Chapter 1

General Introduction

1.1 Nutrient depletion in Sub-Saharan Africa

In sub-Saharan Africa soils are losing nutrients at an alarming rate. Stoorvogel *et al*. (1993) estimated an annual average loss of 22 kg N, 2.5 kg P and 15 kg K per ha for the whole sub-Saharan Africa. Shepherd *et al*. (1994) working in the wet highlands of Western Kenya estimated an annual loss of 63 kg N ha^{-1}. According to Stoorvogel *et al*. (1993), the fast depletion of nutrients in the sub-Saharan Africa is caused by continuous cultivation with little or no use of external inputs.

In the past farmers adopted shifting cultivation systems (Bunderson *et al*., 1991) as a measure to restore the soil fertility. These systems are based on long fallow periods (>15 years), which are only possible at low population densities. During the last century, fallow periods have been tremendously reduced, because of the increasing food demand by the increasing human population. Despite the declining of the soil productivity the farmers in the sub-Saharan Africa are compelled to meet the increasing food demand with their scarce resources. The principal objective of agricultural sustainability is to meet human needs by improving the living standards, alleviating drudgery, and human suffering, and ensuring an improved quality of life for the majority of the rural population (Eswaran, 1993).

Sustained agricultural productivity of soils requires use of proper seedbed and crop residue management, and judicious fertilizer applications and liming (Kang *et al*., 1991). Although the smallholder farmers are well aware of the importance of fertilizer use for sustaining agricultural production (Kang and Spain, 1986), they apply only 20-30% of the recommended fertilizer rate (Makken, 1993) or no inorganic fertilizer at all. Crop production may only be sustained under such conditions of reduced fertilizer inputs by adopting integrated soil fertility management that incorporates organic nutrient sources. Agroforestry is seen as a possible low cost solution to maintain or improve soil productivity under low input farming systems.

However, agroforestry systems are complex and there are still questions about interactions between crops and trees and about the low nutrient use efficiency in such systems.

1.2 Causes of soil infertility in Malawi

Malawi experiences similar problems as the other sub-Sahara African countries. In Malawi, it is reported that N is the most deficient nutrient nearly in all soils (Brown, 1962; Bunderson and Hayes, 1995) and P is the second limiting nutrient especially in light soils (Makumba, 1997). Smaling *et al*. (1997) in their map depicting nutrient depletion status for various African soils indicated that the Malawi soils lose nutrients at annual rates of not less than 40 kg N ha^{-1}, 6.6 kg P ha^{-1}, and 33.2 kg K ha^{-1}; these rates are higher than average for Sub-Saharan Africa.

The rapid population growth is a critical problem. At present the population density is 300-450 persons/km^2 (Akinnifesi and Kwesiga, 2000) and in some areas there is no land to spare for fallowing. The increasing population densities lead to increased pressure on natural resources and force smallholder farmers to expand to more marginal areas. Poor soil and water conservation measures have exacerbated soil degradation in these areas. All this results in (1) decline of land, (2) decline in per capita food production and (3) environmental degradation.

The use of inorganic fertilizers to replenish the lost nutrients has declined by more than 50% in Malawi between 1988 and 1997 (Carr, 1997) because of removal of subsidy on fertilizers by the Government and change in the Government policies towards smallholder credit facilities such that smallholder farmers do not have anymore access to farm input loans. The removal of subsidies on the farm inputs has been followed by exorbitant prices in the markets that are prohibitive to the smallholder farmers. Rural poverty is inextricably linked with small land holdings, poor soil fertility and limited off-farm revenues (*e.g.* Sanchez, 2002). All these problems combined have resulted in intensive cultivation on continuous basis with little or no added external inputs, leading to acute soil fertility problems under smallholder farm conditions (Saka *et al*., 1998). As a result of decline in soil fertility the smallholder farmer has experienced maize yield decline from an average of one ton per ha in 1980 to an average of 750 kg ha^{-1} in the 1990's (The Starter Pack Logistic Unit, 2000).

1.3 Farming in Malawi

1.3.1 Crop and Crop mixtures

In Malawi the cropping pattern is dominated by maize and maize mixtures. Maize and maize mixtures in Southern part of Malawi account for 18% and 69%, respectively, of the total cultivated area (Min. of Agric., 2000). Subsidiary crops are pulses, groundnuts, cassava, tobacco and rice. Maize is grown mixed with pulses, groundnuts or cassava. In smallholder farms maize is intercropped with two or more other crops, *i.e*. maize, pigeonpeas and beans and cassava is sometimes grown as a boundary crop. Because of land pressure the farmers have developed complex intercropping systems. Pulses (Phaseolus bean, pigeonpeas, cowpeas, chick peas and grams) are always intercropped with maize. Pulses in intercrops are planted soon after maize emergence; this prevents the secondary crop from suppressing the growth of maize.

