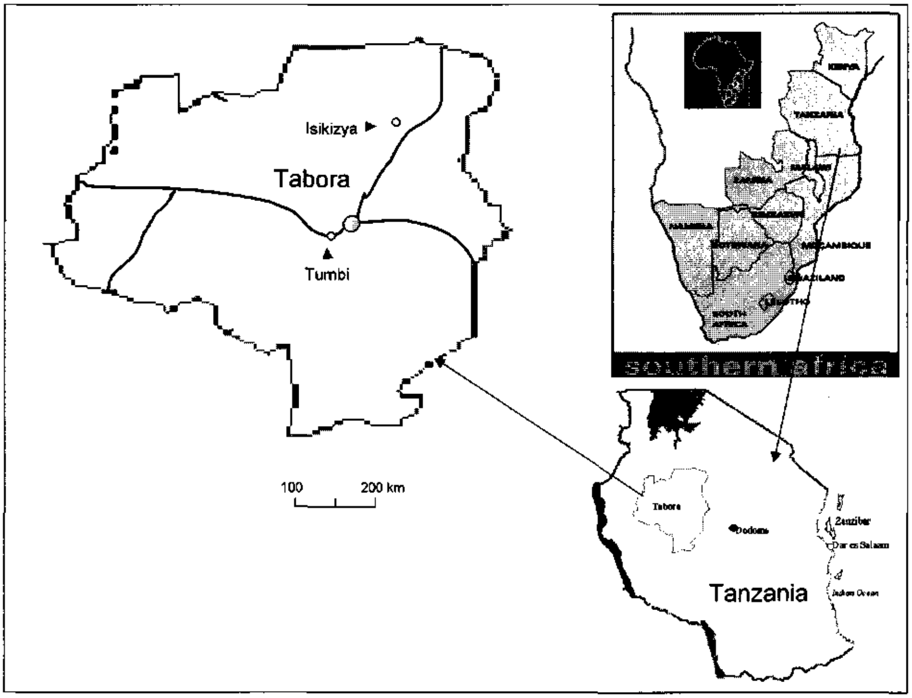

Figure 1.1. A sketch map indicating the location of research sites in Tabora, western Tanzania.

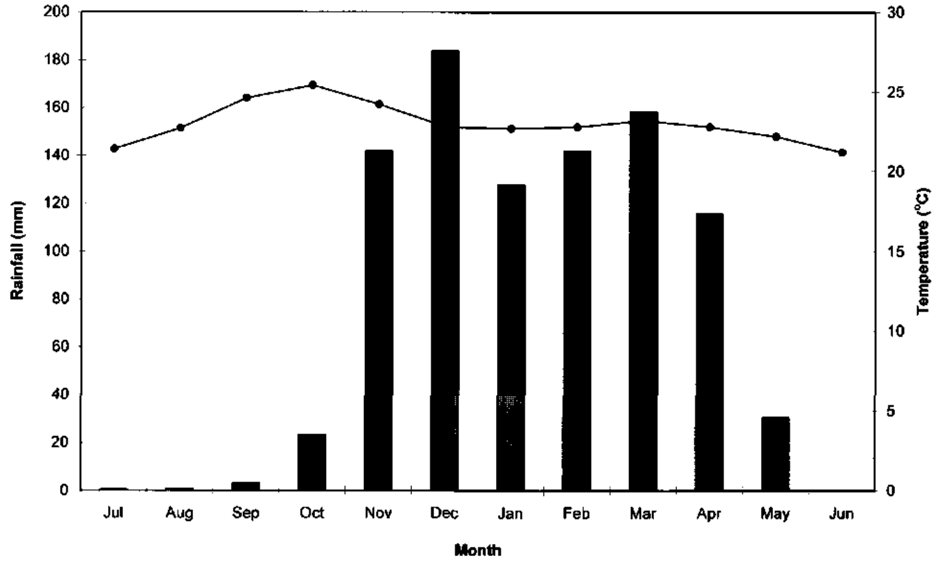

Figure 1.2. Long term (44 years, 1958–2002) mean monthly rainfall and mean monthly temperature at Tumbi, Tabora western Tanzania.

In the middle of the wet season a dry spell of usually two to three weeks occurs somewhere in January and/or February, which can affect crops seriously (Table 1.1). Another unfavourable factor is the annual fluctuation of the total amount of rain ranging from below 570 mm in dry years (La-Niña) to more than 1400 mm in very wet years (El-Niño). Late rains in March and April can be very heavy creating prolonged waterlogged conditions at lower foot-slopes and extensive floods in the valleys.

1.2.1.3 Physiography

The rocks in Tabora region include coarse-grained granites and granodiorites. Both rock types are Precambrian Intrusive associated with the Basement Complex (Heinemann and Kullaya 1978; Mitchell 1984). Soils vary widely, ranging from sandy loam in the south, centre and west, to heavy black alluvial soils in poorly drained areas especially in the north of the region. Most soils are of medium fertility when first cleared of woodland but both structure and fertility decline under continuous cropping without enough fertilizer application.

Tabora region is an area of undulating plains. Most of the region lies at an elevation between 1000–1500 metres above sea level with only two small areas in the northwest and southwest rising to 1800 m (Mitchell 1984). The study area forms a part of a large gently undulating peneplain of Miocene age, which covers almost the whole of Tabora region. On this peneplain, gently sloping ridges alternate with flat-bottomed, seasonally waterlogged valleys.

Table 1.1. Running means of ten days rainfall (mm) during 1978 to 2002 at ARI Tumbi, Tabora, mean of 25 years.

Month	Decade			
	1-10	11-20	21-30	Total
January	46.9	42.6	49.9	139.4
February	50.3	52.4	39.8	142.5
March	51.1	49.1	61.4	161.6
April	49.3	34.2	33.4	116.9
May	23.4	5.2	1.6	30.2
June	0.1	0.0	0.0	0.1
July	0.0	0.2	0.0	0.2
August	0.1	0.6	0.5	1.2
September	1.6	1.6	1.9	5.1
October	2.8	7.6	14	24.4
November	27.4	38.8	55.3	121.5
December	68.9	69.8	57.5	196.2
Total				939.3

Source: Tumbi Agricultural Research Institute (ARI) meteorological station x (953213).

The southwest and north central portions of the region are divided by a watershed, which runs from east to west. Large part of the area is drained by a system of mostly wide and flat-floored valleys better known as 'mbugas'. During the wet season these mbugas become flooded and slowly drain the water to the rivers. Tabora region is drained by the two river systems of the Ugalla - Malagarasi and the Manonga - Wembere. The Malagarasi drains the southern and western part of the region into lake Tanganyika and from there into the Atlantic ocean. The Manonga river drains into the inland lake Eyasi. The extensive Malagarasi swamp covers the extreme (border) western part of the region. The sedimentary Bukoba formation forms a dominant ridgeline, which blocks the drainage to the west resulting in the swampy lowland and broad valleys (mbugas), which penetrates deep into the south-central area of the region. The flat low-lying areas are only flooded during the good rainy seasons. There is no surface flow during the dry season, and most of the mbugas dry out completely.

1.2.1.4 Natural vegetation

The vegetation of the Tabora region consists of a dry Zambezian miombo woodland (White 1983) whose canopy height is usually less than 15 m. It is formed by species highly adapted to long dry periods, e.g., *Brachystegia spiciformis*, *B. microphylla*, *B. busei*, *Isoberlinia globiflora*, *Julbernardia globiflora*. Other common trees are *Burkea Africana*, *Erythrophloeum africanum*, *Albizzia antunesiana*, *Pterocarpus angolensis*, *P. chrysothrix*. Miombo trees are fire resistant and typically deciduous, though there are some evergreen species. The length of the leafless period varies from year to year and according to the location; the wetter the previous season or the lower on the slope, the shorter the leafless period is. There is a flush of new shoots and flowers just before the rains in September - October. A second flowering period occurs in May at the end of the wet season.

Another vegetation type spread in the area is wooded grassland, consisting of the same species as found in the miombo woodland, but with a reduced tree cover (less than 40%). The wooded grassland type of environment is possibly a degraded phase of the miombo woodland (Phillips 1930; Burt 1942; White 1983). The flat valley bottoms are covered by very open woodland dominated by *Acacia*, *Combretum* and *Terminalia* species. The longer the period of seasonal flooding the sparser is the tree growth in mbuga. The dominant grasses are thatching grass (*Hyparrhenia rufa*), lovegrass (*Eragrostis* spp) and *Sporobolus* species with pockets of guinea grass (*Panicum maximum*) and *Setaria* species on well drained fertile sites. The wettest sites usually carry an open grassland vegetation with *Setaria* and *Cyperus* species.

1.2.1.5 Economic activities

Agriculture employs 90% of the labour force. Gold mining is locally an important economic activity in the region. The Ugalla and Kigosi game reserves attract some hundreds of tourists per year in the region. The cropping pattern is characterized by subsistence crops such as maize, cassava, beans, groundnuts, cotton, tobacco, and paddy rice. Most farmers in the region keep cattle, except in the southern and western fringe zones due to the presence of tsetse fly (Glossinade). Saw milling of indigenous species and extensive beekeeping are features of non-settled areas. Small-scale irrigation of vegetables is common at lower foot slopes near the fringe of the mbuga. The main crops here are tomatoes, onions, cabbage, *Amaranthus* spp (mchicha) and Okra (bamia in Kiswahili). Irrigation water is usually obtained from nearby dug ponds and shallow wells. The use of fertilizers is restricted to tobacco (NPK 6:20:18) and maize (urea and calcium ammonium nitrate - CAN).

Flue-cured tobacco, variety K51E and PD4, recommended for Tabora region (Rutekaha and Titus 1994) usually is grown on sandy textured soils. It forms the principal source of cash income for smallholder farmers and accounts for considerable off-farm employment in the extension services, co-operative unions, transportation, and tobacco trading companies. The availability of forest reserves was among the major criteria used by the policy-makers after independence in designating Tabora a major flue-cured tobacco-growing region. Currently, both policy-makers and farmers, are concerned about the rapid deforestation. An important natural resource is being destroyed and the cost of collecting fuel wood is increasing as the distance to sources of fuel wood increases. Traditionally, farmers in Tabora region do not grow trees because until recently, wood was regarded as plentiful and because they lacked information on tree planting and germplasm (NATF 1988). Therefore, farmer's knowledge on planting and management of trees in the region is limited.

1.2.2. Deforestation of Tabora miombo woodlands

On a worldwide scale, the greatest cause of deforestation has been the conversion of forest land to agriculture (Bajracharya 1983; Myers 1984; Shepherd et al. 1996). In western Tanzania, charcoal production for the market, firewood collection and the expansion of agricultural land, particularly for growing tobacco (Figure 1.3), have contributed to deforestation. It is estimated that, in Tabora district alone, about 9,000 ha of miombo woodland are cleared annually for that purpose (Charter and Hince 1997). As a result of the high deforestation rate and subsequent fire-based agricultural land preparation with little or no fertilizer input, soil fertility has declined tremendously in the area. Natural secondary succession in the left bush lands and grasslands is also prevented by constant annual reoccurrence of fire.

Figure 1.3. A heap of firewood collected from the miombo forests ready for curing of tobacco at Isikizya village in Tabora Tanzania. On the background is a traditional tobacco-curing kiln (barn).

The need to look for alternative ways to reduce deforestation in Tabora region is widely acknowledged (e.g. Temu 1979; Solon et al. 1996). However, there have been serious constraints in tree establishment on farmers fields or on marginal lands because of physical difficulties in tree planting, e.g. tree grazing by livestock, grass competition, allelopathy (particularly with *Eucalyptus* species) (FAO 1985), fire susceptibility, termites, as well as low soil fertility. Intensive site preparation and fertilization can overcome most of these problems if suitable tree species are used (Otsamo et al. 1995). Basically there are tree species that can survive and grow in these areas. Given the situation, the Agricultural Research Institute at Tumbi (ARI Tumbi) in collaboration with the Southern Africa Development Co-ordination and the International Centre for Research in Agroforestry (SADC/ICRAF) Project has been screening native and exotic (alien) tree species (mostly Australian *acacia*) for different agroforestry technologies in the western Tanzania miombo woodlands.

1.3 Agroforestry research experiences in Tabora region

1.3.1 Multipurpose trees screening trials

Research on multipurpose trees, particularly with respect to wood production, forage and forage nutrient concentrations, began in Tabora at ARI Tumbi in 1987/88. A total of 12 thornless Australian *Acacia* species (tree species of a north Australian tropical savanna) were introduced (Karachi et al. 1997). Exotic but now commonly grown *Leucaena* species and other indigenous tree species, e.g. *Faidherbia albida*, were also evaluated. After 2.5 years of on-station screening in small plots, high wood yields (60–90 t/ha) were realised from exotic *Acacia* species (Otsyina et al. 1997). Their fast growth and great wood production indicated that they could be used to alleviate the problem of fuel wood shortage in local tobacco industry and for home consumption in western Tanzania. In 1993-1994 season, on-farm research on woodlots using *Acacia* species was initiated by ARI Tumbi, and trees were tested for ‘rotational woodlots’ and boundary plantings.

1.3.2 The concept of rotational woodlots and problem definition

1.3.2.1 Communal woodlots in Tanzania

A woodlot, in social forestry terminology, refers to planting of trees in sole stands (blocks) to provide wood for fuel and construction poles (Otsyina et al. 1999). Over the past two decades woodlots have become very popular among development agencies in Tanzania as a means of improving firewood supply in rural communities (Warner 1993, Skutsch 1985). However, communal woodlots programmes, which were advocated during the 'villagilisation policy' of 1970s to 1980s in Tanzania, were not very successful. Reasons for failures, among other things, were that farmers disliked the species (e.g. eucalyptus) and labour constraints on woodlots establishment (as community tree planting operations suffered from neglect during periods when the demands of crop cultivation were large). Of more importance, farmers were unwilling to cooperate in the establishment of communal woodlots because of the perceived and actual implications of woodlots planting on the tenure of that land. Establishment of a communal woodlot often entailed the transfer of a parcel of land held individually or communally under customary law, to collective ownership under the new village regulations (Skutsch 1985). Shanks (1990) found that in some villages, several years after establishment, people were still uncertain as to whether the woodlot was in fact the property of the village or of the forest department.

From 1985, however, emphasis has been on the encouragement of individual tree planting. This new policy arose logically from moves towards recognition of the importance of private land-holding rights for farmers (Shanks 1990). In recent years, the move has been to train farmers in tree planting through agroforestry approaches in an attempt to increase the number and diversity of multipurpose trees on farms for the provision of products and services. To encourage farmers to plant trees on their farms, rotational woodlots technology has been proposed.

1.3.2.2 Rotational woodlots in western Tanzania

A rotational woodlot-intercrop system has been developed in the Shinyanga and Tabora regions of Tanzania. In the rotational woodlots system, individual farmers intercrop food crops with leguminous trees during the first 2–3 years, to maximise returns to their scarce labour. Then they leave the trees to grow, harvest the trees in about the 5th year, and replant food crops (Otsyina et al. 1996). When crop yields decline to an uneconomical level, the stumps can be allowed to re-grow into a woodlot again. In the rotational woodlot system, just like in some other temporal or sequential mixed systems, the agricultural crop and the tree crop are established at the same time. The tree canopy will eventually close and competition will be such that agricultural cropping will no longer be viable.

The five years or more fallow period is expected to improve soil fertility through N_2 fixation, and nutrient retrieval from below the rooting zone of crops and subsequent roots and litter decomposition. However, this may not be seen in an existing fallow, since much of the nutrient stock will be in the biomass. Fallow clearance and then cropping may accelerate soil nutrient availability, particularly that of N and to a lesser extent that of P, K, Mg and Ca. Trees may also increase the water holding capacity.

Of the species tested by the farmers, the most promising in terms of growth are three newly introduced species from Australia: *Acacia crassicarpa* (also known as northern or red wattle), *A. julifera*, and *A. leptocarpa* (A. Cunn. ex Benth.). When planted on farms, these trees were found (by farmers) to be fast growing and little competitive to the intercropped crops (in the first 2 years of growth) as compared to other trees like *Eucalyptus* species and *Senna siamea* (Otsyina et al. 1997). The food crops grown following the tree harvest are expected to benefit from the increase in soil organic matter, nutrient recycling, and nitrogen fixed by the leguminous trees, but research results to confirm this are not yet available.

By 2002, the mentioned three Australian *Acacia* species had been planted by more than 3,000 farmers in Tabora region alone. Impressive increases in income of smallholders using rotational woodlots with these species have been reported (Ramadhani et al. 2002). Many farmers have realised the importance of this technology to alleviate fuel shortage as well as to avoid deforestation. It is estimated that by year 2005 more than 20,000 small-scale farm families in Southern Africa will have Australian acacia woodlots, on more than 2 hectares each on average (R. Otsyina 2000, pers. com.). Agroforestry technology such as the 'rotational woodlot' could probably improve soil organic matter status (improved quantity and quality), and the economic feasibility of using fertilizers.

However, not much is known on the biomass production and nutrient accumulation of trees in rotational woodlots. The effects of trees on yields of the intercropped crops and on the water and nutrient dynamics of the system are also not quantitatively understood. It has been postulated that the trees accelerate the growth of native fungus (mycorrhizal fungi) in the woodlots. The acacias fix atmospheric nitrogen and accumulate substantial amounts of leaf litter. Their effects on crops after harvesting woodlots are expected to depend on the decomposition of their leaves. Water utilisation by Australian acacia trees was expected to be high due to their high growth rates, as is the case with eucalyptus plantations (Calder et al. 1993; Calder et al. 1992). There were sap flow measurements done by Dye and Olbrich (1992) in South African forest plantations. However, there has been no measurement thus far on rotational woodlot. There is a need to understand the nutrient dynamics as well as water utilisation in rotational woodlots and to see whether there are adverse environmental effects of extending this technology on a wider scale.

1.4 Working hypotheses and objectives

1.4.1 Expectations

The results of this research are expected to improve the understanding of nutrient dynamics and water utilisation in rotational woodlots. More specifically, the study aims at increasing the understanding of (i) the interactions between trees and crops at initial stages of tree growth and of (ii) the effects of tree fallows with regard to crop yields and the use of water and nutrients. This information will be helpful to determine whether the tree species planted in the rotational woodlots have any adverse environmental effects, before widespread extension to farmers in the region. The information will also be useful for choosing appropriate tree species for rotational woodlot technology.

1.4.2 Hypotheses

a. The nutrient dynamics in the rotational woodlot technology is largely determined by the quality and quantity of biomass produced by the specific tree species.
b. Water use in rotational woodlots is greater in Australian acacias than in *Leucaena* and *Senna* tree species.
c. Soil water dynamics is a critical factor in nutrient use of rotational woodlots.
d. The effects of trees on soil fertility can be translated into quantities of nutrients and improvement of nutrient use efficiency.

1.4.3 Main and specific objectives

The overall objective of this research is to improve the understanding of tree-soil-crop interactions in an agroforestry system by examining water and nutrients dynamics in rotational woodlots technology. Specific objectives of this project are:

i). To determine maize yield and the tree performance during the *establishment phase* of the woodlots.
ii). To determine soil water and nutrient dynamics of different tree species, during the *woodlot and tree-fallow phases*.
iii). To determine the *litter production, leaf quality and decomposition* patterns of different tree species in use in woodlots.
iv). To determine the tree biomass, and nutrient removal from the system with the harvested tree biomass *after fallow phase*.
v). To determine maize yield after harvest of trees and the interpretation of fallow impacts in terms of responses to application of N, P, and K fertilisers.

1.5 Choice of crop and tree species

1.5.1 Introductory remarks

Maize (*Zea mays* L.) was chosen as a test crop because it is the regional staple food crop and it is commonly intercropped in western Tanzania. The most promising trees species tested for reforestation programme in most semi-arid tropics have been fast-growing exotics. In this study I used *Acacia* and *Leucaena* species (N_2-fixing) and *Senna* *siamea* (non-N_2-fixing legume) which are exotic species but common plantation tree species in the tropics and which are also widely planted on farms in Tabora region. *Eucalyptus camaldulensis* (exotic non-N_2-fixing species) was planted in 2000 and evaluated in the establishment phase of rotational woodlots. The information on all these species regarding growth performance and influence on the associated maize crop is limited in semi-arid climate. A brief description follows.

1.5.2 *Acacia* and Australian *Acacia* species

Acacia is one of the most important genera of woody plants on earth (Stone 2003). Distributed in all continents, except Antarctica, acacias are dominant shrubs and trees in many tropical and subtropical habitats, particularly in semi-arid regions (Ross 1981). Acacias are commonly key species in such environments, providing food and other resources for an enormous diversity of mammals, birds and invertebrates (e.g. Kruger and McGaviv 1998; Bond and Loffell 2001). Acacias hold great promise as sustainable sources of food for humans and their domestic animals in arid and semi-arid habitats and many species are important in modern agroforestry worldwide (Midgely and Turnbull 2003). *Acacia* species have been described by Turnbull (1986) and Thomson (1994).

Acacia species are known to form symbiotic relations with VAM-endomycorrhizae, which are not much naturally available in miombo woodlands (H'gberg 1982). This makes inoculation an important issue when introducing these trees to miombo area. A study by Maghembe et al. (1994) indicated poor establishment and performance of *Acacia* species in the miombo ecozone when not inoculated by mycorrhizal fungi.

Acacia species belong to the Family: Fabaceae – Mimosoideae. Among the various *Acacia* species introduced to Tabora region, *A. crassicarpa* A. Cunn. Ex Benth. and to a less extent *A. julifera*, *A. leptocarpa* and *A. auriculiformis* constitute the major species planted on farms. These species occur naturally in the tropical lowlands of Northeastern Australia, Papua New Guinea and Eastern Indonesia (Simmons 1981). The species have been among the best in earlier trials in the study area (Karachi et al. 1997). *Acacia* species have been equally promising in several other tropical countries (Turnbull

1987, 1991; Turnbull et al. 1998). In Asia, *Acacia* species especially *A. mangium* has recently become the leading tree species in forestry plantation programs (Turnbull 1998). Characteristically, *Acacia* species are N_2-fixing legumes, robust, adaptable, and can tolerate degraded sites with low fertility (Anonymous 1983; MacDicken 1994).

1.5.3 ***Leucaena pallida*** Britton & Rose

Also *Leucaena* species belong to Family: Fabaceae – Mimosoideae. *Leucaena leucocephala* (Lam.) de Wit. has been used in agroforestry systems as alley cropping to boost productivity in areas of low soil fertility, where farmers are resource poor (Kang et al. 1990) and as feed for ruminants (e.g. Karachi 1998b). The species was a popular agroforestry tree until it was attacked by the leucaena psyllid (*Heteropsylla cubana*) pest to which other species like *L. diversifolia*, *L. esculenta* and *L. pallida* have shown some degree of tolerance (Roothaert and Paterson 1997). After rigorous evaluation of the genus *Leucaena* in Tabora region, *L. pallida* was found to be tolerant to the leucaena psyllid pest attack and to yield much biomass (Otsyina and Msangi 1995; Karachi 1998a). In my research *L. pallida* was included as a good candidate for fuel wood, as a soil quality improver and as a reference tree to which the Australian *Acacia* species can be compared.

1.5.4 ***Senna siamea*** (Lamarck) Irwin et Barneby

Senna siamea is native to south and southeast Asia. However, it has been cultivated for so long that its exact origin is unknown. It is widely planted throughout the tropics, locally naturalised, and mainly appreciated for its quality fuel-wood. In East Africa, is called mjohoro (Kiswahili). *Senna siamea* is a non-N_2-fixing leguminous tree (Family: Fabaceae - Caesalpinioideae), which is commonly found on farms and along the roadside in Tabora region. *Senna* has been widely used in alley cropping trials in West Africa (e.g. Ruhigwa etal. 1992; Tossah et al. 1999; Vanlauwe et al. 2001a; Vanlauwe et al. 2001b). Recently, it has been also introduced in the agroforestry rotational woodlot trials in western Tanzania.

Although *Senna* species has been depicted as an aggressive scavenger for nutrients due to its laterally spreading root system (Hauser 1993), Aihou et al. (1999) and Tossah et al. (1999) concluded that senna trees rely mainly on the subsoil as a source of nutrients. While Vanlauwe et al. (2001a) found only a small recovery of applied ^{15}N-urea in the senna hedgerow during intercropping with maize, Ruhigwa et al. (1992) concluded that senna would compete with the associated food crop in alley cropping systems, as most of its fine root biomass was confined to the top 20 cm of soil. Above observations clearly indicate possible interactions between soil chemical and physical conditions on the one hand and the root distribution and competitive character of senna trees on the other hand.

1.6 Outline of the thesis

In Chapter 2 the performance of tree species intercropped with maize crop in the establishment phase of the rotational woodlot technology, their competitive behaviour, and the possible duration of intercropping trees with maize crop are examined.

Chapter 3 deals with soil water and nitrogen dynamics of these trees when left fallow for two years.

Litter production, organic resource quality and decomposition patterns of leaves from different tree species planted in rotational woodlots are covered in Chapter 4.

Chapter 5 covers aspects of tree biomass, nutrient accumulation in different tree compartments and their removal by wood exportation from the system after five years of tree growth.

The effect of various cleared fallow treatments on performance of next maize and the optimum NPK fertilization following tree fallows in the form of woodlots is covered in Chapter 6.

The general discussion and conclusions of the study are given in Chapter 7.

CHAPTER 2

Rotational woodlot technology in western Tanzania: tree species and crop performance

Abstract

Growing of trees as woodlots on farms for five to seven years in rotation with crops has been considered as a potential technology to overcome the shortage of wood, which is a common problem to many parts of sub-Saharan Africa. This chapter summarizes the results of trials conducted at Tabora and Shinyanga in western Tanzania on rotational woodlots, to evaluate tree species for wood production and yields of maize grown in association with and after harvest of trees.

On acid sandy soils at Tabora, *Acacia crassicarpa* A. Cunn. ex Benth. grew fast and produced 24 to 77 Mg ha^{-1} of wood in four to five years. On alkaline Vertisols at Shinyanga, seven years old woodlots of *Acacia polyacantha* Willd. and *Leucaena leucocephala* (Lam.) de Wit. produced 71 and 89 Mg ha^{-1} of wood, respectively. Intercropping of maize between trees was possible for two years without sacrificing its yield. The first maize crop following *A. crassicarpa* woodlots gave 29 to 113% greater yield than the crop after natural fallow. *Acacia polyacantha* and *L. leucocephala* woodlots also increased the subsequent maize yields over a three-year period. The increase in crop yields after woodlots was attributed partly to accumulation of greater amounts of inorganic N in the topsoil compared to the traditional fallow, and partly to other effects. Thus rotational woodlots are likely to contribute to meet food and wood requirements of rural people and thereby help protect the natural woodlands in sub-Saharan Africa.

Key words: Biomass, Deforestation, Fuel wood, Land degradation, Inorganic N, Soil fertility

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2.1 Introduction

Many regions in Africa are presently facing severe shortages of fuel wood, fodder and food, primarily due to increasing human and livestock populations and crop production using little or no external inputs (FAO 2003; Sanchez 2002). Farmers are forced to extend cultivation to marginal and erosion-prone soils and to encroach forests (Abbot and Homewood 1999). In most parts of sub-Saharan Africa, the traditional long duration fallows and shifting cultivation, which helped to replenish soil fertility to some extent, are no longer possible. The situation in western Tanzania is no exception. Deforestation exacerbated by excessive grazing, shifting cultivation at short intervals and uncontrolled cutting of trees has led to increased scarcity of fuel wood for household and industrial uses. Farmers are experiencing a steady decline in soil fertility and crop productivity because of the poor farming methods and insufficient use of fertilizers. The average population growth of 3.5% per annum by far exceeds the agricultural growth rate (PHC 2003). Thus there is a need for re-introduction of trees and shrubs into existing croplands and grazing areas and their systematic management to obtain fuel wood, building poles and fodder, and to address land degradation problems (Chidumayo 1988).

One of the agroforestry technologies identified to address some of the above stated household and land use problems is that of rotational woodlots. Woodlots are sole stands of trees planted on farms, community lands or degraded lands to produce wood for fuel, construction material and pulp, and land for rehabilitation. Over the past two decades, woodlots have become popular among development agencies in Africa as a means of improving firewood supply to rural communities and income generation for households (Ramadhani et al. 2002). Woodlots have also become important in other parts of Africa (Kanmegne and Degrande 2002), Southeast Asia (Garrity 1997), South Asia (Zoysa et al. 2001) and China (Yin and Hyde 2000) to produce wood, fodder, replenish soil fertility, rehabilitate degraded soils and/or to eradicate perennial weeds.

Several communal woodlots were established in Africa through mass mobilisation of farmers and local organisations, especially women and youth groups. Tree species planted include *Azadirachta indica, Albizia lebbeck, Eucalyptus* species, *Senna siamea, Senna spectabilis,* and *Tectona grandis*. Although some of the tree plantings developed into mature woodlots, farmers still have problems in managing and utilising them on a sustainable basis. This has led to gradual degradation of woodlots and subsequent disinterest among farmers.

Rotational woodlot technology involves growing of trees and crops on farms in three inter-related phases: 1) an initial tree establishment phase in which trees are intercropped with crops, 2) a tree fallow phase, and 3) a cropping phase after harvest of trees (Figure 2.1). Each of these phases can be managed specifically to provide products and services of economic, social and environmental value. The first phase simulates the 'Taungya' system of establishing forest plantations (Chamshama et al. 1992). During this phase, trees benefit from land preparation, weeding and other management operations executed for annual crops. Cropping is discontinued when tree roots and canopy are fully developed and no longer permit economic yields.

During the tree fallow phase, which may last for two to four years, the trees could be managed as 'ngitili' (Mlenge 2002) or fodder banks. The 'ngitili' is a customary Sukuma land use system in Mwanza, Shinyanga and Tabora regions of Tanzania where designated areas are enclosed for natural regeneration of vegetation for livestock sustenance. After harvesting the trees, crops can be grown between the tree stumps exploiting the ameliorated soil conditions. The coppice shoots of tree stumps may be pruned to reduce competition to the food crops and incorporated into the soil or taken out for use as fodder. When crop yields are no longer economic, the coppice shoots may be allowed to grow for another cycle of tree fallow phase.

Research on rotational woodlots in Tabora region was started in 1988–89 at the Tumbi Agricultural Research Institute and in Shinyanga in 1991–92 at Lubaga Field Station of the International Centre for Research in Agroforestry (ICRAF). Preliminary trials in the Tabora region identified four Australian acacias (*A. crassicarpa* A. Cunn. ex Benth., *A. leptocarpa* A. Cunn. ex Benth., *A. auriculiformis* and *A. julifera* Benth.) as promising for fuel wood production (Karachi et al. 1997). Few trials have examined the combined growth of trees and crop yields in association with trees and after their harvest under different soil conditions. As the landscape in western Tanzania is undulating, the landscape position may have an influence on tree performance and consequently on soil fertility improvement. This chapter describes the results of experiments conducted to evaluate the biophysical performance of woodlots using different tree species at Tabora and Shinyanga, which represent two contrasting agro-climates in western Tanzania.

2.2 Materials and methods

2.2.1 Study areas

Tabora has a warm climate with temperatures ranging from a minimum of 13.6° C in June/July to a mean maximum of 32.5° C in October just before the onset of rainy season. It receives an annual average rainfall of 928 mm mostly in one season between November and April (Nyadzi et al. 2003). Soils are oxic Haplustalfs with 80 to 90% sand, slightly acidic (pH in water 5.7 to 6.1), low in organic carbon (4 to 8 g kg^{-1}), total nitrogen (0.1 to 0.3 g kg^{-1}), low to medium in Olsen extractable P (3 to 12 mg kg^{-1}) and low in exchangeable bases (Nyadzi et al. 2003). Shinyanga receives an average annual rainfall of 700 mm. The mean monthly temperatures range between 27.6 °C and 30.2 °C. Soils are mainly calcic Vertisols (calcareous at 80 to 100 cm depth) with a sandy clay loam texture, alkaline (pH in water 7.5 to 8.3), rather high in organic C (14 to 22 g kg^{-1}) and total N (1.2 to 1.6 g kg^{-1}), but low to medium in Olsen extractable P (2 to 10 mg kg^{-1}) and medium in exchangeable bases (Banzi F.M. unpublished data). Therefore, soils in Shinyanga are more fertile than in Tabora.

2.2.2 Trial 1: Tree species and crop performance at Tabora

This experiment was set up at Tumbi Research Station in December 1996 in a randomized complete block design with three replicates. The treatments included five woodlots of different tree species (*Acacia crassicarpa, A. julifera, A. leptocarpa, Leucaena pallida* Britton & Rose, and *Senna siamea* Lam.), natural fallow and sole maize (*Zea mays* L. var. Kilima). The plots were 16 m by 20 m. The trees were planted using 8-week old seedlings at a spacing of 4 m by 4 m (625 trees ha^{-1}). They were intercropped with maize during the first three years after planting (1996 to 1999).

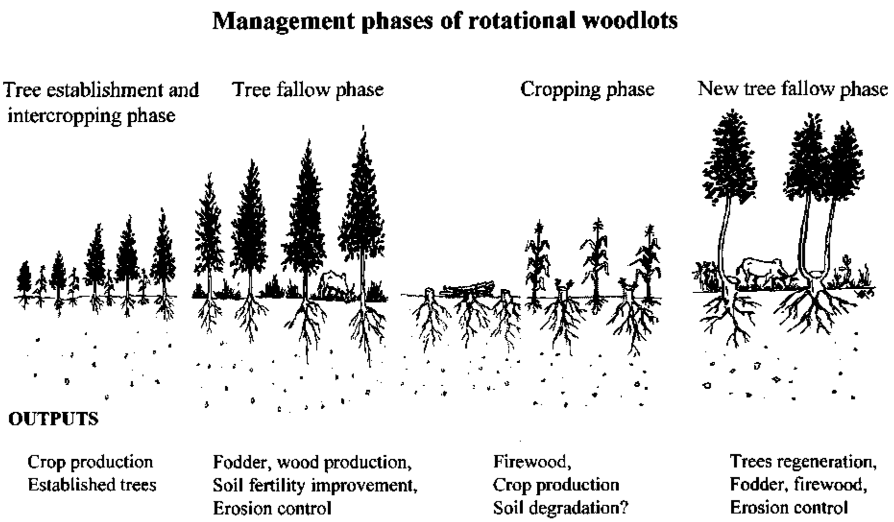


Figure 2.1. Successive phases of the rotational woodlots technology being tested in north-western Tanzania. The approximate length of each phase is 2-3 years.

Maize was planted on ridges at 1.0 m spacing between rows and 0.25 m between plants within the rows. In the first year, maize received fertilizer at the recommended rates of 100, 17 and 33 kg ha^{-1} of N, P and K in the form of urea, triple superphosphate and muriate of potash, respectively. In the subsequent two years, only 50 kg N ha^{-1} was applied, in the form of urea. During the rainy season, all plots except natural fallow were weeded two or three times depending on the need.

Trees were measured at 2.25, 4 and 5 years after transplanting in the field for height, root collar diameter (RCD, measured at 0.1 m above the ground), crown diameter (CD) and diameter at breast height (DBH, at 1.3 m above the ground). At 2.25 years, RCD, height and CD were measured; at 4 years height, RCD and DBH were measured; at 5 years tree survival, height, DBH and biomass were measured. Crown diameter was measured at the widest canopy spread and the axis perpendicular to it and mean of these values are reported. The observations were taken on six trees in a net area of 8 x 12 m in the centre of each plot. Plant height was measured from the ground level to the highest point of the tree using a graduated pole. Diameters at 0.1 and 1.3 m above the ground level were measured using callipers. For species with multiple stems, diameters of all the stems were measured and mean diameter was calculated. Maize grain yields were estimated in each cropping season by harvesting the crop from an area of 16 m x 13 m (208 m^2).

At the beginning of November 2001 when trees were approximately five years old, three trees were cut from each net plot for destructive sampling. The sampled trees were separated into stems, branches, twigs and leaves and their fresh weights were taken. Sub-samples of stems, branches, twigs and leaves were dried at 70 °C for 72 hours to determine oven dry weight. All the remaining trees in each plot were clear-cut to allow land preparation and growing of maize. The wood component (stem and branches) was removed from the plots while leaves, twigs and grass species were incorporated into the soil and ridges were formed using hand hoes. In the case of natural fallow, the same procedure was followed making sure that all the vegetation was properly incorporated into the ridges. Thereafter maize was grown in all plots. In each plot three levels each of N, P and K were superimposed, but yields averaged over the unfertilised treatments are reported only in this chapter, while the detailed descriptions are given in Chapter 6.

2.2.3 Trial 2: Effect of slope position on A. crassicarpa *performance in Tabora*

These trials were established in 1994 and 1995 on farms at Isikizya village in Tabora region. Six farms were selected, two at each the valley bottom, middle and upper slopes of the landscape. The selected farms were previously under tobacco production, which are normally fertilized with 45 kg N, 66 kg P and 113 kg K ha^{-1} per year. The initial site characterization using methods described by Anderson and Ingram (1993), indicated that all soils were acidic (pH 4.7 to 4.9) with low levels of N (0.4 to 0.6 g kg^{-1}) and CEC (3.86 to 4.67 $cmol_c(+)$ kg^{-1}), high levels of Olsen extractable P (25 to 34 mg kg^{-1}) and medium levels of organic C (5.1 to 13.1 g kg^{-1}). The trials were designed by researchers and managed by farmers in terms of all field operations. The woodlots were established using 3-month-old seedlings at 4 x 4 m spacing. The trial at the valley bottom was established in 1994, and those at the other sites in 1995. A natural grass/herb fallow adjacent to each field was cleared and left to rejuvenate naturally at the time of establishing woodlots at the respective farms. Maize was grown as an intercrop at a spacing of 0.25 x 1 m during the first two years of the trees. Thereafter, the woodlots were left to grow for another two or three years as pure woodlots.

The woodlots were cleared in 1999 over an area of 25 x 25 m at each farm and the land was cultivated using hand-hoes for cropping maize. Nine trees from an area of 12 × 12 m at the centre of each plot were sampled for biomass estimation. All components of the tree (stem, branches, twigs and leaves) were weighed green. Sub-samples of each component were dried at 70 °C for 72 hours to determine oven-dry weights. Wood was removed from the field, but tree leaves and litter in woodlot treatments and biomass of natural fallow were incorporated into the soil and ridges were formed. Natural fallow plots were also prepared simultaneously by incorporating the natural vegetation into the soil for growing maize. Each plot was split into three subplots of 8 x 8 m to test three fertilizer treatments: (1) 100 kg N ha^{-1} (recommended rate) as urea applied in two split applications, (2) 50 kg N ha^{-1} applied at one time, and (3) no N. Phosphorus and potassium were applied at an uniform rate of 20 kg P and K ha^{-1} each in the form of triple superphosphate and muriate of potash, respectively. Maize was harvested from the central six rows in each subplot and grain yield was expressed at 13% water content.

2.2.4 Trial 3: Tree species and crop performance at Shinyanga

This study evaluated three different tree species (*Leucaena leucocephala* (Lam.) de Wit, *Acacia polyacantha* Willd. and *Acacia nilotica* (L.) Del.) and a control (no woodlot) in a randomized complete block design replicated four times in plots of 24 m by 33 m. The trees were planted on 4 January 1992 using 3-month old seedlings at a spacing of 3 m by 4 m (833 trees ha^{-1}). An area of 16 x 27 m containing 36 trees excluding borders on all sides was treated as the net plot. Maize (var. Kilima) was grown during the first three years of the study as an intercrop between trees and as a sole crop in the control. No fertilizer was applied to maize. Field operations were executed in the same manner as described for the trials in Tabora. Maize grain yields in each cropping season were estimated by harvesting 5.4 x 7.5 m area in the centre of each plot. After three years the trees were left to grow as pure woodlots and the no-tree treatment as a natural fallow. When the trees were three years old, they were pruned on one-half of the net plot (18 trees) and sampled to determine the wood and twig biomass.

The woodlots and natural fallow were harvested in October 1998 when trees were six years and ten months old in the field (for simplicity referred as seven years old). Six randomly chosen trees from pruned and un-pruned halves of each plot were sampled for biomass estimation. The harvested material was separated into wood, foliage and twig components and weighed immediately. Sub-samples of stems and twigs were dried at 70 ^{0}C for 72 h and dry weights determined. After the harvest of trees and fallow vegetation, maize was grown across all treatments for three years, following the same management as described earlier, to test the residual effects of treatments. At the beginning of each rainy season, soil samples were taken from the top 0 to 30 cm soil horizon at six locations within each plot and a composite sample was prepared. The samples were analysed for inorganic nitrogen following the procedures described by Anderson and Ingram (1993).

2.2.5 Statistical analyses

All data were subjected to analyses of variance (ANOVA). If the '*F*' test indicated significant effects, treatment means were compared based on an *LSD* at $P \leq 0.05$. In Trial 1, yields of maize intercropped with trees in the third year were not normally distributed, so they were transformed to $\log_{10}$ before subjecting to ANOVA. Treatments were compared on means of transformed data based on an *LSD* at $P \leq 0.05$.

2.3 Results

2.3.1 Trial 1: Tree species and crop performance at Tabora

Tree species did not differ significantly in height and crown diameter at 2.25 years after planting in the field; they attained an average height of 4.3 m and a crown diameter of 3.6 m at this stage (Table 2.1). Crown size determines the potential for shading by tree species. *Senna siamea* had the largest crown at 2.25 years (Table 2.1). Although the trees were planted at 4 m apart, branches of all species except those of *A. julifera* nearly covered the alley space by 2.25 years eliminating the possibility for intercropping with maize beyond this age. *Senna siamea* had the thickest and *L. pallida* the thinnest stems.

Table 2.1. Growth of five tree species in woodlots measured at different periods after planting at Tabora, Tanzania.

Species	2.25 years			4 years			5 years				
	HT (m)	RCD (cm)	CD (m)	HT (m)	RCD (cm)	DBH (cm)	Survival (%)	HT (m)	DBH (cm)	Wood ($Mg\ ha^{-1}$)	Total biomass ($Mg\ ha^{-1}$)
Acacia crassicarpa	5.0	9.2 ab	3.5	7.7 a	18.6 a	10.2 a	53.3 b	10.5 a	15.7 a	35.4 ab	52.8 a
A. julifera	3.7	7.5 b	2.9	5.5 bc	14.9 b	7.9 b	66.7 b	6.7 b	9.9 b	20.5 bc	31.7 b
A. leptocarpa	3.8	8.7 ab	3.7	5.6 bc	15.1 b	5.9 c	65.0 b	7.3 b	7.6 bc	40.9 a	57.6 a
Senna siamea	4.5	10.4 a	4.3	5.9 b	14.8 b	6.0 c	98.3 a	5.9 b	7.4 bc	22.1 bc	29.8 b
Leucaena pallida	4.3	4.8 c	3.7	4.9 c	6.8 c	4.3 d	88.3 a	5.6 b	5.1 c	9.6 c	26.0 b
SED	0.47	0.76	0.56	0.38	1.30	0.72	8.87	0.74	1.46	6.14	9.36
F probability	0.13	< 0.01	0.22	< 0.01	< 0.01	< 0.01	<0.01	<0.01	<0.01	<0.01	<0.01

SED = standard error of difference between means. Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$. HT = height, RCD = root collar diameter, DBH = diameter at breast height, and CD = crown diameter.

Differences between species were apparent by four years after planting. *Acacia crassicarpa* was the fastest growing and *L. pallida* the slowest growing among all the species examined (Table 2.1). At the age of four years, *A. crassicarpa* attained a height of 7.7 m, root collar diameter of 18.6 cm and DBH of 10.2 cm. Although *A. julifera* was comparable to *A. leptocarpa* and *S. siamea* in height and root collar diameter, it had significantly thicker stems than the other two. At five years after planting, the *Acacia* species had lower survival rates (in the range of 53 to 67%) compared to *S. siamea* (98%) and *L. pallida* (88%). Obviously, the latter two species were more tolerant to acid soils and less susceptible to termite attack than others. *Acacia crassicarpa* attained the greatest height and DBH, but it did not differ significantly from *A. leptocarpa* for total aboveground biomass. *Acacia leptocarpa* and *A. crassicarpa* produced similar quantity of wood at 41 and 35 Mg ha^{-1} respectively, while *L. pallida* produced the lowest quantity of wood at 10 Mg ha^{-1}.

Maize intercropped with different tree species produced similar yields as sole maize in the first two years after planting the trees, but it produced significantly less yield than sole maize in the third year (Figure 2.2). Maize yields in the second year were greater than in the first year because of less water stress, as rainfall was two times higher in the second year. Woodlots and natural fallow significantly affected the yields of maize grown subsequent to their harvest (Figure 2.2). There were no significant differences among the *Acacia* species in their residual effect on subsequent maize yields, but *A. crassicarpa* had resulted in significantly greater maize yield than *S. siamea*, *L. pallida*, natural fallow and continuous maize systems. The yields after the three *Acacia* species were 33% to 149% greater than the yield after the natural fallow and 88% to 248% greater than the yield of continuous maize.

2.3.2 Trial 2: Effect of slope position on A. crassicarpa *and crop performance on-farms*

Acacia crassicarpa showed remarkably good growth at the age of 4 to 5 years on farms with heights ranging from 11.3 to 15.7 m and DBH from 14.7 cm to 21.5 cm (Table 2.2). The growth on farms was 1.5 to 2 times of that at the research station. Trees at lower and middle parts of the landscape grew significantly better than at the upper part, but it should be kept in mind that trees in the lower position were planted one year earlier.

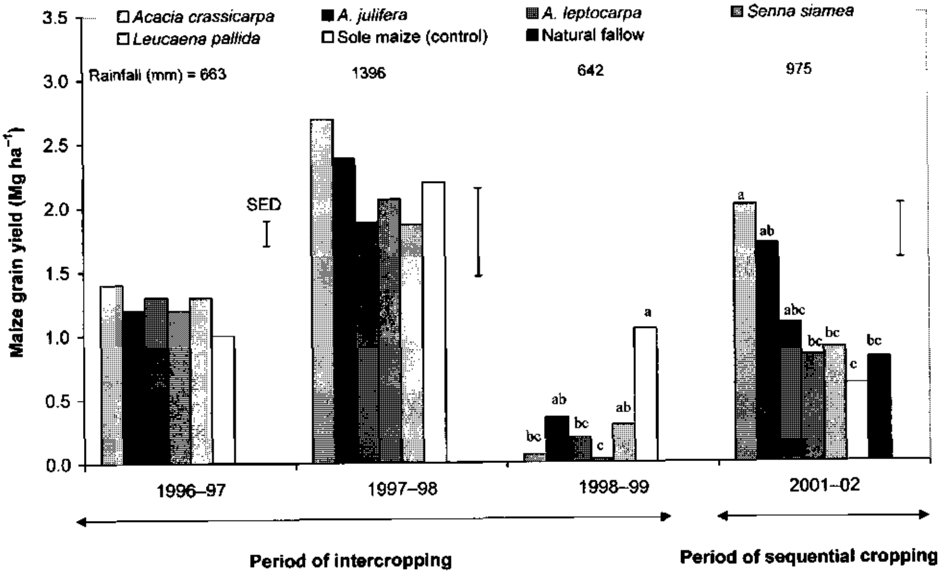


Figure 2.2. Grain yields of maize intercropped between trees during the first three years of woodlots and after harvest of woodlots at Tabora, Tanzania. Bars with the same letters within a season are not significantly different. Vertical lines are the standard error of difference between treatment means (±*SED*) in the respective years.

Table 2.2. Growth characteristics of *Acacia crassicarpa* in 4- or 5-year old woodlots planted on-farms at different slope position at Isikizya, Tabora, Tanzania.

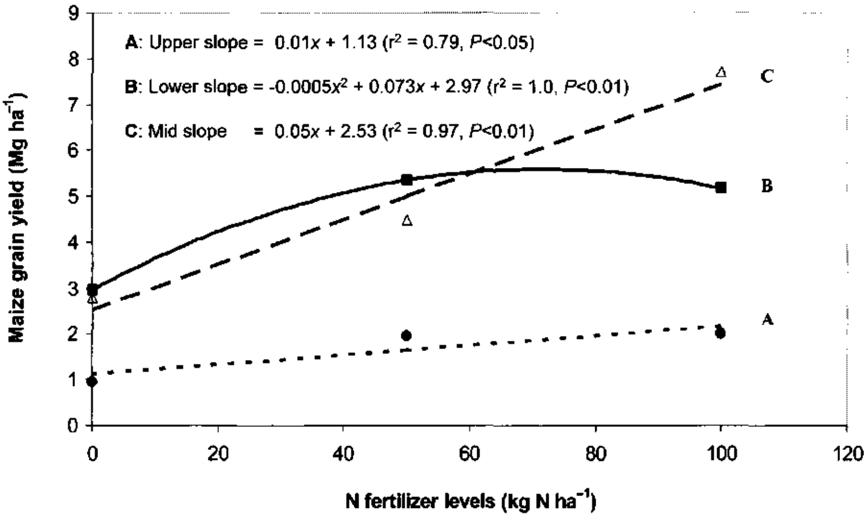
Landscape position	Age (years)	Height (m)	DBH (cm)	Wood (Mg ha^{-1})	Total biomass (Mg ha^{-1})
Lower	5	15.7	17.9	56.4	71.0
Middle	4	14.3	21.5	77.4	95.8
Upper	4	11.3	14.7	24.3	31.4
SED		0.59	1.31	11.52	15.5

SED = standard error of difference between means, and DBH = diameter at breast height.

Trees on the middle slopes produced nearly three times as much wood and total biomass as trees on the upper slopes. The decrease in tree growth from lower to upper slopes was probably due to an increase in the depth of the groundwater table and in soil degradation. Differences in soil characteristics, especially water holding capacity, and tree management by farmers might also have contributed to differences in tree growth across the landscape.

