Chapter 9

General discussion and conclusions

9.1 Major findings of the study

A major problem with agroforestry technologies for soil fertility restoration is the low recovery in the crop of the nutrients released from tree prunings and litter. The low N recoveries are ascribed to (1) lack of synchrony between N mineralization from the tree prunings and the crop's demand for N, and (2) competition for N between crops and trees, especially in simultaneous agroforestry systems.

We set up our experiments to better understand the patterns of mineralization, immobilization and remineralization of N and the interaction of organic materials of widely differing quality under controlled conditions (green house and laboratory) and as well as in the field. We compared the performance of organic materials with the performance of chemical fertilizer (CAN) and expressed the result in the substitution value (SV), *i.e*. the ratio of recovery fractions of the two N sources. We also studied the spatial root stratification of crops and trees in the agroforestry systems, and quantified their impacts on carbon sequestration and nutrients in topsoil and subsoil. Finally we used a simple mineralization model to ameliorate our understanding of the experimental results and to explore options for improvement of N use efficiency.

The major findings below are classified into two major categories:

- quality of organic materials: substitution values and immobilization
- comparison of agroforestry systems: yields, roots, soil fertility changes, carbon sequestration

Quality of organic materials

1. In the field, sesbania gave lower N recovery and substitution values than gliricidia. In the greenhouse experiment, gliricidia initially produced phytotoxins, and therefore performed less than sesbania.

2. The substitution values of gliricidia and sesbania were lower in the greenhouse experiment than in the field experiments, because the growth period in the greenhouse was shorter.

3. Substitution values of gliricidia prunings in the field depended on the time of application. Compared to CAN applied in December, SVs were 0.66, 0.32 and 0.20 for applications in October, December and February, respectively. The decrease in SV's with delayed application was ascribed to shortening of the overlap of mineralization and uptake by the crop, as N mineralization itself was not affected by time of application provided the environmental conditions remained the same.

4. Split application of tree prunings prolonged the availability of N in the topsoil during the crops' growing period but did not increase maize yield and N uptake and N use efficiency.

5. A litterbag experiment in the field showed that the rate of decomposition of prunings, crop residues and their mixtures decreased more or less with increasing C:N ratio in the order: gliricidia > pigeonpea leaves > sesbania > maize stover > pigeonpea roots.

6. Both in the green house and in the field N uptake was higher from tree prunings alone than from mixtures of tree prunings and crop residues

7. In the greenhouse experiment, 1:0.5 and 1:1 mixtures of high quality legume tree prunings and maize stover immobilized 18 and 24% of the plant available N at 28 days after planting (DAP), and 10 and 22% N at 48 DAP. In the field, 1:0.5 and 1:1 mixtures immobilized 6 and 15%, respectively at the time of harvesting in a season with optimum rainfall, and 26 and 35% in a season with less than optimum rainfall.

8. Addition of prunings with low C:N ratio may promote the rate of decomposition of low quality (high C:N ratio) crop residues by furnishing

mineralized N to the microbial biomass, when the soil solution is low in inorganic N.

9. The experiments in greenhouse and field, as well as the modelling exercises, showed that the interaction between high and low quality organic materials, if any, are marginal, and that the effects of the combined materials are almost purely additional

10. According to the modelling exercises, the maximum N immobilization was 9-10 kg per ton of maize stover. This was found after 17 days at standard conditions with a temperature of 25 ^{o}C and no moisture stress. The total period of immobilization and remineralization may last three to four months for maize stover and pigeonpea roots.

Comparison of agroforestry systems

11. Maize grown in a system of Gliricidia-Pigeonpea-Maize out yielded maize grown in a system of Gliricidia-Maize, despite of expected increased competition in such multiple cropping.

12. In such a Gliricidia-Pigeonpea-Maize maize intercropping system, maize was the stronger, and pigeonpea the weaker competitor.

13. Gliricidia root length density was relatively low in the ridge (0-30 cm soil layer) where the maize was growing, ranging from 30 to 460 cm dm^{-3}, but increased to 690 and 960 cm dm^{-3} at a depth of 40 cm in MZ12 and MZ21, respectively. By contrast, maize roots ranged between 900 to 1790 cm dm^{-3} in the top 0-30 cm soil layer and declined sharply down the soil profile.

14. Competition for nutrients between maize and trees was relatively small, because of their different rooting pattern, especially within the ridge where the prunings were applied and maize had higher root densities than trees.

15. After 7-10 years of agroforestry, P Olsen and exchangeable cations had increased slightly in the topsoil, but had decreased in the subsoil. Clearly, the

trees in the agroforestry systems had pumped nutrients from the subsoil and recycled them via prunings into the surface soils. This has resulted in higher yields and by that also in larger outputs of nutrients.

16. The increase of soil organic carbon in the topsoil of agroforestry fields improved bulk density, infiltration rates, permeability, water holding capacity and cation exchange capacity.

17. Carbon sequestered in gliricidia–maize simultaneous intercropping (Gs-Maize) amounted to about 1 t C ha^{-1} y^{-1} in the topsoil (0-20 cm) via repeated application of prunings and crop residues and to about 5 to 9 t C ha^{-1} y^{-1} in 20-200 cm soil layer via root turnover. A total of 17 t C ha^{-1} was contained in the tree biomass (stem and roots) after 7 years. Although carbon sequestration was high, carbon dioxide evolution was also high from soils of agroforestry plots.

18. Soil carbon sequestered in the 0-200 cm soil layer was much higher in gliricidia–maize than in grass fallow after seven years of experimentation.