In southern Malawi pigeonpea is an important food crop, rich in protein and it also increases soil N. Pigeonpea loses a substantial amount of leaves during the growing period (Kumar Rao *et al*., 1990). In addition pigeonpea produces also large amount of root biomass. Both are incorporated in the soil during land preparation. Because of the importance of the pigeonpea crop on the one hand and the acute land shortage on the other hand, farmers intercrop pigeonpea in gliricidia-maize or sesbania-maize agroforestry systems making a gliricidia-maize/pigeonpea intercropping system.

In such mixtures we have organic materials of diverse quality, *i.e.* low quality cereal residues, medium quality litter from the pulse crops, and high quality legume tree prunings. Incorporation of these organic materials of differing qualities may lead to complex decomposition and N release patterns that may not be predicted from the decomposition of the individual components.

1.3.2 Maize cultivation practices

In Malawi maize is grown on ridges, with furrows in between. Smallholder farmers till their pieces of land with traditional hand tools. Land preparation starts in May (soon after harvesting maize) by clearing. The crop residues and weeds are arranged in the furrows and are lightly covered with soil so that the termites and other soil fauna can start breaking down the residues. In this way the poor quality materials are given more time for decomposition than when they are incorporated at the time of ridge making, which comes later in the season. The little rains that fall in June/July provide moisture to enhance decomposition of the semi-buried crop residues. Every season, around October, new ridges are made, about 25-30 cm high, by breaking the old ridges and bringing the soil into the old furrows thus burying the remains of the crop residues. In the position of the old ridge a new furrow is developed. The ridges were spaced 90 cm apart but the new recommendation is 75 cm apart (Min. of. Agric., 1996). Planting of crops in the new ridges starts in November but is sometimes delayed until early January because of fluctuation of rainfall. Experience has shown that when maize is planted in October it suffers at least two weeks from drought between end of October and beginning of November. Weeding is done 3-4 weeks after planting and is repeated after 6-8 weeks. Fig. 1.1 presents a farm calendar depicting some common farm activities and growing periods of various crops mentioned above.

1.4 Agroforestry

Agroforestry is defined 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 (World Agroforestry Center, 2003).

Although improvement of soil fertility is one of the aims of agroforestry, it is by itself not sufficient to make farmers adopt agroforestry. Economic benefits *e.g.* via timber and fuel wood production, form the major incentive in the highly deforested parts of Sub-Saharan Africa. Agroforestry systems for soil fertility improvement are basically grouped into two, namely simultaneous and sequential. In simultaneous systems, the crops and trees co-exist at the same time on the same piece of land *e.g.* in the form of boundary planting, hedgerow intercropping, or contour hedges. In sequential systems, crops and trees take turns in occupying most of the same space; examples are improved fallows, shifting cultivation, *etc*. Although World Agroforestry Center (2003) considers relay cropping as a sequential agroforestry system it is clear from the definition of relay cropping that it falls between simultaneous and sequential cropping. Agroforestry was introduced in Malawi in 1984 by the department of Agricultural Research of the Ministry of Agriculture. Amongst the first agroforestry technologies introduced were hedgerow and alley cropping, and the agroforestry trees/shrubs used were *Gliricidia sepium, Senna spectabilis, Tephrosia vogelii, Leucaena leucocephala and Leucaena diversifolia*.