Yields of maize grown after *A. crassicarpa* woodlot were greater than those after natural fallow (Figure 2.3). The average yield increases ranged from 30% at the upper slope to 113% on farms at the lower landscape. Maize following woodlot and natural fallow responded to N application but generally less at the upper slope than at the other slope positions. The response was linear at the middle and upper slopes, and curvilinear at the lower slopes, after woodlot as well as after natural fallow. Application of the first 50 kg N ha^{-1} to maize following *A. crassicarpa* increased yields by 60 to 103% but the next 50 kg N ha^{-1} resulted in only -3 to 73% increases. In contrast, application of the first 50 kg N ha^{-1} to maize following natural fallow increased yields by 118 to 454% and the next 50 kg N ha^{-1} resulted in 1 to 68% increases. The residual effect of 4- to 5-year-old woodlots was equivalent to 25 to 65 kg N ha^{-1} at different landscape positions (Figure 2.3).

(a) After woodlot



(b) After natural fallow

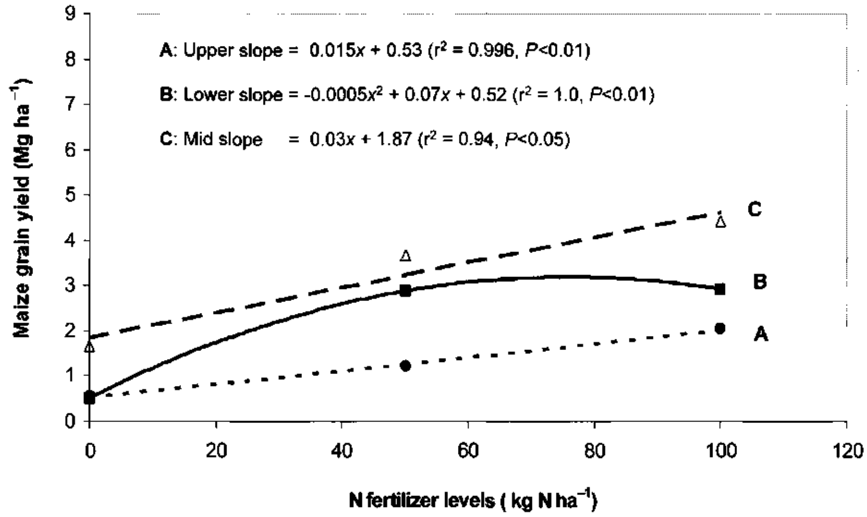


Figure 2.3. Grain yields of maize grown at different landscape positions with different rates of N application after harvest of (a) *Acacia crassicarpa* woodlot and (b) on natural fallow at Tabora, Tanzania.

Table 2.3. Growth and biomass of three tree species planted as woodlots at the age of three and seven years at Shinyanga, Tanzania.

Woodlot species	3 years		7 years		
	Survival (%)	Biomass (Mg ha^{-1})	Height (m)	Wood (Mg ha^{-1})	
				Un-pruned	Pruned
Acacia nilotica	78	2.5	3.9	8.4	6.0
Acacia polyacantha	76	7.8	5.8	70.9	49.7
Leuceana leucocephala	80	15.4	7.7	88.9	34.6
SED	7.2	1.34	0.64	23.5	-

SED = standard error of difference between means.

2.3.3 Trial 3: Tree species and crop performance at Shinyanga

Survival of all three tree species was good (Table 2.3). *Leucaena leucocephala* was the fastest growing species and *A. nilotica* the slowest growing. At the age of seven years and for trees that were not subjected to pruning earlier, *L. leucocephala* woodlot produced 89 Mg ha^{-1} of wood compared to only 8 Mg ha^{-1} by *A. nilotica* (Table 2.3). When trees were pruned at three years after planting, wood production was 39% of the un-pruned trees in the case of *L. leucocephala* and around 70% in the case of *A. polyacantha* and *A. nilotica*.

Yields of maize in association with trees in the first two years were similar to that of sole maize (Figure 2.4), but they were only about 50% of sole maize yield in the third year. Maize following woodlots generally produced greater yields than maize after natural fallow during the three consecutive seasons (Figure 2.4). Yield increases caused by *A. polyacantha* and *L. leucocephala* woodlots over the natural fallow were significant in the first two years. However, the three tree species exercised similar effects on maize in the third year. There was a general decrease in yields from the first to the third crop, probably due to decline in soil nutrient status. There was greater amount of inorganic N accumulated in the top 0 to 30 cm soil horizon under woodlots than under natural fallow (Figure 2.5). The tree species did not differ much in soil inorganic N. The inorganic N content declined from the first cropping year after woodlot to the third year.

2.4 Discussion

Tree growth measured in terms of height and diameter indicates the adaptation of the species in any particular environment (Cannell 1984). Based on these parameters, *A. crassicarpa* and *A. julifera* were well adapted for Tabora, while *L. leucocephala* and *A. polyacantha* were well adapted for Shinyanga.

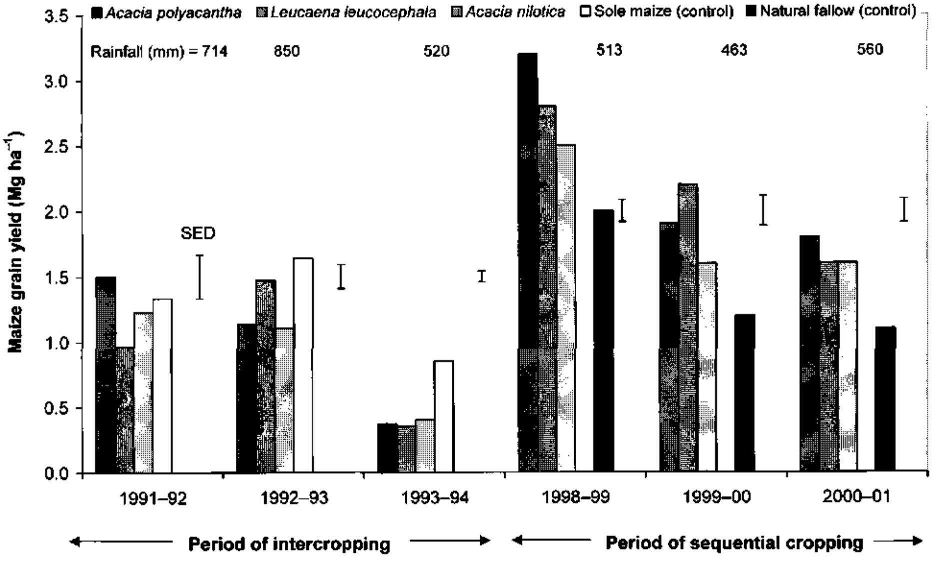


Figure 2.4. Grain yields of maize intercropped between trees during the first three years of woodlots and after clearing woodlots at Shinyanga, Tanzania. Vertical lines are the standard errors of difference between treatment means (±*SED*) in the respective years.

Ngulube et al. (1993) identified the Australian dry zone species *A. auriculiformis*, *A. crassicarpa*, *A. holosericea* and *A. leptocarpa* as the most promising tree species for dry land areas in Malawi. Although we did not test all these species in both the regions, unpublished data indicate that Australian acacias do not grow well in the alkaline soils of Shinyanga.

The biomass production by *Acacia* species at Tabora was similar to that at other sites having comparable rainfall (Thomson 1994). Wood yield of 77 Mg ha^{-1} observed for *A. crassicarpa* on farms at middle slopes is comparable to 84 Mg ha^{-1} produced by a 5-year old planting in southwestern Papua New Guinea where this species occurs naturally (Kiratiprayoon and Williams 1991). Wood obtained from one hectare of unpruned seven years old woodlots of *A. polyacantha* and *L. leucocephala* in the present study is likely to meet the fuel wood requirements of an 8-member family for 12.2 and 15.2 years, respectively, assuming an average fuel wood consumption of 2 kg per person per day (Abbot and Homewood 1999). Our study, therefore, indicates that pressure on forests and natural woodlands can be minimized with the establishment of woodlots on farms. However, they may not be possible in places where population density is high, land is limited and climatic conditions are severe.

Lower yields of maize intercropped with trees compared to sole maize crop in the third year were due to shading of the crop by trees and their competition with crops for water. Maize being a C_4 plant is light sensitive and as the trees were not pruned shading by trees increased over the years, which was evident from the spread of tree canopies across rows. Crop yield reduction under tree canopies progressively increases with age of the trees (Rao et al. 1997).

The increase of soil inorganic N under woodlots over that in natural fallow was probably due to nutrients added through litter fall of trees over the years and their foliage returned to soil at the time of harvest. Many studies have reported improvement in soil fertility underneath the canopies of individual trees (Rao et al. 1997) and woodlots (Jonsson et al. 1996).

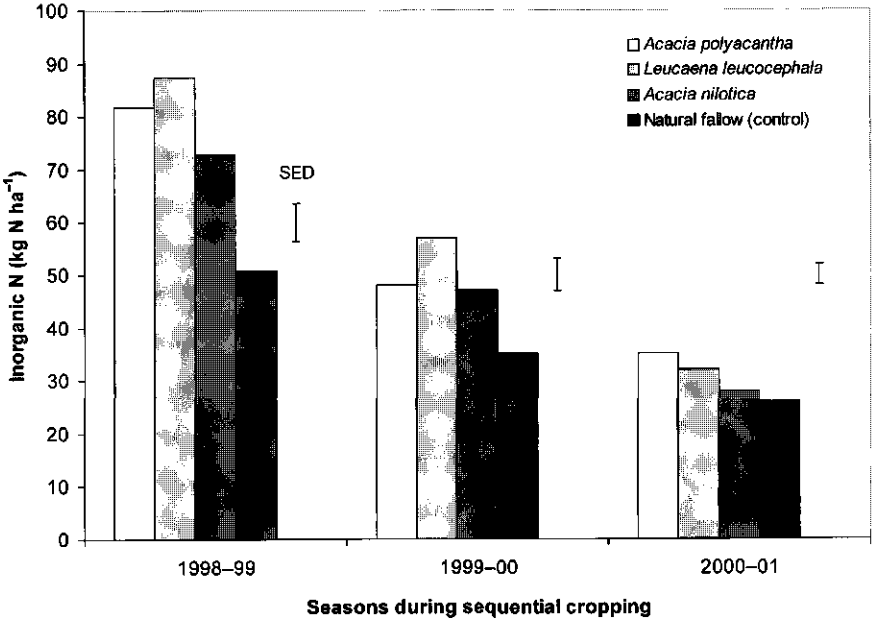


Figure 2.5. Total inorganic nitrogen in the 0 to 30 cm soil horizon at the start of the rainy season in three consecutive years following the harvest of woodlots of three species at Shinyanga, Tanzania. Vertical lines are the standard errors of difference between treatment means (±*SED*) in the respective years.

Generally, trees that grow fast, produce high amount of biomass, fix greater quantities of biological nitrogen and retrieve nutrients from deep soil horizons, are likely to have greater positive effect on soil improvement compared to trees that grow slowly, produce small amount of biomass and do not fix nitrogen (Jonsson et al. 1996; Oliver et al. 2000). For short rotation plantations, the use of N_2-fixing trees is important when attempting to achieve soil fertility replenishment in addition to wood production (Szott et al. 1999).

Increased maize yields following woodlots were probably due to greater amounts of inorganic N that the trees have brought out in the topsoil. Greater maize yields following woodlots of Australian *Acacia* species, *A. polyacantha* and *L. leucocephala* compared to other woodlots in the present studies was because of greater accumulation of inorganic N under these woodlots. The positive residual effect of woodlots on the following crops lasted for only two years as probably the nutrients were used up by the crops and or were lost by leaching. N'Goran et al. (2002) reported that maize yields following six-year old woodlots of *Acacia auriculiformis*, *A. mangium*, and *L. leucocephala* in the humid zone gradually decreased over a period of four years.

Maize yields after natural fallow, even with N fertilizer application, were not comparable to those after woodlots, which suggests that woodlots may have benefited the crop through other mechanisms than increased N supply. The other benefits could be enhanced availability of P, K, and other nutrients (Szott et al. 1999) and improved soil physical properties and consequently soil water status (Rao et al. 1997). Lower residual effect of woodlots at the upper slope indicates that soil at this position was more nutrient-depleted and/or degraded than at the mid and bottom slopes of the landscape.

2.5 Conclusions

Rotational woodlots using fast growing and N_2-fixing tree species such as *A. crassicarpa, A. leptocarpa, L. Leucocephala,* and *A. polyacantha* have the potential to produce 40 to 90 Mg ha^{-1} of fuel wood in five to seven years.

Whereas Australian *Acacia* species are well suited to the Tabora region, *L. Leucocephala,* and *A. polyacantha* are better for Shinyanga.

Food crops such as maize can be grown in association with trees for two years after planting in the field without sacrificing yields. Increased crop yields following harvest of woodlots can be realised for two to three years as a consequence of improved mineral N in the topsoil.

The benefit of *A. crassicarpa* woodlots expressed in terms of maize yield was more pronounced in mid and lower slope positions than at upper slopes.

Evidently, rotational woodlots have the potential to meet the local domestic and industrial wood needs, thereby decreasing deforestation, and at the same time have the advantage of increasing food crop production.

2.6 Acknowledgements

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CHAPTER 3

Water and nitrogen dynamics in rotational woodlots in western Tanzania

Abstract

The objective of this study was to examine soil water and nitrogen dynamics throughout the year in five rotational woodlot fallows, natural fallow and continuous maize (*Zea mays* L.) treatments in western Tanzania. The tree species evaluated were *Acacia crassicarpa* (A. Cunn. ex Benth.), *Acacia julifera* (Berth.), *Acacia leptocarpa* (A. Cunn. ex Benth), *Leucaena pallida* (Britton and Rose), and *Senna siamea* (Lamarck) Irwin & Barneby). The field trial was established in November 1996 in a completely randomized block design replicated three times. Maize was intercropped between the trees during the first three years after planting and thereafter the trees were allowed to grow as pure woodlots for another two years. Transpiration by the trees was monitored when they were 3 years old using sap flow gauges. Soil water content was measured using the neutron probe approach between November 1999 and March 2001. Soil inorganic N profiles were measured when the trees were four years old in all treatments.

The results indicated that the trees transpired more water than natural fallow vegetation during the dry season. Differences in soil water content were most pronounced in deeper soil horizons. In the dry period, the water content in the entire soil profile under woodlots and natural fallow was 0.01 to 0.06 $cm^3\ cm^{-3}$ lower than in the annually cropped plots. This pattern was reversed after rainfall, when woodlots of *A. crassicarpa*, A. *leptocarpa*, *A. julifera, S. siamea* and *L. pallida* stored more water than natural fallow or continuous maize by as much as 0.00 to 0.02, 0.01 to 0.04, 0.01 to 0.04, 0.01 to 0.03 and 0.00 to 0.02 $cm^3\ cm^{-3}$ respectively. Natural fallow plots had the lowest quantity of water in the soil during this period. Transpiration was greatest in *A. crassicarpa* and least in *L. pallida*. All tree species examined were 'scavengers' of N and retrieved inorganic N from soil horizons up to 2-m depth and increased the amount of N close to their trunks.

This study has provided evidence that woodlots can effectively retrieve subsoil N and store more soil water after rains than natural fallow and bare soil in semi-arid environments.

Key words: *Acacia, Leucaena, Senna,* Soil nitrogen, Soil water, Transpiration

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3.1 Introduction

Continuous cultivation as a result of increased population has inevitably replaced shifting cultivation and the bush fallow systems, which were traditionally practiced to regenerate soil fertility in the savanna of eastern and southern Africa. Under continuous cultivation, maintenance of soil fertility remains a daunting challenge in subsistence agriculture. It has been indicated that rotations of short-duration leguminous trees or shrubs followed by crops and biomass transfer systems may improve nutrient cycling and increase crop yields (Nair et al. 1999). The system of rotational woodlots is another promising agroforestry technology for enhancing productivity on smallholders' farms (Ramadhani et al. 2002). In this system, a 5- to 7-year-old woodlot planted with a suitable tree species is rotated with annual crops. The trees can be intercropped with food crops during the first 2 to 3 years and thereafter are left to grow as a pure tree-fallow or woodlot until harvest. After harvesting the woodlot, either food crops are grown as intercrops between the coppicing tree stumps or a new cycle is initiated by a fresh planting of trees after 2 to 3 years of cropping (Otsyina et al. 1996). The rotational woodlots provide fuel wood as substitute for the wood from natural forests, and thus contribute to the conservation of natural forest areas (Ramadhani et al. 2002).

Impressive results have been reported with rotational woodlots in which Australian *Acacia* species have been used to increase smallholders' income (Ramadhani et al. 2002). Many farmers have realized the importance of this technology for alleviating fuel wood shortage. Although farmers, research and development institutions, and other stakeholders in western Tanzania have expressed considerable enthusiasm for the woodlot technology, they also have serious concerns regarding the long-term environmental impacts. The two main concerns are that the trees may over-exploit soil water resources and that the tree litter may immobilize soil nutrients, as the case is with eucalyptus plantations. *Eucalyptus* plantations have been criticized on the grounds that they consume excessive amounts of water (Calder et al. 1992) and compete strongly with crops for this resource. Considerable studies available concerning tree water use have been done using *Grevillea robusta* based agroforestry systems on hill-slopes in semi-arid environments (Ong et al. 1999; 2000). *Acacia*, *Leucaena* and *Senna* species used in rotational woodlots in western Tanzania may also create such problems in semi-arid areas. However, there has been no measurement thus far on rotational woodlot.

Trees in agroforestry systems may increase the nutrient supply to crops by reducing nutrient losses resulting from leaching and erosion and by increasing the quantity of nutrients in the root zone (Nair et al. 1999). Trees may increase the quantity of nutrients in the root zone through biological N_2-fixation and recycling of nutrients from deep soil layers to the surface horizons. They may increase nutrient availability in the top soil following decomposition of the biomass and leaf litter added to the system and by improving soil structure and enhancing biological activity. Trees may also reduce nutrient losses by arresting soil erosion and intercepting nutrients leaching out of the crop root zone with their deep and extensive root systems (Ong et al. 1999). However, a quantitative understanding of N cycling processes is essential to be able to exploit the potential benefits and to identify possible constraints.

Tree species differ in their ability to use soil water and soil N. They also differ in their ability to modify nutrient cycling for the benefit of crops that grow simultaneously or sequentially. An understanding of the water use patterns of trees is essential for developing sustainable rotational woodlot systems. The objective of the present study was to determine the influence of different tree species on water and N dynamics in soil during the woodlot or tree-fallow phase in Tabora region, western Tanzania, where the rotational woodlot technology has great potential for adoption.

3.2 Materials and methods

3.2.1 Study area

The study was conducted at Tumbi Agricultural Research Institute (5°03'S, 32°41'E, altitude 1190 m), which is located within the miombo woodlands of western Tanzania. Long-term average annual rainfall (1958 to 2002) is 928 mm, of which 94% occurs between November and April. Mean maximum and minimum air temperatures are 28 °C and 18 °C, respectively. The soils in the study area are oxic Haplustalfs (Soil Taxonomy) or ferric Acrisols (FAO–UNESCO system). Soils are relatively deep (>1.5 m) but in certain locations have a murram layer at a depth of 50 cm. Average soil characteristics for the 0 to 15 and 15 to 30 cm soil horizons within the experimental area were as follows: pH (H_2O): 6.1 and 5.7, organic C: 5.7 and 4.7 g kg^{-1}, total N: 700 and 500 mg kg^{-1}, extractable P (Olsen): 4.6 and 2.3 mg kg^{-1}, clay: 12 and 13%, silt: 6 and 5% and sand: 82 and 82%, respectively. Exchangeable Ca, Mg and K concentrations in the 0–15 cm soil horizon were 19.0, 3.0 and 1.5 $cmol_c$ kg^{-1} soil, respectively.

3.2.2. Experimental design and establishment of trees

The experiment was set up in December 1996 as a randomized complete block design with three replications. Plot size was 16 m by 20 m. The seven treatments included five woodlots containing different tree species (*Acacia crassicarpa* A. Cunn. ex Benth., *A. julifera* Berth., *A. leptocarpa* A. Cunn. ex Benth., *Leucaena pallida* Britton & Rose, and *Senna siamea* (Lamarck) Irwin et Barneby), natural fallow and continuous sole maize (*Zea mays* L. var. Kilima).

The woodlots were established using 8-week-old seedlings planted at 4 x 4 m spacing (625 trees ha^{-1}). The young trees were intercropped with maize during the first three years (1996 to 1999). In the subsequent two years (2000 and 2001), maize was grown only in the continuous sole cropping treatment. Maize planting and harvest dates varied between seasons depending on the onset of rainfall (Figure 3.1). Maize was planted at a spacing of 0.25 x 1.00 m. In the first year, maize was fertilized with the recommended rates of 100, 18 and 33 kg ha^{-1} of N, P and K, supplied in the form of urea, triple super phosphate and muriate of potash, respectively. In the subsequent two years, only 50 kg N ha^{-1} was applied through urea, as the soil contained reasonable levels of P and K in the top 15 cm horizon. During the rainy season all plots except the natural fallow were weeded whenever necessary. After 1.5 years, a 1.5-m deep and 0.5-m wide trench was dug around each plot to prevent interference from the roots of trees in adjacent plots. This process was repeated annually.

3.2.3. Soil water measurements

Soil water content was measured at monthly intervals over a 17-month period between November 1999 and May 2001, using a Wallingford neutron probe (Bell 1987). Five aluminum 44.5 mm diameter access tubes were installed to a depth of 185 cm within the net area (six trees covering 96 m^2) of each plot. Four tubes were installed at distances of 4 m from each other and the fifth at the centre of the net plot. Soil water content was determined at 20 cm intervals between 35 and 175 cm. An access tube was fixed in the centre of a drum, which was half-filled with water, and neutron probe readings for this access tube (water-filled drum counts) were made before and after each set of field measurements. A calibration curve was established for each soil horizon through regression between the volumetric water content of undisturbed soil samples and the corresponding ratio of neutron probe counts in the field to counts in water-filled drum over a range of soil water contents.

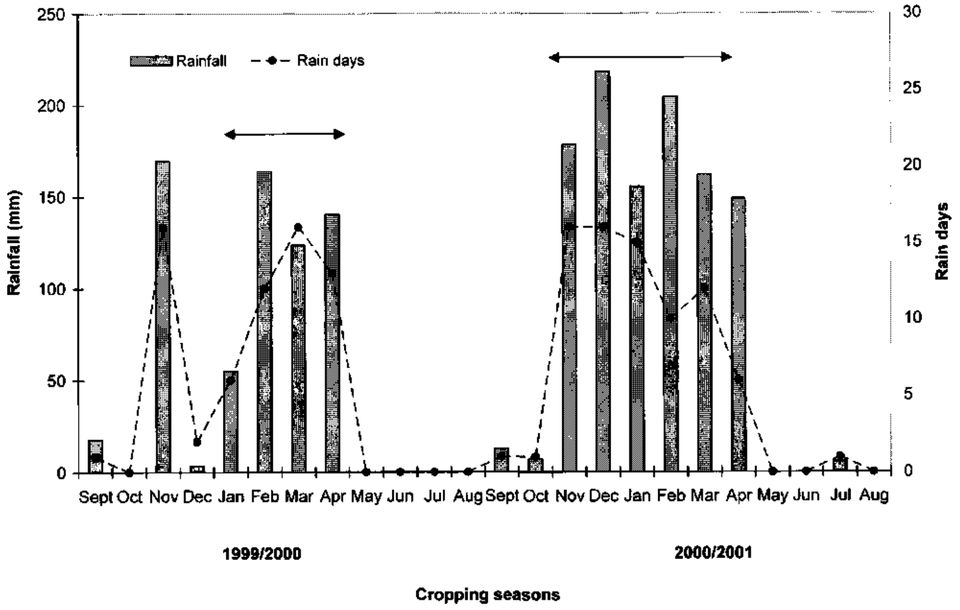


Figure 3.1. Rainfall distribution during the 1999-00 and 2000-01 cropping seasons at the experimental site in Tabora, Tanzania. Arrows indicate the period of maize cropping in the continuous sole maize plots.

The relationship between volumetric soil water and neutron probe counts is given by $y = 0.2756x + 0.0079$, ($r^2 = 0.98$, $P<0.01$), where y = volumetric soil water and x = ratio of counts in the field soil to counts in water-filled drum. This equation was used to determine soil water content of each layer based on the ratios of neutron probe counts taken in the test plots and water drum. Mean soil bulk densities for eight soil horizons measured at depths of 35, 55, 75, 95, 115, 135, 155 and 175 cm were 1.38, 1.47, 1.50, 1.49, 1.46, 1.52, 1.61 and 1.73 g cm^{-3}, respectively.

3.2.4 Transpiration measurements

Heat pulse sap flow gauges manufactured at ICRAF (Nairobi, Kenya), based on the version described by Khan and Ong (1996), were used for continuous sap flow measurements on individual trees. Measurements were done for periods not exceeding 14 days to avoid long-term damage to the stems. Probes were greased before inserting them into holes drilled radially into the trunk, correctly spaced and aligned along the trunk axis (Burgess et al. 1998). Three holes were drilled into the trunk with the help of a steel guide jig with holes pre-set at the required distances, which was held firmly in place against the trunk while the holes were drilled. The sensor probes were embedded in the trunks 5 mm upstream and 10 mm downstream from the heater probe. The sensor probes were constructed from stainless steel needles 1.3 mm in diameter and 3 cm long. The copper and constantan (a nickel and copper alloy) thermocouples were placed inside probes at distances of 0.5, 1.5 and 2.5 cm from the tip (Khan and Ong 1996). The positioning of sensors at different depths within the trunk, allowed any variation in sap flux density across its cross-section to be taken into account (Hatton et al. 1995). The diameters of the trunks at breast height (1.3 m aboveground level) were measured in two perpendicular directions at the position of gauge installation. These diameters were then used to calculate the trunk cross-sectional area for each species. The section of trunk selected for probe insertion was straight, smooth and free from structural, pest or pathogen-induced defects.

Heat pulse velocity (cm h^{-1}) was recorded at 30 minute intervals, averaged over 1 h (Swanson and Whitfield 1981) and stored in an electronic data logger (model CR 21X, Campbell Scientific, Logan, UT), before being downloaded to a laptop computer. Heat pulse velocity was converted to sap flux density (volume of sap moving in the transpiration stream per unit cross-sectional area per unit time) by multiplying sap flow velocity by the trunk cross-sectional area for each tree. Trunk cross-sectional area was calculated based on stem diameter at breast height.

Transpiration measurements for different tree species were made alternately rather than simultaneously, as only one data logger capable of monitoring nine gauges at any one time was available. Transpiration was measured during a 60 day period between October 31, 1999 and December 29, 1999 (Julian Day (JD) 304 to 363). The trees were three years old. The measurement duration differed between species due to the lack of a reliable laptop computer to download the data during the measurement period. Transpiration by *A. crassicarpa* was measured over a 25 day period (JD 304 to 328), *S. siamea* for 10 days (JD 330 to 339), *L. pallida* for 10 days (JD 345 to 354), *A. julifera* for 5 days (JD 354 to 358) and *A. leptocarpa* for 6 days (JD 358 to 363).

Due to the predominantly diurnal pattern of sap flow (Jara et al. 1998), only daytime observations, i.e. between 06.00 am and 19.30 p.m. (EAT) were used for sap flow analysis. Cumulative water uptake was calculated for all tree species.

3.2.5 Soil sampling and analysis

Samples were taken in December 2000 from the 0 to 15, 15 to 30 and 30 to 50 cm horizons at five sampling locations within each plot. Total inorganic N content and pH were measured in composite samples prepared for each horizon within all plots. To investigate N dynamics, field-moist soil samples were collected from four year old woodlots on two occasions; the first sampling was done at the end of the dry season in October 2000 and the second six weeks after the first rains in December 2000.

To minimize sample variability and provide a better representation of variation with distance around individual trees, the area around trees within the net plot was divided into four concentric zones (Figure 3.2). Zone A (2.217 m^2) was located within a 0.84 m radius of the trunk, zone B (3.092 m^2) was situated between 0.84 and 1.30 m, zone C (4.422 m^2) was between 1.30 and 1.76 m, while zone D (6.269 m^2) extended from 1.76 m radius to the edge of the 4 x 4 m^2 net plot area. The areas of these zones progressively increased by a factor of $\sqrt{2}$: 1.000, 1.414, 2.000 and 2.828, and represented

14, 19, 28 and 39%, respectively, of the total 16 m^2 net plot area. Four samples were taken from each zone within the concentric rings from the following horizons: 0 to 15, 15 to 30, 30 to 50, 50 to 100, 100 to 150 and 150 to 200 cm. Pooled samples were prepared for each depth within each zone of treatment plot.

The field-moist soil samples were placed in a cool box with ice immediately after collection to minimize N mineralisation and subsequently kept in a refrigerator at 4 °C prior to analysis within five days. The soil water content of the field-moist soil was determined at the time of extraction in order to calculate the oven-dry weight of extracted soil. Inorganic N was extracted from soil using 2 M KCl in a 1 soil : 5 KCl (w/w) ratio. Ammonium-N concentration in the extract was determined using a colorimetric method (Anderson and Ingram 1993). Nitrate (NO_3) plus nitrite (NO_2) N was determined by cadmium reduction, with subsequent colorimetric determination of NO_2 (Anderson and Ingram 1993). No effort was made to separate NO_3 and NO_2, as the NO_2 concentration was likely to be small relative to NO_3, and the values are reported as NO_3 for the sake of simplicity. All other analyses were done according to Anderson and Ingram (1993).

3.2.6 Statistical analysis

All data were tested for normality before subjecting to analysis of variance (ANOVA). As the data for NH_4 and NO_3 were not normally distributed, they were transformed to a $\log_{10}$ scale using the linear model procedure of the GenStat® program (Payne et al. 2002). The transformed data were then subjected to 2 or 3-way ANOVA depending on the number of factors involved. Treatment means based on untransformed data are reported, but treatment differences are indicated based on an *LSD* test at $P \leq 0.05$ using the transformed data. The soil water data obtained from the five neutron probe access tubes located in each plot were averaged for each soil horizon and subjected to ANOVA. Treatment differences for soil water data were tested using the standard error of difference between means (*SED*).

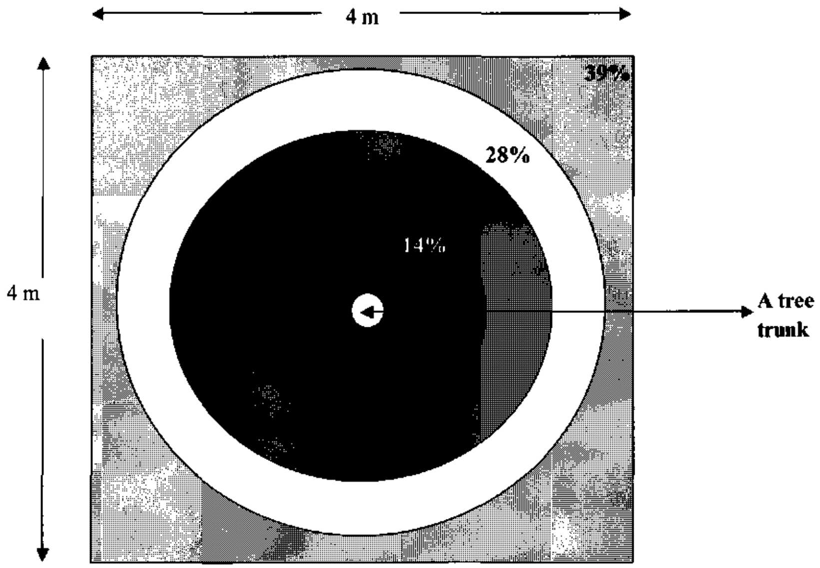


Figure 3.2. Schematic diagram showing the four sampling zones in the 4 x 4 m area surrounding individual trees. The values in the concentric rings refer to the percentage area covered by the zones; the radii from the center of the tree trunk to the rings are respectively 0.84, 1.30, 1.76 and 2.0 m.

3.3 Results and discussion

3.3.1 Soil water distribution between November 1999 and March 2001

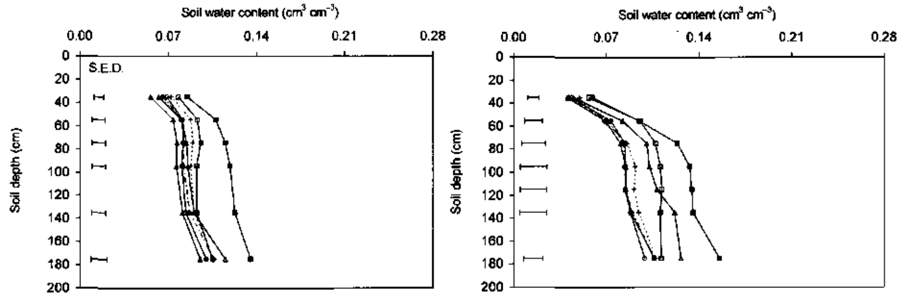
Rainfall during the 1999–2000 growing season was very erratic compared to 2000–2001 due to La-Niña (Figure 3.1). Rainfall was only 3.5 and 55 mm in December 1999 and January 2000, respectively, the lowest values recorded over the 40-year recording period. The treatments differed significantly ($P < 0.05$) in soil water content measured in all months except the dry months of May and September 2000 ($P = 0.23$) (Figure 3.3).

In November 1999, the soil was dry, with water contents ranging between 0.05 and 0.07 $cm^3 cm^{-3}$ in the topsoil and between 0.10 and 0.12 $cm^3 cm^{-3}$ at depths of 60 to 80 cm and 175 cm, respectively (Figure 3.3a). The bare soil of the continuous maize treatment contained significantly more soil water than the fallow system. Water contents were lowest in the *A. crassicarpa* and *A. leptocarpa* woodlot systems. Following rainfall during the period from January to March 2000, soil water content increased, particularly in the 80 to 140 cm horizon of the sole maize, *S. siamea* and natural fallow treatments (Figure 3.3b). Treatment differences were small in the horizons above 80 cm; below 80 cm, the treatments were ranked in the following order: continuous maize > *S. siamea* = natural fallow > *L. pallida* = *A. crassicarpa* = *A. julifera* = *A. leptocarpa*. Interestingly, soil water content was lowest in treatments containing the Australian *Acacia* species.

In May and September 2000, during the dry season, no major treatment differences in soil water content were detected (Figures 3.3c and 3.3d). Soil water content varied between 0.05 and 0.12 $cm^3\ cm^{-3}$ under continuous maize, 0.04 and 0.11 $cm^3\ cm^{-3}$ under *S. siamea* and *A. crassicarpa*, and between 0.03 and 0.09 $cm^3\ cm^{-3}$ under *L. pallida*, *A. julifera*, natural fallow and *A. leptocarpa*. The small differences probably reflect the low rainfall during the preceding rainy season and the prolonged dry season. Following the onset of the rains in November 2000, soil water content increased sharply at all depths (Figure 3.3e). The greatest increase in soil water content was in the 60 to 140 cm horizons, although the differences between treatments were not significant. As high and regular rainfall occurred throughout the season, soil water content continued to increase at depths below 60 cm in all treatments. The soil water distribution pattern observed at the end of March 2001 showed a complete reversal of those obtained during the previous season (Figures 3.3b and 3.3f) as all woodlot treatments exhibited higher soil water contents than the continuously cropped and natural fallow treatments.

Trees appeared to deplete water to a greater extent than sole maize or natural grass/herb fallow during the dry season, when there was no rainfall, and conserve more during the wet season. Le Maitre et al. (1999) also reported greater depletion of soil water by plantations as compared to grasslands during the dry season. Soil water depletion from the deep soil layers was due to water uptake by trees during the dry season. Soil water content did not increase under trees following rainfall in December 1999 and January 2000 because rainfall was low (< 60 mm) and a substantial proportion of this may have been lost as a result of canopy interception.

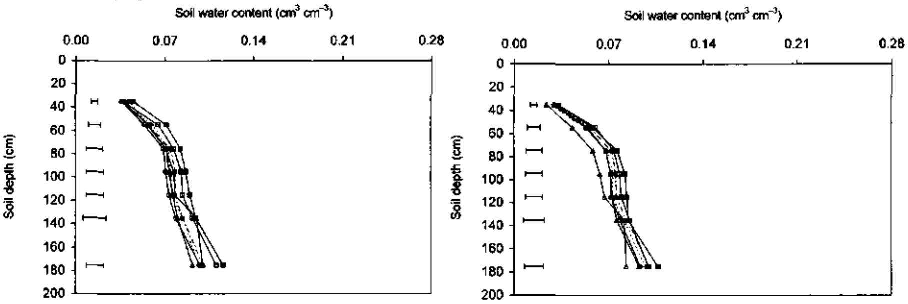
(i) Rainy season 1999-00 (November 1999–April 2000)



(a) 27 November 1999

(b) 25 March 2000

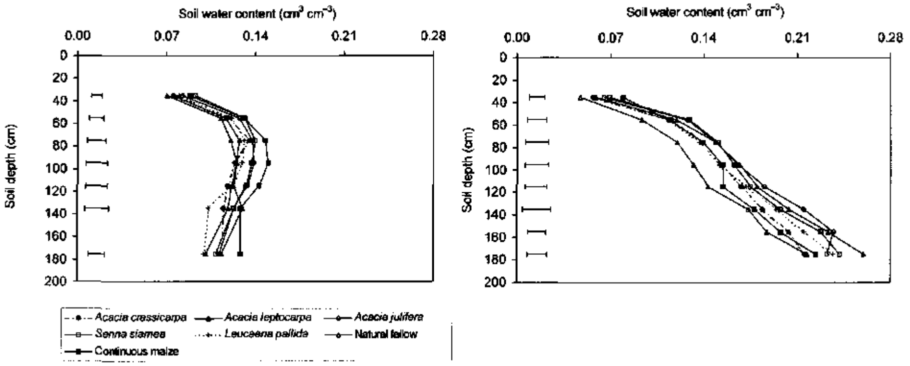
(ii) Dry season (May–October 2000)



(c) 26 May 2000

(d) 26 September 2000

(iii) Rainy season 2000-01 (November 2000–April 2001)



(e) 28 November 2000

(f) 27 March 2001

Figure 3.3. Soil water distribution patterns under woodlots of five tree species, natural fallow and continuous maize between November 1999 and March 2001. Measurements began when trees were three years old. No crop was present in the continuous maize treatment in November 1999 and from May to November 2000. Horizontal bars show standard errors of difference between means (SED) for comparing soil water between treatments per depths.

Canopy interception losses have been reported to be high for small rainfall events (Wallace 1996). In contrast, soil water content under trees increased substantially following the high rainfall (> 300 mm) received in December 2000 and January 2001. These results are also consistent with those reviewed by Rao et al. (1997), who concluded that trees increase water availability by improving soil structure and infiltration and thereby reducing run off.

3.3.2 Transpiration by trees

Figure 3.4 shows the mean diurnal trends of sap flow velocity recorded by heat pulse sensors positioned at depths of 0.5, 1.5 and 2.5 cm beneath the cambium for *A. crassicarpa* (Days 1 to 10, JD 307 to 316), *L. pallida* (Days 1 to 10, JD 345 to 354), and *A. leptocarpa* (Days 1 to 6, JD 358 to 363). The diurnal trends for the different tree species were similar, although the velocities differed substantially between species. Mean sap flow velocity increased from a minimum at 0600 h to a maximum between 1000 h and 1700 h, and then gradually decreased to a minimum at 1930 h. Sap flow was greatest in *A. leptocarpa*, with a maximum of 38.2 cm h^{-1} measured on Day 1 (JD 358); peak values remained relatively constant (28.1 to 30.7 cm h^{-1}) for the remaining five days of measurement. By contrast, *A. crassicarpa* had the lowest sap flow velocity during the first four days of measurement, and increased over time (Figure 3.4). Following rain on Days 4 and 5 (JD 310 and 311), the maximum sap flow velocity increased progressively from 14.2 cm h^{-1} to 29.4 cm h^{-1}over the subsequent six days indicating that soil water content was limiting transpiration initially.

The diurnal patterns of *A. julifera* and *S. siamea* are not shown in Figure 3.4 as their sap flow rates were similar to *L. pallida*. Sap flow velocity was generally greatest at a depth of 0.5 cm below the cambium and lowest at 2.5 cm depth in all species except *A. crassicarpa*, in which there was little difference in sap velocity at depths of 0.5 and 1.5 cm (data not shown). This implies that younger xylem near to the surface of the trunk was more active in transporting water than the older xylem tissues. Any changes in either soil water content or atmospheric demand during each day are likely to cause changes in transpiration rate, particularly in the younger xylem in which sap flow velocities are greatest. Sap flow velocity was lowest and least sensitive to soil and atmospheric changes at a depth of 2.5 cm below the cambium.

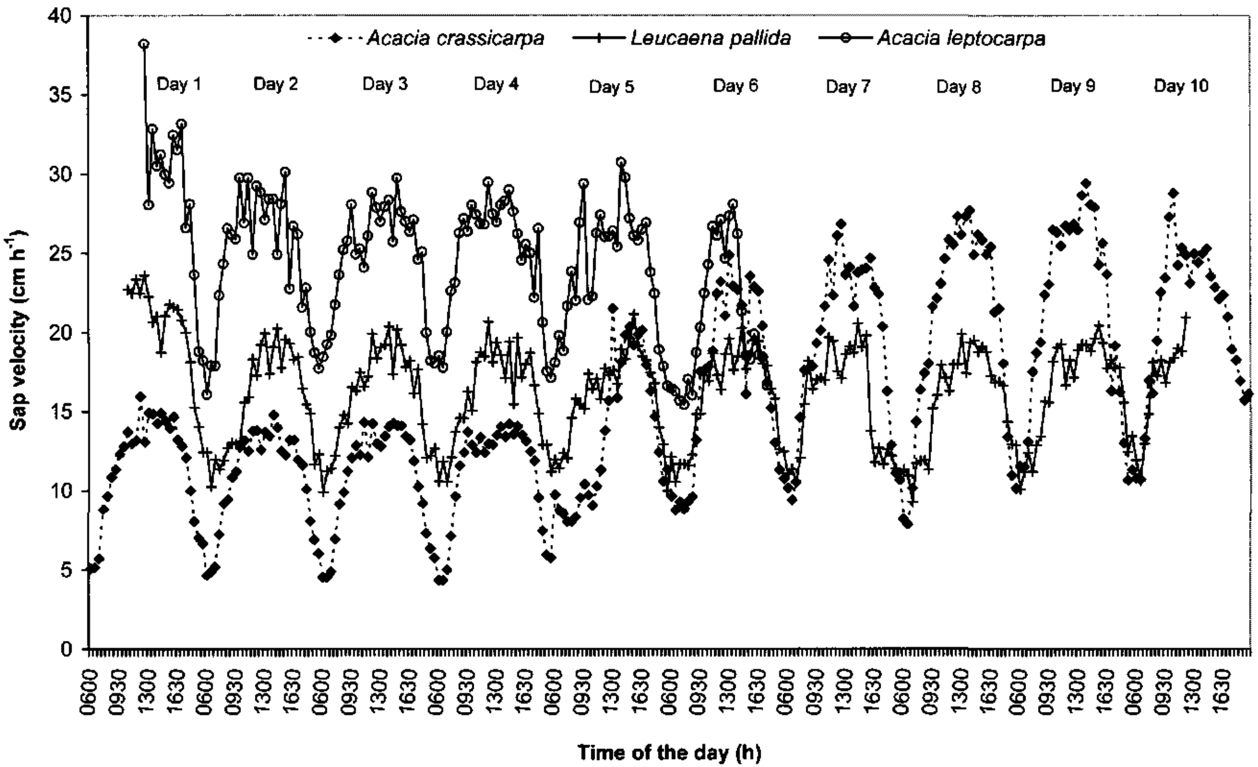


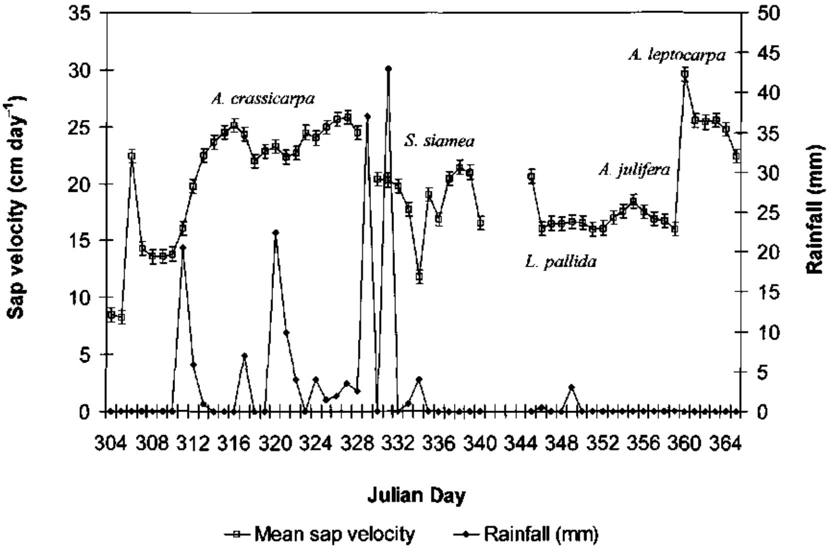
Figure 3.4. Mean diurnal sap flow velocity patterns in the trunks of three tree species measured continuously over 10 day periods at different Julian Days (JD) during the 1999-2000 season (*A. crassicarpa* JD 307–316; *L. pallida* JD 345–354 and *A. leptocarpa* JD 358–363). The values are means of sap flow velocities measured at depths of 0.5, 1.5 and 2.5 cm below the trunk surface.

Sap flow velocities calculated per day of 13 hours are shown in (Figure 3.5a). *Acacia leptocarpa* had the highest daily mean value (30.0 cm d^{-1}) while *S. siamea, A. julifera* and *L. pallida* had similar but lower values (mean of 17 cm d^{-1}). The mean daily sap flow velocity in *A. crassicarpa* was lower (7 to 14 cm d^{-1}) than in *A. julifera, S. siamea* and *L. pallida* (16 to 21 cm d^{-1}) when soil water content was limiting, but was greater (22 to 23 cm d^{-1}) when soil water content was not limiting. The mean daily sap flow velocity in *A. leptocarpa* measured when water was limiting was similar to that in *A. crassicarpa*.

The daily total transpiration rate is shown in Figure 3.5b. The mean values for *A. crassicarpa* ranged between 540 and 1680 g d^{-1} over a 25-day period when there were frequent rains. By comparison, daily transpiration rates ranged between 620 and 1090 g for *S. siamea,* 660 and 780 g for *A. julifera,* 540 and 700 g for *A. leptocarpa* and 360 and 470 g d^{-1} for *L. pallida* during periods when there were little or no rain. *Acacia crassicarpa* exhibited the greatest cumulative water uptake and *L. pallida* the lowest (Figure. 3.6).

The order of cumulative water use within the various woodlot was as follows: *A. crassicarpa* > *S. siamea* > *A. julifera* = *A. leptocarpa* > *L. pallida*. The rate of transpiration was related to stem diameter (greatest in *A. crassicarpa* smallest in *L. pallida* and *A. leptocarpa*), size of the tree canopy and soil water availability. Other environmental factors such as water vapour pressure gradient, wind speed, air temperature, relative humidity and the quantity of incident solar radiation are also likely to have influenced transpiration rate (Allen et al. 1998). *Leucaena pallida* had the lowest transpiration rate due to its relatively small stem and crown diameters (Nyadzi et al. 2002).

(a) Sap flow velocities



(b) Sap flux densities

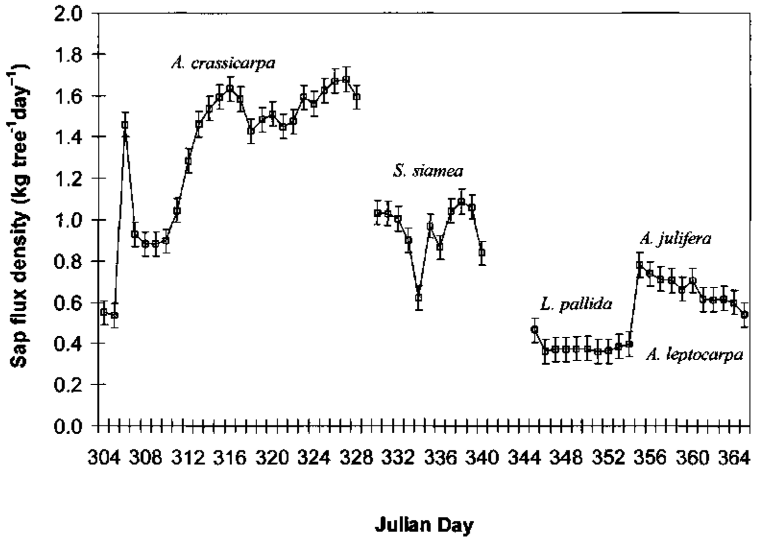


Figure 3.5. Mean daily sap velocities (a) and sap flux densities (b) in the stems of three-year-old trees in woodlots at Tabora, Tanzania. Error bars = ±S.E.

Table 3.1. Soil pH at three depths in 4-year-old fallow systems, including five woodlots each with a different tree species, natural fallow and continuous maize, at Tabora, western Tanzania.

