Chapter 7

Long-term impact of gliricidia-maize simultaneous intercropping systems on carbon sequestration and soil properties

Abstract

Simultaneous agroforestry systems may sequester carbon in soil and standing biomass, and improve soil chemical and physical properties. The present study was undertaken in a 7-year (MZ21) and 10-year (MZ12) gliricidia-maize simultaneous intercropping systems to increase our understanding of its effect on carbon sequestration, CO_2-C efflux, and soil physical and chemical properties. The study was conducted in sole maize cropping (Sole-Maize), Gliricidia-maize simultaneous intercropping (Gs-Maize) and a 7-year old grass fallow (Grass-F). All the crop residues were incorporated within each system at the beginning of each season. Gliricidia prunings were incorporated at each time of tree pruning in the Gs-maize. Amount of organic carbon recycled in the systems via incorporation of crop residues varied from 0.3 to 1.0 t C ha^{-1} per annum in Sole-Maize and 0.8 to 7.5 t C ha^{-1} in Gs-Maize. A net decrease of soil carbon of 6 and 7 t C ha^{-1} in the topsoil (0-20 cm) relative to the initial soil carbon was observed at MZ12 and MZ21 respectively. In Gs-Maize up to 5 t C ha^{-1} was sequestered in the topsoil (0-20 cm) after 10 years of continuous application of tree prunings. Carbon dioxide evolution varied from 10 kg ha^{-1} day^{-1} to 28 kg ha^{-1} day^{-1} in Sole-Maize and 23 to 83 kg ha^{-1} day^{-1} in Gs-Maize. We concluded that Gs-Maize simultaneous intercropping system could sequester more carbon in the soil than Sole-Maize.

7.1 Introduction

The maintenance of physical, chemical and biological soil properties in agricultural land is essential to maintain or enhance soil quality and it can largely be achieved through organic material inputs to the soil. In Sub-Saharan Africa the degraded soils are low in soil organic matter. Soil organic C loss has been exacerbated by continuous cultivation with little or no organic matter amendment and by soil erosion (Follet, 1998). Preparation of land in Sub-Saharan Africa involves tillage and at times burning of crop residues. Carbon stock in agricultural soil under tillage practices declines compared to no-tillage practices (Duiker and Lai, 1999; Kucharik *et al.*, 2001; Mrabet *et al.*, 2001). Tillage and burning practices have been shown to reduce organic matter levels (Chan *et al.*, 1992, Slattery and Surapaneni, 2002) and to increase the potential for soil erosion (Carter and Steed, 1992). Tillage is known to decrease soil organic nitrogen and carbon pools with negative consequences for soil fertility (Kristensen *et al.*, 2003). The decline in soil organic C may have a negative long-term effect on the cation exchange capacity of the soil, and the ability to retain nutrients and to remain fertile.

Application of tree prunings may increase soil organic C (Jones *et al.*, 1996; Kang *et al.*, 1999) and exchangeable cations. The long-term effects on soil nutrient stocks, which influence the sustainability of crop production, are major benefits of regular additions of legume tree prunings and of root turnover. The magnitude of changes of soil organic matter (SOM) depends on the quantity and quality of prunings, soil type, system management, climate, and duration of practice of the system. According to Andrèn and Kätterer (2001), application of high quality organic materials has small effect on soil C build up because most of the substrate C is rapidly returned to the atmosphere through CO_2 evolution.

Most authors showing the improvements of soil organic C in agroforestry systems have concentrated on changes in the topsoil layer, 0-20 cm (*e.g.* Jones *et al*, 1996; Wendt *et al*., 1996; Kang *et al*., 1999). Information is lacking on stocks of organic C in the deeper soil layers where most of the tree roots occur that supply substantial amounts of C through root exudates and fine root turn over. Albrecht and Kandji (2003) in their review on carbon sequestration in tropical agroforestry systems also indicated that there is still paucity of quantitative data on specific systems and recommended that more work need to be done to increase our understanding of carbon sequestration and greenhouse gas mitigation.

Our general hypothesis was that compared to sole-maize systems gliricidia-maize simultaneous intercropping systems sequester more carbon in the soil via continuous application of tree prunings and root turnover and thus improve soil chemical and physical properties. The objectives of the current study were (1) to increase our knowledge on the carbon sequestered in the soil and temporarily stored in the standing biomass of the tree, and (2) to improve our knowledge on the effect of gliricidia trees on soil chemical and physical properties along the soil profile within the system. In this study both topsoil (0-20 cm) and subsoil (up to 200 cm) were considered. Data were obtained from two gliricidia-maize simultaneous intercropping systems of which one was 7 years old, and the other 10 years.