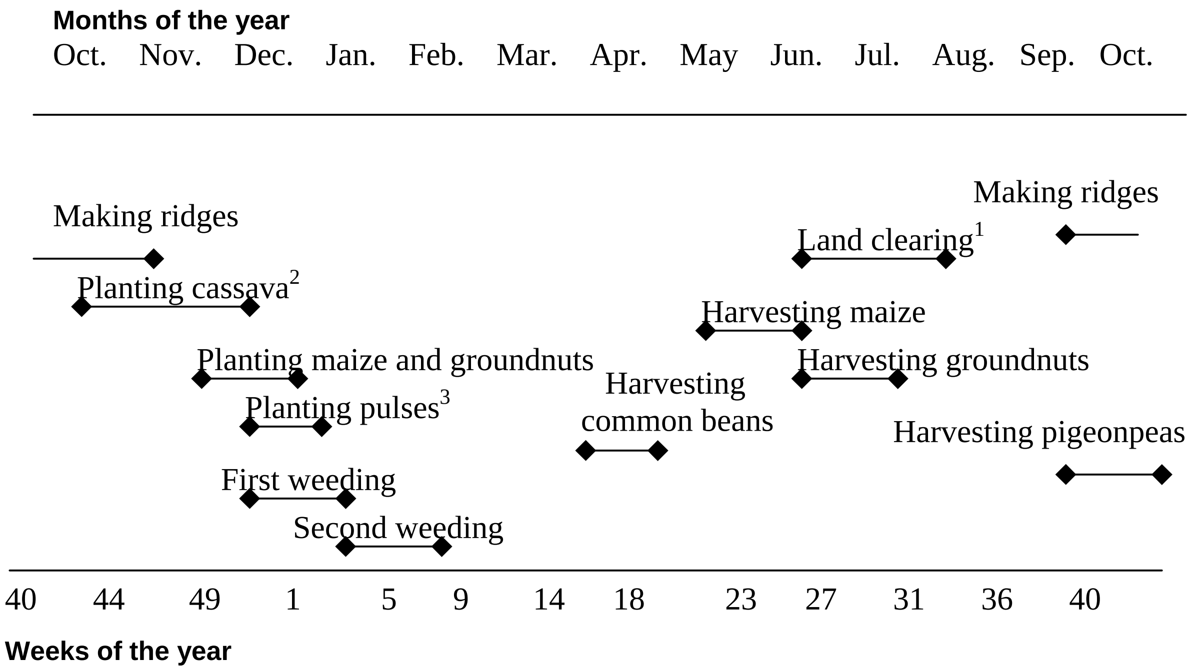

Fig. 1.1 Farm activities and cropping calendar for smallholder farmers in southern Malawi.

Notes:

[1]Land clearing is the first step of land preparation when the crop residues and weeds are arranged in the furrows and partially buried before ridge making

[2]Depending on variety of cassava normally matures after 10 to 12 months but harvesting is done at the will of the farmer since it can only be stored fresh in ground except when they want to dry process the tubers then it is harvested in October when there is a lot of solar radiation.

[3]Pulse crops commonly intercropped with maize include: pigeonpea, common beans, cow beans etc

In southern Malawi the two agroforestry technologies that have been promoted since 1994 by the International Center for Research in Agroforestry (ICRAF) are: (i) gliricidia simultaneous intercropping with maize and (ii) sesbania relay cropping with maize. In gliricidia simultaneous intercropping with maize, trees are planted on the same land along with maize; the maize is grown in alleys between the tree rows. Gliricidia tree heights are maintained at 30 cm. The tree coppices are pruned at the beginning of the season and at regular intervals during the crop-growing season and the biomass is incorporated into the soil providing nutrients for the growth of the associated crop. The system fits well in areas where acute shortage of land makes long fallow periods difficult or impossible. In the sesbania relay cropping, crops are planted at the rain onset, but planting of trees is delayed for about 2 weeks after the maize has been planted. Trees continue growing on the piece of land after the crop has been harvested, forming a short-term fallow during the dry season. Before the next rainy season trees are cut and all the leafy biomass is incorporated into the soil and the poles are harvested for either light construction or fuel wood.

Table 1.1 depicts the differences between the alley cropping introduced by the Department of Agricultural Research and simultaneous intercropping introduced by ICRAF using gliricidia as an example.

Itimu (1997) did comprehensive studies on N dynamics and root distribution of *Senna spectabilis* and *Gliricidia sepium* in alley cropping. Itimu (1997) reported significant increases of soil mineral N in the alley cropping, which resulted in increases in maize yields equivalent to application of 90 kg ha^{-1} inorganic N fertilizer. However, Itimu (1997) imported 1.2 to 1.8 tons of gliricidia prunings from a pure stand of gliricidia elsewhere to make the 2 tons required in his experiment, as the gliricidia in the alley cropping did not produce enough prunings. This is not practical under smallholder farmer’s condition where land is a big constraint. A cut and carry system (biomass transfer) also has high labor requirements for cutting and carrying the biomass to the fields (Sanchez, 2002).

Table 1.1. Characteristics of the gliricidia-maize simultaneous intercropping in this study and those of alley cropping as studied by Itimu (1997) and Kang *et al*. (1999)

	Gliricidia-maize intercropping*	**Alley cropping****
Distance between tree rows	1.5 m	4.5 m
Intra row tree spacing	90 cm	30 cm
Tree population per ha	7400	6700
Biomass production (prunings)	4-6 t ha^{-1}	226-868 kg ha^{-1}
No. of maize rows per alley	2	4
Preparation of ridges at the beginning of the season	Ridges are permanent and are maintained in the same position over the season. The tree prunings are incorporated by splitting open one side of the ridges and after laying the biomass the ridges are reconstituted.	The ridges are shifted every season. During the ridge making the old ridges are moved into the old valleys (Furrows) thus creating new valleys in the old ridge positions.
Maize population	44,400 plants/ha, maize population is the same as in the sole maize cropping system (since the ridges are maintained in the same position and trees are planted in the valleys between the ridges, the trees do not deprive the land area for the maize)	Because of shifting of ridges the tree rows occupy the ridge space such that the land area for the maize is deprived by the trees as such the maize population is not the same as in the maize sole cropping system

Source : *Makumba and Maghembe (1999). **Itimu (1997) and Kang *et al*. (1999).