Treatment	Soil horizon			Mean
	0–15 cm	15–30 cm	30–50 cm	
Acacia crassicarpa	5.0	4.9	5.0	5.0 b
A. julifera	5.2	5.1	5.0	5.1 b
A. leptocarpa	4.9	4.9	4.9	4.9 bc
Leucaena pallida	5.1	5.0	5.0	5.0 b
Senna siamea	5.2	5.0	5.0	5.0 b
Natural fallow	5.3	5.4	5.3	5.4 a
Continuous sole maize	4.9	4.7	4.6	4.7 c
Mean	5.1 a	5.0 a	5.0 a	
SED treatments	0.108 ($P < 0.01$)			
SED horizons	0.043 ($P = 0.27$)			
SED (treatments x horizons)	0.192 ($P = 0.98$)			

Data for woodlot treatments were means of measurements made within 0.84, 1.30, 1.76 and 2.0 m distances from the tree trunks, six weeks after the first rains in 2000. Soil pH at the start of the study in 0–15 and 15–30 cm horizons was 6.1 and 5.7 respectively. *SED* = standard error of the difference between means. Values in parentheses are probabilities of *F* significance; treatment means within a column or row followed by the same letter are not significantly different based on an *LSD* test at $P < 0.05$.

3.3.3 Soil pH

ANOVA of soil pH at the end of four years at various distances from the trees (i.e. zones) and soil depths within the woodlot treatments showed no significant variation associated with distance from trees, soil depth, tree species and their interactions. The data were therefore averaged over all zones and a pooled ANOVA was performed including the data for the natural fallow and continuous maize treatments. There were significant ($P<0.01$) differences in soil pH between woodlots, natural fallow and continuous maize treatments (Table 3.1). Soil pH measured four years after the establishment of trees was 0.8 to 1.2 and 0.2 to 1.0 units lower in the 0 to 15 cm and 15 to

30 cm soil horizons, respectively, than at the start of the trial. The decrease in soil pH was greatest under continuous maize and woodlot systems. Averaged across all soil depths, soil pH was highest under natural fallow and lowest under sole maize.

Differences between treatments in soil pH may reflect differences in the uptake of anions and cations, and in leaching of nitrate and bicarbonate (Cahn et al. 1993; Haynes 1990). Nitrogen fixing trees are known to decrease soil pH (Tornquist et al. 1999). Removal of crop residues from the plots, application of N fertilizer and a subsequent increase in N leaching may have increased acidification in the continuous sole maize relative to the other treatments. The higher pH observed under natural fallow may have occurred because urea was not applied to this treatment.

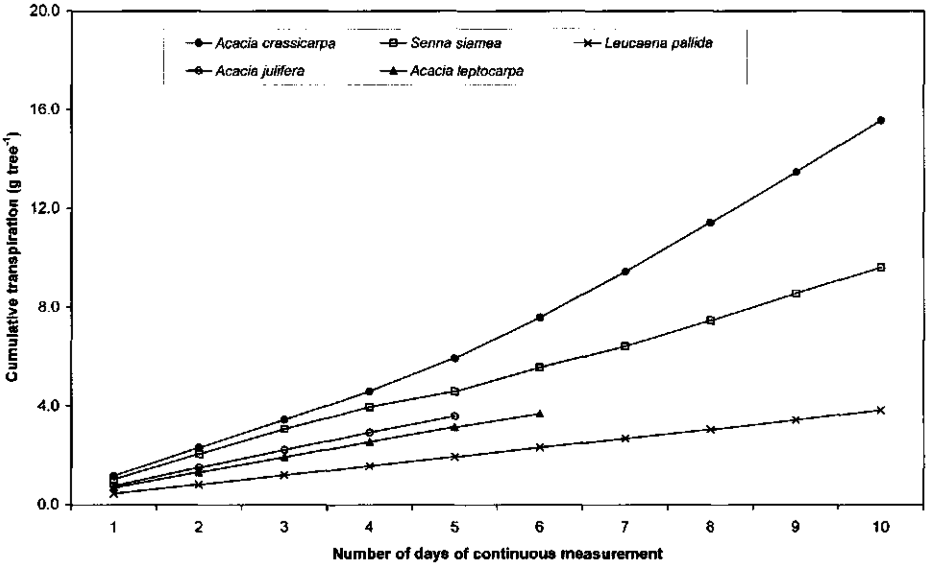


Figure 3.6. Cumulative water uptake (transpiration) by tree species measured at different times during the 1999-2000 season (*A. crassicarpa* JD 307–316; *S. siamea* JD 330–339; *L. pallida* JD 345–354; *A. julifera* JD 354–358 and *A. leptocarpa* JD 358–363).

3.3.4 Soil total N

The different treatments did not influence total soil N content over the four-year study period (Table 3.2). Generally, N content decreased with depth. Compared to the initial levels, total N increased slightly in the 0 to 15 and 15 to 30 cm soil horizons under *A. crassicarpa*, *A. leptocarpa* and continuous maize. The increase in total soil N under sole maize may have resulted from the application of N fertilizer every year, whereas the increase under the *Acacia* species relative to the other tree species was probably due to N_2-fixation.

3.3.5 Soil inorganic N

Differences due to treatments (fallow systems) and soil depth were significant for both forms of inorganic N (ammonium and nitrate), but the interaction between fallow system and soil depth was not significant (Tables 3.3 and 3.4). Soil inorganic N was much greater in the top two soil horizons than in deeper horizons and was much lower under trees than under natural fallow and continuous maize (Tables 3.3 and 3.4), suggesting that the trees in the woodlots made extensive use of the soil N.

Table 3.2. Total soil N (mg kg^{-1}) under 4-year-old woodlots, natural fallow and continuous maize at Tabora, Tanzania.

Treatment	Soil horizon(cm)			Mean
	0–15	15–30	30–50	
A. crassicarpa	1170	640	610	810 a
A. julifera	710	570	780	690 a
A. leptocarpa	890	790	730	800 a
L. pallida	670	580	600	620 a
S. siamea	580	570	520	560 a
Natural fallow	810	690	560	690 a
Continuous sole maize	890	710	620	740 a
Mean	820 a	650 b	630 b	
SED treatments		151.1 ($P = 0.31$)		
SED soil horizons		63.4 ($P < 0.05$)		
SED (interaction)		204.3 ($P = 0.77$)		

SED = standard error of the difference between means. Values in parentheses are probabilities of *F* significance; Treatment means followed by the same letter in a row or column are not significantly different based on an *LSD* test at $P < 0.05$. Average total soil N at start was 700 and 500 mg kg^{-1} for the 0 to 15 and 15 to 30 cm soil horizons, respectively.

Table 3.3. Vertical distribution of soil ammonium-N (mg kg^{-1}) in woodlots, natural fallow and continuous maize at Tabora, western Tanzania.

	Soil horizons (cm)						
Treatments	0–15	15–30	30–50	50–100	100–150	150–200	Mean
Acacia crassicarpa	2.24	1.97	1.54	1.17	1.01	0.70	1.44 c
A. julifera	2.65	1.69	1.36	1.01	1.36	0.81	1.48 c
A. leptocarpa	2.37	1.73	1.58	1.09	1.38	0.90	1.51 c
Leucaena pallida	1.82	1.74	1.42	1.30	0.89	1.51	1.45 c
Senna siamea	2.38	2.00	1.49	1.25	1.29	1.03	1.57 c
Natural fallow	10.10	3.77	1.88	1.10	1.05	1.23	3.19 b
Continuous maize	10.08	6.58	3.14	1.72	1.06	1.28	3.97 a
Mean	4.52 a	2.78 b	1.77 c	1.23 d	1.14 d	1.05 d	
F probability (treatments)				$P < 0.05$			
F probability (soil horizons)				$P < 0.01$			
F probability (interaction)				$P = 0.97$			

Data for woodlot treatments are means of measurements made in four concentric zones with radii of 0.84, 1.30, 1.76 and 2.0 m from the trunks in December 2000, six weeks after the first rains. Treatment means within a column or row followed by the same letter are not significantly different based on ANOVA conducted using $\log_{10}$ transformed data and an *LSD* test at $P < 0.05$.

Nitrogen uptake by the continuous maize systems was confined to the cropping season. There was N accumulation in this treatment in December when there was no crop, which may have been due to N mineralization during the dry season. The natural fallow also exhibited high soil inorganic N concentrations at this time because the plants had nearly died due to drought. Therefore, NO_3 remained relatively high throughout the soil profile in these treatments compared with others (Table 3.4).

Inorganic N was greater in the topsoil than in the subsoil, probably because of the recent additions of N in the form of fertilizers and organic residues. The low inorganic N below 30 cm under the woodlots and natural fallows is likely to have resulted from uptake by the roots of trees and natural vegetation, respectively, as was reported previously for *Sesbania sesban* and natural fallow (Mekonnen et al. 1997). Inorganic N can accumulate in the subsoil under conditions of high rainfall due to leaching and mineralisation exceeding crop uptake (e.g. Buresh and Tian 1997).

Trees can capture nutrients released by weathering in deep soil horizons, which are otherwise unavailable to the shallow-rooted crops (van Noordwijk et al. 1996; Buresh and Tian 1997). Active roots of trees and shrubs can also capture nutrients leached from surface horizons into deeper soil layers. These two concepts are known as 'nutrient pump hypothesis' and 'safety net hypothesis', respectively. The results obtained in the present study support these hypotheses.

3.3.6 Horizontal distribution of soil inorganic N

The greatest concentrations of ammonium-N were found in the zone close to the tree base (zone A) for all tree species (Table 3.5). The ammonium-N concentrations were lower but similar in zones B, C and D. Nitrate-N did not differ significantly between zones (Table 3.6) but the effects of treatments and the treatment x zone interaction term were significant ($P < 0.01$). *Acacia julifera* exhibited the greatest nitrate-N in zone A and also had relatively high concentrations in the other zones compared to the other species examined. *L. pallida* had the least nitrate-N close to the tree base. This observation may reflect the root distribution pattern of these species. *Acacia julifera* may have its active roots spread out from the trunk base in contrast to greater concentration of roots close to the trunk in *L. pallida*. Similarly, the lower nitrate concentration closer to the tree base in *A. crassicarpa* indicates that this species also had greater concentration of its rooting density close to the trunk (Mekonnen et al. 1997).

Senna siamea is a legume, but cannot fix atmospheric N_2. However, it is able to extract soil N effectively (Ladha et al. 1993). It also has a considerable ability to spread its roots laterally, particularly in semi-arid areas (Breman and Kessler 1995). Capture of nutrients by lateral roots from within the crop rooting zone represents a redistribution of nutrients within the soil-plant system rather than a net input (Buresh and Tian 1997). Our results indicate that *Acacia* species and *L. pallida* were also effective scavengers of soil N. The low and similar concentrations of soil ammonium-N under all tree species examined may have resulted from rapid nitrification of ammonium to form nitrate-N followed by its uptake by tree roots.

Table 3.4. Vertical distribution of soil nitrate-N (mg kg^{-1}) in woodlots, natural fallow and maize at Tabora, western Tanzania.

Treatment	Soil horizon (cm)						Mean
	0–15	15–30	30–50	50–100	100–150	150–200	
Acacia crassicarpa	0.63	0.26	0.44	0.57	0.57	0.44	0.49 cd
A. julifera	2.11	0.68	0.22	0.48	0.33	0.43	0.71 c
A. leptocarpa	1.00	0.14	0.35	0.02	0.01	0.00	0.25 d
Leucaena pallida	0.81	0.10	0.09	0.32	0.63	0.40	0.39 d
Senna siamea	1.48	0.38	0.19	0.11	0.09	0.08	0.39 d
Natural fallow	6.30	2.81	2.54	1.79	0.93	0.42	2.46 b
Continuous maize	9.83	7.06	6.50	2.99	2.89	5.10	5.73 a
Mean	3.17 a	1.63 b	1.48 b	0.90 c	0.78 c	0.98 c	
F probability (treatments)			$P < 0.01$				
F probability (soil horizon)			$P < 0.01$				
F probability (interaction)			$P = 0.88$				

Data for woodlot treatments were means of measurements made in four zones (concentric rings with radii of 0.84, 1.30, 1.76 and 2.0 m) around the trees in December 2000, six weeks after the first rains. Treatment means within a column or row followed by the same letter are not significantly different based on ANOVA conducted using $\log_{10}$ transformed data and an *LSD* test at $P < 0.05$.

3.4 Conclusions

Soil water and N dynamics were different in rotational woodlots, natural fallow and continuous maize treatments. Trees depleted soil water more than the natural fallow and continuous maize systems during the dry season. By contrast, in presence of trees, greater proportion of rainfall was stored in the soil than in the other systems.

Acacia crassicarpa exhibited the greatest mean transpiration rate during the measurement period, while *L. pallida* had the lowest values and the other species were intermediate. However, there was no evidence that trees were over-exploiting the water reserves after three to four years.

Although the inorganic N content of the soil was low, all tree species examined were able to retrieve inorganic N from deep soil horizons and increase its concentration close to their trunks. These results have implications regarding the benefits of the rotational woodlot technology in conserving water and nutrient resources for sustainable development.

Before wide scale dissemination of this technology is undertaken, integrated economic and environmental assessments are essential. Such an assessment should also include an appraisal of the impact of large-scale tree planting on landscape hydrology.

3.5 Acknowledgement

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Table 3.5. Soil ammonium-N (mg kg^{-1}) in four soil zones around the tree base in five woodlots, each with a different tree species, at Tabora, western Tanzania.

Treatment	Zone A	Zone B	Zone C	Zone D	Mean
	(0–0.84 m)	(0.84–1.30 m)	(1.30–1.76 m)	(>1.76 m)	
Acacia crassicarpa	1.81	1.29	1.20	1.59	1.47 a
A. julifera	2.16	1.24	1.50	1.02	1.48 a
A. leptocarpa	1.84	1.75	1.33	1.24	1.54 a
Leucaena pallida	1.85	1.37	1.12	1.46	1.45 a
Senna siamea	1.82	1.22	1.73	1.52	1.57 a
Mean	1.90 a	1.37 b	1.38 b	1.37 b	
F probability (treatments)		$P = 0.06$			
F probability (zones)		$P < 0.01$			
F probability (interaction)		$P = 0.10$			

Data were collected for 4-year-old woodlots in December 2000, six weeks after the first rains and averaged over six soil depths. Treatment means within a column or row followed by the same letter are not significantly different based on ANOVA conducted using $\log_{10}$ transformed data and an *LSD* test at $P < 0.05$.

Table 3.6. Soil nitrate-N (mg kg^{-1}) in four soil zones around the tree base in five woodlots, each with a different tree species, at Tabora, western Tanzania. Data were collected in 4-year-old woodlots in December 2000, six weeks after the first rains. Data were averaged over six soil depths.

Treatment	Zone A	Zone B	Zone C	Zone D	Mean
	(0–0.84 m)	(0.84–1.30 m)	(1.30–1.76 m)	(>1.76 m)	
Acacia crassicarpa	0.31 ab	0.53 ab	0.67 a	0.44 ab	0.49 ab
A. julifera	0.95 a	0.66 a	0.55 a	0.67 a	0.71 a
A. leptocarpa	0.47 ab	0.25 b	0.22 a	0.19 b	0.28 b
Leucaena pallida	0.19 b	0.53 ab	0.55 a	0.29 b	0.39 b
Senna siamea	0.46 ab	0.26 b	0.47 a	0.40 ab	0.40 b
Mean	0.48 a	0.45 a	0.49 a	0.40 a	
F probability (treatments)		$P < 0.01$			
F probability (zones)		$P = 0.66$			
F probability (interaction)		$P < 0.01$			

Treatment means within a column or row followed by the same letter are not significantly different based on ANOVA conducted using $\log_{10}$ transformed data and an *LSD* test at $P < 0.05$.

CHAPTER 4

Litter production and leaf quality and decomposition patterns over the year in rotational woodlots in western Tanzania

Abstract

Rotations of fast growing N_2-fixing tree species and crops may provide both valuable wood and high crop yields, and it has been suggested that such rotations are suitable alternatives for the traditional fallows in subsistence agriculture in Sub-Saharan Africa. However, nutrient cycling and transfer between trees and crop are quantitatively not well known. This hinders the development of sound strategies for management of tree residues and other possible nutrient inputs.

A long-term field trial with seven fallow treatments, i.e., *Acacia crassicarpa*, *A. julifera*, *A. leptocarpa*, and *Leucaena pallida*, (N_2-fixing legume trees), and *Senna siamea* (non-N_2-fixing legume tree), natural fallow and continuous cropping, in three replicates, was established at Tabora, western Tanzania in 1996 to evaluate the potential of woody species for wood production, nutrient transfer and soil fertility improvement. Litter fall was measured for 10 months in 2001. Nutrient content and leaf quality over seasons was measured 4 times between 2000 and 2002. Decomposition of tree leaves was studied for 12 months using the litterbag technique.

Results indicate that total litter accumulation over the ten months period was highest in *Acacia* species and lowest in *L. pallida*, ranging from 1.9 to 10.7 Mg ha^{-1}. Litter fall peaked in the dry season. Contents of P, K, Ca, Mg, Mn, Fe, and B in the leaves were low but comparable to those reported elsewhere for these species. Mean N mass fraction was >25 g kg^{-1} for *L. pallida*, and <20 g kg^{-1} for other tree species and natural fallow. Mass fractions of N and P varied with time of sampling and the variations were similar for legumes and non-legumes. Initial P mass fractions, ratios of C to P and lignin to N were the best predictors for the rate of decomposition of the tree leaves. The results suggest that leaves of the studied trees need to be composted or to be amended with fertilizers prior to the cropping phase, to counterbalance the immobilization of N and P during the initial stages of decomposition.

Key words: *Acacia* species, decomposition, immobilization, *Leucaena pallida*, leaf quality, litter fall, *Senna siamea*

4.1 Introduction

Many soils in the Sub-Saharan Africa are deficient in soil nutrients, particularly nitrogen (N) and phosphorus (P). They cannot support sustainable crop production without inputs of nutrient sources (Sanchez and Logan 1992). Smallholders in the tropics have limited access to inorganic fertilizers due to high costs or because the fertilizers are simply unavailable. In such cases, domestication of leguminous multipurpose trees (agroforestry systems) is considered to be a viable and sustainable land use alternative (Sanchez 1995). Throughout the last 25 years, researchers have attempted to replace natural vegetation by selected herbaceous or woody species (Kang et al. 1997). It has been shown that these species provide N to crops and improve crop yields (e.g. Palm 1995; Giller 2001). However, tree performance and the dynamics of biomass production, decomposition and nutrient transfer are highly site-specific, which hinders the development of general guidelines for proper management of these systems.

Leguminous trees such as *Leucaena pallida, Senna siamea* and Acacias (e.g. *Acacia crassicarpa, A. julifera, A. leptocarpa*) are widely used now in agroforestry systems (Karachi et al. 1997; Salako and Tian 2001; Nyadzi et al. 2003a). Both N_2-fixing species such as *L. pallida* and the acacias, and non-N_2-fixing legumes such as *S. siamea* have potential for replenishment of soil fertility (e.g. Buresh and Tian 1997; Giller 2001). The litter produced by these trees is a major source of organic matter. The amount of litter produced depends on species and age of trees, climate, soil fertility and management (Salako and Tian 2001). Australian acacias, e.g., *A. leptocarpa* and *A. auriculiformis*, have a high litter production in sub-humid (Salako and Tian 2001) and semi-arid environments (Karachi et al. 1997), and seem to be suitable tree species for agroforestry from the point of view of biomass production. However, they tend to have a wide range of initial N mass fractions and a wide range of net N mineralization and immobilization rates (Constantinides and Fownes 1994b). This makes the litter of these trees a rather unpredictable source of N.

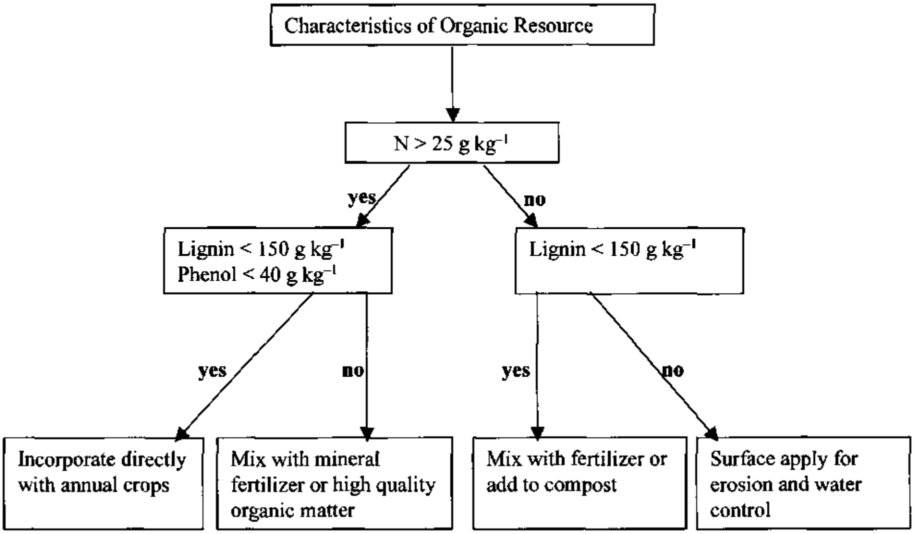

Figure 4.1 A decision tree for guiding the use of organic resources in agriculture (Palm et al. 1997; 2001b).

Decomposition and nutrient release rates are determined by the resource quality of the organic material, the environment, and the decomposer organisms present (Swift et al. 1979). The organic constituents and nutrient contents of the material define the resource quality. The concept of resource quality has attracted a lot of attention because it influences the decomposition/mineralisation dynamics of plant residues (e.g. Cadisch and Giller 1997; Vanlauwe et al. 1996). So far, there is little information on production, quality and decomposition of litter from woody species established in semi-arid environment. As a consequence, the processes and the possible interactions involved in those areas are not well understood, which again hampers the design of sound strategies for the management of agroforestry systems in general and tree and crop residues and other nutrient inputs in particular.

Cadisch and Giller (1997) gave a synthesis of research on plant residue quality and decomposition, which led to the development of the organic resource database (ORD) in tropical farming systems (Palm et al. 2001a). On the basis of this ORD a decision tree (Figure 4.1) was devised to assist in the use of organic resources for soil amendment (Palm et al. 1997; 2001b).

To allow valid comparisons regarding quality characteristics of organic materials it has been suggested to sample and analyse the relevant organic materials by comparable methods (Cadisch and Giller 1997; Vanlauwe et al. 1997). Palm and Rowland (1997) recommended a minimum set of organic resource quality parameters that influence decomposition and nutrient release as well as standard methodologies for measuring these parameters. The minimum data set includes macronutrients, total C, lignin, soluble C, soluble polyphenols, α-cellulose, and ash (Palm et al. 2001a). All these parameters are important as they affect decomposition of organic matter and by that nutrient release patterns (Cadisch and Giller 1997; Palm 1995).

In this study, we examined the quality and decomposition of leaves and the production of litter from various woody leguminous species planted in a rotational woodlot system. The goal was to explore the potentials of these trees for soil fertility replenishment in a semi-arid environment. We hypothesized that the nutrient transfer in the newly established woodlots is affected by the quantity, quality and decomposition of biomass produced by the specific tree species. We assumed that leaf quality differed with age, season (Palm and Rowland 2001) and canopy position (Salako and Tian 2001) and that decomposition was dependent on the initial organic resource quality. This study aims to supplement our previous studies on water and N dynamics (Nyadzi et al. 2003b), and on the responses of maize yield to the planted woodlots (Nyadzi et al. 2003a; Chapter 6). The study is one of a series addressing the potential of rotational woodlots in improving household income (Ramadhani et al. 2002) in western Tanzania.

4.2 Materials and methods

4.2.1 Experimental site

The study was conducted at Tumbi Agricultural Research Institute (5°03'S, 32°41'E, altitude 1190 m), which is located within the miombo woodlands of western Tanzania. Site characteristics, including climate and soil, have been described in Chapters 1 and 2. In short: woodlots of five different tree species (*Acacia crassicarpa, A. julifera, A. leptocarpa, Senna siamea* and *Leucaena pallida*) were established, each in three replicates in 1996, while *Eucalyptus camaldulensis* was established in January 2000. In addition, there were systems with natural fallow and continuous cropping (sole maize).

The measurements discussed in this chapter were conducted between March 2000 and September 2002, and deal with the woodlot systems only.

4.2.2 *Experimental design of the experiments*

4.2.2.1 Assessment of the quality of leafy tree plant materials

Fully matured leaves (blades and petioles) were collected from three trees in the net plots. Leaf collection was done in March 2000 (at the peak of the rain), in November 2000 (start of rain period), in June 2001 (first half dry period) and in September 2002 (collected from the coppicing trees at the peak of the dry period). Three branches of each tree were selected, one in the lower canopy, one from the middle and one from the top of the canopy. Senescent (old) and young leaves were collected from *A. crassicarpa* only, in November 2000. Leaves of *E. camaldulensis* were sampled in June 2001 and September 2002. As trees were harvested in November 2001 (and maize was intercropped between tree stumps; see Chapter 6), samples collected in September 2002 were from trees re-growth (coppices), except for eucalyptus, which was not cut. Samples were taken to the laboratory, air-dried at room temperature (26 °C) for seven days and then sun-dried for two days. Sub-samples were ground to pass through 1 mm sieve and finally oven-dried at 70 °C overnight before chemical analysis.

4.2.2.2 Assessment of litter production

Bi-weekly litter fall was measured from January to October 2001 using the method described by Anderson and Ingram (1993). Litter traps were 0.47 x 0.48 m with a depth of 0.3 m, with sides of wood and with a bottom of a 1-mm nylon mesh. Three litter traps were located randomly in the net plot of six trees that were spaced at 4 x 4 m. They were raised to a height of 0.3 m above the soil surface, in each of the five treatments in each replicate. Any overhanging under-storey obstructing litter fall was removed and accumulated litter was collected every 2 weeks, at the middle and the end of each month. Litter was taken to the laboratory and categorised into leaf, fine wood (<2 mm diameter branches and bark), reproductive parts (flowers, pods, seeds) and others (miscellaneous) that did not belong to the identified litter fractions, following the procedures described by Cuevas and Lugo (1998) and Saharjo and Watanabe (2000). Individual samples from each litter trap were oven-dried at 70 °C for a minimum of 48 hours to constant weight. The mean monthly value for each stand was converted to a unit area basis (Mg ha^{-1}).

4.2.2.3 Assessment of in-situ leaf decomposition

Decomposition of air-dry/fully matured leaves was assessed in-situ using the litterbag technique as described by Gallardo and Merino (1993) and Kuperman (1999). We used dry leaves and not litter in this study because in the system of rotational woodlots fresh leaves are left on the soil at wood harvest (Chapter 5). Dried leaves were used to allow storage of leaves until experiments could be performed. This also represented the natural situation as most litter is produced during the dry season; the fallen leaves remain dry until the next season starts. On this basis then, the use of dried leaves aimed at giving correct results. The decomposition trial was located adjacent to the field trial. Leaves were collected in November 2000. The litterbags of 0.1 x 0.1 m size (Kuperman, 1999) were constructed from nylon with 1-mm mesh. This was considered to be small enough to prevent major losses of the smallest leaves (Gallardo and Merino 1993), yet large enough to permit aerobic microbial activity and small soil animals free entry (Guo and Sims 1999). However, it excludes larger arthropods and earthworms, which are important primary accessors to litter. As a consequence termites, bacteria, fungi and actinomycetes will dominate the litter system (Arunachalam et al. 1998), and the measured leaf decomposition rates could be an underestimation of the potential rates. For the experiment, 5 g of the samples of air-dried leaf material were weighed and placed in a litterbag, and the tops of the filled litterbag was then stitched with nylon threads. This rate is equivalent to 5 Mg ha^{-1}. The filled litterbags were placed in plastic bags for transport and storage in order to minimise spillage (Wieder and Lang 1982). Three extra bags from each of the five leaf types were retained in the laboratory to determine the moisture content (70 ^{o}C) and chemical composition of the air-dried leaves (Section 4.2.3).

The leaves were evenly spread in the litterbags and the bags were buried horizontally in the soil (15 cm depth) in 1 m by 1.5 m plots adjacent to where trees were growing. The plots were distributed in a randomised complete block design with three replications and five treatments (*A. crassicarpa, A. julifera, A. leptocarpa, S. siamea* and *L. pallida*). For each species, 36 litterbags were prepared of which 12 were randomly buried in the appropriate plot in each of the three replicates on 30 December 2000. One litterbag was collected from each plot at 1, 4, 9, 18, 30, 60, 90, 120, 180, 240, 300 and 360 days after installation to follow dry matter and nutrient loss. The litterbags containing plant materials remaining at each time of collection were carefully placed in nylon bags before being taken to the laboratory. Soil particles and roots growing in the litterbags were manually removed and the remaining organic material was washed with distilled water by swirling briefly and carefully decanting through 0.250 mm mesh sieve to remove soil and extraneous matter. According to Anderson and Ingram (1993), such brief washing permits little leaching. The litter was then oven dried at 70 °C, and weighed to determine the remaining material. The samples were ground to pass through 1 mm and used for the chemical analysis of resource quality indicators (total N, C, P, lignin and total soluble polyphenol) for the sample periods of 0, 18, 30, 90, 180, 240 and 360 days as described below.

4.2.3. Analytical procedures

Leaf samples of the five species were characterised for quality parameters according to the recommendations of Palm and Rowland (1997). Six elements (N, P, K, C, Ca, and Mg) were monitored. Samples were digested using the Kjeldahl procedure with concentrated sulphuric acid, salicylic acid, hydrogen peroxide and selenium (Anderson and Ingram, 1993). N and P in the digest were determined colorimetrically (Parkinson and Allen, 1975) and K by flame photometry (Anderson and Ingram, 1993). In the same digests, Ca and Mg contents were measured using atomic absorption spectrophotometer (Anderson and Ingram 1993). Organic C was determined by colorimetric method after wet oxidation with a H_2SO_4 and $K_2Cr_2O_7$ mixture (Anderson and Ingram, 1993). A method based on the Ankom filter bag technique (FBT) in a batch reflux chamber, was used for determining the neutral detergent fibre (NDF), which estimates the contents of cellulose, hemicellulose and lignin, and the acid detergent fibre (ADF) and lignin (L) contents. The Ankom FBT procedure has previously been found not to be statistically different from the Van Soest technique (van Soest, 1963) in a variety of forages and cereals (Komarek et al. 1994). Total extractable polyphenols (PP) were analysed after extraction using 50% aqueous methanol. The plant to extractant ratio was 0.1 g per 50 ml, and phenols were analysed colorimetrically using the Folin-Ciocalteu reagent as described by Constantinides and Fownes (1994b). Samples collected in March 2000 were also analysed for micronutrients (Mn, Fe, B). Mass fractions of K, Ca, Mg, Mn, Fe and B in these samples were determined by inductively coupled plasma atomic emission spectrometer (ICP–AES) using the procedure described by Temminghoff (2000).

Table 4.1. Carbon and nutrient mass fractions (g kg^{-1} for C and macro nutrients and mg kg^{-1} for the micro nutrients Mn, Fe and B) of fully grown leaves of *Acacia*, *Senna*, and *Leucaena* species and natural fallow. Some samples of old and fallen leaves of *A. crassicarpa* were also analysed in some periods. *Eucalyptus* and *Terminalia* species leaves were also analysed.

Species[†]	Period	C	N	P	K	Ca	Mg	Mn	Fe	B	C/N
A. crassicarpa	Mar-00	514	13.6	0.6	8.6	8.4	3 b	252	190	6.7	37.7
	Nov-00	356 b	13.2 b	0.4 e	4.5 d	7.2 d	6.0	–	–	–	27.0 d
	Jun-01	336	15.8 cd	0.7 cd	8.4	2.9 d	4.4	–	–	–	21.5 bc
Average		**402**	**14.2**	**0.6**	**7.2**	**6.2**	**4.5**	**–**	**–**	**–**	**28.7**
A. crassicarpa (old leaves)											
	Nov-00	408 a	7.5 c	0.1 g	7.2 bc	4.3	8.2	–	–	–	54.3 a
A. crassicarpa (fallen leaves)											
	Nov-00	411 a	12.7 b	0.3 f	6.3 bc	6.2	6.6	–	–	–	32.2 bc
	Jun-01	342	16.5 bc	0.6 d	8.4	4.9 c	7.9	–	–	–	20.8 bc
	Sep-02	401	16.2 c	0.5 d	4.5 d	2.6 bc	2.7 b	–	–	–	24.8 bc
Average		**385**	**15.1**	**0.5**	**6.4**	**4.6**	**5.7**	**–**	**–**	**–**	**25.9**
A. julifera	Mar-00	509	25.1	1.1	3.5	11.7	2.3 b	432	183	25.8	20.3
	Nov-00	411 a	12.8 b	0.6 c	7.4 bc	5.7 c	5.2	–	–	–	32.2 bc
	Jun-01	360	18.7 b	0.8 bc	5.9	5.0 c	5.1	–	–	–	19.3 cd
	Sep-02	–	–	–	9.7 a	–	–	–	–	–	–
Average		**427**	**18.9**	**0.8**	**6.6**	**7.5**	**4.2**	**–**	**–**	**–**	**23.9**
A. leptocarpa	Mar-00	523	12.7	0.7	3.8	14.2	5.5 a	382	76	15.8	41.1
	Nov-00	391 ab	11.4 bc	0.5 d	6.0 c	6.6 bc	5.5	–	–	–	34.5 b
	Jun-01	353	13.9 de	0.5 e	5.7	6.5 b	7.1	–	–	–	25.5 ab
	Sep-02	432	19.4 b	0.8 bc	–	1.6 c	2.6 b	–	–	–	22.4 cd
Average		**425**	**14.5**	**0.6**	**5.2**	**7.2**	**5.2**	**–**	**–**	**–**	**30.9**
L. pallida	Mar-00	497	50.9	2.9	11.0	9.9	3.2 b	218	93	15.0	9.8
	Nov-00	352 b	20.9 a	1.0 a	13.7 a	7.2 b	7.3	–	–	–	17.5 e
	Jun-01	334	22.5 a	0.9 a	6.6	7.0 b	6.6	–	–	–	15.0 d
	Sep-02	423	22.4 a	0.9 b	6.4 cd	5.7 a	5.8 a	–	–	–	18.8 de
Average		**402**	**29.2**	**1.4**	**9.4**	**7.5**	**5.7**	**–**	**–**	**–**	**15.3**
S. siamea	Mar-00	508	18.9	1.2	2.3	15.9	2.4 b	213	112	20.8	26.9
	Nov-00	390 ab	13.2 b	0.9 b	8.8 b	11.1 a	4.6	–	–	–	29.6 cd
	Jun-01	381	13.9 de	0.9 ab	7.0	9.5 a	7.5	–	–	–	27.8 a
	Sep-02	385	22.2 ab	1.2 a	8.9 ab	6.5 a	2.3 b	–	–	–	17.5 e
Average		**416**	**17.1**	**1.1**	**6.8**	**10.8**	**4.2**	**–**	**–**	**–**	**25.5**
E. camaldulensis	Jun-01	333	11.5 e	0.6 de	8.2	4.6 c	5.7	–	–	–	28.9 a
	Sep-02	383	12.5 d	0.6 d	7.1 bc	4.5 ab	2.6 b	–	–	–	30.7 a
Average		**358**	**12.0**	**0.6**	**7.7**	**4.6**	**4.2**	**–**	**–**	**–**	**29.8**
T. sericea	Sep-02	421	15.7 c	0.8 c	7.0 bc	1.3 c	2.3 b	–	–	–	26.9 ab
Natural fallow	Nov-00	–	4.6	0.8	6.3	–	–	–	–	–	–
	Jun-01	358	4.5	0.8	4.8	3.2	4.1	–	–	–	92
	Sep-02	445	9.6	1.6	19.3	–	–	–	–	–	46.9
Average		**402**	**6.2**	**1.1**	**10.1**	–	–	**–**	**–**	**–**	**69.5**
Grand average		***414***	***18.8***	***0.9***	***7.0***	***7.8***	***4.8***	***299***	***131***	***16.8***	***24.9***
LSD (species)	Mar-00	–	–	–	–	ns	1.59*	–	–	–	–
	Nov-00	42.5*	4.0***	0.03***	1.33***	1.31***	3.96ns	–	–	–	36.2***
	Jun-01	34.9ns	2.4***	0.11***	2.63ns	1.39***	3.91ns	–	–	–	48.7***
	Sep-02	59.1ns	2.9***	0.12***	2.19**	2.4**	2.0*	–	–	–	39.7***
LSD (period)		15.7***	1.14***	0.03***	2.49***	1.52***	1.13***	–	–	–	14.5***

[†]ANOVA was carried out for the leaves of trees only, means with different letters in the column per each period are significantly different by Fisher's PLSD test (* = $P<0.05$; ** = $P<0.01$; *** = $P<0.001$), ns = no significant differences among the means, – = not determined.

4.2.4 Data processing

The amounts of litter dry weight and nutrients remaining in the litterbag at each sampling time were determined using procedure of Guo and Sims (1999) and Gachengo et al. (1999). The amount of nutrients remaining in the litterbag at each sampling time was determined by multiplying the mass of leaves remaining by the nutrient mass fraction. It has been assumed that release or immobilization of nutrients equals the difference in nutrients contained in the plant materials between day 0 and the sampling time (Gachengo et al. 1999).

The litter disappearance of the leaves was assumed to proceed following first-order kinetics (Olson, 1963):

$$dW/dt = -kW \qquad \text{Equation 4.1}$$

After integration,

$$W_t = W_0 e^{-kt} \qquad \text{Equation 4.2}$$

where W is the weight remaining at time t, W_0 the initial weight, 'e' is the base of natural logarithm, k is a constant, and t is time (days). To estimate k, the above formula was reorganized to:

$$\ln W_t = \ln W_0 - kt \qquad \text{Equation 4.3}$$

$$k = [\ln(W_0/W_t)]/t \qquad \text{Equation 4.4}$$

By plotting $\ln W_t$ versus time, coefficient k was derived from the slope of the linear regression line. Half-life ($t_{0.5}$), the time when 50% of the leaves have been disappeared (or half of the nutrients have been released) was calculated as:

$$t_{0.5} = \ln(0.05)/k = 0.693/k \qquad \text{Equation 4.5}$$

A dynamic decomposition rate, K, and the speed of 'ageing' of the substrate (S) (Janssen 1984; Yang and Janssen 2000) were also determined as coefficient k was found to decrease with time. According Yang and Janssen (2000), the first-order kinetic applies but the relative mineralization rate decreases over time. The average rate between times 0 and t (K) is calculated with Equation 4.4, and is derived directly from data on remaining materials. Next log K is plotted against log t, resulting in a linear relationship:

$\log K = \log R - S \log t$, or $K = Rt^{-S}$ Equation 4.6

in which R (dimension t^{S-1}) represents K at t = 1, and *S* (dimensionless, $1 \geq S \geq 0$) is a measure of the rate at which K decreases over time, also called the speed of 'ageing' of the substrate.

4.2.5 Statistical analysis

Analysis of variance was conducted using ANOVA procedure of GenStat (Payne et al. 2002) to determine the effects of treatments on leaf quality, litter fall, mean percent weight remaining and nutrient release. When data were not normally distributed they were $\log_{10}$ transformed before carrying out the ANOVA. Fisher's $PLSD_{0.05}$-tests were used to separate treatment means differences between the different plant materials when parameters were significantly different at $P < 0.05$.

Table 4.2. Contents of neutral detergent fibre (NDF), acid-detergent fibre (ADF), lignin (L) and total soluble polyphenols (PP) in the *Acacia*, *Senna*, *Leucaena*, and *Eucalyptus* leaf residues.

Treatment	NDF	ADF	L	PP
	%			
Acacia crassicarpa	56.7 a	54.8 a	11.3	6.58 b
A. crassicarpa (fallen leaves)	–	–	11.6	4.62 c
A. crassicarpa (old)	–	–	11.9	1.57 d
A. julifera	46.4 c	47.6 a	11.3	7.29 b
A. leptocarpa	50.3 b	51.4 a	10.5	11.12 a
Leucaena pallida	42.1 d	29.2 b	9.7	10.18 a
Senna siamea	47.8 c	35.6 b	5.3	7.76 b
Eucalyptus camaldulensis	–	24.8 b	3.4	12.49 a
$LSD_{0.05}$	1.73***	11.2***	ns	0.90***

Values followed by different letters in a column are significantly different using Fisher's Protected Least Significant Difference test. *** indicate significance at the 0.1%, ns = not significant and – = not determined.

4.3 Results

4.3.1 Mass fractions of carbon and nutrients in leaves

Carbon and nutrient mass fractions in the leaves varied with plant species and time of sampling (Table 4.1). Carbon mass fractions ranged from 333 to 523 g kg^{-1}, which is in the range of 290 to 700 g kg^{-1} for leaves in the organic resource database (ORD) compiled by Palm et al. (2001a). The mean mass fraction was 414 g C kg^{-1}, and the majority had values between 350 and 445 g kg^{-1} (Table 4.1).

The N mass fraction was significantly higher for *L. pallida* than for *S. siamea* and *Acacia* species at all sampling times (Table 4.1). *Acacia* species had N mass fractions ranging from 11.4 to 25.1 g kg^{-1} with *A. julifera* having the highest content and *A. leptocarpa* the least. Fresh fully-grown leaves of *A. crassicarpa* had higher N mass fraction than old leaves (Table 4.1). In November 2000, leaf N mass fraction was lowest.

The P mass fraction ranged between 0.1 to 2.9 g kg^{-1}, with highest values in *L. pallida* followed by *S. siamea*. Acacia samples had P mass fractions less than 1.0 g kg^{-1} on average. In September 2002, when plant samples were collected from the coppicing trees, *S. siamea* had a significantly higher P mass fraction than acacia and leucaena species.

Mean K mass fractions ranged from 5.2 to 10.1 g kg^{-1}, and were highest in *T. sericea* natural fallow and least in Acacia species. There were significant differences between sampling periods and among species, except in June 2001 (Table 4.1).

Mean Ca mass fractions ranged from 4.6 to 10.8 g kg^{-1}, and were highest in *S. siamea*. Means of species were not significantly different. Mean Mg mass fractions ranged from 4.2 to 5.7 g kg^{-1}. Mean mass fractions for Mn, Fe and B were 299, 131, and 16.8 mg kg^{-1}, respectively. Generally, acacias had relatively high Mn contents.

The neutral detergent fibre (NDF) content ranged from 42 to 57% and was on average lower in *L. pallida* than in *Acacia* and *Senna* species (Table 4.2). Acid-detergent fibre (ADF) and total soluble polyphenols (PP) were significantly (P <0.001) different among species. ADF content followed the order: *Acacia* > *Senna* > *Leucaena* > *Eucalyptus*. Lignin (L) did not differ significantly (P >0.05) between species (Table 4.2). Contrarily, PP was highest in *E. camaldulensis* and lowest in *A. crassicarpa*. ADF was positively correlated with lignin (Figure 4.2a) and negatively with PP (Figure 4.2b). Vanlauwe et al. (2001) reported similar relationships.

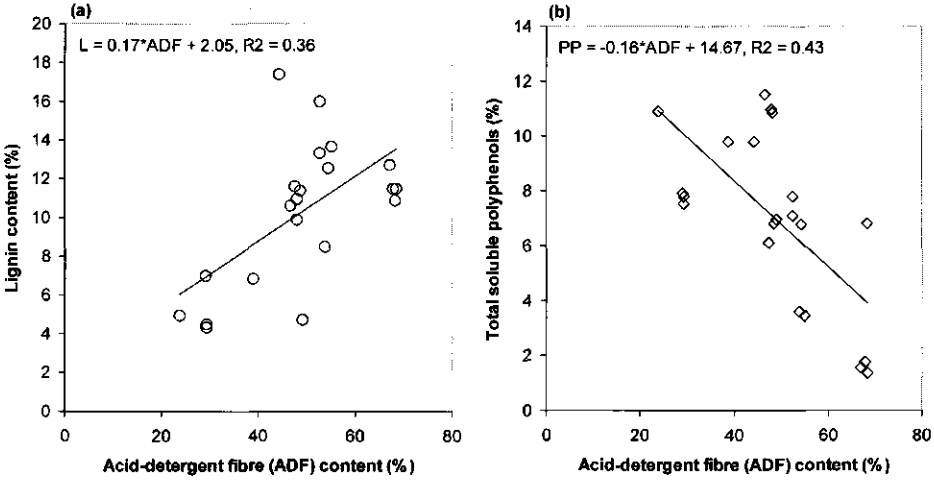

Figure 4.2. Linear relationships between (a) lignin (L) and acid-detergent fibre (ADF) content, and (b) total soluble poly phenol (PP) and ADF contents for *Acacia*, *Senna*, *Leucaena* and *Eucalyptus* leaf residues.

Table 4.3. Resource quality descriptors of tree leaves sampled in November 2000.

Treatment	Quality parameters						
	C:N	C:P†	N:P	K:P	L:N	PP:N	(L+PP): N
Acacia crassicarpa	27.0 d	955 c	35.3 b	12.0 c	8.6 bc	5.0 bc	13.6 abc
A. crassicarpa (fallen leaves)	32.2 bc	1352 b	42.0 b	20.7 b	9.2 b	3.6 c	12.8 bc
A. crassicarpa (old)	54.3 a	3417 a	63.0 a	60.2 a	15.9 a	2.1 c	18.0 ab
A. julifera	32.2 bc	727 d	22.6 c	13.0 c	9.1 b	5.7 b	14.8 abc
A. leptocarpa	34.5 b	792 d	23.0 c	12.1 c	9.2 b	9.8 a	19.0 a
Leucaena pallida	17.5 e	341 f	20.1 cd	13.3 c	5.2 bc	5.1 b	10.3 c
Senna siamea	29.6 cd	434 e	14.6 d	9.8 c	4.0 c	5.9 b	9.9 c
LSD$_{0.05}$	3.6***	***	7.6***	5.2***	4.97**	1.4***	5.8*

Values followed by different letters in each column are significantly different from each other at P <0.05 using Fisher's Protected Least Significant Difference test. *, **, and *** indicate significance at the 5, 1 and 0.01%, respectively. ns = not significant. †C:P ANOVA is from log$_{10}$ transformed data.

The ratios of the nutrient contents in the leaves were significantly different among species (Table 4.3). The leaves of acacias had relatively high C:N, C:P, N:P, K:P and L:N ratios. *Senna siamea* had the lowest N:P, K:P and (L+PP):N ratios. Old leaves tended to have the highest values for C:N, C:P, N:P, K:P and L:N ratios, but not for PP:N and (L+PP):N. The C:N, C:P, N:P and K:P quotients were high compared to those found by Van Reuler and Janssen (1989) and Palm et al. (2001). Leucaena had a lower C:N ratio than other legumes. Mafongoya et al. (1998; 2000) reported similar C:N and L:N ratios for leucaena leaves. Compared to N_2 fixing species, the non-fixing senna had a low N:P ratio.

4.3.2 *Litter fall dynamics*

Monthly litter fall (January–October 2001) ranged from 0.05 to 2.32 Mg ha^{-1} (Figure 4.3). Highest monthly and total (Figure 4.4) litter fall was recorded in *A. julifera* and *A. leptocarpa* followed by *S. siamea*, *A. crassicarpa*, and finally *Leucaena pallida.* Species showed a major peak of litter fall during the dry season (June–August) and a smaller peak in March–April, but in the case of *S. siamea* litter fall consistently increased from January to September.

Percentage contributions of various litter components (leaves, fine wood and other unidentified materials) to the total litter fall differed significantly among species. The contribution of the reproductive parts was higher ($P < 0.05$) in leucaena than in other species (Figure 4.5). Leaves contributed significantly ($P < 0.001$) more than the other components (fine wood, reproductive parts and) in all species except in the case of *L. pallida* (12.1%), where the major contribution was from fine wood (52.2%) and reproductive parts (34.3%).

4.3.3 *Decomposition of leaves*

Percentages of leaf mass remaining in the bags at each sampling date are shown in Figure 4.6. The mass remaining in the litterbags decreased with time for all species. The percentage of litter remaining after 90 days ranged between 17.9 and 61.9% and after 360 days between 10 and 30%, and was least for *L. pallida* and *S. siamea*. The rate coefficient (k) and half-life period ($t_{0.50}$) of leaf disappearance are presented in Table 4.4. Rate coefficient k ranged from 0.0104 (*L. pallida*) to around 0.005 (*Acacia* species), and half-lives from 9.5 to 20 weeks. The regressions of the remaining materials versus time were highly significant ($P < 0.01$) for all species (Table 4.4).

However, the values of R^2 were on average a little higher when the data were fitted to the model of Yang and Janssen (2000) with variable rate coefficient, suggesting indeed that the decomposition rates decreased over time.

Table 4.4. Rate coefficient (k, day^{-1}) and half-life ($t_{(0.5)}$, days) of different species for the litterbag experiments. *R (dimension t^{S-1}) represents variable K at t = 1, and *S* (dimensionless, $1 \geq S \geq 0$) is a measure of the rate at which K decreases over time. R^2 = correlation coefficient.

	Constant k			Variable K		
Species	k	$t_{(0.5)}$	R^2	*R	S	R^2
Acacia crassicarpa	0.0046	150	0.97	2.89	0.47	0.92
A. julifera	0.0050	139	0.90	2.86	0.46	0.94
A. leptocarpa	0.0044	158	0.93	3.05	0.44	0.94
Senna siamea	0.0086	81	0.89	2.11	0.48	0.92
Leucaena pallida	0.0104	67	0.93	1.52	0.53	0.97

Table 4.5. Correlation coefficients (R^2) for linear relationship between disappearance rate coefficients (k) for *Acacia*, *Leucaena* and *Senna* species and initial quality parameters, N and P. Regression lines are of the shape Y = a + b*x*, with Y = rate coefficient k.