7.2 Materials and methods

7.2.1 Organic carbon additions

Amounts of organic C recycled annually through the application of organic materials were estimated from the yields of gliricidia prunings and maize stover. These gliricidia prunings and stover yields have been recorded since 1993 at MZ12, and since 1996 at MZ21. Details of MZ12 and MZ21 were presented in Chapter 2. All the prunings and maize stover harvested at a particular plot were incorporated in the soil at the same plot. At MZ21 only treatments that received 1.5 t ha^{-1} of maize stover for Sole-Maize and 3 t ha^{-1} for Gs-Maize were selected from the treatments reported in Chapter 5, because the amounts of biomass (maize and gliricidia) were close to the biomass applied in the preceding seasons. These quantities of stover were in the same magnitude as those applied in the previous years.

Maize stover and gliricidia pruning samples were dried at 75 ^{o}C and finely ground and total organic C was measured.

In 1999-2000 season no biomass was applied at MZ21 because the experiments reported in Chapter 5 had to be prepared, and that implied that the effects of residual N from the previous seasons' applications should be minimized.

7.2.2 Soil carbon stocks

Carbon contents of the surface soil (0-20 cm), assessed at the establishment of the trials, were used as baseline data for the soil carbon change in sole maize and gliricidia-maize cropping systems. A plot that had been left to grass fallow since 1994 was used as a reference for changes of organic C, and it will be referred to as grass fallow (Grass-F). We decided to use Grass-F as our reference instead of the initial soil data, because at the establishment of the trial soil organic C was only determined in the top 0-20 cm soil layer and no soil information was available of the 20-200 cm soil layer. Soil samples were taken from 0 to 200 cm at 20 cm intervals in three replicates in April 2002. At the time of sampling the experiments were 10 years old at MZ12 and 7 years at MZ21. Soil organic C was determined by "wet" oxidation by acidified dichromate (Anderson and Ingram, 1993).

7.2.3 Carbon dioxide evolution

Carbon dioxide evolution (soil and root respiration) from the soils in Sole-Maize and Gliricidia-Maize intercropping systems was assessed at MZ 21 on a weekly basis between October 2001 and April 2002. A week after incorporating gliricidia prunings, aluminum pipes, 5 cm in diameter and 30 cm long were inserted on a ridge one per plot per treatment in each of the three replicates. CO_2 evolved was trapped in 20 ml of 1 M NaOH in a 25 ml glass vial that was placed in the aluminum pipe and the open end of the pipe was capped with an iron cap. Rubber band was tied round the brim of the cap to minimize gas leakage from the pipe. After 24 hours of incubation the glass vials were removed and immediately capped to prevent exposure to CO_2 from the atmosphere. Amount of CO_2 trapped in the solution was determined by a titrimetric method. First the excess of 1 M NaOH in the CO_2 trap was titrated with 0.5 M HCl to a phenolphthalein endpoint (about pH 8.3). At this pH value, carbonate is converted to bicarbonate, and the remaining bicarbonate as a product of the reaction of CO_2 with NaOH is then titrated to a bromocresol green end-point (about pH 3.8) with standardized 0.1 M HCl (Bundy and Bremner, 1972).

7.2.4 Determination of amounts of carbon in the trees

Five trees were selected at random in the net plots in each of the tree replicates of Gs-Maize intercropping system at MZ21. The experiment at MZ12 is still continuing for long-term observations and destruction of the trees, therefore, was not possible. Since the trees in the simultaneous intercropping system were pruned to a height of 30 cm, the above ground part of the tree consisted of a stump only. The selected trees were carefully dug excavating all its roots (>5 mm diameter) growing up to 200 cm depth. Stumps and roots including the taproot were separated at the root collar, the fresh weights were recorded, and were then chopped into smaller pieces from which samples were taken. The fresh weights of the samples were recorded; then the samples were dried in an oven at 75 ^{o}C until constant weight and the dry weights were recorded. The ratio of dry to fresh weights of the samples was used to translate the fresh weights of the stumps and roots into dry weights. Fine roots (<5 mm diameter) were not included in this study, since it was difficult to retrieve them, using this method, and since a high proportion of these roots dies annually during the dry seasons.