There is as yet little information on the impact of trees on other nutrients than N in the soil profile. Wendt *et al*. (1996) studied the residual effects of P, S and Zn in alley cropping but they only studied the topsoil, while trees mostly feed from the subsoil. Cardoso (2002) found evidence of increased P availability and of increased amounts of organic P relative to inorganic P in the subsoil of agroforestry-coffee systems in Brazil. Radersma (2002) observed that trees mobilize P in and take up P from the subsoil, and that maize may benefit from P mobilized by trees in simultaneous agroforestry systems with *Senna spectabilis* and maize in Kenya. She concluded that negative effects of trees on maize were either due to soil-drying induced P-deficiency, or to a high P demand by trees in absence of soil P mobilizing capacity in the rhizosphere (Radersma, 2002).

Trees do not "produce" nutrients but they affect the cycling of nutrients and may pump nutrients from deep subsoil that otherwise would not be available to agricultural crops. N-fixing trees have the additional benefit of introducing "new" N from the atmosphere into the soil-vegetation systems. Long-term experiments suggest that simultaneous intercropping with woody species has the following general benefits: (1) supply of organic material from the tree prunings throughout the cropping season (*e.g.* Kang *et al*., 1999), (2) nutrient recycling (*e.g.* Mureithi *et al.*, 1994; Lupwayi and Haque, 1998; Makumba *et al*., 2001), and (3) soil conservation (Banda *et al*., 1994)..

There are, however, also concerns about the low nutrient use efficiency in agroforestry systems: (i) the simultaneous planting of the woody trees/shrubs and non-woody crops may result in competition for the belowground resources (Sanchez, 1995), and (ii) asynchrony between the release of nutrients from the organic materials and demand by the crop (Swift, 1987) may lead to nutrient losses. High C:N ratio organic materials initially immobilize nutrients (Sakala *et al*., 2000) and may release them off-season. On the other hand, organic materials with high N and low C:N ratios release most of the nutrients early in the season so that they are susceptible to leaching losses (Hegedorn *et al*., 1997). Competition for belowground resources is discussed further in Section 1.6 and asynchrony and quality of organic materials in Section 1.7.

1.5 Carbon sequestration in agroforestry

From recent date there is awareness that trees within agroforestry may contribute to carbon sequestration (*e.g.* Albrecht and Kandji, 2003). However, quantitative information about the amount of carbon sequestered belowground in agroforestry systems is still scarce.

The basic principle of carbon sequestration potential of land-use systems revolves around the fundamental biological/ecological processes of photosynthesis, respiration and decomposition (Nair and Nair, 2002). Essentially, carbon sequestered is the difference between carbon “gained” by photosynthesis and carbon “released” by respiration of all components of the ecosystem. More than half of the assimilated carbon is eventually transported below ground via root growth and turnover, roots exudation (of organic substances), and addition of litter or tree biomass. As a result, the soil contains a fair proportion of the C stock in an ecosystem.

Trees have conceptually been considered as a terrestrial carbon sink (Houghton *et al*., 1998). This gives hope that perennial tree species included in the agroforestry systems may substantially sequester carbon. In agroforestry systems, where the trees can sequester carbon both *in situ* (biomass and soil) and *ex-situ* (removed poles), it is necessary to assess the following factors for the quantification of sequestered carbon, (1) the increased amount of carbon in standing biomass, (2) the amount of recalcitrant carbon remaining belowground at a specified period of practicing agroforestry, and (3) the amount of carbon sequestered in the woody materials harvested from the system (Johnsen *et al.*, 2001). The third factor is not applicable in simultaneous intercropping system because the intense pruning management does not allow the trees to produce high wood biomass.

In the simultaneous agroforestry system, the soil carbon pool would possibly be increased by high and repeated inputs of the agroforestry tree prunings but the net effect will be small because most of the substrate carbon is rapidly returned to the atmosphere through CO_2 evolution (Andrèn and Kätterer, 2001). Studies have shown that even recalcitrant lignin-type structures in various straws may loose between 65 and 84% of the total carbon as CO_2 within the first 6 months of decomposition (Martin *et al*., 1974). The contribution of fresh leaves of high quality used in agroforestry systems to build up organic carbon stocks in the soil will be practically negligible since the largest portion of the applied organic carbon is lost into the atmosphere as CO_2.

Although agroforestry systems seem to have a potential for C sequestration, little effort has been made to quantify the carbon sequestered, and hence there is little scientific information on the subject matter.

1.6 Below-ground competition in agroforestry

Poor crop growth and low nutrient use efficiency by the crop may arise from competition for both above- and below-ground resources between trees and crops, especially when the trees have more competitive advantage than the crops.