Quality parameter	a	b	R^2
P	0.0003	0.0094	0.95
C:P	0.0132	0.0001	0.90
L:N	0.0139	-0.001	0.82
ADF	0.0161	-0.0002	0.76
N	-0.0018	0.0006	0.68
(PP + L): N	0.0146	-0.0006	0.67
C:N	0.0155	-0.0003	0.59
L	0.0128	-0.0006	0.35
PP:N	0.0102	-0.0006	0.18
PP	0.0036	0.0004	0.06

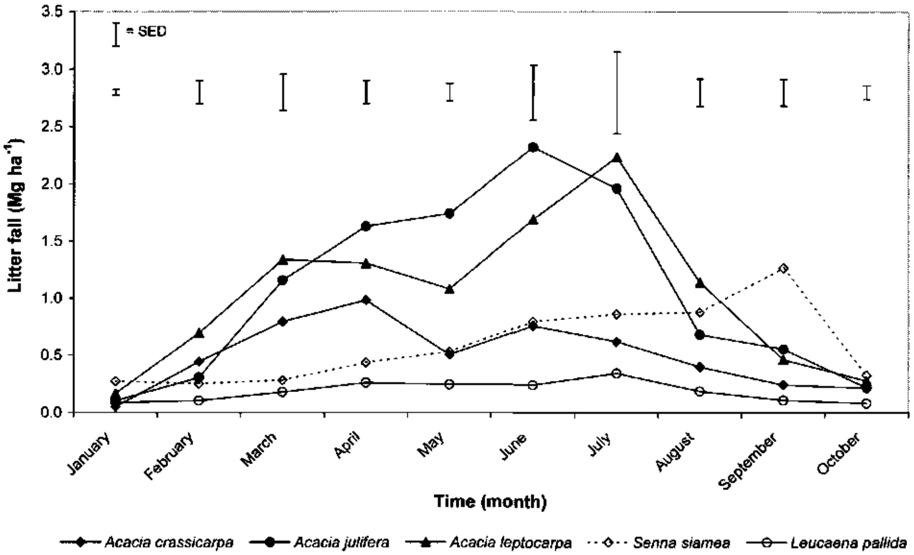

Figure 4.3. Total monthly litter fall (Mg ha^{-1}) of five tree species in rotational woodlots at Tabora Tanzania. SED is the standard error of differences of means.

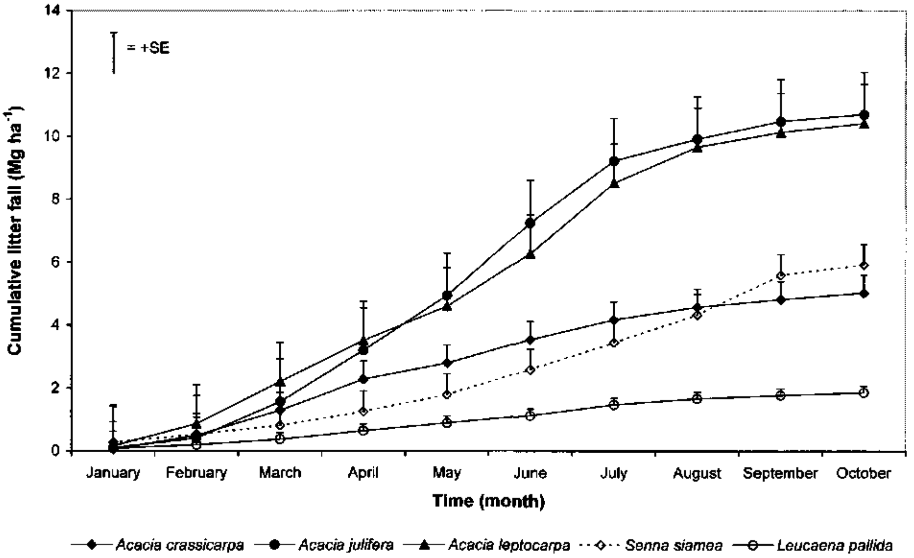

Figure 4.4. Cumulative litter fall (Mg ha^{-1}) of five tree species in rotational woodlots at Tabora Tanzania. SE (+) is the standard error on mean.

When plotting the rate coefficients k against the various initial resource quality parameters, the best correlation was obtained for P mass fractions (Figure 4.7). ADF, C:P and L:N ratios were better correlated with the rate coefficients than N mass fractions, C:N and (L+PP):N ratios. The relationship with L, PP:N, and PP were poor (Table 4.5). However, these results must be verified using more tree species, as we measured only few tree species

4.3.4 Nutrient dynamics in decomposing leaves

Changes of nutrient mass fractions in remaining leaf litter were related to the initial nutrient mass fraction (Table 4.6). The mass fractions of N, P, and Ca showed clear differences among species, but K and Mg did not differ significantly on most sampling dates. This was also the case for the C mass fractions and C:N ratios (Figure 4.8). The C mass fractions of about 300 g kg^{-1} are remarkably low. Therefore we decided to calculate the ratio of mass fraction of nutrients to the mass fraction of carbon (Figure 4.9). The general pattern of the release of nutrients relative to the release of C is shown in Figure 4.9.

Mass fractions of N in the remaining organic material and 100 N:C tended to increase with time (Table 4.6; Figure 4.9). The increase of N was probably due to N accumulation in microbial biomass (Janssen 1996; Giller 2001). Differences in N mass fractions between species remained more or less constant during the incubation period. Phosphorus content tended to decrease with time, but there was quit some variability, suggesting both variations in P mineralization and immobilization and leaching patterns. Leaching of soluble forms of P probably caused the rapid initial loss of P in leaves. Differences in P mass fractions between species tended to decrease with time. Our results agree with those reported by Mafongoya et al. (2000) for local *Acacia* species (*A. karro* and *A. nilotica*) and *Gliricidia sepium* species. All species lost K very rapidly, probably by leaching. This loss was more rapid in leucaena and senna, which were initially rich in K, than in acacia species. As a result, differences among species in K mass fraction became smaller (Table 4.6). Calcium mass fractions remained rather stable during the 360-days incubation period, while Mg was stable in the first half, and decreased in the second half of the incubation period (Figure 4.9).

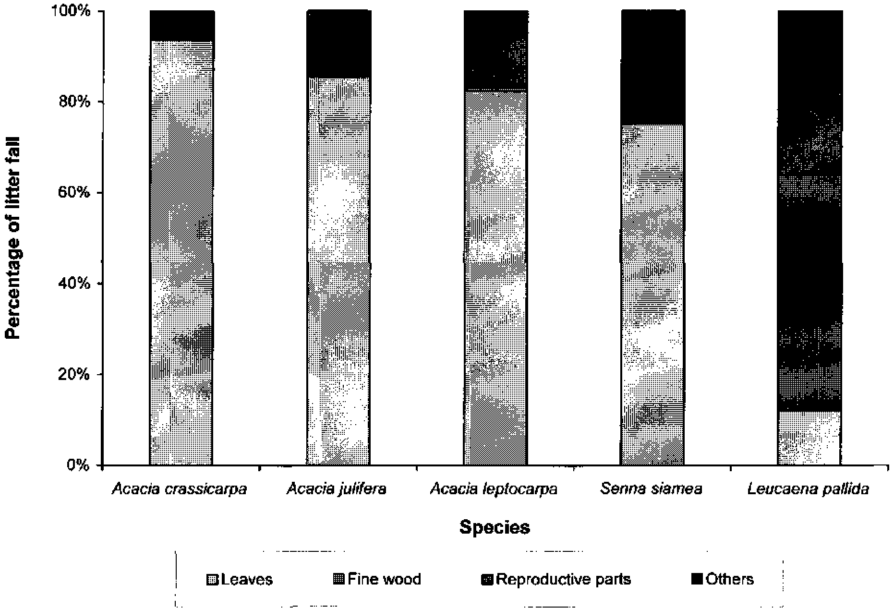

Figure 4.5. Relative contribution of various components to total litter collected from January 2001 to October 2001.

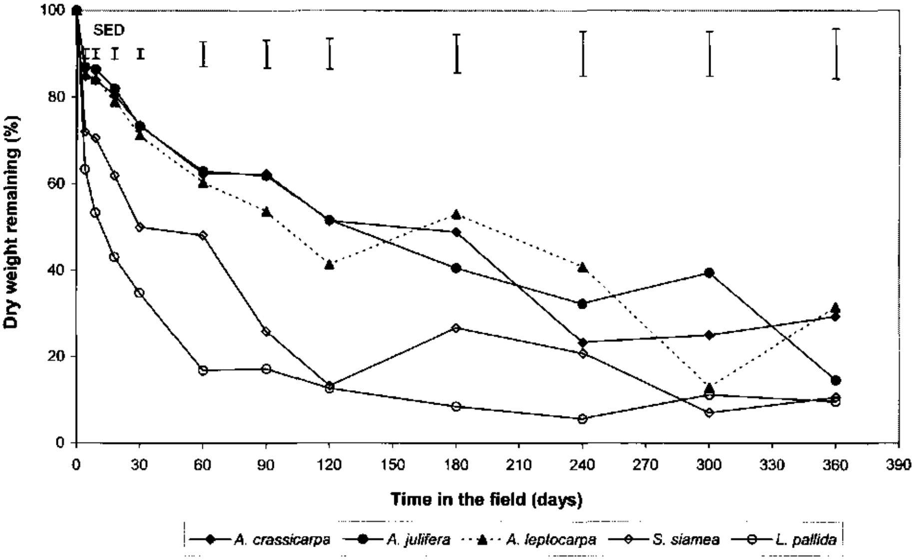

Figure 4.6. Dry weight remaining (%) of the bagged leaf litter of five woody species over the 360-day period. Vertical bars indicate $SED_{0.05}$.

Leucaena pallida released nutrients significantly faster than other species (Figure 4.10). After 90 days more than 80% of the initial amounts of C and nutrients in *L. Pallida* leaves had been released. In contrast, *A. leptocarpa* had released less than 10% of the initial N and Mg, 40% of the initial P and Ca and almost 80% of its initial K.

The initial rapid decrease in C may be ascribed to the rapid release of total non-structural carbohydrates such as sugars, and starches, which can be rapidly utilized by microbes (Mfilinge and Tsuchiya 2002). Given the high mass fractions of NDF in acacia leaves these non-structural carbohydrates were probably low. The slow decreasing rate is related to the increasing contents of structural compounds (such as lignin and celluloses; Figure 4.11) resulting from the loss of the other constituents (sugars and starches). The mass fractions of lignin and ADF increased rapidly in all species, but remained the lowest in *S. siamea.*

After 30 days, about 52, 72, and 94% of N, P, and K had been released from leucaena leaves, 48, 64, 87% from senna leaves and only between 1-26%, 36-46%, and 62-73% from acacias leaves, respectively (Figure 4.10b-d). This clearly indicates that there were large differences in initial rates of nutrient release between tree species. Among acacias, *A. julifera* released N, P and K faster than others. Potassium is not associated with C (Zaharah and Bah 1999), and is almost entirely lost (62-94%) in just 30 days. This is also supported by Figure 4.9 whereby K:C ratio decreased much sharper than others.

4.4 Discussion

4.4.1 Resource quality

Acacia and senna leaves were of lower quality than leucaena leaves (Table 4.1). The N mass fractions of the leaves of all materials except for leucaena were lower than the critical level of 25.0 g kg^{-1}, below which point net immobilization of N from the soil would be expected. The P content of acacia and senna was far below the critical level of 2.5 g kg^{-1} (Kwabiah et al. 2001) and P immobilization would be expected. However, the observed contents are within the range found by others for Sub-Saharan Africa (Karachi et al. 1997; Karachi 1998a, 1998b). In all species the N:P ratio was well over 15, and the K:P ratio was over 10, except in *S. siamea*, indicating deficiency in P (Van Reuler and Janssen 1989).

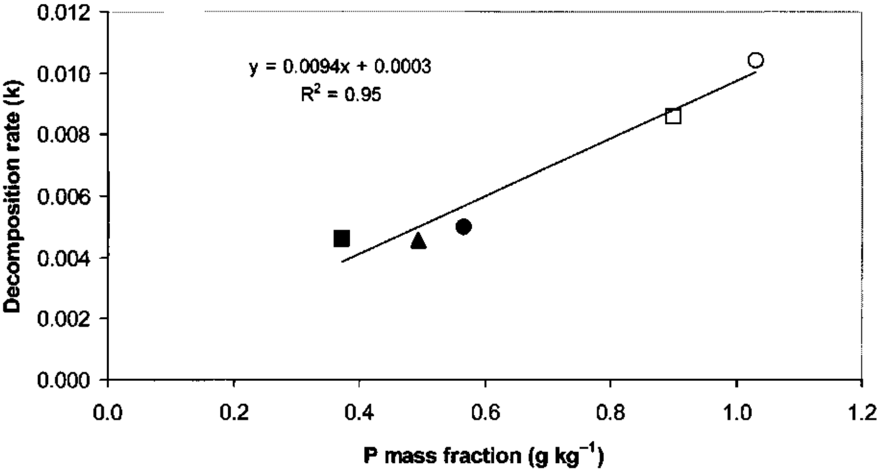

Figure 4.7. The relationship between rate coefficient (k) and the P mass fraction. Open circle = *L. pallida*; open square = *S. siamea*; closed circle = *A. julifera*; closed triangle = *A. leptocarpa*; closed square = *A. crassicarpa*.

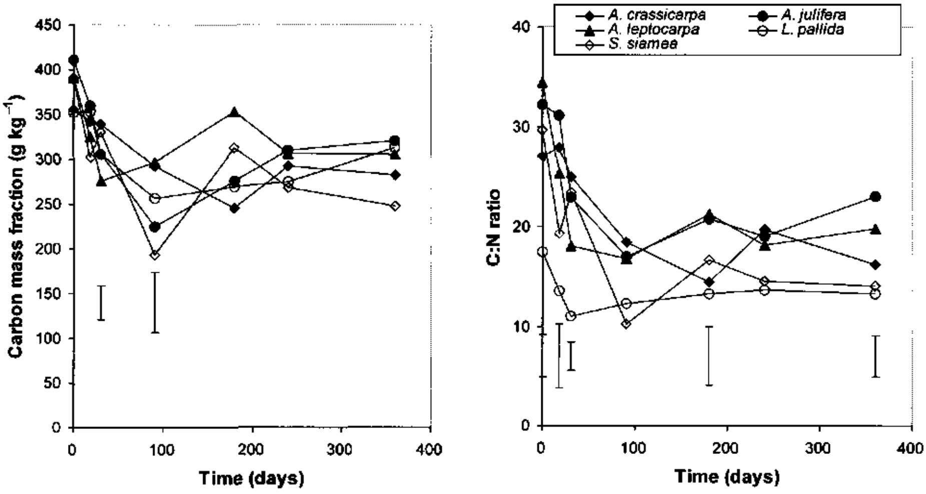

Figure 4.8. Changes in C mass fractions (g kg^{-1}) and C:N ratio of leaves of *Acacia*, *Leucaena* and *Senna* species during the litterbag incubation experiment. Vertical bars indicate $LSD_{0.05}$, only when the treatments are significant different.

Lignin mass fractions in leaves were less than 150 mg g^{-1}, which is lower than expected for Australian *Acacia* species (P. Mafongoya 2000 pers. comm.). Mass fractions of PP ranged between 16 to 125 mg g^{-1}. Most of the samples contained more than 30 mg g^{-1}, which is the median value for fresh leaves (Palm et al. 2001a). According to Constantinides and Fownes (1994a), PP content of green foliage of agroforestry species can be as high as 100 mg g^{-1}, depending in part on the extractant and tissue-to-solvent ratio. Handayanto et al. (1995) found higher PP contents within a given species on soils poor in N than on more fertile soils. This is probably also the case in the present study where soil N content is low. However, the relationship between soil fertility and PP contents in plants is still poorly understood.

For all species the ADF content was positively correlated with the lignin content (Figure 4.2a) and negatively with the PP content (Figure 4.2b). The ADF content were relatively high in *S. siamea* compared to what has been reported by Vanlauwe et al. (2001). The difference may be related to the maturity of the leaf samples. We used relatively mature leaves wherein cell-wall formation and lignification will have started already (Mafongoya et al. 1998). Vanlauwe et al. (1994) observed that the major process that led to a decrease in N content of older leucaena and senna leaves was the increase in cell-wall materials, which contain relatively low amounts of N. This may probably also apply to the *Acacia* species in our study, as these had relatively high lignin and very high ADF contents. Another explanation of high ADF content may be that other cell wall components e.g. hemicelluloses, had been formed.

Based on the decision tree developed by Palm et al. (1997) and presented in Figure 4.1, we conclude that for a quick nutrient release to the subsequent crop the leafy materials used in this study need to be composted or mixed with fertilizer before they are added to soil. Composting of litter, however, is not a practical suggestion. We can only speculate about possible soil organic matter changes over many years when more litter will have been accumulated (Plate 4.1), and in part will have been sequestered in the soil.

Table 4.6. Changes in mass fractions (g kg^{-1}) of C, N, P, K, Ca, and Mg of leaves of *Acacia*, *Leucaena* and *Senna* species during the litterbag incubation.

	Species	Time (days)						
		0	18	30	90	180	240	360
Carbon	*A. crassicarpa*	356	342	339 a	293 a	246	292	283
	A. julifera	411	360	305 ab	225 b	276	310	321
	A. leptocarpa	391	325	276 b	297 a	353	307	305
	L. pallida	352	354	306 ab	257 ab	270	275	313
	S. siamea	390	302	331 a	194 b	313	269	248
	Mean	**380**	**337**	**311**	**253**	**292**	**291**	**294**
	LSD$_{0.05}$	Ns	Ns	37.8*	66.8*	Ns	Ns	ns
Nitrogen	*A. crassicarpa*	13.2 b	12.3 bc	13.6 b	15.9	17.2 b	14.9 c	17.4 b
	A. julifera	12.8 b	11.7 c	13.3 b	13.3	13.2 c	16.0 bc	13.9 b
	A. leptocarpa	11.4 b	12.9 bc	15.3 b	17.7	16.7 b	16.9 abc	15.5 b
	L. pallida	20.9 a	26.4 a	28.0 a	23.8	20.3 a	19.7 a	24.7 a
	S. siamea	13.2 b	15.8 b	14.2 b	18.6	18.7 ab	18.7 ab	18.0 b
	Mean	**14**	**16**	**17**	**18**	**17**	**17**	**18**
	LSD$_{0.05}$	4.90*	3.55***	3.68***	ns	2.23***	3.23*	6.63*
Phosphorus	*A. crassicarpa*	0.37 e	0.23 d	0.28 b	0.29 c	0.34 d	0.34 c	0.32 d
	A. julifera	0.57 c	0.36 c	0.45 b	0.33 c	0.39 cd	0.58 b	0.39 cd
	A. leptocarpa	0.49 d	0.36 c	0.43 b	0.43 c	0.53 c	0.56 b	0.46 bc
	L. pallida	1.03 a	0.71 a	0.84 a	0.70 b	0.71 b	0.53 b	0.57 b
	S. siamea	0.90 b	0.60 b	0.67 a	0.86 a	1.07 a	0.96 a	0.79 a
	Mean	**0.67**	**0.45**	**0.53**	**0.52**	**0.61**	**0.59**	**0.51**
	LSD$_{0.05}$	0.04***	0.06***	0.19***	0.26**	0.14***	0.12***	0.14***
Potassium	*A. crassicarpa*	4.45 d	3.07	2.12	1.13 ab	0.78	0.46	0.38
	A. julifera	7.35 bc	2.81	2.81	1.36 a	0.37	1.04	0.29
	A. leptocarpa	5.96 cd	3.34	3.12	1.27 ab	0.87	0.46	0.69
	L. pallida	13.65 a	3.45	2.65	0.70 bc	0.60	0.27	0.37
	S. siamea	8.81 b	4.31	2.31	0.46 c	0.62	0.63	0.30
	Mean	**8.04**	**3.40**	**2.60**	**0.98**	**0.65**	**0.57**	**0.41**
	LSD$_{0.05}$	1.67***	Ns	ns	0.64*	Ns	ns	ns
Calcium	*A. crassicarpa*	7.20 b	5.17	4.88 cd	3.92 c	6.50 b	4.46 d	5.99 b
	A. julifera	5.69 c	7.99	3.98 d	5.08 bc	5.61 b	9.77 b	5.66 b
	A. leptocarpa	6.58 bc	4.82	6.27 c	5.29 bc	13.65 a	6.33 c	6.45 b
	L. pallida	7.19 b	8.97	8.70 b	7.56 b	6.96 b	5.64 cd	6.28 b
	S. siamea	11.05 a	13.35	14.41 a	14.16 a	8.87 ab	15.54 a	12.09 a
	Mean	**7.54**	**8.06**	**7.65**	**7.20**	**8.32**	**8.35**	**7.29**
	LSD$_{0.05}$	1.19***	Ns	1.71***	2.70***	5.02*	1.51***	1.26***
Magnesium	*A. crassicarpa*	6.02	5.59	7.59	5.92 b	8.60	1.11 e	1.67 a
	A. julifera	5.19	5.19	7.13	6.24 b	6.64	2.19 c	1.91 a
	A. leptocarpa	5.53	5.60	6.26	7.76 a	7.36	6.49 b	1.67 a
	L. pallida	7.30	6.54	7.31	6.87 ab	7.10	6.89 a	1.07 ab
	S. siamea	4.59	4.29	5.95	7.77 a	6.47	1.34 d	1.41 b
	Mean	**5.73**	**5.44**	**6.85**	**6.91**	**7.23**	**3.60**	**1.55**
	LSD$_{0.05}$	ns	Ns	ns	1.40*	Ns	0.20***	0.50*

Means with different letters in the column are significantly different by Fisher's PLSD test (* = $P<0.05$; ** = $P<0.01$; *** = $P<0.001$), ns = No significant differences among the means.

4.4.2 Leaf litter fall

Acacia julifera and *A. leptocarpa* had much larger total litter production than *L. pallida*. The difference in litter fall could be a response to drought stress. The peak of litter fall in the tropics usually coincides with the dry season (Salako and Tian 2001). We observed also a peak in litter fall during the dry season. With the exception of *L. pallida*, the mean annual litter fall in the present study is higher than the 3 to 5 Mg ha^{-1} reported for forests (e.g., Spain 1984; Songwe et al. 1988; Visalakshi 1993; Lisanework and Michelsen 1994; Couteaux et al. 1995), but it is within the range reported for agroforestry systems (Kang et al. 1997; Salako and Tian 2001). Apparently, these introduced tree species produce more litter and by that contribute more to nutrient cycling than the indigenous tree species.

Since leaf fall is the main source of surface litter, it will influence the food supply to macro- and micro-fauna population in the soil. Differences in the seasonal litter fall pattern between planted and natural fallows suggest that the introduction of planted woodlots requires native soil fauna to adjust to the different litter fall patterns exhibited by the planted species (Adejuyigbe et al. 1999). We found that mycorrhizal fungi were flourishing under the woodlots during the fallow phase (Plate 4.2). However, we did not assess possible changes in mycorrhizal association and fauna population. This may be an interesting topic for further research.

4.4.3 Litter decomposition and nutrient release

The rate of decomposition was greater for *L. pallida* and *S. siamea* leaves than for the *Acacia* species. This may be explained by the relatively high levels of N and P, and low levels of lignin, which may form complexes with proteins, in leucaena and senna relative to the acacia species (Handayanto et al. 1994; Mafongoya et al. 2000).

Although the established relationships between resource quality parameters and decomposition rates seem to be generally accepted now, a number of exceptions reveal that the proximate mechanisms of resource quality controls on microbial processes are more complex than initially thought (Heal et al. 1997). In our study, time-course differences in mass losses among woody species were not as directly predictable from initial N, lignin or PP of tree species, and the C:N and lignin plus PP:N ratios, as reported by Palm and Sanchez (1991), and Mafongoya et al. (1998, 2000). Our results indicate that initial P contents, the C:P and L:N ratios were the better indicators for decomposition rate. Recently, Sariyildiz and Anderson (2003)

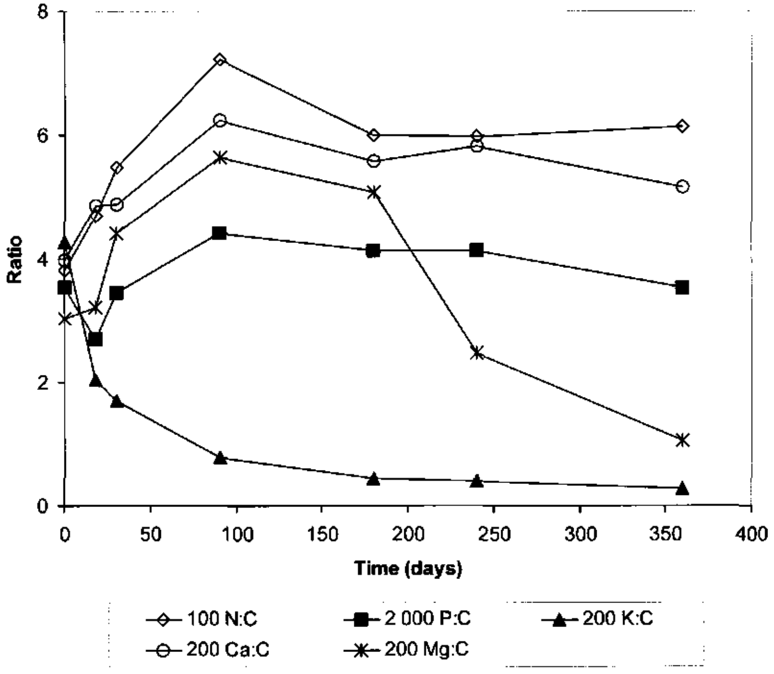

Figure 4.9. Nutrient to carbon ratios of *Acacia*, *Leucaena* and *Senna* species leaves during the litterbag incubation period. The ratios of nutrients to C were chosen in such a way that all fitted to the same scale.

also reported controversial results for woody species. All these results suggest that for leaf litter of woody species in agroforestry systems the relationship between resource quality and rate of decomposition needs further study.

The initial nutrient mass fractions in woodlot leaves were the most important factor for nutrient release (Table 4.5 and Figure 4.10). The slight accumulation of N in acacia leaf residues may be related to conservation of N by decomposers (Mellilo et al. 1984). The extremely low P contents and the high C:N and C:P ratios of acacia and senna tree components suggests that rates of N and P immobilization may be high in the established woodlots, rendering N and P initially unavailable to the subsequent crops.

Evidently, the differences in litter quality and litter production between different agroforestry species have direct implications to soil management. The short-term supply of plant available N by *Acacia* species will be low, but these species have higher litter fall and may add large quantities of organic matter to the soil, which may be beneficial on the long-term.

Though the leaf degradation patterns were similar, *L. pallida* and *S. siamea* degraded faster than *Acacia* species. The slow decomposition rate of leaves of Australian *Acacia* species will result in a slow release of nutrients to subsequent crops. In fact, this feature has been one of the main reasons for opposing the establishment of for example eucalypt plantations in semi-arid areas if not supplemented by inorganic fertilizer during re-cropping after woodlots (Jagger and Pender 2003). Evidently, Australian acacia leaves are not direct sources of N for maize planted after the harvesting of the trees. They may instead be important in improving organic matter levels, and thereby in increasing the cation exchange capacity and structure of soils in the long term. Inputs of soil organic matter play an important role in sustaining soil fertility (Swift et al. 1979).

Mafongoya et al. (1997) observed an improvement in N recovery efficiency when low quality (high C/N ratio) crop residues were amended with high quality (low C/N ratio) pruning materials, but Makumba (2003) indicated that the effects were only additional. The high quality prunings are suggested to provide mineralized N to the microbial community to decompose the low quality prunings. Another option is the amendment of low quality leaf litter with inorganic fertilizers. Addition of small amounts of inorganic sources of N and P to low quality materials such as Australian acacia leaves may decrease the period of N immobilization. This value of fertilizer application is addressed in Chapter 6 of this thesis, where the results are presented of a large 3^3 factorial NPK trial with maize grown on cleared woodlots.

Assessment of residue quality needs to take into account canopy age, as residues may be applied to the soil on system-specific intervals. A one-time measurement of residue quality of one-time sampled leaf materials may not be an appropriate mean estimate of residue quality for specific species (Vanlauwe et al. 2001). In woodlot systems, litter accumulates over three to four years, and trees are cut after four to five years. Inclusion of categories for leaf age in the organic resource database could improve the validity and range of applicability. In our study we used relatively mature leaves, which led to the results indicating a relatively poor quality leaves for all species. In view of the analytical results of the old leaves of *A. crassicarpa* (Table 4.3) old leaves are expected to have an even poorer quality.

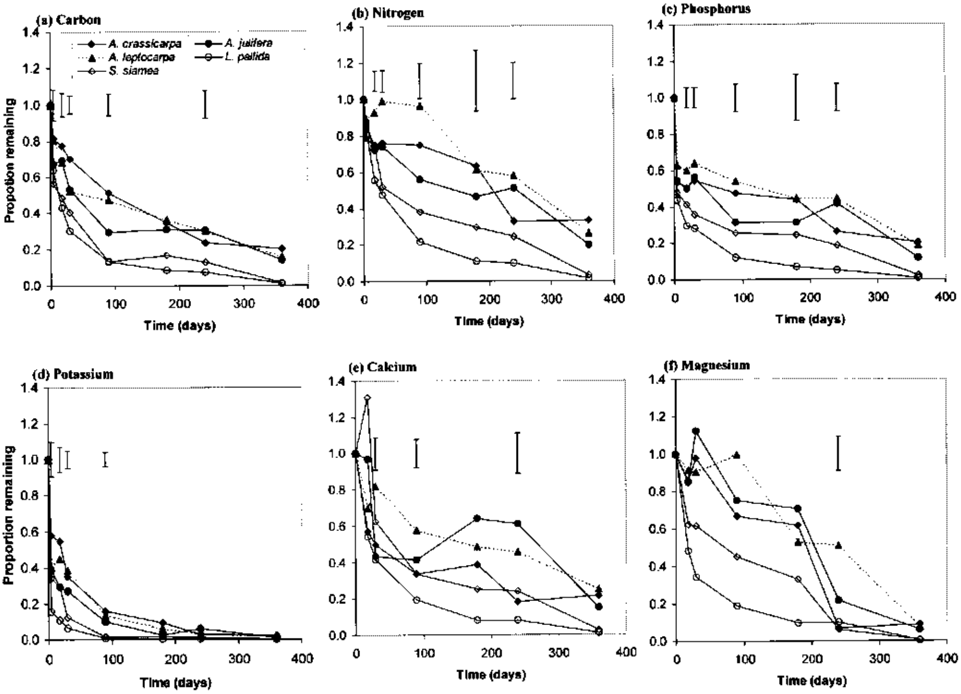

Figure 4.10. Carbon and nutrients release patterns for leaves of *Acacia*, *Leucaena* and *Senna* species in the litterbag incubation experiment. Vertical bars indicating $LSD_{0.05}$, are shown only when the treatments are significantly different.

Plate 4.1. Significant amount of *Acacia crassicarpa* litter accumulates during the fallow phase.

4.5 Conclusion

Tree species significantly differed in litter production, leaf decomposition and nutrient release patterns. Decomposition rates were better related to initial P, C:P and lignin:N ratios than to other quality parameters, such as C:N, (soluble polyphenols plus lignin):N and polyphenols:N ratios. Our study shows clearly that senna and acacia leaves, which were poor in N and P, favoured N and P immobilization, whereas leucaena leaves rich in N, favoured net N mineralization.

In view of the large quantity and the low quality of the litter, we conclude that large amounts of nutrients are initially rendered unavailable to the subsequent crop. This suggests that external inorganic sources of N and P have to be added to the woodlot system to be able to shorten the period of N immobilization. This topic is addressed in Chapter 6.

4.6 Acknowledgements

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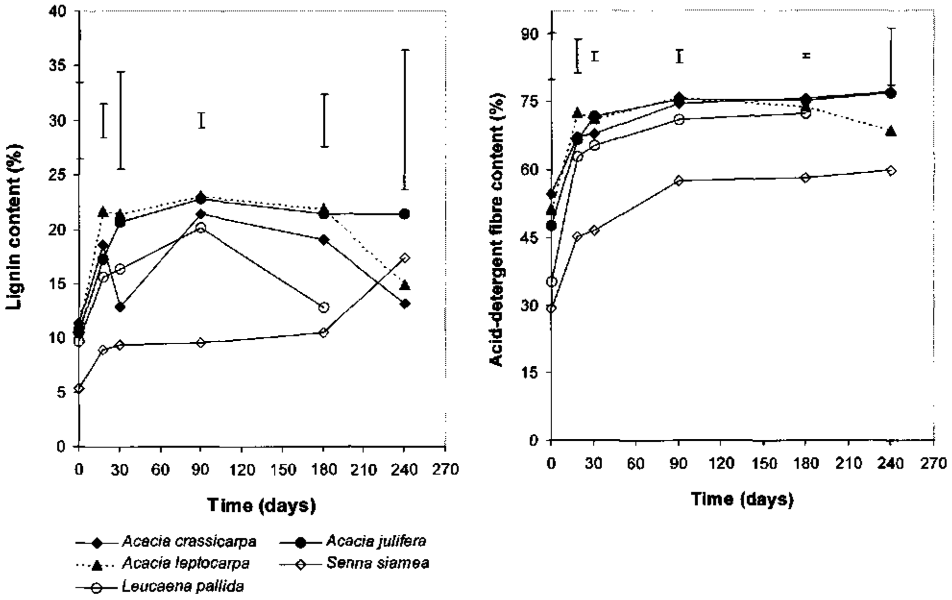

Figure 4.11. Changes in content of lignin and acid-detergent fibre of *Acacia*, *Leucaena* and *Senna* species leaves in the litterbag incubation experiment. Vertical bars indicate $LSD_{0.05}$.

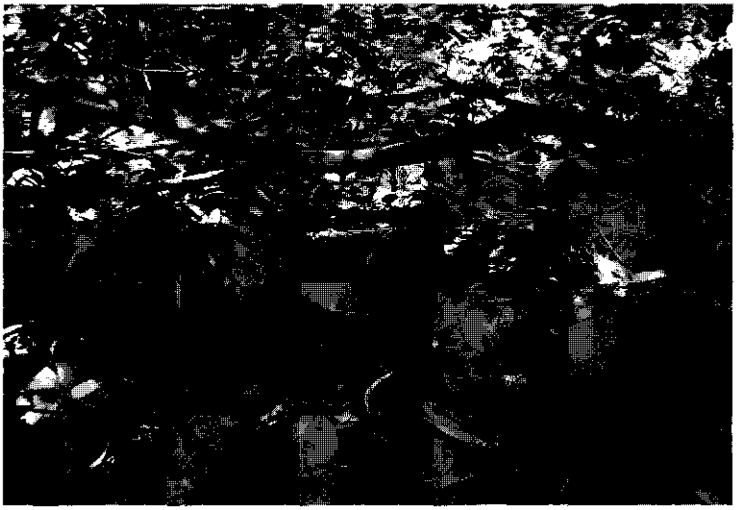

Plate 4.2. Mushrooms (mycorrhizals) flourishing under established woodlots at Tabora Tanzania.

CHAPTER 5

Assessment of tree biomass and nutrient accumulation in rotational woodlot technology in western Tanzania

Abstract

In Sub-Saharan Africa, natural forest resources are diminishing as agricultural expansion and fuel-wood pressure increase in an attempt to satisfy the demand of a growing population. Rotational woodlots have been suggested as a possible alternative for fuel-wood resources and for improving short fallow-crop cycles, but little is known about the carbon (C) and nutrient dynamics.

The objective of this study was to determine the biomass accumulation, and C and nutrients allocation in five fast growing tree species managed in a rotational woodlots system. Trees were planted on a previously cultivated, acidic soil (Acrisol/Alfisol) in western Tanzania and included: *Acacia crassicarpa, A. julifera, A. leptocarpa, Senna siamea* and *Leucaena pallida.* Biomass production of tree compartments, wood density, and C and nutrient storage were measured during tree clearing five years after planting.

The wood component constituted 32 to 85% of the total tree biomass. The rate of biomass production was highest for *Acacia* species while the foliage nutrient accumulation was highest for *L. pallida* and least for *S. siamea.* The amounts of C and total N and P in foliage biomass at tree clearing varied among species and were 1.8 to 7.9 Mg C, 69 to 539 kg N and 4.1 to 21.5 kg P ha^{-1}. Total stocks of K, Ca and Mg also varied among species and among components within species. Substantial amounts of nutrients were exported with the wood of acacia and senna at clearing: 44 to 215, 3.7 to 7.3, 28 to 86, 11 to 115, 10 to 48 kg ha^{-1} for N, P, K, Ca and Mg, respectively. These results suggest that woody species that accumulate large amounts of biomass deplete soil nutrient stocks. Evidently, there is a trade-off between fuel-wood production and soil fertility restoration. The management of woodlots on farms should aim at establishing leguminous short rotation plantations and recycling nutrients through slash and mulch techniques, and through return of ash from the burned fuel-wood back to the fields.

Key words: aboveground biomass, C sequestration, nutrient content, wood production

5.1 Introduction

The objectives of tree plantings in the tropics vary from perpetually 'natural looking forests', development of high yielding and sustainable industrial plantations for wood production, control of land degradation and development of agroforestry systems (Nambiar 1995). High biomass production is an important consideration in all-tropical tree planting programmes aimed at meeting the increasing demand for fuel-wood (firewood and charcoal) and timber. Fast growing plantation trees and secondary forests are also considered as highly efficient carbon sinks (Dyson 1977). The planting of trees and shrubs can mitigate emissions of the greenhouse gas carbon dioxide (CO_2) to the atmosphere (e.g. IPCC 1995).

In western Tanzania, there is an increasingly indiscriminate use of natural miombo forest resources due to the domestic and industrial energy crises (fuel-wood shortages). An alternative to clearing natural miombo forests in the region is to plant multipurpose trees on farmers' fields. However, the trees must be managed such that competition with crops in the cropping phase is minimised (Ong et al. 1996; Lott et al. 2000) and care must be taken that labour requirement for managing the trees suits farmer's labour endowment. Planting of trees in the form of rotational woodlots (a sequential agroforestry system) in farmers' fields has been shown to offer an alternative to clearing natural miombo vegetation (Ramadhani et al. 2002; Nyadzi et al. 2003a). To minimize competition between crop and trees it is crucial to select appropriate tree species and tree spacing design (Ong et al. 2002).

Nutrient accumulation and export from the site have become an important consideration in short-rotation, high-yield plantation systems. Nutrients removed through frequent harvests may exceed the natural rates of nutrient inputs via soil mineral weathering, atmospheric deposition and biological fixation (Hopman et al. 1993). Heavy nutrient drain may have an adverse impact on the long-term site quality as well as on the sustainability of the production. Information on wood biomass, wood quality and nutrient accumulation is required to forecast productivity and C sequestration, and to design schemes for optimum nutrient management and proper felling cycles of rotational woodlots.

The most appropriate measure of biomass is considered to be 'basic density'. In general, tree species with high density, low ash and moisture fractions are favoured as fuel woods, as they show better combustion characteristics (Shanavas and Kumar 2003). According to Fearnside (1997) the 'basic density' of wood or 'basic specific density', calculated as oven-dry weight divided by wet volume, reflects the apportioning of C within the tree and is an important factor in converting forest volume data to biomass. Wood basic density is said to be a strong indicator of successional state in tropical trees, with pioneer species being lighter than mature forest species (Fearnside 1997). Basic density is also a measure that equates to wood quality (strength in compression, tension, fuel-wood quality) (Niklas 1997).

Shade-based control of weeds is also an essential aspect of traditional bush fallow and planted tree fallow systems (Rao et al. 1998). Planted fallows can smother annual and perennial weeds by the combined effect of (i) reduced light leading to initial suppression of aboveground weed growth and (ii) a thick layer formed by the leaf litter (mulch) which subsequently deplete the weed seed-bank (De Rouw 1995).

In western Tanzania *Acacia, Senna* and *Leucaena* species, established in rotational woodlots system, have been shown to grow fast and use water and N differently under semi-arid tropics (Nyadzi et al. 2003a and b). Some of these species have been tested for biomass production in short-term rotational fallows elsewhere (Szott and Palm 1996; Bray et al. 1997; Salako and Tian 2001). Evidently, the selection of proper tree species is key to the success of rotational woodlots; all possible pros and cons need to be assessed before a proper evaluation can be made.

The overall objective of this study was to evaluate the biomass production potential of five fast growing tree species in a rotational woodlot system in semi-arid western Tanzania. Specific objectives were (1) to determine wood density for selecting trees with best qualities for fuel (2) to determine the contribution of various components to biomass production to be able to partition C and nutrients between harvested wood and residues left in the field, (3) to assess nutrient accumulation of different tree species, and (4) to assess the impact of nutrient removal in the harvested biomass on long-term site quality, C sequestration and production sustainability.

5.2 Materials and methods

5.2.1 Study site

A trial was established in 1996 at Tumbi Agricultural Research Institute in Tabora western Tanzania. The site has a warm climate with mean temperature of 23° C and receives an average annual rainfall of 928 mm mostly in one season between November and April (Nyadzi et al. 2003a). Soils are oxic Haplustalfs with 82% sand and 12% clay, slightly acidic (pH in water 5.7 to 6.1), low in organic carbon (4 to 8 g kg^{-1}), total nitrogen (0.1 to 0.3 g kg^{-1}), low to medium in Olsen extractable P (3 to 12 mg kg^{-1}) and low in exchangeable bases (Nyadzi et al. 2003b).

5.2.2 Experimental treatments and design

The trial involved seven fallow treatments, five of which included woodlots, one natural fallow and one continuous cropping. Treatments were arranged in a randomised complete block design with three replications. Woodlots included the following trees species: *Acacia crassicarpa*, *A. julifera*, *A. leptocarpa*, *Senna siamea* and *Leucaena pallida*.. The woodlots were established using 8-week-old seedlings planted at 4 x 4 m spacing (625 trees ha^{-1}) in 16 m by 20 m plots. The young trees were intercropped with maize during the first three years (1996 to 1999). In the subsequent two years (2000 and 2001) trees were left to grow as woodlots. Details of location, climate, soil characteristics, experimental design and planting arrangement of trees within the rotational woodlot set-up were described in Chapters 2 and 3 of this thesis. Procedures for biomass harvest, basic wood density, C and nutrient accumulation analysis are outlined below.

5.2.3 Tree biomass sampling

The aboveground biomass of the trees was sampled during the first week of November 2001 (end of dry season) when trees were approximately 5 years old. Before tree sampling the species composition of the under storey and of the natural fallow treatment was determined. The vegetation cover was scored using a 1–5 visual scale; where 1 = 1–19%, 2 = 20–39%, 3 = 40–59%, 4 = 60–79%, and 5 = 80–100% cover. All weeds were then sorted according to the family they belonged to. After weed species composition assessment, three trees were selected from the net plot of six trees from each treatment for destructive sampling to determine tree biomass production. Trees were categorised into small, medium and large, and per net plot one tree of each category was selected. Only trees that had survived from the initiation of the trial were sampled, implying that if a tree was small because of gap filling (beating up), it was not used. Trees were cut at 15 cm aboveground, separated into foliage (leaves + twigs), branches, and stem, and components fresh weights were assessed. For dry matter determination and nutrient analysis, 200, 500, and 1000 g fresh matter of foliage, branches, and stems, respectively, were retained. The remaining trees of the plots were harvested to allow land preparation and re-cropping of maize. Stem and branches were removed from the plots, while leaves, twigs and grasses were incorporated into the ridges and covered with soil before planting maize, to assess the nutrient availability of the residues. The results of these latter measurements are discussed in Chapter 6.

5.2.4 Determination of wood basic density

Variation in density along the length of trunks is a potential source of bias in biomass estimates, as most density samples come from only one point along the length of the trunk (normally at breast height level i.e. 1.3 m) (Fearnside 1997). In this study, wood basic density was determined following the procedures described by Aldred and Alemdag (1988). Briefly the procedure involved sampling of three disks (wood cores) of about 4 cm thickness from straight boles of the three categorized trees, one at breast height mark (1.3 m from the base), the second at 1/3 and the third at 2/3 of the merchantable stem height. Each disk was wrapped in a paper bag labelled to indicate sample details and immediately air dried to prevent fungal growth. In the laboratory, the disks were soaked in distilled water for at least 72 h in order to regain green condition, after which their volumes were determined by the water displacement technique. After this, samples were kept in an oven at 103 ± 2 °C until a constant weight was reached. Wood basic density (kg m^{-3}) for each disk was calculated as the ratio of oven dry weight to green volume.

Table 5.1. Wood basic density (kg m^{-3}) of 5-year-old woodlots of five different tree species.

Species	Tree category			Weighted mean
	Large	Medium	Small	
Acacia crassicarpa	519	448	660	542 b
A. julifera	580	583	538	567 b
A. leptocarpa	722	635	618	658 a
Leucaena pallida	526	517	519	521 b
Senna siamea	510	498	459	489 b
Mean	571	536	559	555 b
LSD (species)		78.9 (0.002)		
LSD (tree category)		61.1 (0.50)		
LSD (species x tree category)		136.6 (0.16)		

LSD = Least significant difference in means. Values in parentheses are probabilities of F significance. Treatment means within a column followed by the same letter are not significantly different based on LSD at $P < 0.05$.

5.2.5 Plant analysis and calculation of dry mass, C and nutrient accumulation

The foliage sub-samples were immediately transferred to the laboratory in double-sealed polythene bags. After recording the fresh weights, the samples were oven-dried at 70 °C to constant weight. The dried samples were ground to pass through a 2 mm sieve. Ratios of dry weight to fresh weight of the sub-samples were used to calculate the dry mass of the components and of the total tree biomass on per tree category basis. The average biomass of tree parts was then summed to obtain the total wood component and the total aboveground biomass per tree. It was then multiplied by the number of trees per plot and extrapolated to a hectare.

Foliage samples were digested according to Anderson and Ingram (1993) and the digest was analysed for N, P, and cations (K, Ca and Mg). N and P were determined colorimetrically (Parkinson and Allen, 1975), K by flame photometry, and Ca and Mg by atomic absorption spectrophotometer (Anderson and Ingram 1993). In another foliage sub-sample, organic C was determined by colorimetric method after wet oxidation with a

H_2SO_4-$K_2Cr_2O_7$ mixture (Anderson and Ingram, 1993). The ratios of the mass fractions of nutrients in the leaves were calculated and compared with the ratios found in the leaves of primary forests and secondary vegetation reported elsewhere (Van Reuler and Janssen 1989). By multiplying mass fractions of C and nutrients with the dry mass of the foliage, the storage was calculated. Root biomass and chemical composition of tree tissue types and weeds were not measured due to unforeseen budget cuts. Data on nutrient accumulations in wood were estimated based on the ratios of mass fractions in leaves to mass fractions in wood in Table 5.6.

5.2.6 Statistical analysis

Analysis of variance (ANOVA) was carried out using GenStat programme (Payne et al. 2002) to determine the variations among species in biomass production, wood basic density, C, and nutrient mass fractions and accumulations in tree foliage per tree category and per hectare basis. Fisher's protected LSD test at $P < 0.05$ was applied to distinguish groups (classes) of different values.

5.3 Results

5.3.1 Wood basic density and biomass production

Acacia leptocarpa had significantly higher wood basic density than the other species (Table 5.1). Differences among tree categories in wood basic densities were not significant, neither were the interactions of species and category. Total biomass accumulation ranged from 26 to 58 Mg ha^{-1} (Table 5.2). The biomass of foliage (leaves/twigs) ranged from 6.3 to 20.2 Mg ha^{-1} whereas the total wood biomass ranged from 9.6 to 40.9 Mg ha^{-1}. Stem wood differed significantly among species, while branch wood biomass did not differ. *Acacia leptocarpa* and *A. crassicarpa* had significantly higher wood and total aboveground biomass per tree as well as per ha than the other species. Overall, dry mass of wood was larger than that of foliage biomass. The percentage wood biomass of total aboveground biomass decreased in the following order: *S. siamea* (85%)>*A. leptocarpa* (71%)>*A. crassicarpa* (66%)>*A. julifera* (65%)>*L. pallida* (32%). *Senna siamea* was low in foliage biomass because most of the leaves had fallen as litter during the dry season (Chapter 4).

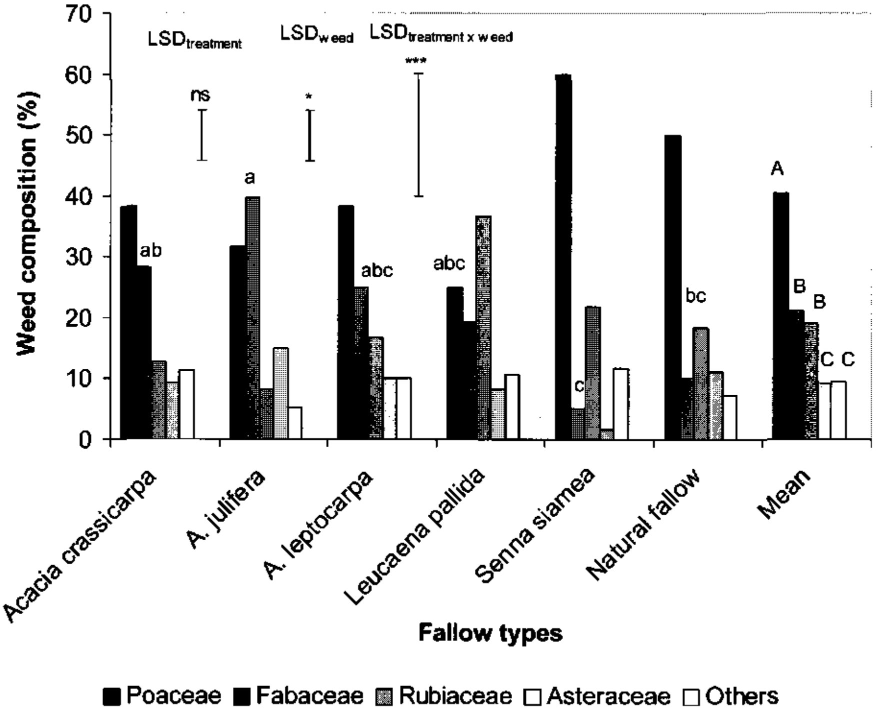

Figure 5.1. Relative weed composition in 5-year-old woodlots of different tree species and in natural fallow plots. LSD = Least significant difference in means; ns = non significant; * and *** = significant at $P < 0.05$ and 0.001, respectively. Treatment means for Fabaceae and within mean treatment followed by the same letter are not significantly different based on LSD at $P < 0.05$.