7.2.5. Soil moisture

Soil moisture was measured in April 2002 as the rain was tailing off. In the Sub-Saharan countries there are frequent dry spells (mid rainy season short drought) during the seasons during which crops suffer much from water stress. Therefore, improving soil moisture retention capacity would help to sustain the crop longer during the dry spells. Gravimetric method was used to determine soil moisture contents in the two land-use systems of sole-maize and gliricidia-maize simultaneous intercropping. At both sites samples were collected from all three replicates. Soil samples were taken at 20 cm soil depth intervals to 200 cm deep, using an Edelman type auger, and placed in plastic bags. The soil samples were weighed in pre-weighed beakers and then dried in an oven at 105 ^{o}C. After 72 hrs of drying the dry weights were recorded.

7.2.6 Soil chemical and physical analysis

Soil samples were collected from the soil profile wall prepared for root mapping (Chapter 6). Soon after root mapping soil samples were collected along the profile at 20 cm depth intervals at MZ 12 and at 10 cm depth intervals at MZ 21 up to 200 cm. The soil samples were air-dried, the lumps were crushed and sieved through a 2 mm mesh sieve. The dry soils were analyzed for pH (H_2O), organic-C, Olsen P, exchangeable cations and texture. For organic-C analysis sub-samples were scooped and further sieved through 0.30 mm sieve. Analytical methods have been discussed in Chapter 2. Soil samples for bulk density analysis were taken from the profile wall using 100 cm^3 core samplers.

Table 7.1. MZ12, maize stover and gliricidia prunings yield (t/ha) and aboveground organic C (t/ha) recycled via the organic materials applied since 1993 (Data source: Akinnifesi *et al.*, (in press))

Treatment	Material	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Biomass yield (t/ha)											
Sole maize	Stover	2.3	1.8	1.7	1.4	0.6	1.3	1.2	0.9	1.0	0.9
Gs-Maize	Stover	1.8	4.3	3.3	5.9	3.7	4.8	5.0	2.6	5.6	4.7
	Gs-Prunings	2.6	3.8	3.7	4.7	5.2	5.3	6.0	3.3	4.4	4.9
	Total	*4.5*	*8.2*	*7.0*	*10.6*	*8.9*	*10.0*	*11.0*	*5.8*	*10.0*	*9.6*
Amount of C recycled (kg/ha)											
Sole maize	Stover	1.0	0.7	0.7	0.6	0.3	0.5	0.5	0.4	0.4	0.4
Gs-Maize	Stover	0.7	1.7	1.3	2.4	1.5	1.9	2.0	1.1	2.3	1.9
	Gs-Prunings	1.2	1.8	1.7	2.2	2.4	2.5	2.8	1.5	2.1	2.3
	Total	*1.9*	*3.5*	*3.0*	*4.6*	*3.9*	*4.4*	*4.8*	*2.6*	*4.4*	*4.2*

Table 7.2. MZ 21, maize stover and gliricidia prunings (t/ha) applied and amount of aboveground organic C recycled into the soil each season since 1995-96 season (1995/96-1999/00 data source: Makumba *et al*., 2000)

Treatment		1995-96	1996-97	1997-98	1998-99	1999-00[b]	2000-01	2001-02
Biomass								
Sole-Maize	Maize stover	1.7	1.7	1.5	1.0	1.2	1.5	1.5
Gs-Maize	Maize stover	1.2	2.4	3.0	3.4	1.4	3.0	3.0
	Gs prunings[a]	0.7	1.6	2.4	5.2	4.0	3.0	3.0
	Total	*1.9*	*4.0*	*5.4*	*8.6*	*5.4*	*6.0*	*6.0*
Amount of C recycled								
Sole-Maize	Maize stover	0.7	0.7	0.6	0.4	-	0.7	0.7
Gs-Maize	Maize stover	0.5	1.0	1.2	1.4	-	1.3	1.3
	Gs prunings	0.3	0.8	1.1	2.4	-	1.4	1.4
	Total	*0.8*	*1.7*	*2.3*	*3.8*	-	*2.7*	*2.7*

[a] The amounts of gliricidia prunings applied were fixed at 3 t ha^{-1} in 2001 and 2002 according to the requirements of experiment reported in Chapter 5.

[b] Organic materials were not incorporated in 1999-00 season (see Section 7.2.1).