Simultaneous cropping of woody species with non-woody crops has more complex belowground interactions among the components than simultaneous cropping of annuals has. Competition between trees and crops for below-ground resources may arise when the roots of the trees and crops grow in the same space and feed from the same sources.

In simultaneous agroforestry systems interactions between component species are essentially a response of one species to the environment as modified by the presence of the other (Akinnifesi *et al*., 1999a). These interactions may have competitive (deleterious), complementary (beneficial) or balanced-off (neutral) overall effects. Managing competitions is crucial for the success and sustainability of any simultaneous agroforestry system.

Competition occurs when species have to share the resources from a limited pool. Depending on management, and on environmental and physiological factors controlling plant growth and functioning, one species may gain at the expense of the other, causing one species to be a winner (strong competitor) and the other a loser (weak competitor) (van Noordwijk *et al*., 1996). Knowledge of root stratification of the trees/shrubs and the associated crops in an agroforestry system is needed in order to predict whether there will be competition between the trees and the crops. Previous root studies have revealed that trees having large and extensive roots will interfere with seedbed preparation or tillage operations. Tree species with lateral roots confined to less than 1 m distance from the tree trunk, are more desirable in simultaneous agroforestry systems that require tillage of the inter-row spaces (Ruhigwa *et al*., 1992; Akinnifesi *et al*., 1999a, 1999b). Shallow rooted tree species that exhibit rapid decline in root mass, length or density with increasing soil depth may compete highly with crops on soil nutrient resources, whereas trees with high concentration of their fine roots in the topsoil but at the same time with a substantial proportion of their fine roots in the deeper soil layers may compete less (Schroth and Zech, 1995) because they explore a large volume of soil. Tree roots at soil depths below the feeding zone of most annual crops may capture nutrients from deeper resources and transfer them to the surface (*e.g.* Van Noordwijk *et al*., 1996).

Figure 1.2 presents a conceptual model depicting belowground processes that may occur in a tree-crop simultaneous cropping agroforestry system. Incorporation of crop residues along with tree prunings could result in an initial mineral N immobilization leading to less N losses via leaching early in the season. Nutrients leached beyond the crop root zone may be captured and recycled by the tree roots growing in the deeper soil layers.

So far root studies were either conducted in systems with trees alone or in alley cropping where the tree rows are 4-5 m apart (*e.g.* Itimu, 1997). We need to understand the spatial rooting of trees and crops in the gliricidia simultaneous intercropping system where the tree rows are spaced at 1.5 m apart and the maize rows are not more than 0.375 m away from the trees. This information is needed to examine the nutrient scavenging behavior of the gliricidia trees in gliricidia simultaneous intercropping systems with maize.

1.7 Quality of organic materials and mineralization

Organic materials have been categorized into the following two major groups based on the chemical composition of the materials: (1) high quality materials: organic materials with high N content, low lignin and polyphenol content and low C:N ratios; (2) low quality materials: organic materials with low N, high lignin and polyphenol content, and high C:N ratio (Fox *et al*., 1990, Mafongoya *et al*., 1998a and 1998b). Gliricidia and sesbania produce high quality prunings.

1.7.1 High quality leguminous prunings

Decomposition studies have shown that gliricidia (Anthofer *et al*., 1998; Cadisch *et al*., 1998) and sesbania (Lupwayi and Haque, 1998; Mafongoya and Dzowela, 1998) prunings decompose rapidly, releasing most of their N within 14 and 28 days after incorporation (Itimu, 1997; Makumba and Maghembe, 1999). Mugendi *et al*. (1999) using *Calliandra callothyrsus* and *Leucaena leucocephala* prunings in alley cropping with maize in sub-humid highlands of Kenya found a peak mineralization at 4 weeks after planting. When high quality organic materials are incorporated too early before planting, most of their N is released early in the growing period, when the N demand by the crop is still low. This mineralized N is prone to leaching or losses in the run-off water, especially when rainfall is high. Hegedorn *et al*. (1997) found that N released from green manure decreased by 50 to 70% within 2-3 weeks after the flush, resulting in N deficits that were accompanied by the typical N hunger signs in the crop (Mugendi *et al*., 1999). Because the N demand of various maize varieties is low initially and gradually increases reaching a maximum between 50 and 90 days after planting (Saka, 1984; van der Meersch, 1991), much of the N released early in the season may not be taken up by the crop. As a result maize growth may be jeopardized later in the season.