5.3.2 Carbon and nutrients mass fractions and stocks

Carbon mass fractions did not differ significantly among species and ranged from 402 to 469 g kg^{-1} (Table 5.3). Nutrient mass fractions varied markedly among species. *Leucaena* leaves had higher N and P than other species, while among the acacias, *A. julifera* had the highest N and P mass fractions. The mass fractions of K and Mg were similar ($P > 0.05$), but Ca mass fraction was different between tree species. The ratios of the nutrient contents in the leaves were significantly different among species with high

C:N, C:P, N:P and K:P quotients in *A. leptocarpa.* Leucaena had a low C:N ratio. The non-fixing senna had a low N:P ratio.

Carbon stock in the foliage and wood at the time of tree cutting ranged from 1.8 to 7.9 and 5.4 to 23.0 Mg C ha^{-1} yr^{-1}, respectively (Table 5.4). The amounts of nutrients tied up in foliage differed significantly among species, except for Ca, with senna having the lowest amount. Amounts of C and nutrients tied up in acacia wood were significantly higher than that in senna and leucaena wood, except for P. Owing to the wide variations in nutrient mass fractions among species, nutrient stocks did not follow a one-to-one correspondence with the biomass.

5.3.3 Composition of under storey natural vegetation

Overall, the composition of weeds in all treatments (except in the continuous maize treatment, which was not examined) revealed that grasses (Poaceae) (e.g. *Agrostis gigantea*, *Cynodon dactylon*, *Eragrostis* spp, *Hyparrhenia rufa*, *Rynchelytrum repens*, *Setaria* spp, and *Sporobolus* spp) represented 40% of the total vegetation cover (Figure 5.1). Fabaceae (*Crotolaria* spp, *Stylosanthes* spp, *Cassia obtusifolia*) followed at 21%, Rubiaceae (*Richardia scabra*) at 19% and Asteraceae (e.g. *Ageratum conyzoides*, *A. hirsutum*, *Acanthospermum hispidum*, *Bidens pilosa*) at 9%. Five unidentified species, each contributing less than 2% contributed to the remaining 9%. *Terminalia sericea* was found only on natural fallow plots. *T. sericea* is one of the pioneer woody species after clearing miombo forests. The natural fallow and *S. siamea* tended to have more Poaceae and Rubiaceae families while legumes favoured the growth of shade loving species (Fabaceae and Asteraceae).

5.4 Discussion

In *L. pallida,* foliage contributed much to the total biomass. The contribution of wood of more than 65% of the total biomass and the high basic density make a very substantial part of the acacias and senna biomass useful as fuel-wood or as construction material. Wood basic densities for acacias were comparable to the ones found in studies conducted elsewhere (Khasa et al. 1995).

Table 5.2. Mean biomass accumulation in 5-year old woodlots of different tree species. Reported here are the mean for three tree categories. This was then multiplied by the number of trees per plot and extrapolated to a hectare.

Species	Stem	Branches	Total wood	Foliage	Total	Stem	Branches	Total wood	Foliage	Total
	kg tree^{-1}					Mg ha^{-1}				
Acacia crassicarpa	49.4 a	6.5	55.9 ab	28.6 a	84.5 a	30.9 a	4.1	35.0 ab	17.9 a	52.8 a
A. julifera	29.5 b	3.2	32.8 bc	18.0 ab	50.8 b	18.5 b	2.0	20.5 bc	11.2 ab	31.7 b
A. leptocarpa	46.7 a	18.8	65.5 a	26.7 a	92.2 a	29.2 a	11.7	40.9 a	16.7 a	57.6 a
Leucaena pallida	10.4 c	4.9	15.3 c	32.4 a	47.7 b	6.5 c	3.1	9.6 c	20.2 a	29.8 b
Senna siamea	29.5 b	5.8	35.3 bc	6.3 b	41.6 b	18.4 b	3.6	22.1 bc	3.9 b	26.0 b
$\text{LSD}_{0.05}$	14.1	18.3	20.3	17.6	30.8	8.8	11.5	12.7	11.0	19.2
F probability	<0.001	0.439	<0.001	0.037	0.005	<0.001	0.439	<0.001	0.037	0.005

LSD = Least significant difference in means. Treatment means within a column followed by the same letter are not significantly different based on LSD at $P < 0.05$.

Table 5.3. Mass fractions of carbon, nitrogen, phosphorus, potassium, calcium and magnesium (g kg^{-1} in dry mass) and the ratios of these mass fractions in tree foliage.

Species	C	N	P	K	Ca	Mg	C:N	C:P	N:P	K:P	N:K
Acacia crassicarpa	406	19.4 c	0.8 c	10.2	5.7 bc	4.9	21.1 b	495 b	23.6 a	12.3 a	1.9 c
A. julifera	469	22.7 b	0.9 bc	7.2	4.6 c	4.2	20.7 b	527 b	25.4 a	7.9 b	3.2 ab
A. leptocarpa	446	16.4 c	0.6 d	6.9	5.4 bc	4.5	27.1 a	736 a	27.0 a	11.1 a	2.5 bc
L. pallida	402	27.8 a	1.1 a	7.9	6.0 b	6.1	14.5 c	378 b	26.1 a	7.5 b	3.6 a
Senna siamea	445	17.7 c	1.0 b	6.7	9.8 a	4.1	25.4 a	431 b	17.1 b	6.4 b	2.7 bc
$LSD_{0.05}$	59.2	3.17	0.15	3.09	1.25	3.34	4.2	18.6	5.7	2.7	0.9
F probability	0.123	<0.001	0.006	0.40	<0.001	0.68	0.001	0.017	0.025	0.004	0.02

LSD = Least significant difference in means. Treatment means within a column followed by the same letter are not significantly different based on LSD at $P < 0.05$.

All species in the present study at an age of 5 years were denser than 14-years old plantation pines (soft wood) grown in southern highlands of Tanzania (Mugasha et al. 1996). Other wood quality parameters such as heat of combustion (calorific values), rapidity of burning, ash content and sapwood to heartwood ratios are also important, but still need to be quantified.

Results presented in Table 5.5 indicate that there is a considerable variation between tree species from different climatic zones in amounts of biomass and nutrient mass fractions in different parts of the vegetation. Nutrient contents of tissue types generally decrease in the order: foliage > branches = roots > stem (Kumar et al. 1998) and the mean ratio of nutrient contents in foliage to wood is between 3.3 and 5.1 (Table 5.6). Linear relationships between nutrient mass fractions in leaves to those in wood were also observed in tropical forests, and in most situations the ratio of mass fractions in leaves to mass fractions in wood was around 4 (Noij et al. 1993). These relationships (Table 5.6) were used to estimate the amount of nutrients tied up in wood during tree harvesting. A comparison of Table 5.5 with Table 5.2 makes clear that above-ground wood biomass in our experiment was much lower than that reported for the sub-humid and bimodal humid tropics for 5-year old woodlots. The observed variations in foliar nutrient contents were generally within the range found elsewhere for these and other but similar species (Table 5.5 and Table 5.3). The foliage biomass is also within the range reported by Silver et al. (2000) for aboveground re-growth in abandoned agricultural fields during the first 20 years. A part of the difference with other studies may be ascribed to differences in the length of growing season with different climatic conditions and soil characteristics.

Table 5.4. Total C (Mg ha^{-1}) and nutrient stocks (kg ha^{-1}) in tree foliage and wood of 5-years old woodlots of different trees.

Species	Foliage						Wood[a]						Foliage+ Wood
	C	N	P	K	Ca	Mg	C	N	P	K	Ca	Mg	C
Acacia crassicarpa	7.3	344 ab	14.7 ab	182 a	102	88 ab	20.0 ab	180 ab	7.3	86 a	88 b	32 ab	27.3 ab
A. julifera	5.3	256 ab	10.0 ab	79 ab	52	46 ab	11.5 c	111 bc	5.2	34 bc	27 cd	19 bc	16.8 bc
A. leptocarpa	7.3	272 ab	10.7 ab	123 ab	91	83 ab	23.0 a	215 a	6.7	28 c	115 a	48 a	30.3 a
Leucaena pallida	7.9	539 a	21.5 a	138 ab	112	145 a	5.4 c	65 c	6.4	34 bc	11 d	11 bc	13.3 c
Senna siamea	1.8	69 b	4.1 b	26 b	39	16 b	12.4 bc	44 c	3.7	54 b	52 bc	10 c	14.2 c
$LSD_{0.05}$	6.3	387	15.9	117	87	124	7.99	74.7	4.4	21.1	37.1	21.8	12.4
F probability	0.25	0.018	0.023	0.01	0.30	0.023	0.006	0.004	0.44	0.001	0.001	0.018	0.039

LSD = Least significant difference in means. Treatment means within a column followed by the same letter are not significantly different based on LSD at $P < 0.05$. [a] Estimates based on the ratios of nutrient mass fraction of foliage to nutrient mass fraction of wood (Table 5.6), wood was assumed to contain 560 g C kg^{-1}.

Table 5.5. Dry biomass yield (Mg ha^{-1}), nutrient mass fractions (g kg^{-1}) and nutrient stocks in the biomass (kg ha^{-1}) in 2.5 to 5-years-old short-rotation trees at semi-arid (SA) (Karachi et al. 1997; Karachi 1998b), sub-humid (SH) (Salako and Tian 2001), and humid (H) (Kumar et al. 1998) sites.

Biomass type	Site	Species*						
		AA	AC	AJ	AL	LL	LP	SS
Leaf/twigs	SA	-	-	-	-	-	-	-
	SH	16	-	-	17	3.5	-	15
	H	129	-	-	-	4.1	-	-
Wood	SA	-	-	-	-	-	-	-
	SH	77	-	-	78	76	-	143
	H	129	-	-	-	62	-	-
Roots	H	16.3	-	-	-	12.0	-	-
Nutrient mass fractions (leaf/twigs)								
N	SA	28.9	24.4	17.8	13.4	34.9	28.0	
	SH	20.4	-	-	18.2	24.6	Nd	20.6
	H	23.19	-	-	-	40.51	-	-
P	SA	0.8	0.8	0.7	1.0	1.6	1.8	-
	SH	0.4	-	-	0.5	0.7	-	0.6
	H	0.81	-	-	-	1.71	-	-
K	SA	6.5	4.5	11.0	6.0	29.4	4.0	-
	SH	14.0	-	-	9.2	15.7	-	11.4
	H	10.82	-	-	-	13.92	-	-
Ca	SA	10.5	7.5	12.4	10.5	11.1	10.0	-
	SH	14.1	-	-	12.8	25.9	-	19.1
	H	-	-	-	-	-	-	-
Mg	SA	2.5	3.3	3.2	3.8	2.7	6.0	
	SH	4.0	-	-	3.3	3.5	-	3.8
	H	-	-	-	-	-	-	-
Nutrient mass fractions (Wood)								
N	SA	-	6.1	4.2	-	-	7.0	-
	SH	7.1	-	-	5.1	4.3	-	2.4
	H	5.18	-	-	-	5.94	-	-
P	SA	-	0.2	0.2	-	-	1.1	-
	SH	0.1	-	-	0.2	0.2	-	0.1
	H	0.31	-	-	-	0.57	-	-
K	SA	-	1.5	1.1	-	-	2.0	-
	SH	1.6	0.6		4.2	2.6	-	4.2
	H	2.62	-	-	-	1.34	-	-
Ca	SH	5.3	-	-	6.0	4.0	2.0	4.5
Mg	SH	0.6	-	-	1.0	1.2	1.0	0.4

* AA = *Acacia auriculiformis*; AC = *A. crassicarpa*; AJ = *A. julifera*; AL = *A. leptocarpa*; LL = *Leucaena leucocephala*; LP = *L. pallida*; SS = *Senna siamea*; - = not determined.

SA = semi-arid; SH = sub-humid; H = humid

Table 5.6. Calculated ratios of nutrient mass fractions in foliage to nutrient mass fractions in wood, based on the data from literature (Karachi et al. 1997; Kumar et al. 1998; Salako and Tian 2001).

Species	N	P	K	Ca	Mg
Acacia auriculiformis	3.9	3.3	4.2	2.3	5.4
A. crassicarpa	4.0	4.0	4.3	-	-
A. julifera	4.2	3.5	10.0	-	-
A. leptocarpa	3.1	3.8	1.8	1.9	3.6
Leucaena leucocephala	6.5	3.5	8.4	4.6	2.6
L. pallida	4.0	1.6	2.0	5.0	6.0
Senna siamea	8.6	6.0	2.7	4.2	9.5
Mean	4.3	3.3	5.1	3.5	4.4

In all species the N:P ratio was well over 15, and the K:P ratio was over 10 in acacias except in *A. julifera*. Compared to leaves of secondary vegetation, primary forest trees, and perennial crops at optimum nutrition (as cited by Van Reuler and Janssen 1989; Palm et al. 2001), the ratios point to shortage of P. This confirms also our results presented in Chapter 4, where relative shortage of P followed from measured nutrient mass fractions in leaves of standing biomass and in decomposing leaves in the soil. Relative shortage of P also follows from the high C:P ratios. The ability of N_2-fixing acacias and leucaena to secure their N supply in nutrient-poor environments (Noij et al. 1993), is indicated by the relatively high ratios of N:P compared to those in senna.

Nutrient removal from the site at harvest depends on both nutrient mass fractions and the biomass yield of the different components (Kumar et al. 1998). With wood harvesting, acacias and senna withdrew substantial amounts of nutrients. Fast growing trees such as *Acacia* species gave a marked export of nutrients via whole tree harvesting. However, if the branches and stem wood alone are removed (wood exportation), leaving the foliage and roots at the site (recycling nutrients through slash and mulch techniques), nutrient export from the site can be reduced substantially. Noij et al. (1993) observed a high total productivity at low soil fertility sites, which was entirely ascribed to high root productivity and a fast turnover of fine roots. A similar situation may exist at our study site with its low fertility (Nyadzi et al. 2003b). Unfortunately, there is limited data on amounts of nutrients accumulated by roots, which makes it impossible to draw firm conclusions about the total nutrient recycling. This indicates that for firm conclusions it is necessary to quantify the accumulation of nutrients in roots too.

Our results presented in Tables 5.3 and 5.4 have highlighted that the trees affected C sequestration differently due to their biomass allocation patterns and C mass fractions. *Acacia* species were superior in C sequestration, and among the *Acacia* species, *A. leptocarpa* and *A. crassicarpa* sequestered almost twice as much as *A. julifera*, especially in the wood fraction. The total storage of C in foliage plus wood ranged from 13.3 to 30.3 Mg ha^{-1} at 5 years, indicating that all species do have the potential for C sequestration and thereby to mitigate CO_2 emissions into the atmosphere (Fearnside 2000; Sanchez 2000). Agroforestry plantations, such as rotational woodlots, are clearly a carbon reservoir. However, the duration of the carbon offset that a rotational woodlot represents depends on its life span and fate (Kort and Turnock 1999). If the woodlot coppices after biomass harvesting, the fixation of C in the woodlots could be considered to be an on-going process but if the woodlot is simply destroyed or removed at the end of its lifespan, the C removed from the atmosphere would return to the atmosphere due to organic C decomposition and vegetation burning (Fearnside 2000). Usually farmers in the study area slash and burn the major part of the natural fallow vegetation and crop residues. By means of ash, nutrients (P, K, Ca and Mg) are added to the soil while considerable amounts of N and C are lost (Van Reuler and Janssen 1996). Woodlot plantations on farms reduce the dependence on natural forest for wood fuel. Hence, woodlot plantations on farms do contribute to saving natural miombo forest ecosystems, to nearby provision of wood fuel and to a net C sequestration.

Different trees had different effects on the composition of weed species, suggesting that the potential of the trees in woodlots for weed suppression also differed (e.g. De Rouw 1995; Rao et al 1998). Two of the commonest weeds in western Tanzania, *Stylosanthes* spp and *R. repens*, appeared to dominate in tree fallows and natural fallow, respectively. Farmers in the study area believe that these are indicators of improvement in soil fertility and of depletion in soil fertility, respectively (B. Gama 2002, pers. comm.).

5.5 Conclusions

The study aimed to assess wood biomass, and nutrient accumulation and removal during harvest of five multipurpose tree species in semi-arid environment. There was a rapid accumulation of C and nutrients in aboveground woody components and in foliage. Wood constituted 32 to 85% of the total aboveground biomass. *Leucaena pallida* had the smallest wood proportion but retained the largest part of foliar materials in the field during clear cutting. Trees also played a role in weed control.

Clearly, planted woody fallows can contribute to C sequestration, and *Acacia* species are promising in this regard. When the goal is a high production of wood biomass with high wood density that can be used in fuel-wood and charcoal industries, *Acacia* species are preferred species. When the goal is dual, i.e. production of wood biomass and soil fertility restoration, *L. pallida* seems to be the preferred species.

Large amounts of nutrients are withdrawn with the harvested wood biomass, making application of nutrients from external sources (e.g. fertilizers) essential. An imbalance in N and P in tree components can be expected when grown on soils having relatively poor fertility characteristics such as those of this study. Evidently, supplementation of nutrients from external sources is needed during cropping after clear cutting of trees in order to have a productive and sustainable rotational woodlot system.

5.6 Acknowledgements

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Acacia crassicarpa root nodules (Courtesy: Dr. Festus Akinnifesi)

A bunch of *Acacia crassicarpa* nodules (Courtesy: Dr. Festus Akinnifesi)

CHAPTER 6

Analysis of the effects of rotational woodlots on the nutrition and yields of maize in western Tanzania

Abstract

Farmers in western Tanzania are establishing rotations of trees and crops in an attempt to solve the problems of deforestation and low soil fertility. The current study compares the influence of 5-year old agroforestry tree fallows, with *A. crassicarpa*, *A. julifera*, *A. leptocarpa*, *L. pallida* and *Senna siamea,* with traditional bush fallow and continuous sole maize (*Zea mays* L.), each with or without NPK fertilizers, on maize yield and nutrition. The analysis included the influence of tree fallows and NPK fertilizers on maize grain, cob and stover yields. The agronomic, uptake and utilization efficiencies of NPK fertilizer applications were also assessed.

The effects of fertilizer were much stronger than those of fallow types. Fertilizer N improved yields more than fertilizer P, while K did not bring about clear effects. Maize crop following woodlots without fertilizer application gave significant greater yield (0.8 to 2.0 Mg ha^{-1}) than the crop after natural fallow (0.8 Mg ha^{-1}) and continuous sole maize (0.6 Mg ha^{-1}), and had a higher harvest index (0.42 to 0.53) than natural fallow and sole maize (both 0.37). Non-N_2-fixing *S. siamea* and N_2-fixing *L. pallida* tended to give low yields. Upon fertilizer application the influences of fallow types became weaker. Maize yields showed positive N to P interactions; there was little response to P if no N was applied. Response curves for N and P showed that 20 kg ha^{-1} of P was optimal. N recovery efficiency was improved by the application of P and vice versa. When fertilizers were applied, differences in maize yields between tree fallows and natural fallow vary from 300 (for *Acacia julifera*) to minus 250 (for *Senna siamea*) kg/ha. A yield increase of 300 kg can also be obtained by application of 10 kg fertilizer N or 8 kg fertilizer P.

In short: the significance of rotational woodlots is in the supply of wood rather than in the improvement of soil fertility.

Key words: Acacia, agronomic efficiency of fertilizers, harvest index, internal nutrient utilization efficiency, Leucaena, Senna, recovery efficiency of fertilizers, woody fallows

6.1 Introduction

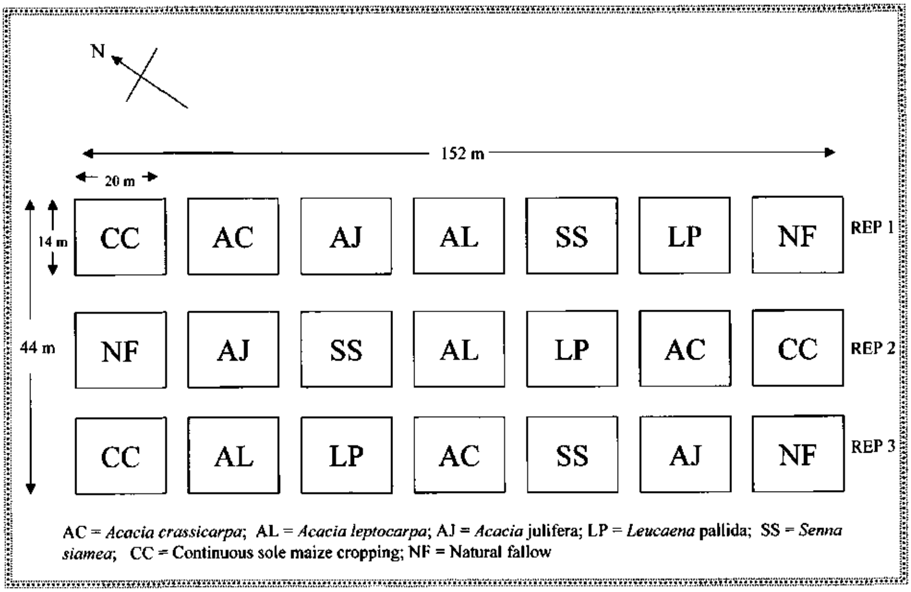
The decline in the fertility of agricultural soils in Sub-Saharan Africa has been well documented in recent years, with most of the attention being focused on so-called fertilizer elements N, P, and K (Stoorvogel et al. 1993; Hartemink 2003). Over decades, smallholder farmers have removed large quantities of nutrients from their soils without using sufficient quantities of manure or fertilizer to replenish the soil. The traditional ways to overcome nutrient depletion is by leaving the land fallow for a number of years or by the application of mineral fertilizers. However, the fallow period has been strongly shortened because of the high population pressure. Moreover, few farmers use inorganic fertilizers because of insufficient cash to buy the fertilizer in time, high cost of fertilizer due to the long distances from the distribution points and poor infrastructure of the rural areas. In some cases fertilizers are simply not available. Since early 1990s subsidies on fertilizers have been abolished in many countries. In Africa, fertilizers cost two to six times as much as in developed countries (Sanchez 2002). Some farmers are aware of the value of farmyard manure, but the quantity available is too small to cover the area of land cultivated, and manure quality generally is poor. Besides, not all farmers own livestock. Crop residues are often used as livestock fodder or are burnt during land preparation. Hence, the amount of organic inputs and the quality of these inputs frequently are insufficient to meet crop nutrient requirements (e.g. Mafongoya et al. 2000). Furthermore, large distances to the fields make transport of the bulky organic inputs difficult.

Alternative organic sources are thought to be agroforestry techniques through trees and shrubs grown in situ (e.g. Sanchez 1995), particularly those based on N_2-fixing legumes (Giller 2001). Planting of fast growing N_2-fixing trees, as improved fallows, were found to increase productivity in many parts of Africa (Sanchez et al. 1997). However, the soil ameliorating effect of trees in fallows varies according to the tree species (Tian et al. 2001; N'goran et al. 2002), age of plantation (Kang et al. 1994), residue management after fallow clearing (Tonye et al. 1997; Kato et al. 1999), soil type and climate (Palm 1995). Jama et al. (1995) recommended growing woodlots (sole blocks) of *Leucaena leucocephala* and crops instead of alley cropping in semi-arid areas, where competition for water is severe compared to sub-humid regions. In semi-arid western Tanzania, rotational woodlots using *Acacia crassicarpa* (a woody legume) have been found to improve crop yield (Nyadzi et al 1999) and retrieve leached N from the subsoil (Nyadzi et al. 2003).

Traditionally, many farmers in the tropics burn the slashed secondary vegetation as part of the shifting cultivation system (e.g. Kato et al. 1999), and farmers may apply the same method when clearing planted woodlots. However, the burning practice is a controversial one, because of the volatilisation of nitrogen (N) and sulphur (S) (Weil and Spider 2000), and the dispersion of ash and fine solids containing phosphorus (P), potassium (K) and other nutrients. Those losses can be eliminated by preparing fields without the use of fire, offering the hope of more efficient nutrient cycling and improved sustainability (Kato et al. 1999). However, mulching or incorporation of slashed vegetation modifies the soil environment for plants and soil biota. The slowly decomposing plant residues do not provide nutrients as readily to the first crops in the cycle as ashes, resulting into crop yield reduction (Van Reuler and Janssen 1996). Moreover, the farmers may not easily accept the technology of mulching or incorporation in the soil of slashed vegetation (Cairns and Garrity 1999).

Increased availability of plant nutrients has played a key role in the mean global increase of maize yields since about 1950, and the dominant plant nutrient causing this increase has been N (Russell 1991; Olson and Sander, 1999). Several studies present information on the improvement of the internal N utilization efficiency (i.e. unit grain produced per unit of N taken up by the crop), and yield response to N application of new maize hybrids. However, limited information is available about the internal N utilization efficiency and yield response of maize planted after woodlot fallows. The response of maize to application of various combinations of N, P, and K fertilizers in rotational woodlot systems with slashed and incorporated mulch from harvested woody agroforestry trees has not been studied so far.

In the current study, we tested the hypotheses that maize yield response is higher after fallows of N_2-fixing trees than after that of non-N_2-fixing trees, and that low levels of NPK fertilizer applications will result in increased maize yields, especially after tree fallows that leave low quality litter in the field (see Chapter 4). The specific objectives of this study were (a) to evaluate yield and harvest index of maize grown after various



AC = *Acacia crassicarpa*; AL = *Acacia leptocarpa*; AJ = *Acacia* julifera; LP = *Leucaena* pallida; SS = *Senna siamea*; CC = Continuous sole maize cropping; NF = Natural fallow

Figure 6.1 The field layout, randomisation and replications of main treatments (fallow types).

fallow types with mulches incorporated into the soil, (b) to determine the effects of various combinations of NPK fertilizer on maize yield after various fallow types, again with mulches incorporated into the soil (c) to determine nutrient recovery and internal utilization efficiencies of maize after woodlots clearance and following applications of various combinations of NPK fertilizers.

6.2 Materials and methods

6.2.1 Experimental site

The experiment was set up at Tumbi Research Station in semi-arid western Tanzania, which has a 44-year average of 928 mm rainfall with a mono-modal distribution and a mean temperature of 23 ^{0}C. The landscape has a flat to undulating relief and the soil at the experimental site is classified as a Ferric Acrisol (Alfisols–Oxic

Haplustalf), characterised by low base saturation and a low cation exchange capacity. The surface texture is loamy sand overlying sandy clay loam subsoil. The natural vegetation is deciduous forest and dry woodlands (miombo), but is severely degraded by human activities, especially agriculture, bushfire, overgrazing, commercial charcoal production, collection of fuel wood and building poles, beehives and timber exploitation.

Soil fertility characteristics are presented in chapters 1 and 2. Soils are oxic Haplustalfs with 80 to 90% sand, slightly acidic (pH in water 5.7 to 6.1), low in organic carbon (4 to 8 g kg^{-1}), total nitrogen (0.1 to 0.3 g kg^{-1}), low to medium in Olsen extractable P (3 to 12 mg kg^{-1}) and low in exchangeable bases (Nyadzi et al. 2003).

6.2.2 Experimental design of the woodlot technology trial

In December 1996, a randomised complete block design experiment with seven treatments and three replicates was set-up. The treatments, henceforth denoted by fallow types, included five different tree species (*Acacia crassicarpa* A. Cunn. ex Benth., *A. julifera* Berth., *A. leptocarpa* A. Cunn. ex Benth., *Leucaena pallida* Britton & Rose, and *Senna siamea* (Lamarck) Irwin et Barneby), natural fallow and sole maize (*Zea mays* L. var. Kilima). The layout of the trial is shown in Figure 6.1. The plots were 16 m by 20 m. The trees were planted using 8-week old seedlings at a spacing of 4 m by 4 m (625 trees ha^{-1}). Trees were intercropped with maize for the first three years (1996 to 1999).

Maize was planted on ridges at 1.0 m spacing between rows and 0.25 m between plants within the rows. In the first year, maize received fertilizer at the recommended rates of 100, 17.4 and 33 kg ha^{-1} of N, P and K in the form of urea, triple superphosphate and muriate of potash, respectively. In the subsequent two years, only 50 kg N ha^{-1} was applied, in the form of urea. Tree growth performance and the effects on intercropped maize in the first three years of growth have been reported in Chapter 2. Trees were harvested when they were 5 years old (Chapter 5) after which maize was cropped again. Wood components (stem and branches) were removed from the plots before land preparation. Tree leaves, twigs and grasses were incorporated into the soil to a depth of approximately 15 cm by new ridges formed by hand hoeing as commonly practised by farmers in the region. In the case of natural fallow, the same procedure was followed making sure that all materials were properly incorporated into the ridges.

Table 6.1 Allocation of the 27 NPK fertilizer combinations to the sub-blocks and sub-sub blocks* in each fallow type (see also text).

Rep	Sub-sub-blocks	Sub-blocks								
		a			b			c		
I	n	110	101	122	002	011	020	200	221	212
	m	220	211	202	100	121	112	010	001	022
	s	000	021	012	210	201	222	120	111	102
II	n	110	121	102	020	001	012	200	211	222
	m	000	011	022	210	221	202	120	101	112
	s	220	201	212	100	111	122	010	021	002
III	n	000	011	022	220	201	212	110	121	102
	m	210	221	202	100	111	122	020	001	012
	s	120	101	112	010	021	002	200	211	222

* a, b and c denote sub blocks a, b and c, respectively, where as n, m, and s denote north, middle and south slope position of the fields (sub-sub blocks).

6.2.3 Experimental design of the NPK fertilizer trials

In order to quantify the soil fertility replenishment, brought about by the woodlots, an NPK fertilizer trial was imposed in each of the seven treatments (*A. crassicarpa*, *A. julifera*, *A. leptocarpa*, *S. siamea*, *L. pallida*, natural fallow, and continuous sole maize) in three replicates.

The experimental design was a 3^3 factorial in three replicates, i.e. 27 sub-treatments per fallow type (Table 6.1). The purpose of this design was to allow the quantitative translation of the effects of the fallow types into equivalent amounts of fertilizer N, P and K (Janssen 2000a). The blocks with 27 sub-treatments were subdivided into three sub-blocks each containing 9 treatments, and into 9 sub-sub-blocks each containing three treatments, according to the procedures given by Cochran and Cox (1992). Each experimental unit consisted of four ridges of 16 m length and per ridge there were 9 sub-plots. The number of maize plant per ridge of a sub-block was seven; leaving one plant out at both ends gives a net number of 5 plants per ridge per sub-block. So, the net number of maize plants per experimental unit was 20. The net area was 5 m^2. The factors investigated were nitrogen, phosphorus and potassium. Application rates were 0, 50 and 100 kg N ha^{-1} as urea ($CO(NH_2)_2$, 46% N); 0, 20 and 40 kg P ha^{-1} as triple superphosphate ($Ca(H_2PO_4)_2.H_2O$, 46% P_2O_5) and 0, 20 and 40 kg K ha^{-1} as muriate of potash (60% K_2O). The fertilizer N application was split into two equal parts, at sowing time and at 8 weeks after sowing. Triple superphosphate and potash fertilizers were applied once, at maize sowing.

At harvest in each experimental unit, plant stand was recorded and three plants were chosen randomly, separated into cobs (grain + rachis) and stover (stem + leaves + husks), weighed, dried to constant weight at 70 ^{0}C and ground to pass through a 1-mm screen using a micro hammer mill. The remaining maize plants in the net plots were harvested for total biomass (grain, rachis and stover) and harvest index (HI) estimates. Yields including all grain yields, are expressed on an oven-dry basis.

6.2.4 Selection of experimental units for chemical analysis

The large number of experimental units and the limited budget for the study made it impossible to chemically analyse the samples of all units. An important question was how to make the most strategic and effective selection of the experimental units to be used for chemical crop analysis. The selected units included the extreme treatments corresponding to expected maximum dilution and maximum accumulation, as well as treatments corresponding to balanced ratios of N, P, and K.

According to Janssen (2000b) the appropriate fertiliser treatments (denoted by the levels 0, 1 and 2) were:

	N	P	K
For maximum dilution:	022	202	220
For maximum accumulation:	200	020	002
For balanced nutrition:	000	111	222.

Table 6.2. Two-way table of replicates and fallow treatments for control yields and average yields of all 27-fertilizer treatments (Mg ha^{-1}).

		Fallow types*)							
Fertilizer	Rep	AC	AJ	AL	LP	SS	CM	NF	Mean
(A)									
None	1	0.92	0.77	0.56	0.35	0.60	0.88	0.67	0.68
	2	2.94	2.63	1.61	1.00	1.09	0.49	0.56	1.48
	3	2.17	1.68	1.09	1.33	0.82	0.44	1.19	1.24
	Mean	2.01	1.70	1.09	0.89	0.83	0.60	0.81	1.13
(B)									
Average	1	2.77	2.60	2.04	2.30	1.81	2.96	2.24	2.39
	2	2.00	2.41	3.27	2.99	2.66	2.22	2.39	2.56
	3	2.36	3.74	2.43	2.52	2.61	2.28	3.17	2.73
	Mean	2.38	2.91	2.58	2.60	2.36	2.49	2.60	2.56

*) AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; CM = continuous maize; NF = natural fallow.

Considering a 3^3 factorial as a cube, the selected treatments represented the eight corners and the pivot of the cube. It was considered to be not necessary to sample these nine experimental units in each of the three replicates of a certain treatment, i.e. in each 3^3 factorial. They were organised in groups of three units, which came down to three units per replicate of 27 experimental units or only 11% of the total number of units selected for chemical analysis. Mass fractions for the remaining 18 experimental units were calculated as shown in APPENDIX 6.1.

6.2.5 Chemical analyses of maize components

Nutrient (N, P, K, Mg and Ca) mass fractions of the dry plant samples were assessed in the ground sub-samples using Kjeldahl procedure (Parkinson and Allen, 1975; Anderson and Ingram, 1993). Essentially, quantities of about 0.200 g of ground plant samples were digested in a mixture of Se, $LiSO_4$, H_2O_2, and H_2SO_4. Hydrogen peroxide was added as an additional oxidising agent. Selenium took the place of the traditional mercury catalyst, while $LiSO_4$ was used to raise the boiling point. Only one digestion was required to bring all the nutrients into solution. The total N and P in the digest were measured by spectrophotometer, total K by flame photometer while Ca and Mg were determined by an atomic absorption spectrophotometer.

6.2.6 Data processing and statistical analysis

Total dry matter yields for each fallow type plot were calculated as shown in Equation 6.1. Harvest index was calculated as the ratio of grain dry mass to total dry mass (Equation 6.2). Nutrient (N, P, and K) uptake was calculated using Equation 6.3.

$$\text{Total dry matter} = (GY + CY + SY) \qquad \text{Equation 6.1}$$

$$\text{Harvest index, } HI = GY/(GY + CY + SY) \qquad \text{Equation 6.2}$$

$$\text{Nutrient uptake} = [(NCG*GY) + (NCC*CY) + (NCS*SY)] \qquad \text{Equation 6.3}$$

where, GY, CY, and SY are grain, cob, and stover yields on dry matter basis; NCG, NCC, and NCS are nutrient mass fractions in grain, cob, and stover, respectively.

The agronomic efficiency was calculated as the difference in yield between two fertilizer levels, divided by the difference in added fertilizer nutrient. Fertilizer nutrient recovery efficiency was calculated as the difference in nutrient uptake (total nutrient uptake in the above-ground dry matter yield of plant) divided by the difference in added fertilizer nutrient. Nutrient utilization efficiency was the ratio of grain yield to nutrient uptake.

All data were subjected to analysis of variance (ANOVA) using GenStat© statistical software after checking for normality distribution (Payne et al. 2002). Tests of significance between treatment means were performed using the Fisher's protected least significant differences (LSD) test at a level of 95% probability. Linear and non-linear (parabolic) models were fitted to describe the relationship between grain yield and fertilizer rates as well as between grain yield and nutrient uptake for each fallow type.

Table 6.3. Two-way table of reps and fallow treatments for harvest index (HI) of control treatments and averaged over all 27-fertilizer treatments (kg kg^{-1}).

		Fallow types*)							
Fertilizer	Rep	AC	AJ	AL	LP	SS	CM	NF	Mean
None	1	0.37	0.50	0.42	0.45	0.40	0.49	0.39	0.43
	2	0.41	0.50	0.48	0.38	0.44	0.31	0.38	0.41
	3	0.54	0.60	0.36	0.42	0.43	0.30	0.34	0.43
	Mean	0.44	0.53	0.42	0.42	0.42	0.37	0.37	0.42
Average	1	0.49	0.47	0.45	0.47	0.44	0.48	0.42	0.46
	2	0.42	0.47	0.48	0.45	0.42	0.47	0.39	0.44
	3	0.47	0.50	0.43	0.45	0.48	0.42	0.44	0.46
	Mean	0.46	0.48	0.45	0.46	0.44	0.46	0.41	0.45

*) See Table 6.2.

The relationships between grain yield and uptake of N, P, and K by maize were analysed using linear regression.

6.3 Results

6.3.1 Main treatments: effects of fallow types

The average results of the sub-blocks (a, b and c) and the sub-sub-blocs (n, m s) showed that the position of the experimental units within the replicates did not affect yields and harvest indices. Therefore, no further attention is paid to within-block variability.

Table 6.2 presents the yields of Treatment 000 and the average yields of all fertilizer treatments. Mean 000 grain yields varied from 0.6 (SM) to 2.0 (AC). Replicate 1 had the lowest grain yields when no fertilizer was applied. Yields averaged over all 27 fertilizer treatments varied from 2.36 (SS) to 2.91 (AJ) Mg ha^{-1}. Means of replicates did not differ much (Table 6.2).

Table 6.4. Nutrient uptake in relation to fallow types. Values of 000 treatments (control) and averaged over all 27 fertilizer treatments (kg ha^{-1}).

		Fallow types*)							
Fertilizer	Nutrient	AC	AJ	AL	LP	SS	CM	NF	Mean
000	N	48.2	29.0	21.9	16.9	12.4	11.8	16.6	22.4
	P	8.4	6.6	3.2	4.0	4.3	2.9	4.1	4.8
	K	27.6	27.0	9.8	16.9	12.7	6.9	5.8	15.2
Average	N	53.0	58.4	57.1	51.2	48.2	51.7	53.2	53.2
	P	12.0	16.0	11.7	12.2	12.3	11.6	13.3	12.7
	K	28.8	50.1	29.5	50.6	34.5	23.4	19.4	33.8

*) AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; CM = continuous maize; NF = natural fallow.

Harvest indices (HI) were affected by fallow types but not by replicates (Table 6.3). Natural fallow had the highest dry matter yields (Table 6.2; APPENDIX 6.3) but the lowest HI (Table 6.3).

Table 6.4 presents the uptakes of N, P and K for Treatment 000 and averaged over all fertilizer treatments. The averaged uptakes of N and P follow more or less the pattern of the average yields: AJ> AL=LP > AC = SM = NF > SS. The uptake of K is not exactly in line; this issue is further discussed in Section 6.3.3.

6.3.2 Sub-treatments: effects of NPK fertilizer applications

6.3.2.1 Yields

Grain yields responded strongly to N, moderately to P, but hardly to K application (Table 6.5; APPENDIX 6.2). Yield differences between 0 and 50 kg N were on average 1.48 Mg ha^{-1}, about twice as large as the average difference of 0.72 Mg ha^{-1} between 50 kg and 100 kg N ha^{-1}. The differences in yields between 20 and 40 kg P ha^{-1} were not significant. Yields were slightly greater at 20 than at 40 kg K ha^{-1}. There was a positive interaction between N and P, as is shown in Figure 6.2. Maximum yields, i.e. yields at

Table 6.5. Grain yields as function of NPK fertilizer treatments and fallow types (Mg ha $^{-1}$).

		Fallow types*)							
Nutrient	Level	AC	AJ	AL	LP	SS	CM	NF	Mean
N	0	1.29	1.67	1.35	1.23	0.80	1.40	1.61	1.33
	50	2.42	3.05	3.16	2.75	2.76	2.92	2.63	2.81
	100	3.42	4.02	3.23	3.82	3.52	3.49	3.22	3.53
P	0	1.89	2.66	2.05	2.13	2.21	2.24	2.07	2.18
	20	2.52	2.92	2.62	2.69	2.40	2.73	2.58	2.64
	40	2.72	3.16	3.06	2.99	2.48	2.84	2.82	2.87
K	0	2.50	2.66	2.78	2.43	2.20	2.67	2.16	2.49
	20	2.45	3.01	2.49	2.65	2.42	2.55	2.76	2.62
	40	2.18	3.07	2.47	2.73	2.46	2.57	2.54	2.57

*) AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; CM = continuous maize; NF = natural fallow.

N100, P40, were higher after fallows with N-fixing trees (acacias and *L. pallida*) than after the other fallows. Similar results were found for total biomass and harvest index (APPENDICES 6.3 and 6.4).

6.3.2.2 Nutrient uptake and recovery fractions

In APPENDIX 6.5, nutrient mass fractions are presented of the nine experimental units of which plant samples have been analysed. From these data, mass fractions for the other treatments were calculated according to the procedure indicated in APPENDIX 6.1. The uptakes of N, P and K, averaged over the three replicates, are given in APPENDIX 6.6.

The uptake of N was clearly affected by fertilizer N and also by fertilizer P, but hardly by fertilizer K. The uptake of N, averaged over the three K levels and over all seven fallow types, has been plotted against N application in Figure 6.3. The uptake of N

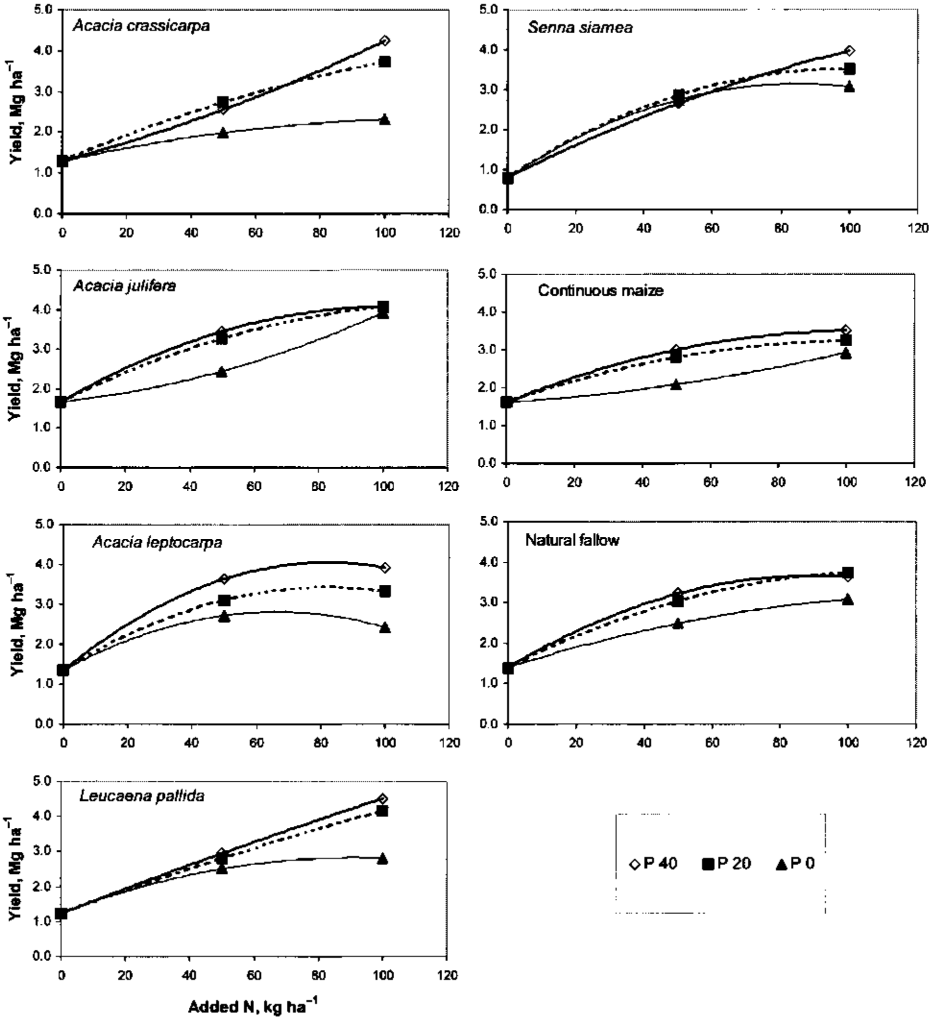


Figure 6.2. Mean relations between grain yield and fertilizer N for three levels of fertilizer P, and for all seven fallow systems. Each point is the average of 9 yields (3 replicates; 3 K levels).

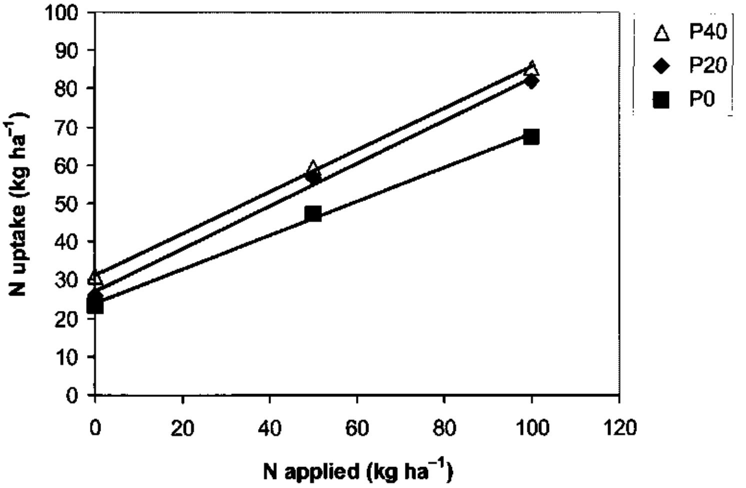


Figure 6.3. Relation between N uptake and N applied for three levels of P. Each point is the average of 81 yields (3 replicates; 7 fallow types; 3 K levels).

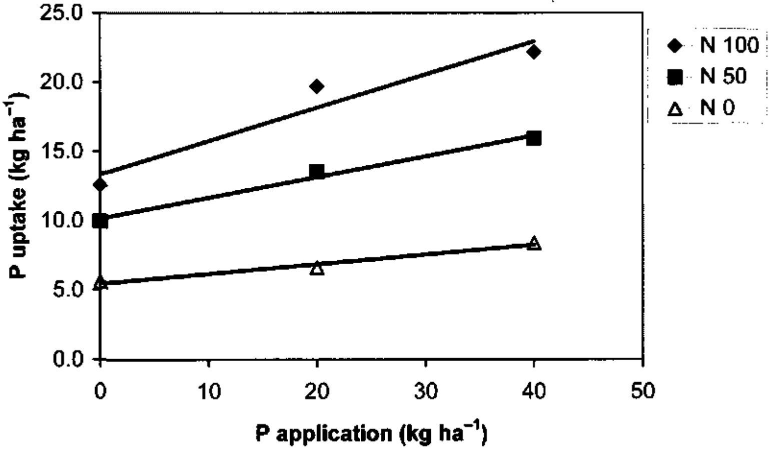


Figure 6.4. Relation between P uptake and P applied for three levels of N. Each point is the average of 81 yields (3 replicates; 7 fallow types; 3 K levels).

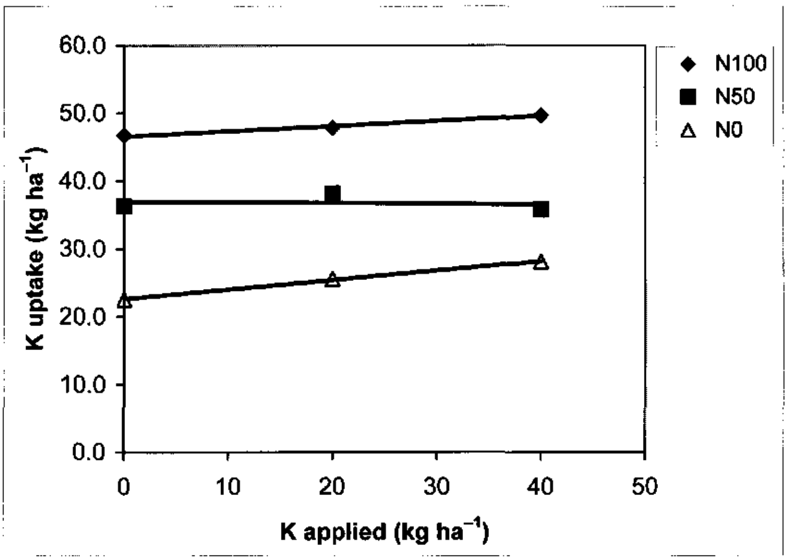


Figure 6.5. Relation between K uptake and K applied for three levels of N. Each point is the average of 81 yields (3 replicates; 7 fallow types; 3 P levels).

proved linearly related to N application. The recovery fractions of fertilizer N (Table 6.6) were about 0.55 at P20 and P40, and 0.44 at P0. Also the N uptake from the soil was affected by P level: 24, 27 and 31 kg N per ha for P0, P20 and P40, respectively.

The uptake of P was more strongly affected by fertilizer N than by fertilizer P, and hardly by fertilizer K. The uptake of P, also averaged over the three K levels and over all seven fallow types, has been plotted against P application (Figure 6.4). The uptake of P proved linearly related to P application, at N0 and N50, and somewhat curvilinear at N100. The recovery fractions of fertilizer P were about 0.07, 0.15 and 0.24 at N0, N50 and N 100, respectively. The P uptake from the soil was affected by N level: 5.5, 10.2 and 13.3 kg P per ha for N0, N50 and N100, respectively (Table 6.6).