7.3 Results

7.3.1 Additions of aboveground organic carbon to soil

Tables 7.1 and 7.2 show the yields of aboveground biomass of maize stover and gliricidia prunings, and amounts of recycled carbon calculated from the organic carbon content of the biomass incorporated. At MZ12, the amount of carbon added declined in Sole-Maize from 1.0 t ha^{-1} in 1993 to 0.4 t ha^{-1} after 2000, and increased in Gs-Maize from 1.9 to 4.8 t ha^{-1}. At MZ21, organic carbon applied in Sole-Maize via the organic materials decreased between 1995 (0.7 t C ha^{-1}) and 1998 (0.4 t C ha^{-1}). Yields at MZ12 were higher than those at MZ 21. This likely was caused by the higher initial soil fertility in MZ12 than in MZ21; especially P was higher (P-Olsen was 26 in MZ12 compared to 10 mg kg^{-1} in MZ21). In 2000 and 2001 the amount of maize stover incorporated was fixed at 1.5 t ha^{-1}, corresponding to 0.7 t C ha^{-1}. Because of increased maize and the combination with gliricidia prunings the amount of organic C applied was much higher in Gs-Maize than in Sole-Maize. During the 7 years of organic material incorporation, organic carbon addition varied between 0.8 and 3.8 t ha^{-1}.

7.3.2 Carbon sequestered in soil and temporarily stored in trees

At both sites soil organic carbon decreased with depth (Table 7.3) with significant ($P<0.001$) accumulation in the top 0-40 cm soil layer. In Sole-Maize only a trace of C was detected in the sub-soil below 140 cm. In the surface soil layer (0-20 cm) amounts of organic carbon were larger in Gs-Maize at MZ12 (11 t ha^{-1}) and at MZ21 (10 t ha^{-1}) than in Sole-Maize. Compared to the initial soil organic carbon, at both sites topsoil (0-20 cm) carbon had decreased in Sole-Maize and increased in Gs-Maize and Grass-F. Analysis of variance (Table 7.4) shows that there were significant ($P<0.001$) treatment differences. Grass-F had higher organic carbon in the top 0-40 cm than Gs-Maize at MZ21 but much lower in the sub-soil below 40 cm. Gs-Maize had 26 t C ha^{-1} per 200 cm more than Grass-F.

Table 7.5 shows that 17 t ha^{-1} of carbon was temporarily stored in the trees (stumps and roots) in the field after 7 years of practice at MZ21.

Table 7.3. Amount of soil organic C (t/ha/20 cm soil layer) in the soil profiles 0-200 cm 10 years after the start of the trial at MZ 12 and 7 years at MZ 21

Soil layer (cm)	MZ 12[a]			MZ 21[a]					
	Sole-Maize	Gs-Maize	C_1	Sole-Maize	Gs-Maize	Grass-F	C_1	C_2	C_3
0-20	19 a	30 a	11	22 a	30 a	32 a	8	10	2
20-40	18 a	22 b	4	18 a	26 a	28 a	8	10	2
40-60	12 b	15 c	3	14 b	19 b	16 b	5	2	-3
60-80	6 c	13 c	7	7 c	15 b	13 b	8	6	-2
80-100	6 c	11 c	5	5 cd	12 bc	11 b	7	6	-1
100-120	3 c	9 d	6	5 cd	14 b	9 c	9	4	-5
120-140	Trace	9 d	9	2 d	10 bc	6 c	8	4	-4
140-160	Trace	5 e	5	Trace	9 c	5 c	9	5	-4
160-180	Trace	6 e	6	Trace	7 c	2 d	7	2	-5
180-200	Trace	3 f	3	Trace	7 c	1 d	7	1	-6
0-200 cm	64	123	59	73	149	123	72	50	-26
Initial (0-20 cm)	25			29					

[a] In a column means followed by a common letter are not significantly different at 5% level by DMRT

[b] C_1 = difference between Gs-Maize and Sole maize,

[c] C_2 = difference between Grass-F and Sole-Maize,

[d] C_3 = difference between Grass-F and Gs-Maize

Table 7.4 Analysis of variance of soil organic carbon in various treatments and depths at MZ12 and MZ21.