1.7.2 Low quality organic materials

Organic materials with high C:N ratio, and high lignin and polyphenol content decompose slowly (Constantinides and Fownes, 1994; Seneviratne *et al*., 1998) initially immobilizing the soil available inorganic N. Thus they initially decrease the quantity of N available to the crop, while the later release of N proceeds at a low rate. Maize stover has a high C:N ratio such that it typically immobilizes inorganic N (Sakala, *et al*., 2000). In a pot experiment Lefroy *et al*. (1995) found that wheat yield was decreased following application of high C:N ratio wheat straw. Although pigeonpea can contribute up to 40 kg N ha^{-1} through litter fall of a sole pigeonpea crop (Dalal, 1974), the pigeonpea leaf litter is reported to initially immobilize N (Palm and Sanchez, 1991, Sakala *et al*., 2000). In a laboratory incubation study Nnandi and Balasubramanian (1978) found that pigeonpea roots immobilized N for the whole period of 12 weeks incubation. Constantinides and Fownes, (1993) showed that the leaves and twigs of the species had different decomposition rates and their mixtures were intermediate of the two rates. Under improved fallow systems the bulk part of organic materials incorporated in the soil at the end of the fallow period is the litter that accumulated on the ground during the fallow period. As normally in plants before defoliation, N is reallocated from the senescing leaves to younger growing leaves, the senescent leaves have low N content and are more lignified than the younger leaves. Therefore, use of such litter, which is comprised of senescent, lignified leaves and woody twigs, may result in significant immobilization of soil N. Nitrogen immobilization during the decomposition tends to increase with increasing lignin and decreasing N content of the organic material (Melillo *et al*., 1982). Many smallholder farmers have been frustrated with the low quality crop residues due to lack of immediate response to their crop growth (Saka *et al*., 1998).

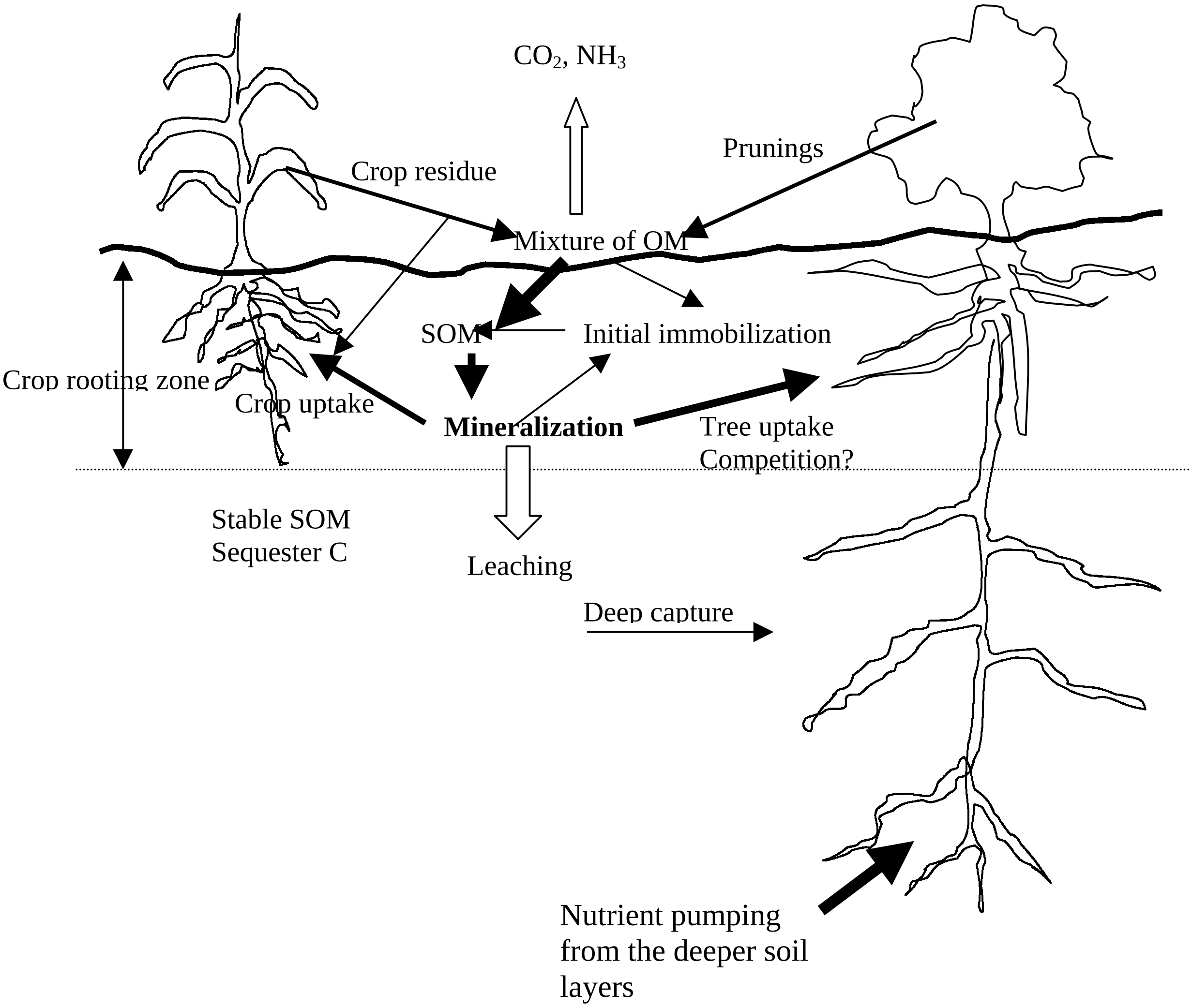

Fig. 1.2 Conceptual diagram of processes occurring in a simultaneous intercropping system