The relation between the uptake and the application of K was obvious at N0 and N100, but not at N50 (Figure 6.5). The recovery of K was maximally 0.14. The K uptake from the soil was strongly affected by N level: 23, 37 and 47 kg K per ha for N0, N50 and N100, respectively.

Table 6.6. Regression coefficients and R-square values of the equations for the relation between nutrient uptake and fertilizer nutrients applied. Equations are of the shape: Y = a + bX, where Y = uptake (kg ha^{-1}) and X = rate of nutrient application (kg ha^{-1}). They refer to Figures 6.3, 6.4 and 6.5 for N, P and K, respectively.

Response		Regression coefficients		R-square
Nutrient	At	a	b	
N	P40	31.3	0.55	0.999
	P20	27.1	0.56	0.997
	PO	24.1	0.44	0.997
P	N100	13.3	0.24	0.929
	N50	10.2	0.15	0.987
	NO	5.5	0.07	0.973
K	N100	46.6	0.08	0.978
	N50	37.0	-0.01	0.034
	NO	22.6	0.14	0.998

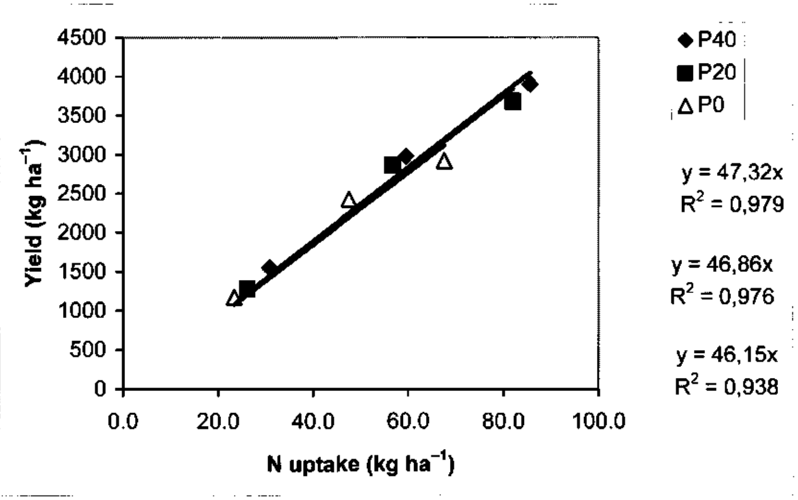


Figure 6.6. Relation between yield and N uptake, for three levels of P. Each point is the average value of 81 values (3 replicates; 7 fallow types; 3 K levels).

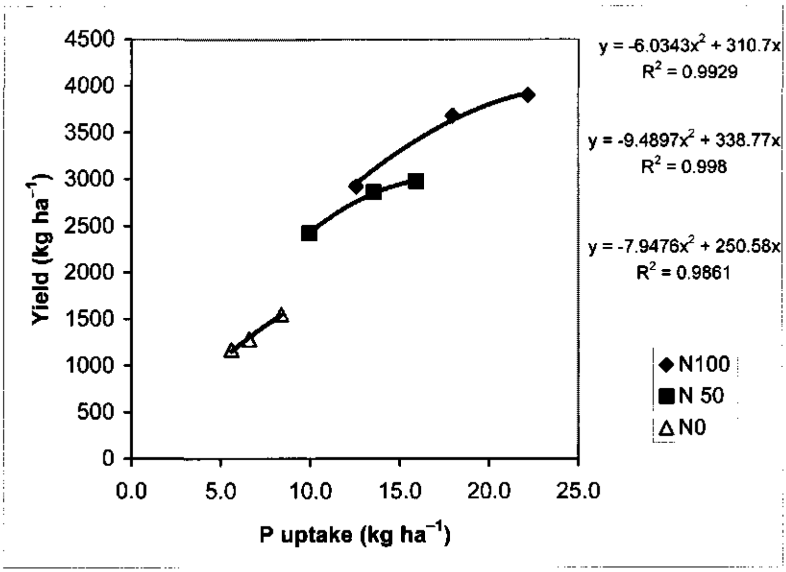


Figure 6.7. Relation between yield and P uptake, for three levels of fertilizer N. Each point is the average value of 81 values (3 replicates; 7 fallow types; 3 K levels).

6.3.2.3 Relation between yield and absorbed nutrients (internal utilization efficiency)

The relations between yields and nutrient uptakes, averaged over all fallow types, are shown in Figures 6.6, 6.7 and 6.8 for N, P and K, respectively. The regression lines are forced through the origin. The relation between yield and N uptake was practical linear and the regression coefficient decreased only a little with decreasing level of P (Figure 6.6). The relation between yield and P uptake had a curvilinear shape. The curves were positioned higher with increasing levels of N (Figure 6.7). The relation between yield and K uptake was rather poor. The average ratio of yield to K uptake or internal utilization efficiency of K (IUEK) was 53, 77 and 74 at N0, N 50 and N100, respectively. Again it is obvious that yields were not depending on K uptake, but on N and P uptake.

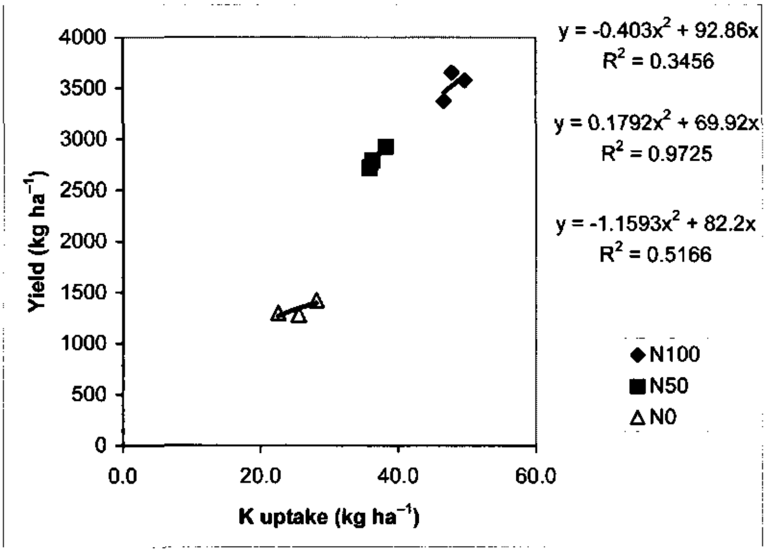


Figure 6.8. Relation between yield and K uptake, for three levels of N. Each point is the average value of 81 values (3 replicates; 7 fallow types; 3 P levels).

6.3.3 Interactions between fallow types and responses to NPK

6.3.3.1 Choice of appropriate fertilizer treatments

For the study of the interactions between fallow type and fertilizer nutrients, the appropriate treatments should be used. In general this implies that the study of the interaction between a particular nutrient and the fallow types should not be 'hindered' by possible limitations of other nutrients. Decisions were taken in view of the results presented in Sections 6.3.1 and 6.3.2. For N, the average results were used of the following six PK fertilizer treatments: x-20-0, x-20-20, x-20-40, x-40-0, x-40-20, x-40-40, where x stands for one or more levels of N, depending on the topic of the study. For P, the average results were used of three NK fertilizer combinations: 100-y-0, 100-y-20, 100-y-40, where y stands for the appropriate level of P. For K, average results were used of two NP fertilizer combinations: 100-20-z, 100-40-z, where z stands for the appropriate level of K.

Table 6.7. Average yields (in kg per ha) at the indicated fertilizer nutrient applications and agronomic efficiencies (AE) of fertilizer N, P and K as functions of fallow types. AE is expressed in kg grain yield increase per kg fertilizer nutrient applied. For N, average yields were used of N0 and N50 (YN0, YN50), for P the yields were YP0 and YP20, and for K the yields were YK0 and YK20.

Indicator	Fallow type*)						
	AC	AJ	AL	LP	SS	CM	NF	Mean
YN50	2644	3357	3375	2873	2761	2899	3129	3005
YN0	1238	1688	1523	1309	809	1818	1525	1416
AEN	28.1	33.4	37.0	31.3	39.0	21.6	32.1	31.8
YP20	3720	4073	3331	4157	3514	3239	3743	3683
YP0	2304	3922	2432	2806	3078	2926	3081	2936
AEP	70.8	7.6	44.9	67.6	21.8	15.7	33.1	37.3
YK20	4154	4183	3752	4691	3897	3745	4060	4069
YK0	3968	3534	3484	3928	3480	3252	3596	3606
AEK	9.3	32.5	13.4	38.2	20.8	24.6	23.2	23.1

*) AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; CM = continuous maize; NF = natural fallow.

6.3.3.2 Agronomic efficiency of fertilizer nutrients

Table 6.7 presents the agronomic efficiencies (AE) of fertilizer N, P and K. To get the maximum values we took the difference between the lowest fertilizer rate and the control. The agronomic efficiency was calculated as the difference in yield between these two levels, divided by the added fertilizer nutrient.

The average AE values of 31.8, 37.3, and 23.1 for N, P and K are high, normal and low, respectively, compared to default values of 25, 40, and 35 that can be derived for balanced nutrition from the QUEFTS model (Janssen et al., 1990). They reflect that N was most limiting and K the least. Fallow types that have a high AE for one nutrient

Table 6.8. Average nutrient uptake at the indicated fertilizer nutrient applications and recovery fractions (RF) of fertilizer N, P and K in relation to fallow types. RF is the ratio of the difference in uptake of the nutrient to the amount of fertilizer nutrient applied (kg/kg). For N, uptakes were used of N0 and N50 (UN0, UN50), for P the data were UP0 and UP20, and for K the uptakes were UK0 and UK20.

Indicator	Fallow type*)							
	AC	AJ	AL	LP	SS	CM	NF	Mean
UN50	55	63	68	52	54	58	57	58
UN0	26	37	32	22	15	39	28	29
RFN	0.58	0.51	0.72	0.61	0.77	0.37	0.58	0.59
UP20	18.4	20.4	15.6	19.9	17.8	15.2	18.4	18.0
UP0	7.9	18.3	8.8	13.3	14.9	12.3	12.5	12.6
RFP	0.52	0.11	0.34	0.33	0.14	0.15	0.29	0.27
UK20	49	39	47	47	64	37	45	47
UK0	55	39	47	43	52	36	42	45
RFK	-0.27	0.04	0.01	0.20	0.61	0.06	0.13	0.11

*) AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; CM = continuous maize; NF = natural fallow.

usually have low AE values for the others, e.g. *A. crassicarpa* is high in AEP, but low in AEN and AEK, while *S. siamea* is high in AEN, but rather low in AEP and AEK. The lowest AEP is for *A. julifera*, but AEN and AEK are rather high. It is striking that natural fallow takes a middle position for all three, AEN, AEP and AEK.

6.3.3.3 Recovery efficiency of fertilizer nutrients

The same treatments as used for maximum agronomic efficiencies were used for the calculation of maximum recovery efficiency or recovery fraction (Table 6.8). The recovery fraction (RF) of fertilizer N was high as compared to the default value of 0.5 used in QUEFTS. The lowest RFN and the highest UN0 were found for continuous maize; this might be a result of the fertilizer N applications in the foregoing years. Values of 0.6 for RFN in maize were also found in Malawi (Makumba, 2003) with comparable climatic conditions. Apparently, the risk of leaching is rather restricted under these conditions, and hence not much fertilizer N gets lost. Also the RF of P is high; if we

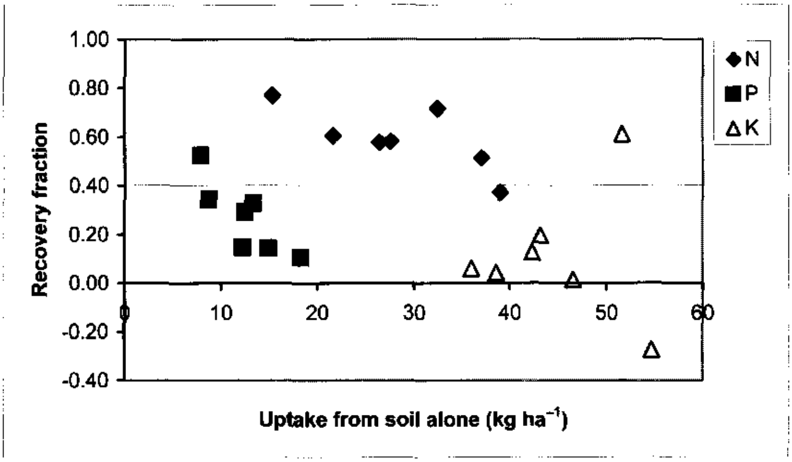


Figure 6.9. Relation between recovery fraction and nutrient uptake from the soil alone. Data refer to Table 6.8.

disregard the unlikely high value of 0.52 for *A. crassicarpa,* the average RFP is 0.23, still very high compared to the default value of 0.1. The likely reason for this high RFP is the sandy texture of these soils; P fixation likely does not occur. The values of RFK are too irregular to draw firm conclusions. Again disregarding *A. crassicarpa*, the average RFK would be 0.18, low compared to the value of 0.5 that is considered to be the default value in QUEFTS. The fallows of *L. pallida* and *Senna siamea* are poorest in N, *Acacia crassicarpa* and *A. leptocarpa* in P, while there are no real differences in K among the fallow types.

Of course the values of the recovery fractions are related to the indigenous soil nutrient supply. In Figure 6.9 the maximum recovery fractions of fertilizer N, P and K have been plotted against the uptake of the particular nutrient from the soil alone (UN0, UP0 and UK0 in Table 6.8). Although relating RF to U0 is tricky as U0 is included both in x- and y-axis, it is obvious again that K does not show the behaviour of a limiting nutrient. The outlier of 0.6 RFK is from *S. siamea.*

Table 6.9. Internal nutrient utilization efficiency (IUE), calculated as the ratio of the average yield of a fallow type to the average nutrient uptake of that fallow type (kg kg^{-1}).

Quantity	Fallow type*)							
	AC	AJ	AL	LP	SS	CM	NF	Mean
IUEN	43.5	48.9	44.0	50.8	48.9	48.2	48.8	47.6
IUEP	191.8	194.4	214.8	213.5	192.4	214.3	196.0	202.5
IUEK	82.5	58.2	87.5	51.4	68.4	106.3	64.4	74.1
RYUN	42.2	49.8	42.7	45.7	48.5	45.5	44.8	45.6
RYUP	164.9	200.9	191.9	203.9	203.9	193.1	202.1	194.4
RYUK	72.1	84.6	79.3	88.6	70.7	93.0	75.0	80.5

*) AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; CM = continuous maize; NF = natural fallow. N.d. = not determined.

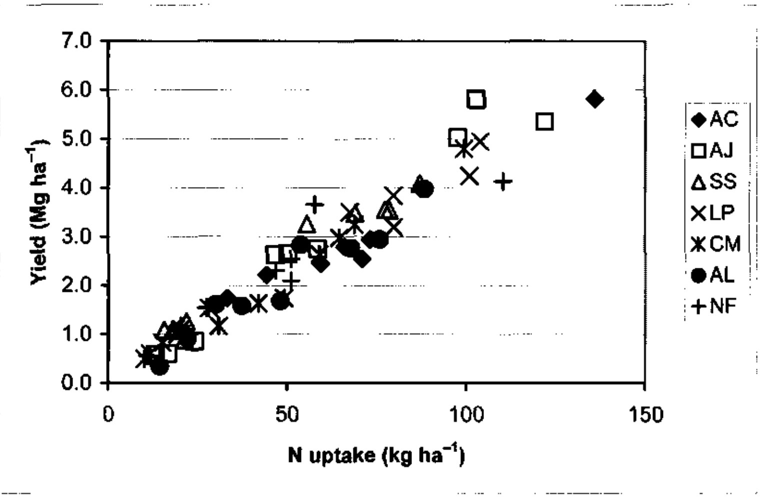


Figure 6.10. Relation between yield and uptake of N for the analysed experimental units. AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; CM = Continuous maize; NF = natural fallow.

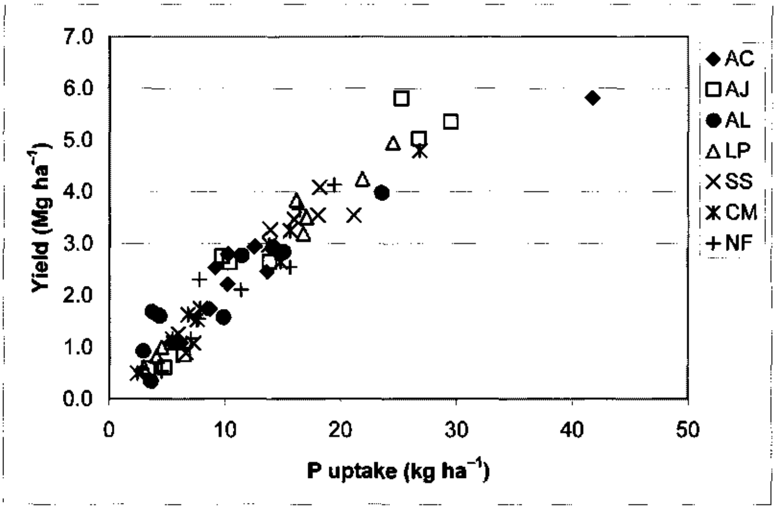


Figure 6.11. Relation between yield and uptake of P for the analysed experimental units. AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; CM = Continuous maize; NF = natural fallow.

6.3.3.4 Internal utilization efficiency of absorbed nutrients

The internal utilization efficiency (IUE) was calculated in two ways. In Table 6.9, IUE was calculated as the ratio of the average yield of a fallow type to the average nutrient uptake of that fallow type. The values of RYU, standing for the regression coefficient between yield and uptake, were derived from Figures 6.10, 6.11 and 6.12. Per fallow type, the data were used of the nine experimental units of which the crops had been chemically analysed (APPENDIX 6.5). Regression lines were forced through the origin, and the slopes of the lines are presented in Table 6.9. The values of IUE are in general a little higher than those for RYU.

The values for the internal utilization of N could be divided into three classes. The highest value of 50.8 was for *A. julifera,* and the lowest two of 43.5 and 44.0 for *A. crassicarpa* and *A. leptocarpa.* In between were *L. pallida, S. siamea,* continuous maize and natural fallow. Also the values for the internal utilization efficiency of P could be divided in three classes.

The highest class contained only *L. pallida*; the medium class consisted of *A. leptocarpa*, *A. julifera*, *S. siamea*, continuous maize and natural fallow, the lowest value obviously was for *A. crassicarpa*. The values for the internal utilization efficiency of K likely are less reliable; the highest IUEK was found for continuous maize, *A. crassicarpa* and *A. leptocarpa*, indicating that these fallow types were relatively short in K. The middle group consisted of *S. siamea* and natural fallow, the lowest values of IUEK were found in *A. julifera* and *L. pallida*. Although it is difficult to draw firm conclusions, *A. crassicarpa* can be considered as the poorest fallow type as far as it concerns nutrient use efficiency, while *L. pallida* and *A. julifera* are the best. The others do not differ much.

6.3.3.5 Apparent soil supply of nutrients

The apparent soil supply of nutrients (ASS) was calculated by extrapolation of the lines relating nutrient uptake to fertilizer nutrient application, as shown in Figures 6.3, 6.4 and 6.5. Using equations of the form $Y = a + bX$, with Y being uptake and X the amount of fertilizer nutrient applied, the apparent soil supply of nutrients was estimated as: $ASS = -a/b$. The procedure is essentially the one proposed by Fried and Dean (1952) for the so-called A-value. Because the relation between uptake and application was practically linear for N and P, we considered it a justified procedure for these nutrients. Figure 6.5 shows that it would not make sense to do such for K. The values of ASS represent the soil N and P that have the same availability to crops as fertilizer N and P; it could be expressed in 'equivalent fertilizer N or P.

From the results presented in Table 6.10, it follows that continuous maize was high in ASSN, which can be ascribed to the former N applications. It may also be an 'artefact' resulting from the low recovery of fertilizer N found for CM (Table 6.8), which could have been caused by the presence of maize stover with high C:N ratios. Among the other fallow types, *A. julifera* and *A. leptocarpa* were the best, *Acacia crassicarpa, Senna siamea* and *L. pallida* were low, and natural fallow was medium.

As far as it concerns P, the absolute best fallow type is *A. julifera*. The good performance of *A. julifera* is probably related to its high litter production and the relatively high N and P mass fractions in its leaves (Chapter 4). The relatively good ASSP of *Senna siamea* is also in agreement with its high leaf P (Chapter 4). *Acacia* *crassicarpa* and *A. leptocarpa* were low in ASSP, in agreement with the low P found in their leaves. Although its leaves were relatively high in N and P, *L. pallida* did not perform very well and this must be ascribed to its low litter production.

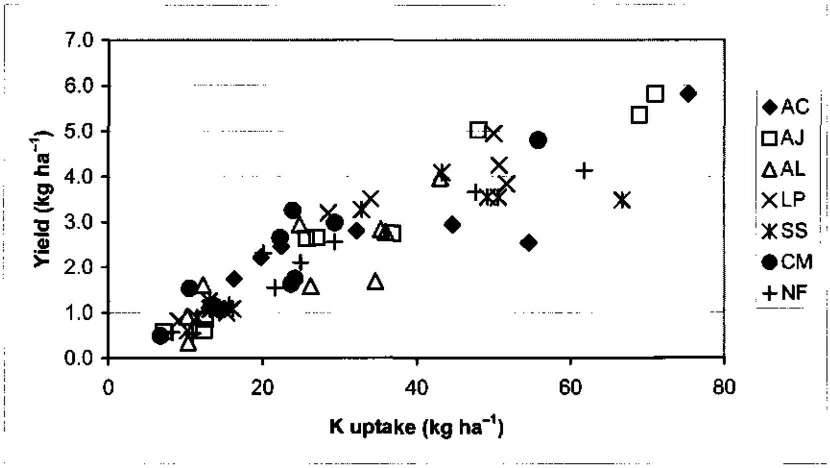


Figure 6.12. Relation between yield and uptake of K for the analysed experimental units. AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; CM = Continuous maize; NF = natural fallow.

Table 6.10. Apparent soil supply of N and P, expressed in units of 'equivalent fertilizer nutrients' ('A-value').

Nutrient	Fallow type*)							
	AC	AJ	AL	LP	SS	CM	NF	Mean
ASSN	36.1	87.0	71.1	29.1	25.6	123.5	50.3	60.4
ASSP	16.8	244.4	23.4	62.2	91.4	82.3	60.3	83.0

*) AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; CM = continuous maize; NF = natural fallow.

6.3.4 *Evaluation of the fallow types*

It is risky to evaluate the fallow types in terms of improvement of chemical soil fertility, as the differences among the fallow types are small and irregular.

In Table 6.11, yields and nutrient uptake are compared. It is obvious that *A. julifera* is the best fallow type, and that the four fallows with leguminous trees do better than the other fallow types. The major cause of the differences is the supply of N (Figure 6.13). Surprisingly, continuous maize supplies the same quantities as *A. julifera*, which is likely the result of the repeated N application in the past. The difference between natural fallow and *S. siamea* is 14 kg N; *S. siamea* must have taken up more N than natural fallow and accumulated it in the wood. The better performance of the fallow of *A. julifera* compared to the fallows of the other leguminous trees may be ascribed to the higher supply of P and K. This could mean that *A. julifera* is mining the soil for these nutrients. All in all, Table 6.11 gives a clear evaluation of the impact the fallow types have on chemical soil fertility.

6.4 Discussion

This study has shown that N and P are the most limiting nutrients in the study area and that N and P must be applied to get high yields of maize after clearing woodlots. This was reflected by the high values of recovery fractions. The results confirm the study by Kato et al (1999) who also indicated that incorporation of the fallow vegetation, as a fire-free alternative cannot supply sufficient nutrients to the subsequent crops in the short run. There is no need to apply fertilizer K in the study area. Application of 50 to 100 kg N and 20 kg P per hectare will generally suffice to get maize yields of about 4 to 5 tons per ha after woodlots.

The internal utilization efficiencies of N and P were not very high and were not much affected by fallow and fertilizer treatments. Maximum values reported are 70 for N, 600 for P and 130 for K (Janssen et al. 1990; Van Reuler and Janssen 1996; Janssen 1998). From Table 6.9, it follows that internal utilization efficiency was relatively higher for N (average 45; 45/70 = 0.64) and K (80/130 = 0.62) than for P (200/600 =0.33). The values for N and P are rather low in view of the response to fertilizer N and P, suggesting that the used maize cultivar is, as far as it concerns nutrient 'elasticity', certainly not

Table 6.11. Rating of fallow types on the basis of yields and nutrient uptake.

	Fallow treatment*)						
Quantity	AC	AJ	AL	LP	SS	CM	NF
Yields *(Mg ha^{-1})*							
At 000	2.01	1.70	1.09	0.89	0.83	0.60	0.81
Average	2.38	2.91	2.58	2.60	2.36	2.49	2.60
Maximum	5.19	6.64	5.38	5.43	5.24	4.60	5.10
Maximum uptake from soil alone *(kg ha^{-1})*							
UN	31.2	42.1	35.4	24.4	15.3	41.1	29.0
UP	7.9	18.3	8.8	13.3	14.9	12.3	12.5
UK	49.8	56.3	43.3	45.4	45.1	33.8	22.3
Ranking							
Yields							
At 000	1	2	3	4	5	7	6
Average	6	1	4	2.5	7	5	2.5
Maximum	5	1	3	2	4	7	6
Maximum uptake from soil alone							
UN	4	1	3	6	7	2	5
UP	7	1	6	3	2	5	4
UK	2	1	5	3	4	6	7
Sum	25	7	24	20.5	29	32	30.5
Final ranking	**4**	**1**	**3**	**2**	**5**	**7**	**6**
Class	**B**	**A**	**B**	**B**	**C**	**C**	**C**

*) AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; CM = Continuous maize; NF = natural fallow.

flexible for P. It may be worthwhile to consider other maize cultivars than those used here. These results, however, do agree with those found for maize in West Africa (Janssen 2003; Saidou et al. 2003, Struif Bontkes et al. 2003).

Maize harvest index (HI) was affected by fallow types and NPK fertilizer applications suggesting that maize reacted to improvement of nutrients supply by increasing the weight of grains relatively to the vegetative biomass; this was especially the case in natural fallow and senna fallows.

Upon fertilizer application the influences of fallow types became weaker. When fertilizers were applied, the differences in maize yields between tree fallows and natural fallow vary from 300 (for *Acacia julifera*) to minus 250 kg per ha (for *Senna siamea*) kg/ha. A yield increase of 300 kg, however, can also be obtained by application of 10 kg fertilizer N or 8 kg fertilizer P. After *Senna siamea* about 8 kg extra fertilizer N is needed than after natural fallow. The widest difference in fertilizer need after various fallow types is not more than say 20 kg fertilizer N and some kg of fertilizer P.

6.5 Conclusion

This study has demonstrated the variations that woody fallows and NPK fertilizer can bring about in terms of maize yields, nutrient recovery and nutrient utilization efficiencies. Clearly, N and P are the most limiting nutrients in the study area. Fertilizer N and P must be applied to get high maize yields after clearing woodlots. Application of 50 to 100 kg N and 20 kg P per hectare will suffice to get maize yields of about 4 to 5 tons per ha after woodlots, and the fallow type has little effect on it. There was no need to apply fertilizer K in the study area.

The best fallow type for soil fertility improvement was *Acacia julifera,* most likely because of the increase in soil P that was brought about.

In short, the general and disappointing conclusion is that the significance of rotational woodlots lies in the supply of wood rather than in the improvement of soil fertility.

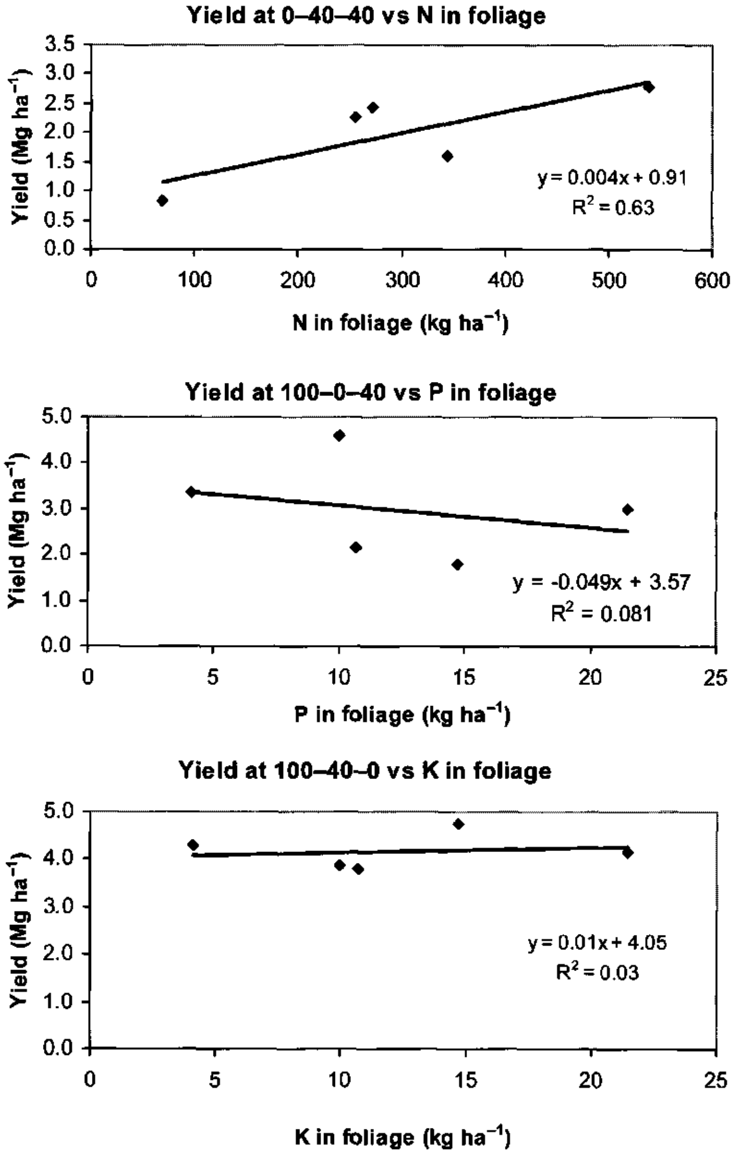


Figure 6.13. Relations between nutrients in tree foliage and maize grain yield of appropriate fertilizer treatments.

6.6 Acknowledgements

The financial support obtained from the International Foundation for Science (IFS, Stockholm Sweden), Tanzania Agriculture Research Project phase II (TARP II) and the African Network for Agroforestry Education (ANAFE) to this research is acknowledged.

APPENDICES

APPENDIX 6.1 Estimation of mass fractions of the 18 not-analysed experimental units on the basis of the measured experimental units (eight corners and the pivot of the cube, i.e. 000, 002, 020, 022, 200, 202, 220, 222, 111).

Code	Subject	Calculation procedure
A	Average of 8 corner treatments	(000, 002, 020, 022, 200, 202, 220, 222)/8
B	Average 4 treatments at N0	(000, 002, 020, 022)/4
C	Average 4 treatments at N2	(200, 202, 220, 222)/4
D	P effect N0	(020, 022 - 000, 002)/4
E	P effect at N2	(220, 222 - 200, 202)/4
F	P effect at N1	(D + E)/2
G	K effect at N0	(002, 022 - 000, 020)/4
H	K effect at N2	(202, 222 - 200, 220)/4
I	K effect at N1	(G + H)/2
J	Average at 111	Z* A
	Z for grain, rachis, stover	0.94, 0.89, 0.78
	Calculations for not analysed treatments	
	Treatment	
	001	B – D
	010	B – G
	011	B
	012	B + G
	021	B + E
	100	J – F – I
	101	J – F
	102	J – F + I
	110	J – I
	111	J
	112	J + I
	120	J + F – I
	121	J + F
	122	J + F + I
	201	C – E
	210	C – H
	211	C
	212	C + H
	221	C + E

* Z was derived from the relation between measured value at 111 and the calculated values of Code A and proved to be different for grain, rachis and stover.

APPENDIX 6.2 Effect of N, P, and K fertilizers on maize yield after different fallows.

Code	N	P	K	AC	AJ	AL	LP	SS	NF	SM	Mean
	---------kg ha^{-1}------			---------------------------------Mg ha^{-1}---------------------------							
000	0	0	0	2.01	1.70	1.09	0.89	0.83	0.81	0.60	1.13
001	0	0	20	1.38	1.54	1.14	1.62	0.56	1.07	1.56	1.27
002	0	0	40	0.76	1.63	0.75	0.72	1.00	1.53	1.44	1.12
010	0	20	0	1.65	1.09	1.83	1.46	0.61	1.38	1.22	1.32
011	0	20	20	0.80	2.08	1.67	0.41	1.15	1.73	1.95	1.40
012	0	20	40	0.92	1.13	0.76	1.43	0.67	1.09	1.90	1.13
020	0	40	0	1.36	2.26	1.38	0.90	0.87	2.02	1.29	1.44
021	0	40	20	1.09	1.32	1.06	0.88	0.73	1.17	1.99	1.18
022	0	40	40	1.61	2.25	2.44	2.79	0.82	1.76	2.56	2.03
100	50	0	0	1.28	2.35	2.91	2.07	2.61	2.58	1.78	2.23
101	50	0	20	2.64	2.46	2.66	2.67	2.58	3.02	2.35	2.63
102	50	0	40	2.03	2.52	2.61	2.77	3.06	1.87	2.12	2.42
110	50	20	0	3.07	2.99	3.17	2.44	3.08	2.79	2.84	2.91
111	50	20	20	2.78	4.06	3.32	3.90	2.59	3.27	2.85	3.25
112	50	20	40	2.35	2.75	2.83	2.05	2.91	3.05	2.71	2.67
120	50	40	0	2.57	3.26	4.68	3.50	2.12	3.91	2.62	3.24
121	50	40	20	2.60	3.35	2.88	2.33	3.25	2.42	3.44	2.89
122	50	40	40	2.50	3.73	3.37	3.01	2.61	3.34	2.94	3.07
200	100	0	0	2.66	3.21	2.99	2.75	2.75	3.37	2.60	2.90
201	100	0	20	2.45	3.96	2.17	2.67	3.13	2.18	3.21	2.82
202	100	0	40	1.80	4.59	2.14	3.00	3.36	3.70	2.98	3.08
210	100	20	0	3.19	3.20	3.15	3.69	2.67	3.36	3.26	3.22
211	100	20	20	4.22	4.33	3.10	4.60	4.08	3.92	3.50	3.96
212	100	20	40	3.75	4.69	3.74	4.19	3.80	3.95	2.96	3.87
220	100	40	0	4.75	3.87	3.81	4.17	4.29	3.83	3.25	3.99
221	100	40	20	4.09	4.04	4.41	4.79	3.72	4.20	3.99	4.18
222	100	40	40	3.88	4.33	3.56	4.58	3.91	2.88	3.28	3.77
	Mean			2.38b	2.91a	2.58b	2.60b	2.36b	2.60b	2.49b	2.56
LSD$_{0.05}$ (Mean treatment)											0.42
LSD$_{0.05}$ (Fertiliser levels)				1.11	2.06	1.25	1.26	1.33	1.30	1.22	
F probability				<0.001	0.005	<0.001	<0.001	<0.001	<0.001	<0.001	

AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; NF = natural fallow; SM = sole maize.

APPENDIX 6.3 Effect of N, P, and K fertilizers on total biomass yield after different fallows.

	N	P	K	AC	AJ	AL	LP	SS	NF	SM	Mean
	--------kg ha^{-1}-------				--------------------------------Mg ha^{-1}----------------------------						
000	0	0	0	2.54	1.51	1.48	1.30	1.13	1.44	1.01	1.49
001	0	0	20	1.94	1.36	2.22	1.64	0.66	2.39	2.22	1.77
002	0	0	40	0.93	1.76	1.08	0.86	0.82	1.95	1.62	1.29
010	0	20	0	1.34	1.29	2.01	1.68	0.83	2.16	1.66	1.57
011	0	20	20	1.46	2.40	2.19	0.68	1.74	3.28	1.93	1.96
012	0	20	40	1.28	1.80	0.90	1.64	0.93	1.64	3.32	1.64
020	0	40	0	1.14	2.23	2.53	1.00	0.95	2.92	1.46	1.75
021	0	40	20	1.60	1.39	1.32	1.19	0.89	1.72	2.91	1.57
022	0	40	40	1.58	2.67	2.16	3.27	1.34	2.72	2.74	2.35
100	50	0	0	1.57	2.47	3.75	2.84	3.00	4.15	2.87	2.95
101	50	0	20	3.44	3.06	3.69	2.87	3.27	3.95	2.09	3.19
102	50	0	40	2.08	3.17	2.48	3.78	2.99	3.15	2.82	2.93
110	50	20	0	3.61	3.07	3.76	3.73	4.40	4.44	3.79	3.83
111	50	20	20	3.03	4.09	4.31	3.92	3.54	4.23	3.29	3.77
112	50	20	40	2.72	3.54	3.44	3.43	3.67	4.09	3.26	3.45
120	50	40	0	3.33	4.10	5.00	4.58	3.83	5.76	4.04	4.38
121	50	40	20	3.47	2.96	3.93	3.03	5.39	3.01	4.15	3.71
122	50	40	40	3.05	4.56	3.77	3.73	3.93	4.63	3.49	3.87
200	100	0	0	4.56	2.95	3.13	3.02	2.91	3.28	3.08	3.28
201	100	0	20	2.53	3.52	2.37	2.88	3.13	2.90	2.71	2.86
202	100	0	40	2.11	3.80	2.45	3.56	3.50	4.71	2.73	3.26
210	100	20	0	3.50	4.00	3.27	4.34	4.09	4.49	2.89	3.80
211	100	20	20	3.94	3.80	3.65	4.14	3.58	3.82	3.56	3.78
212	100	20	40	5.26	5.10	3.56	3.05	3.67	5.01	3.23	4.12
220	100	40	0	3.50	4.23	3.67	4.24	4.89	4.68	2.88	4.01
221	100	40	20	4.54	3.48	4.38	4.69	4.78	4.59	4.47	4.42
222	100	40	40	3.74	4.97	3.50	4.82	4.34	4.12	3.39	4.12
	Mean			2.73	3.08	2.96	2.96	2.90	3.53	2.87	3.00

AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; NF = natural fallow; SM = sole maize.

APPENDIX 6.4 Effect of N, P, and K fertilizers on maize harvest index (HI) after different fallows.

	N	P	K	AC	AJ	AL	LP	SS	NF	SM	Mean
	kg ha^{-1}			HI							
000	0	0	0	0.44	0.53	0.42	0.41	0.42	0.37	0.37	0.42
001	0	0	20	0.42	0.56	0.32	0.51	0.45	0.29	0.42	0.42
002	0	0	40	0.44	0.44	0.41	0.41	0.53	0.44	0.52	0.45
010	0	20	0	0.55	0.45	0.48	0.51	0.37	0.39	0.41	0.45
011	0	20	20	0.37	0.45	0.41	0.38	0.39	0.34	0.51	0.41
012	0	20	40	0.42	0.40	0.45	0.43	0.41	0.40	0.38	0.41
020	0	40	0	0.54	0.46	0.31	0.46	0.49	0.39	0.47	0.45
021	0	40	20	0.44	0.50	0.44	0.39	0.46	0.42	0.40	0.44
022	0	40	40	0.51	0.43	0.52	0.43	0.37	0.37	0.48	0.45
100	50	0	0	0.42	0.48	0.44	0.42	0.49	0.39	0.37	0.43
101	50	0	20	0.43	0.45	0.43	0.48	0.45	0.43	0.48	0.45
102	50	0	40	0.49	0.43	0.51	0.42	0.51	0.35	0.43	0.45
110	50	20	0	0.47	0.49	0.46	0.39	0.41	0.39	0.43	0.43
111	50	20	20	0.48	0.50	0.43	0.51	0.41	0.43	0.47	0.46
112	50	20	40	0.46	0.44	0.45	0.37	0.44	0.44	0.46	0.44
120	50	40	0	0.44	0.45	0.48	0.43	0.35	0.40	0.40	0.42
121	50	40	20	0.43	0.52	0.42	0.43	0.37	0.44	0.46	0.44
122	50	40	40	0.45	0.45	0.47	0.45	0.41	0.41	0.46	0.44
200	100	0	0	0.38	0.52	0.49	0.48	0.48	0.52	0.45	0.47
201	100	0	20	0.47	0.51	0.47	0.48	0.50	0.42	0.55	0.49
202	100	0	40	0.44	0.55	0.46	0.46	0.47	0.44	0.49	0.47
210	100	20	0	0.47	0.44	0.51	0.46	0.39	0.42	0.53	0.46
211	100	20	20	0.52	0.52	0.46	0.52	0.53	0.50	0.49	0.51
212	100	20	40	0.42	0.47	0.50	0.59	0.51	0.44	0.48	0.49
220	100	40	0	0.57	0.46	0.49	0.51	0.47	0.45	0.53	0.50
221	100	40	20	0.47	0.53	0.51	0.51	0.43	0.48	0.47	0.49
222	100	40	40	0.50	0.46	0.51	0.46	0.48	0.42	0.49	0.48
	Mean			0.46 ab	0.48 a	0.45 b	0.46 ab	0.44 b	0.41c	0.46 ab	0.45
LSD$_{0.05}$ (Mean treatment)											0.022
LSD$_{0.05}$ (Fertilizer levels)											
F probability				<0.001	0.005	<0.001	<0.001	<0.001	<0.001	<0.001	

AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; NF = natural fallow; SM = sole maize.

APPENDIX 6.5 Nitrogen, phosphorus and potassium mass fractions (g kg^{-1}) on grain, rachis and stover from different fallow types.

	Treatment	AC	AJ	AL	LP	SS	SM	NF	Mean
		Grain							
N	000	15.53	11.67	12.46	11.68	9.48	13.43	13.30	12.50
	002	13.65	13.53	13.38	11.70	12.75	15.40	12.30	13.24
	020	14.05	12.98	12.28	9.63	11.25	15.20	11.50	12.41
	022	15.15	14.33	17.61	10.13	13.63	15.93	12.40	14.17
	111	13.58	12.79	14.35	14.15	12.70	13.35	12.04	13.28
	200	14.15	14.65	15.87	14.43	15.35	16.39	13.75	14.94
	202	15.08	17.03	17.61	17.48	16.85	14.98	16.70	16.53
	220	17.74	11.24	15.13	13.45	14.10	15.98	14.15	14.54
	222	14.15	13.06	16.38	13.85	12.38	14.80	16.49	14.44
	Mean	14.79	13.47	15.01	12.94	13.17	15.05	13.63	14.01
P	000	3.50	3.42	1.94	3.58	3.31	4.07	4.33	3.45
	002	4.45	4.13	3.75	3.99	3.98	3.44	4.87	4.09
	020	4.89	4.01	4.49	3.76	4.64	4.10	4.20	4.30
	022	4.68	4.74	1.66	4.21	5.11	4.11	4.73	4.18
	111	4.09	3.88	3.32	4.47	3.46	4.60	4.15	4.00
	200	2.73	3.16	4.12	3.63	3.84	3.75	3.00	3.46
	202	3.31	5.04	1.68	4.72	4.57	3.79	4.11	3.89
	220	6.56	4.31	5.29	4.40	4.94	5.13	5.42	5.15
	222	4.69	4.75	5.35	4.35	3.86	4.06	4.82	4.56
	Mean	4.32	4.16	3.51	4.12	4.19	4.12	4.40	4.12
K	000	4.88	5.47	3.36	4.63	4.25	5.38	5.63	4.80
	002	6.88	5.38	5.88	5.13	5.50	5.00	6.25	5.71
	020	6.47	7.13	6.38	5.10	6.13	5.60	5.50	6.04
	022	6.88	6.25	3.86	5.75	6.47	6.00	5.88	5.87
	111	5.38	6.22	4.75	6.34	4.75	6.25	5.97	5.67
	200	4.35	5.47	6.22	5.00	5.63	4.98	5.00	5.23
	202	5.38	6.38	3.86	6.88	6.00	5.85	6.25	5.80
	220	8.83	5.72	6.88	5.88	6.84	6.75	6.75	6.81
	222	6.13	6.09	6.88	5.88	5.38	5.13	6.84	6.04
	Mean	6.13	6.01	5.34	5.62	5.66	5.66	6.01	5.77
		Rachis							
N	000	9.80	8.28	6.60	8.60	7.28	8.23	6.12	7.84
	002	6.19	7.16	14.05	6.57	9.30	4.90	6.87	7.86
	020	10.63	11.65	8.90	8.03	7.39	6.48	6.34	8.49
	022	5.23	8.58	7.64	4.85	8.28	5.75	10.73	7.29
	111	6.59	5.55	8.18	7.34	6.65	7.83	4.33	6.64
	200	6.58	8.00	9.43	7.23	5.95	5.15	5.87	6.88
	202	4.25	10.10	8.80	4.48	5.60	6.35	7.71	6.76
	220	5.78	7.30	6.75	8.93	8.53	4.58	8.31	7.17
	222	10.40	5.38	5.95	6.12	6.20	9.23	7.94	7.31
	Mean	7.27	8.00	8.48	6.90	7.24	6.50	7.13	7.36
P	000	0.99	1.08	0.49	1.37	1.00	1.16	0.48	0.94
	002	0.63	1.62	2.89	0.99	1.25	0.44	1.18	1.29
	020	1.46	1.82	1.14	0.83	1.62	1.74	0.56	1.31

	022	0.59	1.56	1.27	0.92	1.41	0.51	2.12	1.20
	111	0.68	0.67	0.86	0.71	0.73	1.29	0.35	0.76
	200	0.47	0.66	0.88	1.01	1.18	0.51	0.43	0.73
	202	0.29	1.24	0.55	0.56	0.76	0.57	0.64	0.66
	220	0.42	0.97	1.05	0.96	1.11	0.38	0.83	0.82
	222	1.32	0.69	1.01	0.65	0.69	1.22	0.64	0.89
	Mean	0.76	1.15	1.13	0.89	1.08	0.87	0.80	0.95
K	000	1.88	2.26	1.10	1.75	1.60	2.30	1.14	1.72
	002	1.94	2.19	2.09	1.77	2.20	1.33	1.77	1.90
	020	2.20	1.30	1.73	1.38	1.52	2.08	1.67	1.69
	022	0.83	2.03	2.06	1.65	2.13	1.89	1.95	1.79
	111	1.44	1.28	1.50	1.32	1.98	1.33	0.95	1.40
	200	1.53	1.33	1.40	0.55	1.17	1.13	1.74	1.26
	202	1.03	1.00	2.28	1.08	0.80	0.88	1.86	1.27
	220	0.85	1.58	1.30	1.55	1.64	1.28	1.17	1.34
	222	1.48	0.98	0.72	1.19	0.98	1.29	1.39	1.15
	Mean	1.46	1.55	1.58	1.36	1.56	1.50	1.52	1.50
		Stover							
N	000	5.90	5.33	5.45	4.08	3.30	2.71	3.66	4.35
	002	4.00	6.53	6.04	4.78	4.80	5.63	2.85	4.95
	020	3.18	8.40	3.83	4.95	3.68	3.33	3.23	4.37
	022	6.78	6.94	6.00	4.90	5.60	5.38	2.83	5.49
	111	5.30	4.58	4.63	5.28	3.28	5.12	3.23	4.49
	200	5.05	4.78	9.88	5.50	6.85	7.84	6.83	6.67
	202	9.43	6.93	7.43	7.58	5.70	4.58	7.48	7.01
	220	10.60	6.70	6.22	5.57	6.92	5.58	4.45	6.58
	222	6.32	6.07	6.17	8.53	7.88	4.43	5.78	6.45
	Mean	6.28	6.25	6.18	5.68	5.33	4.95	4.48	5.59
P	000	0.43	0.35	0.76	0.42	1.46	0.32	0.42	0.60
	002	0.41	1.78	1.45	0.52	0.86	0.38	0.74	0.88
	020	0.73	1.58	0.45	0.67	1.57	0.88	0.43	0.90
	022	0.43	1.37	1.51	0.53	1.31	0.47	1.30	0.99
	111	0.41	0.40	0.33	0.33	0.71	0.46	0.29	0.42
	200	0.32	0.22	0.57	0.42	0.50	0.46	0.37	0.41
	202	0.36	0.50	0.32	0.43	0.48	0.34	0.40	0.40
	220	1.23	0.74	0.63	0.36	0.86	0.56	0.59	0.71
	222	0.41	0.48	0.47	0.64	0.74	0.46	0.42	0.52
	Mean	0.53	0.82	0.72	0.48	0.94	0.48	0.55	0.65
K	000	1.65	1.00	0.98	1.53	1.90	0.80	1.19	1.29
	002	1.38	1.58	1.19	1.70	1.72	1.18	1.18	1.42
	020	2.13	1.15	1.15	0.80	1.03	0.38	1.08	1.10
	022	1.08	0.95	1.65	0.82	0.80	0.80	1.18	1.04
	111	0.72	1.33	0.93	0.70	1.10	0.27	1.58	0.95
	200	1.40	1.70	1.43	1.88	1.40	1.32	0.85	1.42
	202	1.45	1.85	1.83	0.43	2.55	0.53	1.53	1.45
	220	1.83	0.95	1.74	0.97	1.57	1.43	1.03	1.36
	222	0.47	0.77	1.02	1.17	3.45	0.43	0.98	1.18
	Mean	1.34	1.25	1.32	1.11	1.72	0.79	1.17	1.25

AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; NF = natural fallow; SM = sole maize.