Source of variation	d.f.	s.s.	m.s.	F	sign. level
MZ 12					
Replicate	2	58	29	5.29	
Treatment (T)	1	500	500	90.04	<0.001
Depth (D)	9	3348	372	66.98	<0.001
T*D	9	81	9	1.61	0.147
Error	38	211	6		
Total	59	4198			
MZ 21					
Replicate	2	4	2	0.26	
Treatment (T)	2	978	489	62.76	<0.001
Depth (D)	9	6062	674	86.48	<0.001
T*D	18	153	9	1.09	0.382
Error	58	452	8		
Total	89	7648			

Table 7.5. MZ21, gliricidia stumps and structural root standing biomass (t ha^{-1}) and total C (t ha^{-1}) temporarily stored in the stumps and roots in August 2002

Part of the tree	Biomass	Carbon
Tree stumps	16	7
Roots > 5 mm	19	10
Total	35	17

7.3.3 Carbon dioxide evolution

Carbon dioxide evolution was low for about a period of a month after organic material application showing a time lag to decomposition for both treatments, Sole-Maize and Gs-Maize (Fig. 7.1). A peak CO_2 evolution was observed between December and February, with a maximum of 83 kg CO_2-C ha^{-1} day^{-1} for Gs-Maize, and of 28 kg ha^{-1} day^{-1} for Sole-Maize in January. After the rain season the release per ha per day was reduced for Gs-Maize and Sole-Maize to 23 kg and 10 kg CO_2-C ha^{-1} day^{-1}, respectively.

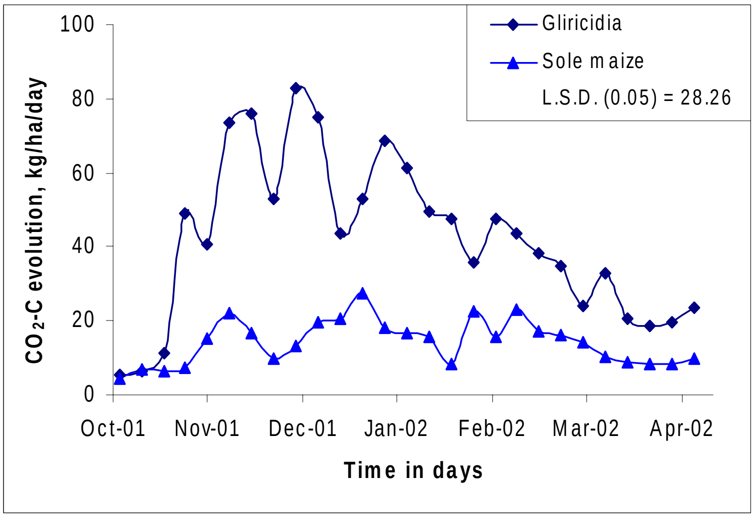

Fig.7.1. Carbon dioxide evolution in Sole Maize and Gs-Maize simultaneous between October 2001 and March 2002 at MZ 21

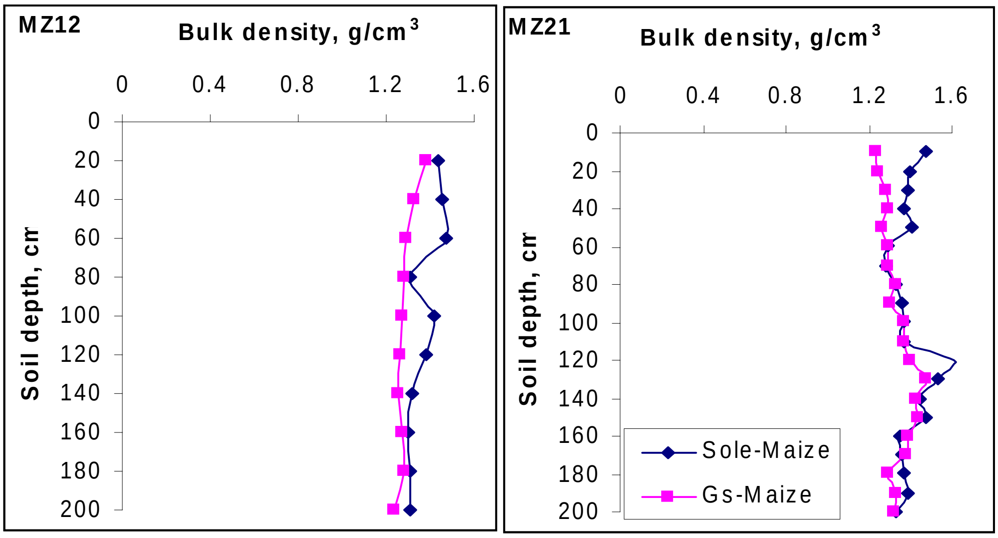

Fig. 7.2. Soil bulk density along soil profile in Sole-Maize and Gs-Maize cropping systems at MZ12 and MZ21

7.3.4 Soil physical and chemical properties

7.3.4.1 Soil Physical properties

Soil bulk density in Sole-Maize at both sites was higher than in Gs-Maize throughout the soil profile (Fig. 7.2). At MZ12 in Sole Maize bulk density in the topsoil (0-60 cm) was higher than the initial bulk density.