1.7.3 Synchronization of N release by organic materials and uptake by the crop

The current concern about low nutrient use efficiency in agroforestry-based systems has focused attention on the need to synchronize the nutrients released by the organic materials and the demand by the associated crops. The general objective of the synchrony concept is to maximize nutrient capture in the soil-plant system through (1) optimization of time of application, (2) mixing organic materials differing in chemical composition, (3) combining organic matter with inorganic fertilizer. These three strategies follow from hypotheses 1 and 2 (Table 1.2) formulated by the Tropical Soil Biology and Fertility (TSBF) for management of N sources in order to achieve synchrony (Myers *et al.*, 1997). Hypothesis 2 makes use of the properties of high and low quality materials as discussed in Sections 1.7.1 and 1.7.2. The capacity of organic materials with high C:N ratio to immobilize inorganic N offers the possibility to let such materials capture N released from high quality organic materials. Becker *et al*. (1994) found that mixing rice straw with *Sesbania* prunings in flooded rice significantly reduced N losses. Whitbread *et al*. (1999) corroborated that combining sesbania prunings and rice stubbles reduced N loss in flooded rice. Mixtures can also be composed of different plant parts with contrasting qualities of the same single species. Constantinides and Fownes (1993) investigated the effects of mixing leaves and twigs of the same plant and found the mixtures of the leaves and twigs gave mineralization results that deviated from those expected from leaves and twigs acting independently. These findings provide evidence that mixing of organic materials of differing quality or combining organic materials with inorganic fertilizers can be used to prolong nutrient availability in the soil, in order to minimize nutrient losses and increase the efficiency of nutrient transfer from organic inputs to crops.

The decomposition patterns of mixtures may be the direct weighted mean of the decomposition patterns of the component organic materials, in which case there is no interaction between the components, and each component is behaving as it would if it were not in a mixture. Alternatively, there may be interactions between the component organic materials, such that the rates of decomposition and N release are altered and/or the amount of the N released may not be predicted. Some studies have been conducted to test the regulation of N release through mixing of organic materials of different quality and/or manipulation of leaf quality (Becker *et al*., 1994; Handayanto *et al*., 1997). So far, it is not yet clear whether the N mineralization kinetics of high and low quality organic materials in mixtures are interactive or simply additive. Since under field conditions there are many natural confounding factors it is recommended to examine such questions in pot trials and to test the trends obtained under controlled conditions in pot trials later under field conditions.

Table 1.2. Twelve synchrony hypotheses developed by TSBF (Myers *et al*., 1997)

1. The maximum crop yield achievable by the use of inorganic (mineral fertilizer) inputs can be approached or exceeded by optimizing the time of application, placement and quality of organic nutrient sources.
2. In environments where significant leaching or denitrification occurs, plant uptake of mineral N applied at planting can be increased by simultaneous application of low organic material which temporarily immobilizes N early in the crop growth cycle and remineralizes N later on.
3. Stabilization of organic matter in the soil is enhanced by the addition of mineral nitrogen simultaneously with the addition of organic materials of high C:N ratio.
4. Residues high in lignin will result in low net mineralization and plant uptake in the first cropping season, but will produce a greater residual effect in subsequent seasons.
5. Residues high in tannins exhibit delayed nutrient release, but will after a lag period release nutrients rapidly.
6. Immobilization of P by microbes, or blocking of P sorption and fixation sites, following addition of organic material can prevent fixation of P.
7. Nutrient uptake efficiency increases with the longetivity of the plant.
8. The nutrient uptake efficiency of the system will be increased by plants that have more rapidly growing, deeper and more extensive roots.
9. Incorporation of organic inputs, as opposed to surface application, accelerates the release of nutrients, thereby providing another option for modifying nutrient use efficiency.
10. Improvement of nutrient uptake efficiency due to the use of organic inputs is more likely when crop growth and soil processes are less constrained by water deficits.
11. Quality and quantity of organic can influence faunal composition and activity, thus affect the synchrony of nutrient supply and crop demand.
12. The need for exact synchrony and crop demand can be reduced by storage of nutrients within the crop in excess of the crop's immediate requirement for growth.