APPENDIX 6.6 Uptake of N, P and K, averaged over the three replicates

Nitrogen uptake

N	P	K	AC	AJ	AL	LP	SS	SM	NF	MEAN
0	0	0	48.2	29.0	21.9	16.9	12.4	11.8	16.6	22.4
		20	31.1	28.1	28.7	27.5	9.5	32.7	22.3	25.7
		40	14.4	33.8	18.4	12.9	17.6	31.0	26.0	22.0
	20	0	32.7	23.2	33.5	24.7	9.9	24.0	25.6	24.8
		20	19.5	44.5	36.8	8.0	22.0	38.6	33.5	29.0
		40	20.2	28.1	18.3	23.8	14.3	47.9	19.6	24.6
	40	0	25.1	49.9	28.9	14.2	14.0	25.7	34.2	27.4
		20	26.6	24.9	20.6	14.9	12.6	42.2	20.3	23.2
		40	34.6	51.6	56.8	44.2	19.2	55.6	32.5	42.1
50	0	0	25.8	42.2	60.8	38.4	43.9	37.3	50.1	42.6
		20	53.2	48.6	60.2	48.0	47.5	42.6	57.6	51.1
		40	37.3	52.3	56.6	56.1	55.6	42.7	40.6	48.7
	20	0	64.3	52.9	61.5	44.4	55.7	56.5	51.8	55.3
		20	54.8	71.3	70.6	69.4	46.6	56.9	53.9	60.5
		40	46.5	57.3	63.1	43.3	57.0	53.0	59.6	54.3
	40	0	57.0	61.0	84.5	58.8	42.4	53.9	68.4	60.9
		20	57.2	58.6	59.7	40.9	66.8	67.3	42.8	56.2
		40	52.3	75.3	70.5	54.7	54.9	57.6	63.7	61.3
100	0	0	61.7	63.7	78.0	57.3	61.6	64.8	68.0	65.0
		20	53.0	86.3	57.1	60.9	69.6	66.8	53.7	63.9
		40	44.8	107.0	56.6	76.7	76.4	58.2	97.2	73.8
	20	0	76.9	66.0	75.2	78.1	67.8	70.7	73.3	72.6
		20	94.3	85.4	77.7	96.1	84.0	74.9	84.4	85.2
		40	95.6	105.2	88.3	87.6	79.7	61.3	99.8	88.2
	40	0	116.6	72.4	81.0	82.9	95.9	67.0	78.4	84.9
		20	103.2	71.2	96.7	98.9	84.5	85.7	90.8	90.2
		40	82.8	85.9	79.6	101.9	80.9	67.8	73.1	81.7
	average		53.0	58.4	57.1	51.2	48.2	51.7	53.2	53.2

Phosphorus uptake

N	P	K	AC	AJ	AL	LP	SS	SM	NF	MEAN
0	0	0	8.42	6.63	3.16	3.98	4.31	2.93	4.12	4.79
		20	6.49	7.37	5.85	7.20	2.78	6.82	6.37	6.13
		40	3.79	9.79	4.72	3.42	4.76	5.60	9.08	5.88
	20	0	7.96	5.43	7.21	6.50	3.66	6.28	6.85	6.27
		20	4.31	11.62	7.41	2.05	7.15	8.91	10.36	7.40
		40	4.78	7.84	3.52	6.86	4.09	8.62	7.06	6.11
	40	0	7.73	12.72	7.64	4.08	5.55	6.91	9.81	7.78
		20	7.51	7.63	5.99	4.27	4.46	10.63	7.71	6.88
		40	8.26	14.43	7.19	13.70	5.97	11.83	12.15	10.50
50	0	0	4.92	8.82	10.95	8.55	11.71	7.79	10.36	9.01
		20	9.62	10.99	9.60	11.27	11.70	9.02	13.10	10.76
		40	6.85	12.89	8.21	12.67	13.24	7.74	9.23	10.12
	20	0	15.00	12.43	13.78	10.47	16.19	13.47	12.67	13.43
		20	12.81	17.87	13.01	16.60	11.48	15.24	14.87	14.55
		40	10.41	15.36	11.26	10.03	14.56	10.98	16.07	12.67
	40	0	15.44	15.38	23.07	15.31	13.15	13.89	19.64	16.55
		20	15.10	16.85	14.13	10.71	19.30	16.57	12.87	15.08
		40	13.76	22.13	15.27	14.47	14.96	13.22	19.40	16.17
100	0	0	8.82	11.13	14.32	11.63	12.45	11.17	11.36	11.55
		20	8.27	18.06	7.50	12.59	15.06	13.27	8.94	11.96
		40	6.69	25.65	4.50	15.81	17.25	12.34	17.33	14.23
	20	0	17.26	14.16	17.07	17.14	14.92	15.89	16.41	16.12
		20	20.56	20.94	14.89	21.90	20.11	16.42	18.87	19.10
		40	17.44	26.05	14.94	20.69	18.35	13.32	19.91	18.67
	40	0	34.67	20.04	22.85	20.45	25.65	18.13	23.76	23.65
		20	26.78	20.67	26.42	23.66	20.29	20.94	24.04	23.26
		40	20.68	23.21	21.15	23.02	18.26	15.56	15.80	19.67
		average	12.01	14.67	11.69	12.19	12.27	11.61	13.26	12.53

Potassium uptake

N	P	K	AC	AJ	AL	LP	SS	SM	NF	MEAN
0	0	0	27.6	27.0	9.8	16.9	12.7	6.9	5.8	15.2
		20	20.2	26.4	16.2	56.6	7.6	17.5	7.2	21.7
		40	10.9	32.4	10.0	56.0	11.2	15.0	11.5	21.0
	20	0	19.2	21.0	17.7	47.8	8.3	11.3	9.4	19.2
		20	15.1	41.3	19.6	52.2	17.0	17.3	14.5	25.3
		40	12.9	23.4	9.0	86.2	9.1	25.0	10.3	25.1
	40	0	18.2	46.5	21.6	73.7	9.5	10.0	13.4	27.6
		20	18.1	20.5	12.4	78.0	10.4	21.7	11.1	24.6
		40	18.1	47.7	24.1	97.0	10.3	25.2	15.9	34.0
50	0	0	16.2	37.9	30.0	85.8	27.8	20.4	17.8	33.7
		20	30.2	44.2	29.4	93.9	33.4	18.3	20.8	38.6
		40	17.6	44.0	21.9	79.1	37.6	18.1	14.0	33.2
	20	0	38.3	41.6	33.5	16.6	37.1	28.4	16.9	30.3
		20	24.3	65.7	33.8	22.3	29.6	22.3	31.6	32.8
		40	23.1	48.9	30.0	26.0	42.8	21.9	26.6	31.3
	40	0	36.3	49.9	50.0	25.6	29.3	27.5	21.3	34.3
		20	33.3	47.7	34.6	33.5	50.2	29.6	15.6	34.9
		40	26.7	66.6	36.6	19.6	43.0	23.0	21.6	33.9
100	0	0	39.8	49.9	36.6	34.2	32.0	29.5	12.5	33.5
		20	26.5	67.5	26.8	20.3	42.0	27.1	14.7	32.1
		40	22.2	91.9	26.9	32.5	54.5	23.4	33.0	40.6
	20	0	43.6	54.2	41.6	50.1	41.8	34.6	25.6	41.6
		20	46.4	71.6	40.2	57.6	55.4	33.3	27.1	47.4
		40	43.3	88.8	39.8	40.6	64.9	22.9	33.9	47.7
	40	0	65.9	64.7	51.6	51.8	61.5	37.3	28.9	51.7
		20	52.2	57.5	53.5	53.9	72.4	41.0	33.3	52.0
		40	31.7	73.4	38.5	59.6	80.7	23.3	28.7	48.0
		average	28.8	50.1	29.5	50.6	34.5	23.4	19.4	33.8

AC = *Acacia crassicarpa;* AJ = *A. julifera*; AL = *A. leptocarpa*; LP = *L. pallida*; SS = *Senna siamea*; NF = natural fallow; SM = sole maize.

CHAPTER 7

General discussion and conclusions

7.1 Introduction

It is generally accepted now that in order to enhance food security in the developing world, the additional food production will have to come from the agricultural systems located in countries where the additional people will live in, and especially where the majority of the people are concentrated (Conway, 1997; Pinstrup-Andersen and Cohen, 2000). An estimated 1.4 billion people live in diverse and risk-prone rainfed areas in the south, where farming systems as yet have not much benefited from mainstream agricultural technologies. Their systems are usually located in areas too marginal for intensive agriculture and remote from markets and institutions. In order to let the poor more directly benefit, emphasis should be on whole farming systems at the regional level, and should simultaneously tackle the following objectives (Altieri, 2002):

- poverty alleviation;
- food security and self-reliance;
- ecological management of productive resources;
- empowerment of rural communities; and
- establishment of supportive policies.

The current study was part of an integrated research project aimed at developing and describing agroforestry practices and technologies to reduce poverty, food insecurity, deforestation and environmental degradation and lessen the adverse impact of HIV/AIDS in the communities in eastern and southern Africa. Agroforestry systems have been implemented to solve some of the immense problems in this area.

Rotational woodlot is a particular technology of agroforestry in which suitable tree species are rotated with annual crops. Essentially, the technology involves inter-cropping food crops with leguminous trees during the first two to three years, followed by a two to three year period in which the trees are allowed to grow ("fallow period"). The trees are harvested for the production of poles and fire-wood in the 5th year, and the land is replanted with food crops. The crops are suggested to benefit from the plant nutrients that mineralize from the tree litter that is left in the field. It has been indicated that rotational woodlots in Tanzania help farmers to generate income and at the same time conserve natural forest (Ramadhani et al. 2002). So far, farmers and other stakeholders in western Tanzania have shown considerable enthusiasm about this technology, but have also serious concerns regarding the long-term sustainability. Over-exploitation of soil water resources is ascribed to growing trees on farms in the semi-arid tropics. It has also been indicated that tree litter may immobilise soil nutrients, as has been shown for eucalyptus plantations. Such possible pitfalls undermine and even threat a successful implementation of the woodlot technology at larger scale. Evidently, without proper understanding of the interactions and possible competition between trees and crops, the potential benefits of this agroforestry technology will not be realised.

The study described in this thesis was focused on improving the understanding of tree-soil-crop interactions in the planted woody species by examining water and nutrients dynamics in rotational woodlots. The field studies were conducted in Tabora, western Tanzania, a semi-arid area. Supplementary information on the performance of trees established under rotational woodlots was gathered from a sister project in Shinyanga, north-western Tanzania. We evaluated the performance of five tree species (*Acacia crassicarpa*, *A. julifera*, *A. leptocarpa*, *Leucaena pallida* and *Senna siamea*), in comparison to continuous maize (*Zea mays* L.) and natural fallow vegetation. The specific objectives addressed in this research were to determine:

1. the tree performance during the establishment phase of the woodlots,
2. soil water and nitrogen dynamics of different tree species, during the woodlot and tree-fallow phases,
3. the litter production, leaf quality and decomposition patterns,
4. the tree biomass, and nutrient removal from the system with the harvested tree biomass, and
5. maize yield after harvest of trees and the interpretation of fallow impacts in terms of responses to application of N, P, and K fertilisers.

To be able to achieve these objectives, I had to make use of existing long-term field experiments, as the period of my PhD thesis project was limited to three years, while examining the woodlot technology described in this thesis would have required at least five years. Hence, I had to rely in part on existing long-term field experiments.

This final chapter summarises and discusses the major findings of my study.

7.2 Major findings

This chapter summarises the major findings of this study, classified into two categories:

- tree biomass and wood production,
- water and nutrient dynamics.

Tree biomass and wood production

1. The trees in the rotational woodlots grew fast, probably because they benefited from the land preparation, weeding and other management operations executed for cropping of the land.
2. Trees grew more rapidly in low and mid slope positions than at the top due to the more favourable moisture and nutrient conditions at the lower positions.
3. Differences between species were apparent by four years after planting. *Acacia crassicarpa* grew fastest and *L. pallida* the slowest.
4. At five years after planting, *Acacia* species had lower survival rates (53% to 67%) than *L. pallida* (88%) and *S. siamea* (98%), respectively. Obviously, the latter two species were more tolerant to acid soils and less susceptible to termite attack than the *Acacia* species.
5. Rotational woodlots using fast growing and N_2-fixing tree species such as *A. crassicarpa, A. leptocarpa, L. Leucocephala,* and *A. polyacantha* have the potential to produce 30 to 90 Mg ha^{-1} of fuel wood within a period of five years. They greatly reduce the dependence of subsistence farmers on natural forest for fuel wood. Thereby, woodlot plantations on farms contribute to saving natural miombo forest ecosystems.
6. The rate of biomass production was highest for *Acacia* species while the foliage nutrient accumulation was highest for *Leucaena* species. The wood component varied greatly among species, ranging from 32 to 85% of the total tree biomass.
7. Carbon sequestered in the aboveground wood biomass of rotational woodlots ranged between 13 and 30 Mg C ha^{-1} at the end of the five year growing period. The total amount is much larger when C in litter fall and root turnover is included, but this C remains in the field and is conducive to decomposition. We have no estimates about the amount of C from woodlots that is retained by soil. Recently, Makumba (2003) indicated that gliricidia-maize simultaneous inter-cropping system could sequester up to 9 Mg ha^{-1} $year^{-1}$ via root formation. Evidently,

introduction of woodlot systems in abandoned and degraded agricultural and pasture lands has potential to sequester C through aboveground biomass, and likely also belowground.

8. Inter-cropping of maize between trees planted at 4 x 4 m, was possible for the first two years of tree establishment without sacrificing maize yield. All trees were competitive to crops after two years of inter-cropping due to large canopy cover, eliminating the possibility for inter-cropping with maize beyond this age.
9. The average daily domestic household firewood requirement is 2 kg per person per day (Abbot and Homewood 1999). The amount of wood obtained (30 to 90 Mg ha^{-1}) from 5 to 7 years old woodlots of *Acacia*, *Senna* and *Leucaena* species is likely to meet an average firewood consumption for at least 5 to 15 years, assuming an 8-member family. Hence, a one-ha rotational woodlot supplies sufficient firewood for one or two families.
10. Farmers in Tabora region cultivate on average about 1 ha of tobacco each year, which yields 610 kg ha^{-1} green leaf yield (TLTC 1996). The wood needed to cure this amount of tobacco using traditional wood-burning kilns is estimated at about 37.2 Mg ha^{-1} or 61 kg wood kg^{-1} tobacco (Ramadhani et al. 2002). This means that the wood obtained from 1 ha of 5 to 7 years old woodlots is enough to cure 0.8 to 2.4 ha of tobacco. Similarly, almost an equal area of natural forest is saved from clear cutting when the firewood from high-yielding rotational woodlots are used for curing an hectare of tobacco leaves. However, the amount of required fuel wood may be reduced if fuel wood saving technologies such as improved tobacco kilns and wood stoves are used. The adoption of rotational woodlots and improved fuel wood saving technologies can have an important effect on reducing pressure on forests and natural woodlands.

Water and nutrient dynamics

11. Trees scavenged more rain and stored more water in the soil after rains than continuous maize and natural fallow. During the dry season, this surplus amount of soil water was transpired again. Soil water depletion extended to greater depth in woodlot treatments than in natural fallow treatment.
12. Transpiration was greatest in *A. crassicarpa* and lowest in *L. pallida*. The rate of transpiration was related to stem diameter, size of the tree canopy and soil water availability.

13. All tree species were 'scavengers' of soil N; they retrieved inorganic N from soil horizons up to 2-m depth. Trees increased N contents close to their trunks, in part by capturing N from within the crop rooting zone by its lateral roots.
14. Soil inorganic N was much greater in the top 30 cm than in deeper soil horizons, and was much lower under trees than under natural fallow and continuous maize, suggesting that the trees in the woodlots made extensive use of the soil N.
15. Litter fall peaked during the dry season. Acacia trees had high litter fall but the quality of the leaves was poor. These leaves were low in P and N, which led to N and P immobilization. In contrast, leucaena leaves were rich in N, which favoured mineralisation. Evidently, Australian acacia leaves are not direct sources of N for maize.
16. Phosphorus content, C:P, and L:N were better parameters for the prediction of decomposition rates of leaves than N content, C:N ratio and lignin plus total soluble polyphenols:N ratio. The predictors of litter decomposition could be used to facilitate the screening of agroforestry trees for their nutrient-supplying capacity.
17. Substantial amounts of nutrients were exported with the wood of acacia and senna at clearing, ranging from 44 to 215 kg ha^{-1} for N, 3.7 to 7.3 for P, 28 to 86 for K, 11 to 115 for Ca, and 10 to 48 kg ha^{-1} for Mg. Nutrient mining by wood exportation is therefore a major threat for the sustainability of woodlots, when the exported nutrients are not supplemented via external sources.
18. Woody species that accumulate large amounts of wood deplete soil nutrient stocks. Evidently, there is a trade-off between fuel-wood production and soil fertility restoration.
19. For soil fertility restoration, the management of woodlots on farms should aim at establishing leguminous short rotation plantations and at recycling nutrients through slash and mulch techniques, and through return of the ashes from the burned fuel-wood to the fields as much as possible.
20. Maize yields were higher after growing trees in woodlots than after natural fallow and continuous maize. The increase in crop yields after woodlots was attributed in part to accumulation of more inorganic N in the topsoil compared to the traditional fallow. Increased crop yields following harvest of woodlots could be realised for at least two years (Chapter 2). Evidently, the use of N_2-fixing trees is important

when attempting to achieve soil fertility improvement in addition to wood production.

21. Agroforestry plots responded to fertiliser N; the agronomic efficiency was about 30 kg grain per kg N applied at a rate of 50 kg fertilizer N, and between 15 kg/kg between 50 and 100 kg N applied.
22. Application of more than 20 kg/ha of P or K did not significantly increase maize yields.
23. There was a significant correlation between N in tree foliage biomass and maize grain yield; grain yield increased by 4 kg per kg N in foliage biomass.
24. The benefits of tree fallows compared to natural fallows were very modest, in terms of maize yield increases. After *Acacia crassicarpa, Leucaena pallida* and *Senna siamea*, yields were even lower than after natural fallow.
25. The benefit of rotational woodlots is primarily caused by the extra uptake of about 10 kg N, in the case of N fixing trees, resulting in yield increases of 100 to 500 kg grain per ha if no fertilizers are used.
26. In view of the improved agronomic and recovery efficiency of the use of nutrients (naturally and external inputs), there is a potential in the agricultural sector in well-designed and managed agroforestry systems, provided external nutrient sources are available.

7.3 Where and why continue with rotational woodlots?

Rotational woodlots have greatest potential in areas where farmers struggle to collect firewood, but still have land that they leave fallow (Ramadhani et al. 2002). When forests and other off-farm sources of wood become scarce, the cost of growing trees becomes less than the cost of collecting wood. Hence, planting trees on farms becomes essential (Franzel and Scheer 2002; Ramadhani et al. 2002).

The results of my study indicate that woodlots do provide substantial amounts of wood to be used for poles or firewood. As such they contribute to preserving natural forest from clearing and also to income generation for the local farmers. Based on present evidence of one year's data we also conclude that woodlots transpire more soil water into the atmosphere than natural fallow vegetation, but the trees of woodlots scavenged more rainwater so that the net effect on the water balance is minimal. However, long term data is required to be certain about impact on landscape hydrology.

After harvesting of the trees, the subsequent maize crop does benefit from the improved soil fertility, mainly through the increased availability of N in the soil. Part of this N is from the fixation of atmospheric N_2 by the trees, part also from the subsoil, as indicated by the soil mineral N profiles (Chapter 3). We did not assess the uptake of other nutrients from the subsoil, but Makumba (2003) recently showed that trees grown in combination with maize plants do take up P and other nutrients from the subsoil and transfer part of this P and other nutrients to the surface soil via litter fall. This pumping of other nutrients than N may also have taken place in our experiments.

My experiments clearly show that the maize crop grown in the woodlot after harvesting the trees out-yielded continuous maize, and these increased crop yields contribute to the sustainability of the system. Breman and Kessler (1997) also observed consistent improvement in soil water availability and nutrient recovery in Sahel region after planting selected trees. The results of Chapter 6, however, do emphasize that there are trees that have a negative effect on yields (*Acacia crassicarpa, Leucaena pallida, Senna siamea).*

The groundcover by fallow vegetation in the woodlots may contribute to enhancing soil biological activity and to flourishing of mycorrhizal fungi growth, as discussed in Chapter 4. The replenishment of soil organic matter probably led to regeneration of biological activity and subsequently to a greater soil porosity and less soil compaction. These effects may in part also explain the relatively high water content under tree fallows compared to continuous maize cropping.

Woodlots may also contribute to carbon sequestration in the soil, conserving topsoil by minimizing erosion, and they may contribute to pest management through increasing biodiversity (e.g. Altieri, 2002). However, I did not quantify these additional three potential effects of woodlots.

7.4 Pitfalls of rotational woodlots

Though the benefits of woodlots seem to be manifold, there are also pitfalls. With the harvest of increased maize yields, larger amounts of nutrients are withdrawn from the system than in the case of the traditional system with natural fallow vegetation. Moreover, substantial amounts of nutrients are withdrawn from the system via the harvested wood. Though the N_2-fixing trees will replenish N, they cannot replenish the other essential nutrients, except from scavenging them from the sub soil.

The results of the leaves and litter analyses have indicated that nutrient contents were very low, particularly P. As a consequence, the decomposition of the litter was retarded and N (and P) from the soil solution was immobilized initially, especially in treatments with acacia trees. Hence, the microbial community in the soil is competing with the roots of trees and crop for available N and P. This immobilization will negatively affect crop growth, as the soil is already poor in available N and P. Evidently, the woodlot technology will be not sustainable in the long-term without input of nutrients from external sources, and especially P.

My results also show that some trees were better in furnishing wood, while others were better in transferring nutrients and improving soil fertility. This trade-off between wood production and soil fertility restoration is key to selecting the proper trees in woodlot technology. Tree leaves of leucaena and senna had higher levels of polyphenols and lower levels of lignin than acacia trees. These characteristics are also important in selecting tree species, as lignin and polyphenols affect the decomposition of leaves (e.g. Giller and Cadish 1997; Harborne 1997; Palm et al. 2001a).

Selecting the proper tree species is essential. There are culprits of woodlots, when wrong species are used and planted in the wrong landscapes. Experiences with eucalyptus plantations are illustrative in this respect; it has been reported that diminished amounts of surface water ruined prospects of growing food crops, and people's traditional lifestyle were left in tatters (e.g. Calder et al. 1997; Le Maitre et al. 1999; Jagger 2003).

7.5 Rotational or permanent woodlots?

Although I did not examine the benefits of rotational woodlots (with intercropping) versus permanent woodlots (with adjacent permanent cropping), it is worth to speculate about it. Evidently, woodlots are important for the purpose of supplying fire-wood, poles and timber for the rural community, and for meeting the demands by pulp and paper industry. But should all subsistence farmers in sub-Saharan Africa now implement rotational woodlot systems on their farms? Are all farmers able to manage such systems properly, under all environmental conditions? Are permanent woodlots next to permanent crop land, but amended with external nutrient sources, also an option? Are rotational woodlots for subsistence farmers and permanent woodlots and permanent crop land for the larger farmers?

Both types of woodlots may contribute to beneficial effects to the wider environment by transferring carbon to the soil (C sequestration), affecting climate, keeping water tables in place, helping to sustain freshwater supplies and reducing soil and water runoff (Hui 1997). Woodlots may also provide protection to landscapes. Trees may increase the rate that rainwater recharges groundwater as well as control the rate that water is released in watersheds (FAO 1993). Woodlots are also an important habitat for wildlife such as forest dwelling birds, plants and insects. Permanent woodlots seem to have greater potential in restoring biodiversity. If the intention is to manage both ecological diversity and wood/timber harvesting, the selective removal of trees should be considered. In this respect permanent woodlots may be preferred.

Rotational woodlots have the advantage of the synergistic effects provided by simultaneous cropping and tree growth during the first years of establishment. The crop and soil management appears to be beneficial to tree growth, while crop yield does not suffer from the trees yet. Rotational woodlots also provide the potential advantage of the safety net function and the function of pumping up nutrients from the subsoil to the topsoil. Hence, the nutrient use efficiency in crop growing may be enhanced in rotational woodlots, compared to continuous cropping.

Rotational woodlots also have the advantage of topsoil conservation in erosion-prone areas, even during the cropping phase. Clearly, this holds also for permanent woodlots, but not for continuous cropped land. Clearing permanent woodlots for agricultural purposes increases the risk on land degradation by wind and water erosion, loss of biodiversity, and on increasing greenhouse gas emissions. Clear cutting removes all of the trees and removes most of the ecological diversity of animals. In dry areas, woodlot removal may cause soil water tables to drop; in wet areas, water tables can rise to the surface (Le Maitre et al. 1999). Evidently, woodlot removal or poor forest management destroys their revenue-generating potential.

Evidently, the question of rotational woodlots with intercropping versus permanent woodlots with adjacent permanent cropping is not easy to answer. There are many factors that influence the answer to this question, including the multiple objectives of the woodlots, farmers' skill, site, soil and climatic conditions, availability of land, tree species and external nutrient sources, mechanization potential, and market conditions.

7.6 General conclusion

Research presented in this thesis has provided significant insight into the understanding of water and nutrient dynamics of trees species in rotational woodlots in western Tanzania. The system has shown to offer fuel-wood resources, enhance productivity and improve short fallow-crop cycles. Increased maize yields following woodlots of N-fixing leguminous trees were due in part to the increased soil nitrogen that the trees have brought in the topsoil, either by fixation or through scavenging within the soil profiles.

The major benefits of rotational woodlots of N-fixing leguminous trees, apart from the added value of wood in the system, are the improved water availability, C sequestration, nutrient use efficiency and modestly increased crop yields.

The harvesting of wood and increased crop yields contribute to increased withdrawal of scarce plant nutrients from the soil. Evidently, the trade-off between fuel-wood production and soil fertility restoration poses a question on the sustainability of rotational woodlots; the greater the fire-wood production and crop yields, the greater the reliance on external inputs of plant nutrients.

This study has demonstrated that N and P are the most deficient nutrients in the study area. The P content in plant residues was too low to meet P requirements for crop production. Therefore, external inputs of especially P are needed in this area.

7.7 Future perspectives

1. My research shows that there are large differences between tree species in wood biomass and litter production and nutrient release. This offers the potential for selecting the best tree species for each environment, adapted to the local needs. Currently, only very few varieties of leguminous tree species are in use for rotational woodlots. The number of suitable tree species for woodlots must be increased, also as a means of enhancing biodiversity and reducing risk of single species dependence.
2. There is need for quantification and optimizing C sequestration in the soil through litter fall and root turnover in the top soil and sub soil. There is also a need for the quantification of the long-term nutrient use efficiency and sustainability of the systems; for how long can the trees replenish nutrients withdrawn from the topsoil by pumping up nutrients from the sub soil, and supplemented by biologically fixed N_2.

3. Whereas the analyses in this study were primarily at the woodlot technology level, increased adoption of woodlots will permit assessment of crop productivity and environmental impacts on community and regional scales. There is a particular need to examine the environmental impacts of rotational woodlots practised on a landscape scale.
4. Woodlots management options depending on the ecological and economic sustainability of the system need to be addressed and quantified at farm and eco-regional levels.

REFERENCES

Abbot J.I.O. and Homewood K. 1999. A history of change: causes of miombo woodland decline in a protected area in Malawi. Journal of Ecology 36: 422–433.

Adejuyigbe C.O., Tian G. and Adeoye G.O. 1999. Soil microarthropod populations under natural and planted fallows in southwestern Nigeria. Agroforestry Systems 47: 263–272.

Aihou K. Vanlauwe B. Sanginga N. Lyasse O. Diels J. and Merckx R. 1999. Alley cropping in the moist savanna zone of West-Africa: Restoration and maintenance of soil fertility on 'terre de barre' soils in Southern Benin Republic. Agroforestry Systems 42: 213–227.

Aldred A.H. and Alemdag I.S. 1988. Guidelines for Forest Biomass Inventory. Information Report PI-X-77. Petawawa National Forestry Institute. Canadian Forestry Service, Ontario, Canada, 134 pp.

Allen R.G., Pereira L.S., Raes D. and Smith M. 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome, Italy, 300 pp.

Altieri M.A. 2002. Agroecology: the science of natural resource management for poor farmers in marginal environments. Agriculture, Ecosystems and Environment 93: 1-24.

Anderson J.M. and Ingram J.S.I. 1993. Tropical Soil Biology and Fertility: A Handbook of Methods. 2nd edition. CAB International, Wallingford, UK, 221 pp.

Anonymous. 1983. Mangium and Other Fast-growing Acacias for the Humid Tropics. Innovations in Tropical Reforestation. National Academy Press, Washington, USA, 65 pp.

Arunachalam A., Arunachalam K.M., Pandey H.N. and Tripathi R.S. 1998. Fine litter fall and nutrient dynamics during forest regrowth in the humid subtropics of north-eastern India. Forest Ecology Management 110: 209–219.

Bajracharya D. 1983. Deforestation in the food/fuel context: Historical and political perspectives from Nepal. Mountain Research and Development 3: 227–240.

Bell J.P. 1987. Neutron Probe Practice. Report 19, 3rd edition, Institute of Hydrology, Wallingford, UK, 29 pp.

Bond W.J. and Loffell D. 2001. Introduction of giraffe changes acacia distribution in a South African savannah. African Journal of Ecology 39: 286–294.

Bray R.A, Palmer B. and Ibrahim T.M. 1997. Performance of shrub legumes at four sites in Indonesia and Australia. Tropical Grasslands 31: 31–39.

Breman H. and Kessler J.J. 1995. Woody Plants in Agro-Ecosystems of Semi-Arid Regions: With an Emphasis on the Sahelian Countries. Springer-Verlag, Berlin, Germany, 340 pp.

Breman H. and Kessler J.J. 1997. The potential benefits of agroforestry in the Sahel and other semi arid regions. European Journal of Agronomy 7: 25–33.

Buresh R.J. and Tian G. 1997. Soil improvement by trees in sub-Saharan Africa. Agroforestry Systems 38: 51–76.

Buresh R.J., Sanchez P.A. and Calhoun F. (eds). 1997. Replenishing Soil Fertility in Africa. Soil Science Society of America Publication No 51. SSSA-ASA Madison, Wisconsin, USA, pp 251.

Burgess S.S.O., Adams M.A., Turner N.C. and Ong C.K. 1998. The redistribution of soil water by tree root systems. Oecologia 115: 306–311.

Burt B.D. 1942. Some East African vegetation communities. Journal of Ecology 30: 67–146.

Cadisch G. and Giller K.E. (eds). 1997. Driven by Nature: Plant Litter Quality and Decomposition. CAB International, Wallingford, UK, 409 pp.

Cahn M.D., Bouldin D.R., Cravo M.S. and Bowen W.T. 1993. Cation and nitrate leaching in an Oxisol of the Brazilian Amazon. Agronomy Journal 85: 334–340.

Cairns M. and Garrity D.P. 1999. Improving shifting cultivation in Southeast Asia by building on indigenous fallow management strategies. Agroforestry Systems 47: 37–48.

Calder I.R., Hall R.K. and Prasanna K.T. 1993. Hydrological impact of Eucalyptus plantation in India. Journal of Hydrology 150: 635–648.

Calder I.R., Hall R.L. and Adlard P.G. (eds). 1992. Growth and Water Use of Forest Plantations. John Wiley & Sons, Chichester, UK, 381 pp.

Calder I.R., Rosier P.T.W., Parsanna K.T. and Parameswarappa S. 1997. Eucalyptus water use greater than rainfall input–possible explanation from southern India. Hydrology and Earth System Sciences 1: 249–256.

Cannell M.G.R. 1984. Woody biomass of forest stands. Forest Ecology and Management 8: 299–312.

Chamshama S.A.O., Monela G.C., Sekiete K.E.A. and Persson A. 1992. Suitability of the taungya system at North Kilimanjaro forest plantation, Tanzania. Agroforestry Systems 17: 1–11.

Charter S. and Hince B. (eds). 1997. ICRAF Annual Report 1997. International Centre for Research in Agroforestry, Nairobi, Kenya, 204 pp.

Chidumayo E.N. 1988. Integration and role of planted trees in a bush-fallow cultivation system in Central Zambia. Agroforestry Systems 7: 63–76.

Cleaver K.M. and Schreiber G.A. 1994. Reversing the Spiral; the population, agriculture, and environment nexus in sub-Saharan Africa. World Bank, Washington, DC, USA.

Cochran W.G. and Cox G.M. 1992. Experimental Designs. 2nd Ed. Wiley, New York, 615 pp.

Constantinides M. and Fownes J.H. 1994a. Nitrogen mineralization from leaves and litter of tropical plants: relationship to nitrogen, lignin and soluble polyphenol concentrations. Soil Biology and Biochemistry 26: 49–55.

Constantinides M. and Fownes J.H. 1994b. Tissue-to-solvent ratio and other factors affecting determination of soluble polyphenols in tropical leaves. Communication in Soil Science and Plant Analysis 25: 3221–3227.

Conway G.R. 1997. The Double Green Revolution. Penguin, London.

Couteaux M.M., Bottner P. and Berg B. 1995. Litter decomposition, climate and litter quality. Trees 10: 63–66.

Cuevas E. and Lugo A.E. 1998. Dynamics of organic matter and nutrient return from litter fall in stands of ten tropical tree plantation species. Forestry Ecology and Management 112: 263–279.

de Foresta H. and Michon G. 1997. The agroforests alternative to *Imperata* grasslands: when smallholder agriculture and forestry reach sustainability. Agroforestry Systems 36: 105–120.

De Rouw A. 1995. The fallow period as a weed-break in shifting cultivation (tropical wet forest). Agriculture, Ecosystem and Environment 54: 31–43.

Drechsel P. and Zech W. 1991. Foliar nutrient levels in broad-leaved tropical trees: A tabular review. Plant and Soil 131: 29–46.

Drechsel P., Glaser B. and Zech W. 1991. Effect of four multipurpose tree species on soil amelioration during tree fallow in central Togo. Agroforestry Systems 16: 193–202.

Dye P.J. and Olbrich B.W. 1992. Heat pulse observations of *Eucalyptus grandis* transpiration in South Africa. In: Calder I.R., Hall R.L. and Adlard P.G. (eds). Growth and Water Use of Forest Plantations. John Wiley & Sons, Chichester, UK, pp 167–179.

Dyson F.J. 1977. Can we control the carbon dioxide in the atmosphere? Energy (Oxford) 2: 287–291.

Edmeades G.O., Bolaños J., Chapman S.C., Lafitte H.R. and Bänziger M. 1999. Selection improves drought tolerance in tropical maize populations: I. Gains in biomass, grain yield, and harvest index. Crop Science 39: 1306–1315.

FAO (Food and Agriculture Organization of the United Nations). 1993. The Challenge of Sustainable Forest Management: What Future for the World's Forest? FAO, Rome, Italy.

FAO (Food and Agriculture Organization of the United Nations). 1985. The Ecological Effects of *Eucalyptus*, FAO Forestry Paper No. 59. FAO, Rome, Italy.

FAO (Food and Agriculture Organization of the United Nations). 2003. Wood Energy. Unasylva Series No. 211 Volume 53. FAO, Rome, Italy, 60 pp.

Fearnside P.M. 1997. Wood density forest biomass in Brazilian Amazonia. Forest Ecology and Management 90: 59–87.

Fearnside P.M. 2000. Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Climate Change 46: 115–158.

Float M.J.S. 1970. Decomposition of organic materials from hill soils and pastures. II. Comparative studies on the mineralization of carbon, nitrogen, and phosphorus from soil. Soil Biology and Biochemistry 2: 173–494.

Franzel S. and Scherr S.J. 2002. Trees on the farm. Assessing the Adoption Potential of Agroforestry Practices in Africa. CAB International, Wallingford, UK. 197 pp.

Fried M. and Dean L.A. 1952. A concept concerning the measurement of available soil nutrients. Soil Science 73: 263–271.

Gallardo A. and Merino J. 1993. Leaf decomposition in two Mediterranean ecosystems of South Spain: influence of substrate quality. Ecosystem 74: 152–161.

Garrity D.P. (ed.) 1997. Agroforestry Innovations for *Imperata* Grassland Rehabilitation. Kluwer Academic Publishers, Dordrecht, Netherlands, 284 pp.

Giller K.E. 2001. Nitrogen Fixation in Tropical Cropping Systems. 2nd Edition. CAB International, Wallingford, UK, 423 pp.

Guo L.B. and Sims R.E.H. 1999. Litter decomposition and nutrient release via litter decomposition in New Zealand eucalypt short rotation forests. Agriculture, Ecosystems and Environment. 75: 133–140.

Guo L.B. and Sims R.E.H. 2001. Effects of light, temperature, water and meatworks effluent irrigation on eucalypt leaf litter decomposition under controlled environmental conditions. Applied Soil Ecology 17: 229–237.

Gupta R. and Rout S.K. 1992. Litter dynamics and nutrient turnover in a mixed deciduous forest. In: Singh K.P. and Singh J.S. (eds). Tropical Ecosystems: Ecology and Management. Wiley Eastern, New Delhi, India.

H'gberg P (1982) Mycorrhizal associations in some woodland and forest trees and shrubs in Tanzania. New Phytologist 92: 407–415.

Handayanto E., Cadisch G. Giller K.E. 1994. Nitrogen release from prunings of legume hedgerow trees in relation to quality of the prunings and incubation method. Plant and Soil 160: 237–248.

Handayanto E., Cadisch G. Giller K.E. 1995. Manipulation of quality and mineralization of tropical legume tree prunings by varying nitrogen supply. Plant and Soil 176: 149–160.

Harborne J.B. 1997. Role of phenolic secondary metabolites in plants and their degradation in nature. In: Cadisch G and Giller K.E. (eds). Driven by Nature: Plant Litter Quality and Decomposition. CAB International, Wallingford, UK, pp 67–74.

Hartemink 2003. Soil Fertility Decline in the Tropics: With Case Studies on Plantations. CAB International, Wallingford, UK, 360 pp.

Hatton T.J., Moore S.J. and Reece P.H. 1995. Estimating stand transpiration in a *Eucalyptus populnea* woodland with the heat pulse method: measurement errors and sampling strategies. Tree Physiology 11: 185–196.

Hauser S. 1993. Root distribution of *Dictyladenia (Acioa) barteri* and *Senna (Cassia) siamea* in alley cropping on Ultisol. I. Implication for field experimentation. Agroforestry Systems 24: 111–121.

Haynes R.J. 1990. Active ion uptake and maintenance of cation-anion balance: A critical examination of their role in regulating rhizosphere pH. Plant and Soil 126: 247–264.

Heal O.W., Anderson J.M. and Swift M.J. 1997. Plant litter quality and decomposition: an historical overview. In: Cadisch G. and Giller K.E. (eds).

Driven by Nature: Plant Litter Quality and Decomposition. CAB International, Wallingford, UK, pp 3–45.

Heinemann G.R. and Kullaya I.K. 1978. Detailed Soil Survey of Tumbi Research Farm. Ministry of Agriculture, Tumbi Agricultural Research Institute, Tabora, Tanzania, 69 pp.

Hopman P., Stewart H.T.L. and Flinn D.W. 1993. Impacts of harvesting on nutrients in eucalypt ecosystem in southeastern Australia. Forest Ecology and Management 59: 29–51.

Hui S. 1997. Deforestation: Humankind and the global ecological crisis. http://www.aquapulse.net/knowledge/deforestation.

IPCC 1995. The Intergovernmental Panel on Climate Change (IPCC) Second Assessment: Climate Change 1995. Publication by World Meteorological Organization (WMO) and United Nations Environment Programme (UNEP). Bracknell, UK.

Jagger P. and Pender J. 2003. The role of trees for sustainable management of less-favoured lands: the case of eucalyptus in Ethiopia. Forest Policy and Economics 5: 83–95.

Jama B.A., Nair P.K.R. and Rao M.R. 1995. Productivity of hedgerow shrubs and maize under alley cropping and block planting systems in semiarid Kenya. Agroforestry Systems 31: 257–274.

Janssen B.H. 1984. A simple method for calculating decomposition and accumulation of 'young' organic matter. Plant and Soil 76: 297–304.

Janssen B.H. 1996. Nitrogen mineralization in relation to C:N ratio and decomposability of organic materials. Plant and Soil 181: 39–45.

Janssen B.H. 1998. Efficient use of nutrients: an art of balancing. Field Crops Research 56: 197–201.

Janssen B.H. 2000a. Organic matter supply and crop yields. In: Organic matter and soil fertility. Wageningen Agricultural University, Sub-dept. Soil Science and Plant Nutrition, pp 223–234.

Janssen B.H. 2000b. Report of a visit to Shinyanga and Tabora, Tanzania, 5-10 December 2000, 16 pp.

Janssen B.H., Guiking F.C.T., Van der Eijk D., Smaling E.M.A., Wolf J. and Van Reuler H. 1990. A system for the quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46: 299–318.

Janssen B.H. 2003. Adaptation of the QUEFTS model to agro-ecological conditions and crops in West Africa. A report for IFDC-Africa. Wageningen University, Department of Environmental Sciences, Sub-department of Soil Quality, 91 pp.

Jara J., Stockle C.O. and Kjelgaard J. 1998. Measurement of evapotranspiration and its components in a corn (*Zea mays* L.) field. Agricultural and Forest Meteorology 92: 131–145.

Jonsson K., Stahl L. and Hogberg P. 1996. Tree fallows: a comparison between five tropical tree species. Biology and Fertility of Soils 23: 50–56.

Kachaka S., Vanlauwe B. and Merckx R. 1993. Decomposition and nitrogen mineralization of prunings of different quality. In: Mulongoy K. and Merckx R (eds). Soil Organic Matter Dynamics and Sustainability of Tropical Agriculture, pp 199–208. John Wiley and Sons, Chichester, UK.

Kang B.T., Akinnifesi F.K. and Ladipo D.O. 1994. Performance of selected woody agroforestry species grown on an Alfisol and an Ultisol in the humid lowland of West Africa and their effects on soil properties. Journal of Tropical Forest Science 7: 303–312.

Kang B.T., Reymonds L. and Atta-Krah A.N. 1990. Alley Farming. Advances in Agronomy 43: 315–359.

Kang B.T., Salako F.K., Chianu J.N., Akobundu I.O. and Pleysier J.L. 1997. Role of some perennial leguminous and natural fallow species in the amelioration of a degraded oxic paleustalf-effect on soil properties and crop performance. Soil Use and Management 13: 130–136.

Kanmegne J. and Degrande A. 2002. From alley cropping to rotational fallow: Farmers' involvement in the development of fallow management techniques in the humid forest zone of Cameroon. Agroforestry Systems 54: 115–120.

Karachi M. 1998a. The performance and nutritive value of *Leucaena* in a unimodal rainfall environment in western Tanzania. Tropical Grasslands 32: 105–109.

Karachi M. 1998b. Variation in the nutritional value of leaf and stem fractions on nineteen Leucaena lines. Animal Feed Science Technology 70: 305–314.

Karachi M., Shirima D. and Lema N. 1997. Evaluation of 15 leguminous trees and shrubs for forage and wood production in Tanzania. Agroforestry Systems 37: 253–263.

Kato M.S.A., Kato O.R., Denich M. and Vlek P.L.G. 1999. Fire-free alternatives to slash-and-burn for shifting cultivation in the eastern Amazon region: the role of fertilizers. Field Crops Research 62: 225–237.

Khan A.A. and Ong C.K. 1996. A low cost heat pulse technique for measuring tree root water uptake. Agroforestry Forum 7(2): 19–22.

Khasa P.D., Li P., Vallee G., Magnussen S. and Bousquet J. 1995. Early evaluation of *Racosperma auriculiformis* and *R. mangium* provenance trials on four sites in Zaire. Forest Ecology and Management 78: 99–113.

Kiratiprayoon S. and Williams E.R. 1991. Standing above ground yields of some tropical acacias. In: Turnbull J.W. (ed) 1991. Advances in Tropical Research: ACIAR Proceedings No. 35. Canberra, Australia, pp 48–51.

Komarek A.R., Robertson J.B. and Van Soest P.J. 1994. A comparison of methods for determining ADF using the litter bag technique versus conventional filtration. ASAS/ADSA Meetings, USA.

Kort J.and Turnock R. 1999. Carbon reservoir and biomass in Canadian prairie shelterbelts. Agroforestry Systems 44: 175–186.

Kruger O. and McGavin G.C. 1998. The insect of *Acacia* species in Mkomazi Game Reserve, north eastern Tanzania. Ecological Entomology 22: 440–444.

Kumar M.B., George S.J., Jamaludheen V. and Suresh T.K. 1998. Comparison of biomass, tree allometry and nutrient use efficiency of multipurpose trees grown in woodlot and silvopastoral experiments in Kerala, India. Forest Ecology and Management 112: 145–163.

Kuperman R.G. 1999. Litter decomposition and nutrient dynamics in oak-hickory forests along a historic gradient of nitrogen and sulphur deposition. Soil Biology and Biochemistry 31: 237–244.

Ladha J.K., Peoples M.B., Garrity D.P., Capuno V.T. and Dart P.J. 1993. Estimating dinitrogen fixation of hedgerow vegetation using the nitrogen-15 natural abundance method. Soil Science Society of America Journal 57: 732–737.

Lara C.D., Chavez L.G., Macedo I.V., Casares R.G. and Carrillo J.T.R. 1999. Two techniques for measuring neutral detergent (NDF) and acid detergent fibres (ADF) in forages and by-products. Archivos de Zootecnia 48: 351–354.

Le Maitre D.C., Scott D.F. and Colvin C. 1999. A review of information on interaction between vegetation and groundwater. Water SA 25(2): 137–152.

Leakey R. 1996. Definition of agroforestry revisited. Agroforestry Today 8: 5–7.

Lisanework N. and Michelsen A. 1994. Litter fall and nutrient release by decomposition in three populations compared with a natural forest in the Ethiopian highland. Forestry Ecology and Management 65: 149–164.

Lott J.E., Howard S.B., Ong C.K. and Black C.R. 2000. Long-term productivity of a *Grevillea robusta*-based overstorey agroforestry system in semiarid Kenya: I. Tree growth. Forest Ecology and Management 139: 175–186.

MacDicken K.G. 1994. Selection and Management of Nitrogen-fixing Trees. FAO, Bangkok and Winrock International, Morrilton, Arkansas, 272 pp.

Mafongoya P.L., Barak P. Reed J.D. 2000. Carbon, nitrogen and phosphorus mineralization of tree leaves and manure. Biology of Soil Fertility 30: 298–305.

Mafongoya P.L., Giller K.E. and Palm C.A. 1998. Decomposition and nitrogen release patterns of tree prunings and litter. Agroforestry Systems 38: 77–97.

Maghembe J.A. Chirwa P.W. and Kwesiga F. 1994. Performance of some Australian Acacias 3.5 years after planting at Makoka, Malawi. Journal of Tropical Forest Science, 9: 546–553.

Makumba W. 2003. Nitrogen use efficiency and carbon sequestration in legume tree-based agroforestry systems. A case study in Malawi. PhD thesis Wageningen University, The Netherlands, 208 pp.

Makundi W.R. 2001. Potential and cost of carbon sequestration in the Tanzanian forest sector. Mitigation and Adaptation Strategies for Globe Change 6: 335–353.

Mbuya L.P., Mshanga H.P., Ruffo C.K., Birnie A. and Tengnas B.1994. Useful trees and shrubs for Tanzania: Identification, Propagation and Management for Agricultural and Pastoral Communities. Regional Soil Conservation Unit (RSCU), Swedish International Development Authority (SIDA).

Mekonnen K., Buresh R.J. and Jama B. 1997. Root and inorganic nitrogen distributions in sesbania fallow, natural fallow and maize fields. Plant and Soil 188: 319–327.

Melillo J.M., Naiman R.J., Aber J.D., Linkins A.E. 1984. Factors controlling mass loss and nitrogen dynamics of plant litter decaying in northern streams. Bulletin of Marine Sciences and Fisheries 35: 341–356.

Mfilinge P.L. and Tsuchiya M. 2002. Nutrient dynamics and leaf litter decomposition in a subtropical mangrove forest at Oura Bay, Okinawa, Japan. Trees 16: 172–180.

Midgely J.T. and Turnbull J.W. 2003. Domestication and use of Australian acacias: case studies of five important species. Australian Systematic Botany 16: 89–102.

Mitchell A.J.B. (ed). 1984. Land Evaluation and Land Use Planning in Tabora Region. Land Resources Development Centre. Report No. 35, UK,/ Tabora, Tanzania, 198 pp.

Mlenge W. 2002. Revival of customary landcare in Shinyanga Region, Tanzania. Forests, Trees and People 46: 21–28.

Mugasha A.G., Chamshama S.A.O., Iddi S. and Nshubemuki L. 1996. Survival, growth and wood density of *Pinus kesiya* and *Pinus oocarpa* provenances at Kihanga Arboretum, Sao Hill, Tanzania. Forest Ecology and Management 87: 1–11.

Muoghalu J.I., Akanni S.O. and Eretan O.O. 1993. Litter fall and nutrient dynamics in a Nigerian rainforest seven years after a ground fire. Journal of Vegetation Science 4: 323–328.

Myers, N., 1984. The Primary Source: Tropical Forests and Our Future. General Publication Co., Ontario.

Nair P.K.R., Buresh R.J., Mugendi D.N. and Latt C.R. 1999. Nutrient cycling in tropical agroforestry systems: myths and science. In: Buck L.E., Lassoie J.E. and Fernandes E.C.M. (eds). Agroforestry in Sustainable Agricultural Systems. Lewis Publishers, Washington DC, USA, pp 1–31.

Nambiar E.K.S. 1995. Relationship between water, nutrients and productivity in Australian forests: Application to wood production and quality. Plant and Soil 168: 427–435.

NATF (National Agroforestry Task Force). 1988. A Blueprint for Agroforestry Research in the Uni-modal Upland Plateau of Tanzania. AFRENA Report No. 6. ICARF, Nairobi, Kenya, 30 pp.