9.2 Decomposition of tree prunings, crop residues and their mixtures

Decomposition patterns of pure materials obtained in our studies are similar to those earlier found by others (*e.g*. Budelman *et al.*, 1988; Mwiinga *et al.*, 1994; Itimu, 1997; Hartemink and Sullivan, 2001), but what is of more interest in the current study are the trends of decomposition of the mixtures of high and low quality materials. In the litterbag experiment the decomposition rate constants for the mixtures were in between those of individual components in the beginning but suddenly increased after 70 days. These trends could be explained by the modelling exercises MINIP in Chapter 8. Because of the N deficiency in the crop residues there is initially N immobilized from its surrounding soil solution. When there is not sufficient inorganic N in the soil solution, N mineralized from the high quality material may promote the decomposition of the crop residues.

9.3 N release and substitution values of gliricidia and sesbania prunings

In our field trials during both seasons, application of tree prunings before planting produced a peak of soil mineral N in December. The mineral N of December was important for crop's high N uptake, as suggested by the high correlation coefficient (r^2 = 0.73) between soil mineral N in December and total N uptake at harvest. Late applications had the same mineralization rate as the October application but the released N came too late for the crop's demand resulting in low N recoveries and low substitution values. For synchronization of supply and demand, N should become available to the plant in the period before 50 days after planting.

Table 9.1 shows that the substitution values of gliricidia were comparable for the field trials, but varied across seasons because of different quantities and distribution of rainfall. The substitution values were lower in the greenhouse experiment than the two field experiment because the greenhouse experiment did not run long enough to allow for complete decomposition of the added organic material.

Table 9.1 Substitution values for gliricidia and sesbania prunings obtained from different experiments compared to CAN

Experiment	Sesbania	Gliricidia
Greenhouse at 48 DAP, in 2000	0.44	0.38[a]
Agroforestry systems at 180 days, in 2000-01	0.52	0.69
Biomass transfer, in 2001-02	-	0.65

[a] Uncertain value because of initial production of phytotoxins

9.4 Competition for soil resources

The agroforestry system that received most attention in this work was the association of gliricidia–pigeonpea-maize in simultaneous intercropping; it is a unique practice that has seldom been reported elsewhere. As it is usually expected that competition is immense under high density intercropping system it is astounding that maize yields were higher under gliricidia-pigeonpea-maize than under gliricidia-maize Gs-Maize (Table 6.3). In this system maize competed with pigeonpea and gliricidia trees but maize apparently was the winner due to the intelligent cropping system with maize and pigeonpea growing on ridges and trees in furrows in between. Incorporation of tree prunings in the ridge provided the maize more chances of benefiting from the nutrients than the trees. Yields of pigeonpea were relatively low, but the pigeonpea left large amounts of crop residues, which served as nutrient source for the next crop.

Because of the low competition between the trees and crops, high biomass production and high maize yielding, gliricidia simultaneous intercropping is more successful than hedgerow intercropping and alley cropping that have shown to be unsuccessful (Smithson and Giller, 2002). In Hedgerow intercropping and alley cropping biomass yield is very low (Itimu, 1997), and competition for water and nutrients outweighs the positive fertility effects (Fernandes *et al.*, 1993; Mathuva *et al.*, 1998). In gliricidia simultaneous intercropping biomass production is high and competition between trees and crops is minimized through the intensive tree pruning and planting of trees in furrows and crops on ridges (ICRAF, 1998, Ikerra *et al*., 1999; Makumba *et al.*, 2000, 2001; Akinnifesi *et al.,* (in press)).

9.5 Effects on soil carbon and nutrients

In their review on carbon sequestration in tropical agroforestry systems, Albrecht and Kandji, (2003) concluded that there is still some work to be done to improve our understanding of carbon sequestration in agroforestry systems. Our results presented in chapter 7 are important in this respect. The results clearly show the potential of simultaneous agroforestry systems for carbon sequestration. Most interesting is also the larger sequestration of carbon in the subsoil than in the topsoil, as it is generally assumed that most carbon accumulates in the topsoil. According to Feller *et al*. (2001) effective sequestration can only be seen after a few decades. Our results indicate that measurable increases in the amounts of carbon in both topsoil and subsoil may occur within a period of 10 year in gliricidia - maize simultaneous agroforestry systems.

Chapters 6 and 7 clearly show that the trees pump nutrients from the subsoil beyond the maize rooting horizon and recycle them to the surface soil. The increase of soil carbon in the soil improves soil fertility and increases infiltration rates and water holding capacity. With the unreliable rainfall and frequent midseason drought, it will be clear that a high water harvesting capacity and a high soil water holding capacity are essential in sustaining the crop during water stress periods. These physical and chemical improvements of the soil resulted in higher crop yield in Gs-Maize than in Sole-Maize, as found in Chapter 5. The higher yields caused an extra nutrient export from the field, and that explains why the increase of the nutrient stock in the topsoil was smaller than the decrease of the nutrient stock in the subsoil.

9.6 General conclusion

The system of gliricidia–pigeonpea-maize simultaneous intercropping is an efficient system as long as the subsoil has not been depleted yet. For the fields of the Makoka Agricultural Research Station it was estimated that the sub-soils would be depleted in next period of 6 years. Once the subsoil has been depleted, soil fertility is much lower than it was before the practice of agroforestry started. Hence, from the point of view of chemical soil fertility, agroforestry without any external inputs cannot be considered as a sustainable system, and cannot replace inputs of organic or inorganic fertilizers from elsewhere in the long run. Apart from soil fertility, agroforestry has other important advantages for the farmer, such as the provision of firewood and timber. It should be realized, however, that sooner or later input of nutrients from outside the agroforestry fields will become indispensable.

Pigeonpea litter (photo was taken in the month of September)