1.7.4 Nitrogen mineralization modeling

Modeling offers an easy and cheap tool for extrapolating scientifically proven results to other areas without conducting experiments every time. **MI**neralization of **NI**trogen and **P**hosphorus (MINIP) is a computer model that was developed to predict N and P mineralization from organic materials. MINIP is based on the simple method for calculating organic matter decomposition (Janssen, 1984), and it has been used and incorporated in larger models dealing with nutrient cycling (Noij *et al*., 1993). Studies are going on to test whether the performance of the model can be improved when the decomposition is described according to the method of Yang (Yang, 1996, Yang and Janssen, 2000, Van Schaik, 2003). So far MINIP can handle mixtures of organic materials in case of additive mineralization. In case the mineralization of the organic material mixtures is interactive, modifications are required to accommodate the interaction.

1.8 Scope and outline of this thesis

This study addresses the low nitrogen use efficiency in agroforestry systems, as experienced in legume tree crop mixtures in Malawi. If the cause of the low nitrogen use efficiency is indeed asynchrony between N mineralization of added prunings and crop residues and N demand by the crop, than it should be possible to develop sound strategies for the timing of application and the mixing of high quality prunings and low quality crop residues so as to improve the nitrogen use efficiency. This should be tested under conditions in practice. Maize is the dominant crop in Malawi, but it is grown mostly in mixtures with pigeonpea, which provides high quality protein and large amounts of above and below ground residues. Introducing leguminous trees such as gliricidia and sesbania in these crop mixtures furnishes high quality tree prunings and below ground root biomass, but also increases competition effects. More insight is needed in the complexity of these systems, to be able to manage such systems properly.

The objectives of the current study are to increase the understanding of

(1) possible interactions between low and high quality materials during their decomposition and nitrogen mineralization in soil, and their subsequent effects on nitrogen use efficiency of maize grown in agroforestry systems;

(2) rooting patterns of maize – pigeonpea crop mixtures and trees, and their relationship with the distribution of soil mineral N and P with depth in simultaneous agroforestry system, and

(3) carbon and nutrients sequestered in gliricidia-maize simultaneous agroforestry systems.

The understanding of these processes will help to improve the management and judicious use of organic materials resulting in increased nutrient use efficiency and sustainability of the legume-tree based agroforestry systems, as currently practiced in Malawi. To achieve this general objective several studies were conducted at different sites: a greenhouse experiment at Wageningen University, The Netherlands; field trials at Makoka Agricultural Research Station in Zomba, Malawi; incubation experiments, chemical analyses, and computer supported studies, at both Makoka Agricultural Research Station Zomba, Malawi and Wageningen University, The Netherlands.

Nitrogen use efficiency of applied fertilizers and/or organic materials is usually conceptualized as comprising three components (*e.g.* Simonis, 1998): (i) agronomic efficiency, (ii) recovery efficiency, and (iii) utilization efficiency. In addition, more grain N per unit of N taken up may be linked to a higher dry matter partitioning to grains than to vegetative plant portion (increased harvest index). In this study, we used the so-called difference method to obtain

(i) Agronomic N efficiency (ANE) (ANE = $[Y_f - Y_o]/N$)

(ii) Nitrogen Recovery Efficiency (NRE) or shortly

(iii) Recovery Fraction RF (NRE = RF = $[NR_f – Nr_o]/N$)

Where,

Y_f and Y_o = yield of fertilized and unfertilized maize, respectively

NR_f and Nr_o = N recovered by fertilized and unfertilized crops, respectively

N = amount of N applied via fertilizers and/or organic materials

These parameters, i.c. ANE and NRE, were used to assess N use efficiency. Instead of $NR_f – Nr_o$ we used the term Delta N.

Chapter 2 of this thesis describes the general materials and methods used in the field experiments and the site characteristics. The greenhouse and incubation experiments are subjects of Chapter 3. In the glasshouse experiment N immobilization and remineralization by low and high quality organic materials were studied and N uptake from gliricidia and sesbania prunings was compared with uptake from an inorganic N source. Nitrogen mineralization of the organic materials was also studied in an incubation experiment using pepsin as extraction agent and the results were compared with the pot experiment. The results from the greenhouse experiment were instrumental in deciding the combinations of low and high quality organic materials for further testing under field conditions. Chapter 4 compares the effect of gliricidia prunings with inorganic fertilizer under field conditions and also looks at the course of N release from the organic materials applied at different times during the maize growing period. Chapter 5 gives the results of maize grain and biomass yields, N uptake, mineral N dynamics as a function of added mixtures of organic materials. In Chapter 6, the root distribution of maize, pigeonpea and gliricidia in a simultaneous agroforestry system and the soil mineral N distribution with soil depth are discussed. Chapter 7 deals with carbon sequestration in gliricidia-maize system, evolution of CO_2 after application of the green prunings and long-term effects of simultaneous intercropping on soil chemical and physical parameters. Chapter 8 describes the performance of the MINIP and its applications in predicting N mineralization of organic materials. A summary and the general discussion of the findings are given in Chapter 9.