N'Goran A., Gnahoua G.M., Oualou K. and Balle P. 2002. Evolution of maize yield after tree fallow in a humid forest zone of Cote d'Ivoire. Cahiers d'Etudes et de Recherches Francophones/Agricultures (France) 11: 145–149.

Ngulube M.R., Chapola G.B.J. and Mwabumba L. 1993. The potential of Australian dry zone acacias for agroforestry in Malawi. Forestry Ecology Management 56: 83–97.

Niklas K.J. 1997. Mechanical properties of black locust (Robinia pseudoacadia) wood: Correlations among elastic and rupture moduli, proportional limit, and tissue density and specific gravity. Annals of Botany 79: 479–485.

Noij I.G.A.M, Janssen B.H., Wesselink L.G. and van Grinsven J.J.M. 1993. Modelling Nutrient and Moisture Cycling in Tropical Forests. The Tropenbos Foundation III, Wageningen, The Netherlands, 195 pp.

Nyadzi G.I., Otsyina R.M., Banzi F.M., Bakengesa S.S., Gama B.M., Mbwambo L. and Asenga D. 2003a. Rotational woodlot technology in northwestern Tanzania: Tree species and crop performance. Agroforestry Systems 59: 253–263.

Nyadzi G.I., Gama B.M., Otsyina R. and Msalilwa J. 1999. Nitrogen dynamics in rotational woodlots with Acacia crassicarpa in Tabora Tanzania. In: Anderson J.R. (ed). Agricultural Technology: Policy Issues for the International Community. CAB International, Wallingford, UK, pp 24–29.

Nyadzi G.I., Janssen B.H., Otsyina R.M., Booltink H.W.G., Ong C.K. and Oenema O. 2003b. Water and nitrogen dynamics in rotational woodlots of five tree species in western Tanzania. Agroforestry Systems. Agroforestry Systems 59: 215–229.

Nyadzi G.I., Otsyina R.M. and Ong C.K. 2002. Growth and water resource utilization of *Acacia crassicarpa*, *Senna siamea* and *Leucaena pallida* tree species established in rotational woodlots agroforestry systems in western Tanzania. In: Juren J. (ed.) Proceedings of 12th International Soil Conservation Organisation Conference (ISCO) held at Beijing 26–31 May, 2002. Vol. III. Tsinghua University Press, Beijing, China, pp 410–414.

Oliver R., Njiti C.F. and Harmand J.M. 2000. Soil fertility characterisation in trees fallow cultivation system in North Cameroon. Etude et Gestion des Sols (France) 7: 278–308.

Olson J.S. 1963. Energy storage and the balance of producers and decomposers in ecological systems. Ecology 44: 322–331.

Olson R.A. and Sander D.H. 1999. Corn production. p. 639–686. In: Sprague G.F. and Dudley J.W. (ed.) Corn and corn improvement. Agronomy Monograph 18. 3rd ed. ASA, CSSA, and SSSA, Madison, WI, USA.

Ong C. K., Wilson J., Deans J. D., Mulatya J., Raussen T. and Wajja-Musukwe N. 2002. Tree–crop interactions: manipulation of water use and root function. Agricultural Water Management 53: 171–186.

Ong C.K., Black C.R., Marshall F.M., and Corlett J.E. 1996. Principles of resource capture and utilisation of light and water. In: Ong C.K., Huxley P.A. (eds). Tree–Crop Interactions in Agroforestry Systems: a Physiological Approach. CAB International, Wallingford, UK, pp 73–158.

Ong C.K., Black C.R., Wallace J.S., Khan A.A.H., Lott J.E., Jackson N.A., Howard S.B. and Smith D.M. 2000. Productivity, microclimate and water use in *Grevillea robusta* based agroforestry systems on hill-slopes in semiarid Kenya. Agriculture, Ecosystem and Environment 80: 121–141.

Ong C.K., Deans J.D., Wilson J., Mutua J., Khan A.A. H. and Lawson E.M. 1999. Exploring belowground complementarity in agroforestry using sap flow and root fractal techniques. Agroforestry Systems 44: 87–103.

Otsamo A., Adjers G., Hadi T.S., Kuusipalo J., Tuomela K and Vuokko R. 1995. Effect of site preparation and initial fertilization on the establishment and growth of four plantation tree species. Forest Ecology and Management 73:271–277.

Otsyina R. and Msangi R. 1995. Leucaena production and quality at Tabora, Tanzania. Leucnet News 2: 7–8.

Otsyina R., Minae S. and Cooper P. 1996. A never-ending story: rotational woodlots for soil conservation, wood and fodder. Agroforestry Today 8(2): 8–10.

Otsyina R., Msangi R., Gama B., Ramadhani T., Nyadzi G. and Shirima D. 1997. SADC/ICRAF Agroforestry Project Tumbi, Tabora, Tanzania. Annual Progress Report No. 114. ICRAF, Nairobi, Kenya, 105 pp.

Otsyina R., T. Ramadhani and D. Asenga. 1999. Rotational woodlots – An approach to mitigate deforestation and natural resource degradation in Tanzania. Faculty of Forestry & Nature Conservation Record 72: 122–130.

Palm C.A. 1995. Contribution of agroforestry trees to nutrient requirements in intercropped plants. Agroforestry Systems 30: 105–124.

Palm C.A. and Rowland A.P. 1997. Chemical characterization of plant quality for decomposition. In: Cadisch G and Giller K.E. (eds). Driven by Nature: Plant Litter Quality and Decomposition. CAB International, Wallingford, UK, pp 379–392.

Palm C.A. and Sanchez P.A. 1991. Nitrogen release from the leaves of some tropical legumes as affected by their lignin and polyphenolic contents. Soil Biology and Biochemistry 23: 83–88.

Palm C.A., Gachengo C.N., Delve R.J., Cadisch G. and Giller K.E. 2001a. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agriculture, Ecosystems and Environment 83: 27–42.

Palm C.A., Giller K.E., Mafongoya P.L. and Swift M.J. 2001b. Management of organic matter in the tropics: translating theory into practice. Nutrient Cycling in Agroecosystems 61: 63–75.

Palm C.A., Myers R.J.K. and Nandwa S. 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and nutrient replenishment. In: Buresh R.J. and Sanchez P.A (eds). Replenishing Soil Fertility in Africa. ASSA, CSSA, SSSA, Madison, WI, USA, pp 193–217.

Parkinson J.A., and S.E. Allen. 1975. A wet oxidation procedure suitable for the determination of nitrogen and mineral nutrients in biological materials. Communication in Soil Science and Plant Analysis 6: 1–11.

Payne R.W., Murray D., Harding S., Baird D., Soutar D and Lane P. 2002. GenStat® for Windows Release 6.1. Lawes Agricultural Trust, Rothamsted, UK.

PHC (Population and Housing Census). 2003. Tanzania Population and Housing Census for 2002. Tanzania National Website, www.tanzania.go.tz

Phillips J. 1930. Some important vegetation communities in the Central Province of Tanganyika territory (formerly German East Africa). Journal of Ecology 28: 13–234.

Pinstrum-Andersen P. and Cohen M.J. 2000. The present situation and coming trends in world food production and consumption. In: Chang, T.T. (ed.) Food Needs of the Developing World in the Early 21st Century. Proceedings of the Study-Week of the Pontificial Academy of Science, Vatican City, pp 27–56.

Pinstrup-Andersen P., Pandhya-Lorch R. and Rosengrant M.W. 2000. Food Security: Problems, Prospects and Policies. International Food Policy Research, Washington, DC. http://www.ifpri.org

Ramadhani T., Otsyina R. and Franzel S. 2002. Improving household incomes and reducing deforestation using rotational woodlots in Tabora District, Tanzania. Agriculture, Ecosystems and Environment 89: 229–239.

Rao M.R., Nair P.K.R. and Ong C.K. 1997. Biophysical interactions in tropical agroforestry systems. Agroforestry Systems 38: 3–50.

Roothaert R.L. and Paterson R.T. 1997. Recent work on the production and utilization of tree fodder in East Africa. Animal Feed Science Technology 69: 39–51.

Ross J.H. 1981. An analysis of the African *Acacia* species: their distribution, possible origins and relationships. Bothalia 13: 389–413.

Ruhigwa B.A., Githuru M.P., Mambani B. and Tariah N.M. 1992. Root distribution of *Acioa barteri*, *Alchornea cordifolia*, *Cassia siamea* and *Gmelina arborea* in an acid Ultisol. Agroforestry Systems 19: 67–78.

Russell W.A. 1991. Genetic improvement of maize yields. Advances in Agronomy 46: 245–298.

Rutekaha C.S. and Titus W.L.M. 1994. PD4: A flue-cured tobacco cultivar released for Tabora region, Tanzania. Research and Training Newsletter 9: 16–17, Dar-es-Salaam.

Saharjo B.H. and Watanabe H. 2000. Estimation of litter fall and seed production of *Acacia mangium* in a forest plantation in South Sumatra, Indonesia. Forestry Ecology and Management 130: 265–268.

Saidou A., Janssen B.H. and Temminghoff E.J.M. 2003. Effects of soil properties, mulch and NPK fertilizer on maize yields and nutrient budgets on ferralitic soils in southern Benin. Agriculture, Ecosystems and Environment 100: 265–273.

Salako F.K. and Tian G. 2001. Litter and biomass production from planted and natural fallows on a degraded soil in southwestern Nigeria. Agroforestry Systems 51: 239–251.

Sanchez P.A. 1976. Properties and Management of Soils in the Tropics. Wiley, New York, 619 pp.

Sanchez P.A. 1995. Science in agroforestry. Agroforestry Systems 30: 5–55.

Sanchez P.A. 2000. Linking climate change research with food security and poverty reduction in the tropics. Agriculture, Ecosystems and Environment 82: 371–383.

Sanchez P.A. 2002. Soil fertility and hunger in Africa. Science 295: 2019–2020.

Sanchez P.A. and Logan T.J. 1992. Myth and science about the chemistry and fertility of soils in the tropics. In: Lal R. and Sanchez P.A. (eds). Myths and Science of Soils of the Tropics, pp 34–46. SSSA Special Publication No. 29. ASA, CSSA, and SSSA, Madison, WI, USA.

Sanchez P.A., Buresh R.J. and Leaky R.R.B. 1997. Trees, soils and food security. Philosophical Trans. R. Soc. London, Ser. B 353: 949–961.

Sariyildiz T. and Anderson J.M. 2003. Decomposition of sun and shade leaves from three deciduous tree species, as affected by their chemical composition. Biology and Soil Fertility 37: 137–146.

Schwartz M.W. and Caro T.M. 2003. Effect of selective logging on tree and understory regeneration in miombo woodland in western Tanzania. African Journal of Ecology 41: 75–82.

Shanavas A. and Kumar M. 2003. Fuelwood characteristics of tree species in home gardens of Kerala, India. Agroforestry Systems 58: 11–24.

Shanks E. 1990. Communal woodlots in Tanzania: Farmers' Response and an Evolving Extension Strategy. Overseas Development Institute, Social Forestry Network Paper 11c. London, UK, 12 pp. http://www.odifpeg.org.uk/publications/

Shepherd G., Kiff L. and Robertson D. 1996. The Importance of Common Property Issues, Tenure and Access Rights in Relation to Land Use Planning at the Forest/Agriculture Interface, Natural Resources Institute.

Silver W.L., Ostertag R. and Lugo A.E. 2000. The potential for carbon sequestration through reforestation of abandoned tropical agricultural and pasture lands. Restoration Ecology 8: 394–407.

Singh O., Sharma D.C., Negi M.S., Singh R. 1994. Leaf litter production and decomposition in *Dalbergia sissoo* and *Bombax ceiba* plantation in Uttar Pradesh. Indian Forestry 120: 682–688.

Skutsch M.M. 1985. Forestry by the People for the People: some major problems in Tanzania's village aforestation programme. International Tree Crops Journal, Vol 3 (2/3): 147–170.

Smaling E.M.A, Nandwa S.M. and Janssen B.H. 1997. Soil fertility in Africa is at stake. In: Buresh R.J., Sanchez P.A. and Calhoun F. (eds). Replenishing Soil Fertility in Africa. Soil Science Society of America Publication No 51. pp. 47–62, SSSA, Madison, Wisconsin, USA.

Smaling E.M.A. (Guest Ed.). 1998. Agriculture, Ecosystems and Environment 71: 1–283.

Solon L., Barraclough G. and Krishma B.G. 1996. Deforestation in Tanzania beyond simplistic generalisations. The Ecologist 26: 104–109.

Songwe N.C., Fasehun F.W. and Okali D.U.U. 1988. Litter fall and productivity in a tropical rainforest, Southern Bakundu Forest Reserve, Cameroon. Journal of Tropical Ecology 1: 333–350.

Spain A.V. 1984. Litter fall and standing crop of litter in three tropical Australian rainforests. Journal of Ecology 72: 947–961.

Stone G.N. 2003. Preface to 'Biology of Acacia. Advances in Legume Systematics Part 11. Australian Systematic Botany 16: i-ii.

Stoorvogel J.J., Smaling E.M.A. and Janssen B.H. 1993. Calculating soil nutrient balances in Africa at different scales. Fertilizer Research 35: 227–285.

Struif Bontkes T.E., Wopereis M.C.S., Tamelokpo A., Ankou K.A., and Lamboni D. 2003. The use of QUEFTS in search of balanced fertilizer recommendations for maize in Togo. In: Struif Bontkes, T.E. and Wopereis (eds). Decision support tools for smallholder agriculture in Sub-Saharan Africa. IFDC and CTA, muscle Shoals and Wageningen, The Netherlands, pp 68–84.

Sundarapandian S.M. and Swamy P.S. 1999. Litter production and leaf-litter decomposition of selected tree species in tropical forests at Kadayar in the Western Ghats, India. Forest Ecology and Management 123: 231–244.

Swanson R.H. and Whitfield D.W.A. 1981. A numerical analysis of heat pulse velocity theory and practice. Journal of Experimental Botany 32: 221–239.

Swift M.J., Heal O.W. and Anderson J.M. 1979. Decomposition in terrestrial ecosystems. Studies in Ecology, Vol. 5. University of California Press, Berkeley, California, USA.

Szott L.T. and Palm C.A. 1996. Nutrient stocks in managed and natural humid tropical fallows. Plant and Soil 186: 293–309.

Szott L.T., Palm C.A. and Buresh R.J. 1999. Ecosystem fertility and fallow function in the humid and subhumid tropics. Agroforestry Systems 47: 163–196.

Tam N.F.Y. and Wong Y.S. 1998. Variations of soil nutrient and organic matter content in a subtropical mangrove ecosystem. Water, Air and Soil Pollution 103: 245–261.

Taylor B.R., Parkinson D. and Parsons W.F.J. 1989. Nitrogen and lignin content as predictors of litter decay rates: a microcosm test. Ecology 70: 97–104.

Temminghoff E.J.M. (ed). 2000. Methodology of Chemical Soil and Plant Analysis. Environmental Sciences, Wageningen University, The Netherlands, 177 pp.

Temu A.B. 1979. Fuelwood Scarcity and Other Problems Associated with Tobacco Production in Tabora Region, Tanzania. Sokoine University of Agriculture, Morogoro, Tanzania, 22 pp.

Thomson L.A.J. 1994. *Acacia aulacocarpa*, *A. cincinnata*, *A. crassicarpa* and *A. wetarensis*: an annotated bibliography. CSIRO, Canberra, Australia, 131 pp.

Tian G, Olimah J.A., Adeye G.O. and Kang B.T. 2000. Regeneration of eathworm populations in a degraded soil by natural and planted fallows under humid tropical conditions. Soil Science Society of American Journal 64: 222–228.

Tian G. 1998. Effect of soil degradation on leaf decomposition and nutrient release under humid tropical conditions. Soil Science 163: 897–906.

Tian G., Salako F.K. and Ishida F. 2001. Replenishment of C, N, and P in a degraded Alfisol under humid tropical conditions: effect of fallow species and litter polyphenols. Soil Science 166: 614–621.

TLTC. 1996. Tobacco Leaf Tanzania Company Report. Tabora, Tanzania.

Tonye J., Ibewiro B. and Duguma B. 1997. Residue management of a planted fallow on an acid soil in Cameroon: crop yields and organic matter fractions. Agroforestry Systems 37: 199–207.

Tornquist C.G., Hons F.M., Feagley S.E. and Haggar J. 1999. Agroforestry system effects on soil characteristics of the Sarapiqui region of Costa Rica. Agriculture, Ecosystems and Environment 73: 19–28.

Tossah B.K., Zamba D.K., Vanlauwe B., Sanginga N., Lyasse O, Diels J. and Merckx R. 1999. Alley cropping in the moist savanna zone of West-Africa: II. Impact on soil productivity on a North-to-South transect in Togo. Agroforestry Systems 42: 229–244.

TRDD. 1989. Tabora Region Development Strategy. Tabora Region Development Director. Regional planning division, 85 pp.

Turnbull J.W. (ed). 1987. Australian acacias in developing countries: Proceedings of an international workshop held at the Forestry Training Centre, Gympie, Qld., Australia, 4–7 August 1986. ACIAR proceedings No. 16: 151–196, ACIAR, Canberra, Australia.

Turnbull J.W. (ed). 1991.Advances in tropical Acacia research: Proceedings of an international workshop held in Bangkok, Thailand, 11–15 February 1991. ACIAR proceedings No. 35, 234 pp.

Turnbull J.W. 1986. Multipurpose Australian trees and shrubs lesser-known species for fuelwood and agroforestry. ACIAR Monograph No. 1 Canberra, Australian, 316 pp.

Turnbull J.W., Midgley S.J. and Cossalter C. 1998. Tropical acacias planted in Asia: An overview. In: Turnbull J.W., Crompton H.R. and Pinyopusarerk K. (eds). Recent developments in acacia planting. Proceedings of an international workshop held in Hanoi, Vietnam, 27–30 October 1997. ACIAR, Canberra, Australia, pp 14–28.

Van Noordwijk M. 1999. Scale effects in crop–fallow rotations. Agroforestry Systems 47: 239–251.

van Noordwijk M., Lawson G., Soumare A., Groot J.J.R. and Hairiah K. 1996. Root distribution of trees and crops: Competition and/or complementarity. In: Ong C.K. and Huxley P. (eds). Tree-Crop Interactions: A Physiological Approach. CAB International, Wallingford, UK, pp 319–364.

Van Reuler H. and Janssen B.H. 1989. Nutrient constraints in secondary vegetation and upland rice in south-west Ivory Coast. In: Proctor J. (ed). Mineral Nutrients in tropical Forest and Savanna Ecosystems. Special publication number 9 of The British Ecological Society. Blackwell Scientific Publications, Oxford, pp 371–382.

Van Reuler H. and Janssen B.H. 1993. Nutrient fluxes in the shifting cultivation system of south west Cote d'Ivoire. Plant and Soil 154: 169–177.

Van Reuler H. and Janssen B.H. 1996. Comparison of the fertilizing effects of ash from burnt secondary vegetation and of mineral fertilizers on upland rice in south-west Cote d'Ivoire. Fertilizer Research 45: 1–11.

Van Soest P.J. 1963. Use of detergents in the analysis of fibrous feeds. II. A rapid method for determination of fibre and lignin. Journal of Association of Agricultural Chemistry 46: 829–835.

Vanlauwe B., Aihou K., Aman S., Tossah B.K., Diels J., Sanginga N. and Merckx R. 2001. Leaf quality of selected hedgerow species at two canopy ages in the derived savannah zone of West Africa. Agroforestry Systems 53: 21–30.

Vanlauwe B., Dendiroven L, Merckx R. 1994. Residue fractionation and decomposition: the significance of the active fraction. Plant and Soil 158: 263–274.

Vanlauwe B., Sanginga N and Merckx R. 1997. Decomposition of four Leucaena and Senna prunings in alley cropping systems under sub-humid tropical conditions: the process and its modifiers. Soil Biology and Biochemistry 29: 131–137.

Vanlauwe B., Sanginga N. and Merckx R. 2001a. Alley cropping with *Senna siamea* in South-western Nigeria: I. Recovery of ^{15}N labelled urea by the alley cropping system. Plant and Soil 231: 187–199.

Vanlauwe B., Sanginga N. and Merckx R. 2001b. Alley cropping with *Senna siamea* in South-western Nigeria: II. Dry matter, total N, and urea-derived N dynamics of the *Senna* and maize roots. Plant and Soil 231: 201–210.

Vanlauwe B., Nwoke O.C., Sanginga N. and Merckx R. 1996. Impact of residue quality on the C and N mineralization of leaf and root residues of three agroforestry species. Plant and Soil 183: 221–231.

Visalakshi N. 1993. Litter fall, standing crop of litter and their nutrient in two tropical dry evergreen forests of India. International Journal of Ecology and Environmental Science 19: 163–180.

Wallace A. 1989. Evaluation of the cause for an acid-soil infertility for a dicot plant species, *Phaseolus vulgaris*. Soil Science 147: 454–456.

Wallace J.S. 1996. The water balance of mixed tree–crop systems. In: Ong C.K. and Huxley P. (eds). Tree–Crop Interactions: A Physiological Approach. CAB International, Wallingford, UK, pp 189–233.

Warner K. 1993. Patterns of Farmer Tree-Growing in Eastern Africa: A Socio-economic Analysis. Oxford Forestry Institute, Oxford and International Centre for Research in Agroforestry, Nairobi, Kenya.

White F. 1983. The Vegetation of Africa. UNESCO, Paris.

Winterbottom R. and Hazelwood P.T. 1987. Agroforestry and sustainable development: making the connection. Ambio 16: 100–110.

World Bank. 1996. Development indicators. World Bank, Washington, DC, USA.

World Bank/FAO. 1996 Recapitalization of Soil Productivity in Sub-Saharan Africa. Washington DC, USA and Rome, Italy.

Yam N.F.Y. and Wong Y.S. 1998. Variations of soil nutrient and organic matter content in a subtropical mangrove ecosystem. Water, Air and Soil Pollution 103: 245–261.

Yang H.S. and Janssen B.H. 2000. A mono-component model of carbon mineralisation with a dynamic rate constant. European Journal of Soil Science 51: 517–529.

Yin R. and Hyde W.F. 2000. Trees as an agriculture sustaining activity: the case of northern China. Agroforestry Systems 50: 179–194.

Zaharah A.R. and Bah A.R. 1999. Patterns of decomposition and nutrient release by fresh Gliricidia (*Gliricidia sepium*) leaves in an ultisol. Nutrient Cycling in Agroecosystems 55: 269–277.

Zoysa M., de Zoysa M. and Sharma J.K. 2001. Community woodlot development programme of Kirindi Oya Irrigation and Settlement Project: farmers' perception, communication and research needs. In: Varma R.V., Bhat K.V., Muralidharan E.M. (eds). Tropical Forestry Research: Challenges in the New Millennium. Proceedings of the International Symposium, Peechi, India, pp 223–229.

SUMMARY

Tropical regions, particularly Sub-Saharan Africa, are presently facing severe shortages of food, fuel wood, and fodder primarily due to increasing human and livestock populations and crop production using little or no external inputs. Growing agricultural crops without replenishment with organic or inorganic fertilizers implies that nutrients are removed from the soil via the agricultural produce and crop residues resulting into a decline of the soil fertility. Farmers have been experiencing a steady decline in soil fertility and crop productivity because of the poor farming methods and insufficient use of fertilizers. In this situation farmers are forced to extend cultivation to marginal and erosion-prone soils and to encroach forests.

Fallowing is known as a biological approach to regenerating the fertility of degraded soil in the tropics. In most parts of Sub-Saharan Africa, the traditional long duration fallows, which helped to replenish soil fertility to some extent, are no longer possible. Moreover, deforestation exacerbated by excessive grazing, shifting cultivation at short intervals and uncontrolled cutting of trees has lowered the water table and increased scarcity of fuel wood for household and industrial uses.

Agroforestry systems involving re-introduction of trees and shrubs into existing croplands and grazing areas with systematic management options to obtain fuel wood, building poles and fodder, and addressing land degradation problems are considered sound approaches to remedy some of the mentioned problems. One of such agroforestry technologies with great promise of reducing deforestation as well as increasing crop production in semi-arid areas is the ‘rotational woodlot’. The system of rotational woodlots is a sequential tropical agroforestry system. Rotational woodlot technology involves growing of trees and crops on farms in three phases: 1) an initial tree establishment phase in which trees are intercropped with crops, 2) a tree fallow phase, and 3) a cropping phase after harvest of trees. Each of these phases can be managed specifically to provide products and services of economic, social and environmental value. However, quantitative information on the nutrient and water dynamics of this system is lacking which hinders the development of sound strategies for management of tree residues and other possible nutrient inputs.

The major objectives for executing this study were to improve the understanding of tree-soil-crop interactions in agroforestry systems in semi-arid areas, by examining water and nutrients dynamics in rotational woodlots technology for

primary wood and food production. The study also aims to contribute to the development of sound management strategies and options that improve the nutrient use efficiency in sequential agroforestry systems. The specific objectives were to determine:

(1) the tree growth performance during the *establishment phase of woodlots*;

(2) soil water and nitrogen dynamics of different tree species, during the *woodlot and tree-fallow phases*;

(3) the litter production, leaf quality and decomposition patterns of different tree species *in woodlots*;

(4) the tree biomass, nutrient accumulation and removal from the system *after fallow phase*;

(5) the effects of various tree species on maize production after harvest of trees and their interactions with different levels of N, P, and K fertilisers (*cropping phase*).

In order to achieve these objectives several field and laboratory studies were conducted in Tabora and Shinyanga Tanzania, in Sub-Saharan Africa. The main studies were conducted in long-term agroforestry field trials that were set up to evaluate woody tree species for their potentials on biomass production, nutrient transfer and soil fertility improvement. Trees included three Australian *Acacia* species, local *Acacia* species and *Leucaena* species (N_2-fixing legume trees), *Eucalyptus* and *Senna* species (non-N_2-fixing legume trees). The background of the study, the overview of the development and the definition of the rotational woodlots technology in Tanzania, are presented in **Chapter 1**.

Chapter 2 summarises the findings of the experiments with rotational woodlots conducted both in Tabora and Shinyanga regions, Tanzania, to evaluate tree species for wood production and yields of maize grown in association with and after harvest of trees on two soils with contrasting characteristics. On acid sandy soils at Tabora, *Acacia crassicarpa* grew fast and produced 24 to 77 Mg ha^{-1} of wood in four to five years. On alkaline Vertisols at Shinyanga, seven years old woodlots of *Acacia polyacantha* and *Leucaena leucocephala* produced 71 and 89 Mg ha^{-1} of wood, respectively. Differences between species were apparent by four years after planting with *A. crassicarpa* growing faster than other species. The trees in the rotational woodlots grew fast, probably because they benefited from the land preparation, weeding and other management operations executed for cropping of the land. Trees grew more rapidly in low and mid slope positions of the landscapes than at the tops due to the more favourable moisture and nutrient conditions at the lower positions.

Inter-cropping of maize between trees planted at 4 x 4 m, was possible for the first two years of tree establishment without sacrificing maize yield. All trees were competitive to crops after two years of inter-cropping due to large canopy cover, eliminating the possibility for inter-cropping with maize beyond this age. The first maize crop following clear cutting of four and five year-old *A. crassicarpa* woodlots gave 29 to 113% greater yields than the crop after natural fallow. *Acacia polyacantha* and *L. leucocephala* woodlots also increased the subsequent maize yields over a three-year period. Whereas Australian *Acacia* species are suited to the acidic soils, *L. Leucocephala*, and *A. polyacantha* were better for the alkaline soils. Increased crop yields following harvest of woodlots could be realized for two to three years as a consequence of improved mineral N in the topsoil. The benefit of *A. crassicarpa* woodlots expressed in terms of maize yield was more pronounced in mid and lower slope positions than at upper slopes. This is ascribed to the soil fertility improvement and soil moisture availability.

In **Chapter 3**, we compare the effects of woodlots of five tree species, continuous maize and natural fallow on soil water and nitrogen dynamics. Tree species differ in their ability to use soil water and modify nutrient cycling for the benefit of simultaneous and sequential crops. An understanding of the water use patterns of trees is essential for developing sustainable rotational woodlot systems. We measured transpiration by the trees when they were 3 years old using sap flow gauges and soil water content was measured using the neutron probe. Soil inorganic N profiles to 2-m depth were measured when the trees were four years old.

The results suggest that rotational woodlots influence the dynamics of soil water and N during the fallow phase, compared to natural fallow or continuous maize. Evidently, trees scavenged more rain and stored more water in the soil after rains than continuous maize and natural fallow systems. During the dry season, this surplus amount of soil water was transpired again. Transpiration was greatest in *A. crassicarpa* and lowest in *L. pallida* and the rate was related to stem diameter, size of the tree canopy and soil water availability.

Trees were 'scavengers' of soil N and they retrieved inorganic N from soil horizons up to 2-m depth. Trees also increased N contents close to their trunks, in part by capturing N from within the crop-rooting zone by its lateral roots. On the other hand soil inorganic N was much greater in the top 30 cm soil depths than in deeper horizons and was much lower under trees than under natural fallow and continuous maize, suggesting that the trees in the woodlots made extensive use of the soil N.

In Chapter 4 we monitored litter production of five tree species for 10 months. We also measured nutrient content and leaf quality over three seasons. Decomposition of tree leaves was studied for 12 months using the litterbag technique. Results indicate that total litter accumulation was highest in Acacia species and lowest in *L. pallida*, ranging from 1.9 to 10.7 Mg ha^{-1}. Litter fall peaked in the dry season. However, acacia trees had poor quality leaves. These leaves were low in N and P, which led to N and P immobilization. In contrast, leucaena leaves were rich in N, which favoured mineralization. Evidently, Australian acacia leaves are not direct sources of N for maize. To counterbalance the immobilization of N and P during the initial stages of decomposition these leaves and litter will have to be amended by composting or by mixing with high quality leaves or fertilizers prior to the cropping phase.

Phosphorus content, C:P, and lignin:N were better parameters for the prediction of decomposition rates of leaves than N content, C:N ratio and lignin plus total soluble polyphenols:N ratio. The predictors of litter decomposition could be used to facilitate the screening of agroforestry trees for their nutrient-supplying capacity.

Chapter 5 discusses the assessment of wood biomass, and nutrient accumulation and removal during harvest of five multipurpose tree species in this semi-arid environment. There was rapid accumulation of the woody component and foliage. Wood constituted 32 to 85% of the total aboveground biomass. *Leucaena pallida* had the smallest wood proportion but retained the largest part of foliar materials in the field during clear cutting. Trees also played a role in weed control. Clearly, the trees in rotational woodlots played an important role in the contribution to aboveground C sequestration and *Acacia* species are promising in this regard.

Our results also show that substantial amounts of nutrients were exported with the wood of acacia and senna at clearing, ranging from 44 to 215 kg ha^{-1} for N, 3.7 to 7.3 for P, 28 to 86 for K, 11 to 115 for Ca, and 10 to 48 kg ha^{-1} for Mg. Nutrient mining by wood exportation is therefore a major threat for the sustainability of woodlots, when the exported nutrients are not supplemented via external sources. Evidently, shortages of N and P should be expected when trees are grown on relatively poor soils such as those of this study.

When the goal is the high production of wood biomass with high wood density that can be used in fuel-wood and charcoal industries, *Acacia* species are preferred species. However, large amounts of nutrients are withdrawn with the harvested wood biomass, jeopardizing the sustainability of the technology, without external sources of nutrients. On the other hand, when the goal is dual, i.e. production of wood biomass and soil fertility restoration, *L. pallida* seems to be the preferred species.

Analysis of the effects of rotational woodlots on the nutrition and yields of maize as presented in **Chapter 6** indicated that agroforestry plots responded to fertiliser N; the agronomic efficiency was about 30 kg grain per kg N applied at a rate of 50 kg fertilizer N, and 15 kg/kg between 50 and 100 kg N applied. Application of more than 20 kg/ha of P or K did not significantly increase maize yields. There was a significant correlation between N in tree foliage biomass and maize grain yield; grain yield increased by 4 kg per kg N in foliage biomass. The benefits of tree fallows compared to natural fallows were modest, in terms of maize yield increases. The benefit of rotational woodlots is primarily caused by the extra uptake of about 10 kg N per ha, in the case of N fixing trees, resulting in yield increases of 100 to 500 kg grain per ha.

In summary: medium-term rotational woodlots have the potential to meet the domestic and industrial wood needs and at the same time to reduce deforestation in semi-arid sub-Saharan Africa. Evidently, there is a trade-off between fuel-wood production and soil fertility restoration. The management of woodlots on farms should aim at establishing leguminous short rotation plantations and recycling nutrients through slash and mulch techniques, and through return of the ashes from the burned fuel-wood back to the fields as much as possible. These results have implications regarding the benefits of the rotational woodlot technology in conserving water and nutrient resources for sustainable development.

SAMENVATTING

Veel tropische gebieden, met name in Afrika ten zuiden van de Sahara, worden tegenwoordig geconfronteerd met ernstige tekorten aan voedsel, brandstof en veevoer, voornamelijk als gevolg van de toenemende bevolking en veestapel en van de produktie van gewassen met weinig of geen externe aanvoer van nutriënten. De teelt van landbouwgewassen zonder gebruik van organische of anorganische meststoffen brengt met zich mee dat nutriënten uit de grond verwijderd worden via de oogstprodukten en gewasresten, hetgeen uitmondt in een vermindering van de bodemvruchtbaarheid. Boeren hebben ervaren dat de bodemvruchtbaarheid en gewasproduktie gestaag afnamen wegens de gebrekkige landbouwmethoden en het onvoldoende gebruik van meststoffen. In deze situatie worden boeren gedwongen de teelt van gewassen uit te breiden naar marginale en erosie-gevoelige gronden en bosgronden aan te spreken.

Het braak leggen van land wordt gezien als een biologische benadering om de vruchtbaarheid te herstellen van gedegradeerde gronden in de tropen. In het grootste deel van Sub-Sahara Afrika, zijn de traditionele langdurige braakperioden, die hielpen om de bodemvruchtbaarheid in meerdere of mindere mate te herstellen, niet langer mogelijk. Bovendien heeft ontbossing, verergerd door excessieve begrazing, zwerflandbouw met korte intervallen en ongecontroleerde houtkap, de grondwaterstand verlaagd en de schaarste van brandhout voor huishoudelijk en industrieel gebruik vergroot.

Agroforestry-systemen waarbij bomen en struiken opnieuw worden geïntroduceerd in bestaande akker- en graasgebieden met beheersopties voor het verkrijgen van brandhout, bouwmateriaal of veevoer, en waarbij landdegradatieproblemen worden aangepakt, worden beschouwd als geëigende benaderingen om de genoemde problemen te verhelpen. Een van de agroforestry-technologieën die veelbelovend is om de ontbossing tegen te gaan en de gewasproduktie in semi-aride gebieden te verhogen, is die van 'boomteelt in rotatie' ('rotational woodlot'). Boomteelt in rotatie is een 'sequentieel' ('volgend') tropisch agroforestry-systeem. Bij boomteelt in rotatie wordt de groei van bomen en gewassen onderscheiden in drie fasen: 1) een initiële vestigingsfase waarbij tussen de bomen gewassen worden verbouwd, 2) een fase met bosbraak, en 3) een fase met gewasteelt na de oogst van de bomen. In ieder van deze fasen kan het beheer specifiek gericht worden op de levering van produkten en diensten van economische, sociale en mlilieukundige waarde. Kwantitative informatie over de dynamiek van nutriënten en water van dit systeem ontbreekt echter en dat belemmert de ontwikkeling van degelijke strategieën voor het beheer van boomresten en mogelijke andere aanvoeren van nutriënten.

Het belangrijkste doel van deze studie was een betere kijk te krijgen op de wisselwerkingen tussen bomen, grond en gewas in agroforestry-systemen onder semi-aride gebieden, door middel van onderzoek naar de water- en nutriëntendynamiek in systemen van boomteelt in rotatie voor de primaire hout- en voedselproduktie. De studie wil ook een bijdrage leveren aan de ontwikkeling van solide managementstrategieën en -opties die de gebruiksefficiëntie van nutriënten in sequentiële agroforestry-systemen verbeteren. De specifieke doelstellingen waren:

(1) de groei van de bomen vast te stellen tijdens de *vestigingsfase van de bomen*;

(2) de water- en stikstofdynamiek te bepalen van verschillende boomsoorten tijdens de *bosbraakfase*;

(3) de strooiselproduktie, de kwaliteit en het afbraakpatroon te bepalen van bladeren van verschillende boomsoorten *die in rotatie worden geteeld*;

(4) de biomassa en de nutriënteninhoud van de bomen te meten, en de afvoer van nutriënten uit het systeem *na de bosbraakfase*;

(5) de effecten vast te stellen van verschillende bomen op de maisproduktie na de oogst van de bomen en de interacties met verschillende niveaus van N, P en K meststoffen (*gewasteeltfase*).

Om deze doelstellingen te bereiken werden verschillende veld- en laboratoriumstudies uitgevoerd in Tabora en Shinyanga, Tanzania, in Sub-Sahara Afrika. De belangrijkste studies werden uitgevoerd in langlopende agroforestry veldproeven die waren opgezet om enkele boomsoorten te beoordelen op hun vermogen biomassa te produceren, nutriënten over te dragen en de bodemvruchtbaarheid te verbeteren. Tot deze bomen hoorden drie Australische *Acacia*-soorten, lokale *Acacia*-soorten en *Leucaena*-soorten (N_2-bindende boom-leguminoos), *Eucalyptus*- en *Senna*-soorten (boom-leguminoos die geen N_2 bindt). De achtergrond van de studie, een overzicht van de ontwikkeling en de beschrijving van de technologie van boomteelt in rotatie in Tanzania worden gepresenteerd in **Hoofdstuk 1.**

Hoofdstuk 2 vat de bevindingen samen van de proeven met boomteelt in rotatie die in het gebied van Tabora en Shinyanga, Tanzania, op twee gronden met contrasterende eigenschappen werden uitgevoerd ter beoordeling van de houtproduktie van enkele boomsoorten en van de opbrengsten van mais die werd verbouwd tussen de bomen of na de oogst van de bomen. Op zure zandgrond in het gebied van Tabora groeide *Acacia crassicarpa* snel en produceerde 24 to 77 Mg ha^{-1} aan hout in vier tot vijf jaar. Op de alkalische Vertisols in het gebied van Shinyanga, produceerden zeven jaar oude bomen die in rotatie werden geteeld van *Acacia polyacantha* en *Leucaena leucocephala* respectievelijk 71 en 89 Mg ha^{-1} aan hout. Verschillen tussen de soorten werden vier jaar na planten duidelijk, met *A. crassicarpa* als de soort die sneller groeide dan de andere. De bomen groeiden snel, waarschijnlijk omdat ze profiteerden van de grondbewerking, het wieden en de andere maatregelen die ter verzorging van het gewas werden uitgevoerd. De bomen groeiden sneller onderaan en halverwege de hellingen dan aan de top, dankzij de gunstiger vocht- en voedingsomstandigheden op de lagere plaatsen.

Mais kon gedurende twee jaar zonder opbrengstderving verbouwd worden tussen de in een verband van 4 x 4 m geplante, jonge bomen. Na twee jaren concurreerden alle bomen met het gewas door de grote boomkruinen, zodat hierna de tussenteelt van een gewas onmogelijk was. De opbrengst van het eerste gewas mais na de kap van vier en vijf jaar oude *A. crassicarpa* bomen was 29 tot 113% groter dan van het gewas na natuurlijke braakvegetatie. Ook *Acacia polyacantha* en *L. leucocephala* verhoogden de opbrengst van de daaropvolgende mais gedurende een periode van drie jaren na de kap. Terwijl de Australische *Acacia*-soorten zeer geschikt bleken voor de zure gronden, deden *L. Leucocephala* en *A. polyacantha* het beter op de alkalische gronden. Hogere gewasopbrengsten volgend op de oogst van de bomen konden gedurende twee tot drie jaren worden gerealiseerd als gevolg van een beter niveau van N-mineraal in de bovengrond. Het profijt van *A. crassicarpa* dat tot uitdrukking komt in maisopbrengst was meer uitgesproken halverwege en onderaan op de helling dan hogerop. Dit wordt toegeschreven aan de betere bodemvruchtbaarheid en vochtbeschikbaarheid.

In **Hoofdstuk 3** vergelijken we de effecten op de dynamiek van water en stikstof van vijf in rotatie geteelde boomsoorten met die van mais in continu-teelt en van natuurlijke braakvegetatie. Boomsoorten verschillen in hun vermogen bodemvocht te benutten en de nutriëntenkringloop te modificeren ten gunste van gelijktijdige en volgende gewassen. Voor de ontwikkeling van duurzame systemen met boomteelt in rotatie is het essentieel de waterhuishouding van bomen te begrijpen. Met sapstroommeters maten we de verdamping door 3 jaar oude bomen, en met een neutronensonde het bodemvochtgehalte. Anorganische-N-profielen tot 2 m diepte werden gemeten toen de bomen vier jaren oud waren.

De resultaten suggereren dat, vergeleken met natuurlijke braakvegetatie of mais in continu-teelt, bomen invloed hebben op de dynamiek van bodemvocht en N gedurende de bosbraakfase. Klaarblijkelijk maakten de bomen beter gebruik van de regen dan de continue mais en natuurlijke braakvegetatie, en sloegen ze na de regens meer water in de bodem op. Gedurende het droge seizoen werd dit extra bodemvocht weer getranspireerd. De verdamping was het grootste in *A. crassicarpa* en het laagst in *L. Pallida*, en de verdampingssnelheid was gerelateerd aan stamdiameter, grootte van de boomkruin en de beschikbaarheid van bodemvocht.

Bomen waren 'vergaarders' van bodem N en ze onttrokken anorganische N van bodemhorizonten tot 2 m diepte. Bomen verhoogden ook de N-gehalten dicht bij hun stam, ten dele door met hun laterale wortels N weg te halen uit de door het gewas bewortelde zone. Aan de andere kant was het niveau van anorganische N veel hoger in de bovenste 30 cm van de bodem dan in diepere lagen en veel lager onder bomen dan onder natuurlijke vegetatie en continue mais, wat erop wijst dat de bomen uitgebreid gebruik maakten van de N in de bodem.

In **Hoofdstuk** 4 volgden we de strooiselproduktie van vijf boomsoorten gedurende 10 maanden. We maten ook het nutriëntengehalte en de bladkwaliteit gedurende drie seizoenen. De afbraak van boombladeren werd gedurende 12 maanden bestudeerd met behulp van strooiselzakjes. De resultaten geven aan dat de totale strooiselaccumulatie het hoogst was onder Acacia-soorten en het laagst onder *L. pallida*, en uiteen liep van 1.9 tot 10.7 Mg ha^{-1}. Er was een piek in de bladval in het droge seizoen. De acacia-bomen hadden een geringe bladkwaliteit. Deze bladeren waren arm aan N en P, wat leidde tot N- en P-immobilisatie. De leucaena-bladeren daarentegen waren rijk aan N, wat de mineralisatie bevorderde. De bladeren van de Australische acacia's zullen beslist geen directe N-bron voor mais zijn. Als tegenwicht tegen de immobilisatie van N en P gedurende het begin van de afbraak, zullen deze bladeren en strooisels verbeterd moeten worden door ze, voorafgaand aan de gewasteeltfase, te composteren of met bladeren van hoge kwaliteit of met meststoffen te mengen.

Het fosfaatgehalte en de verhoudingen C:P en Lignine:N waren betere parameters voor de voorspelling van de afbraaksnelheden van de bladeren dan het N-gehalte, de verhouding C:N en de verhouding van lignine plus totaal oplosbare polyfenolens tot stikstof. De parameters voor de voorspelling van de afbraaksnelheid van strooisel zouden gebruikt kunnen worden om de zoektocht naar agroforestry-bomen met nutriëntenleverend vermogen te vergemakkelijken.

Hoofdstuk 5 bespreekt de bepaling van hout-biomassa, van de ophoping van nutriënten en van de verwijdering van nutriënten tijdens de oogst van vijf boomsoorten in deze semi-aride omgeving. Er was een snelle toename van hout en blad. Hout vormde 32 tot 85% van de bovengrondse biomassa. *Leucaena pallida* had het kleinste aandeel aan hout, maar behield bij de kap het grootste deel aan bladmateriaal in het veld. Bomen speelden ook een rol in de onkruidbeheersing. De boomteelt in rotatie leverde duidelijk een zeer belangrijke bijdrage aan de bovengrondse vastlegging van C, en *Acacia* soorten zijn veelbelovend in dit opzicht.

Onze resultaten laten ook zien dat bij de kap substantiële hoeveelheden nutriënten werden afgevoerd met het hout van acacia en senna, uiteenlopend van 44 tot 215 kg ha^{-1} voor N, 3.7 tot 7.3 voor P, 28 tot 86 voor K, 11 tot 115 voor Ca, en 10 tot 48 kg ha^{-1} voor Mg. Het 'mijnen' van nutriënten door de afvoer van hout is daardoor een belangrijke bedreiging voor de duurzaamheid van boomteelt in rotatie, wanneer de afgevoerde nutriënten niet worden aangevuld via externe bronnen. Het is duidelijk dat tekorten aan N en P zijn te verwachten wanneer bomen worden geteeld op relatief arme gronden zoals die in deze studie.

Wanneer een hoge produktie wordt nagestreefd van hout met een hoge dichtheid dat kan worden gebruikt als brandstof en in de houtskoolindustrie, zijn Acacia-soorten te prefereren. Daarbij worden echter grote hoeveelheden nutriënten met het geoogste hout onttrokken, hetgeen zonder externe aanvoer van nutriënten de duurzaamheid van de technologie in gevaar brengt. Van de andere kant, wanneer het doel tweeledig is, i.e. houtproduktie en herstel van de bodemvruchtbaarheid, lijkt de voorkeur te moeten uitgaan naar *L. pallida*.

Analyse van de effecten van boomteelt in rotatie op de voeding en opbrengst van mais zoals gepresenteerd in Hoofdstuk 6 gaf aan dat de agroforestry-veldjes reageerden op meststof N; de landbouwkundige efficiëntie was ongeveer 30 kg grain per kg N toegediend bij een gift van 50 kg meststof-N, en 15 kg/kg bij giften tussen 50 en 100 kg N. Giften boven 20 kg/ha P of K leidden niet tot significante meeropbrengsten van mais. Er was een significante correlatie tussen N aanwezig in de bladeren van de boom en de korrelopbrengst van mais; de korrelopbrengst nam toe met 4 kg per kg N in de bladeren. In termen van toename van maisopbrengst, waren de voordelen van bosbraak in vergelijking met natuurlijke braak zeer bescheiden. Het voordeel van boomteelt in rotatie wordt, in het geval N-bindende bomen, voornamelijk veroorzaakt door de extra opname van ongeveer 10 kg N per ha, resulterend in opbrengstverhogingen van 100 to 500 kg graan per ha wanneer geen meststoffen worden gebruikt.

Samenvattend: met boomteelt in rotatie kan bij een gemiddelde groeiduur van de bomen voorzien worden in de huishoudelijke en industriële behoeften aan hout, en kan tegelijkertijd de ontbossing in de semi-aride delen van sub-Sahara Afrika worden tegengegaan. Er bestaat duidelijk een wisselwerking tussen brandhoutproduktie en herstel van de bodemvruchtbaarheid. Het beheer van bomen op boerenland moet gericht zijn op kortdurende rotaties, en op het hergebruik van nutriënten. Het laatste wordt bevorderd door geschikte kap- en mulchtechnieken toe te passen en door de as van het verbrande hout zo veel mogelijk naar de velden terug te brengen. Deze resultaten hebben gevolgen met betrekking tot de voordelen van boomteelt in rotatie bij het instandhouden van water- en nutriëntenvoorraden voor duurzame ontwikkeling.

Curriculum vitae

Gerson Gibson Isaac Cossam Nyadzi[1] was born in Makambako, Njombe District in Iringa Region, Southern Highlands of Tanzania on November 2, 1965. He attended primary school at Kwamkoro, Amani Tanga between 1975–1980. He was at Galanos (Tanga Region) and at Kibaha (Coast Region) for his secondary school education between 1981–1987. In 1988 he was on compulsory national service at Mlale National Service Camp in Songea. After his graduation (B.Sc. Soil Science Option) at Sokoine University of Agriculture in 1991, he was employed as Agricultural Research Officer responsible for Agroforestry Research under the Ministry of Agriculture, and was posted to Tumbi Agricultural Research and Training Institute (ARI Tumbi), Tabora, Tanzania. In 1993 he was assigned to the Southern African Development Centre – International Centre for Research in Agroforestry (SADC-ICRAF) Project (now World Agroforestry Centre – WAC), as a collaborative scientist. He was responsible for development of research on agroforestry technologies. Between September 1994 and August 1996, he followed the M.Sc. course at Ghent University, Belgium, specialising in Soil Fertility and Eco-pedology. He was awarded the MSc degree (Soil Science) with Distinction, and re-joined ARI Tumbi and SADC-ICRAF project.

In 1999 he obtained a three-year research grant from the International Foundation for Science (IFS). His research was upgraded to a Ph.D. study, and in April 2000, he was granted a sandwich scholarship by the University of Wageningen and the Carolina MacGillavry PhD fellowships of IFS, to pursue a Ph.D. study at Wageningen University and Research Centre (WUR). This doctoral thesis is a result of the research he carried out in the Department of Soil Quality of WUR, ARI Tumbi, and the SADC-ICRAF, Tabora and Shinyanga, Tanzania. The fieldwork was conducted in Tabora while most of the analyses were done at the Laboratory of Soil and Plant Analysis at WAC in Shinyanga and at Sokoine University of Agriculture, Morogoro Tanzania. As part of the research, he spent four weeks at the World Agroforestry Centre in Kisumu and Nairobi, Kenya.

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