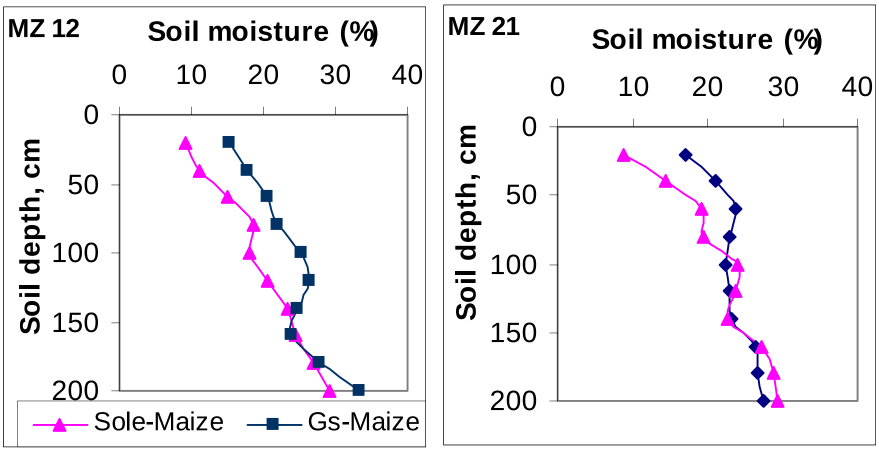

Fig. 7.3. Soil moisture content (%) as influenced by Sole-Maize and Gs-Maize cropping systems at MZ12 and MZ21 determined in March 2002 at the end of rainfall. L.S.D (0.05) of means for treatments were 1.86 (MZ12) and 1.39 (MZ21); for Depth: 4.17 (MZ12) and 3.12 (MZ21); and Treatment*Depth 5.89 (MZ12) and 4.41 (MZ21).

Soil moisture content in April, two weeks after rain had stopped was higher in Gs-Maize intercropping system than in Sole-Maize cropping system in 0-120 soil layers at MZ12 and 0-80 cm at MZ21 (Fig. 7.3). In the deeper soil layers soil moisture contents in the two land use systems did not differ for both sites. At both sites the soil moisture increased down the soil profile. Statistical analysis shows that soil moisture in Gs-Maize was significantly higher than in Sole-Maize (Table 7.6).

7.3.4.2 Soil chemical properties

At MZ12, the quantity of exchangeable cations in Sole-Maize was slightly lower in the surface soil and slightly higher in the deeper soil than in Gs-Maize (Fig. 7.4, Appendix 7.1). The trends were less clear at MZ21. The quantity of exchangeable cations tended to increase down the soil profile, but less in Gs-Maize than in Sole-Maize (Appendix 7.2). A calculation was made of the total quantity of Olsen P and of exchangeable K, Ca and Mg present in the soil layers 0-60, 60-120, and 120-200 cm and in the total soil 0-200cm (Table 7.7). The subsoil has lost more nutrients than the topsoil has received, especially in the case of Ca. The negative balance for the total soil layer of 200 cm must be ascribed to the higher yields obtained at Gs-Maize, which have caused an extra nutrient export from the field. The decrease in nutrient stock varies from 0 to maximally 50% (for P at MZ21) of the original values in 1992 (MZ12) and 1996 (MZ21). This could mean that after another 6 years MZ21 might be deprived of P.

Table 7.6 ANOVA table for soil moisture

Source of variation	d.f.	s.s.	m.s.	F	sign. level
MZ 12					
Replicate	2	30	15	1.19	
Treatment (T)	1	248	248	19.51	<0.001
Depth (D)	9	1768	196	15.45	<0.001
T*D	9	98	11	0.85	0.574
Error	38	483	13		
Total	59	2627			
MZ 21					
Replicate	2	22	11	1.58	
Treatment (T)	1	41	41	5.75	0.021
Depth (D)	9	1190	132	18.58	<0.001
T*D	9	197	22	3.08	0.007
Error	38	270	7		
Total	59	1721			

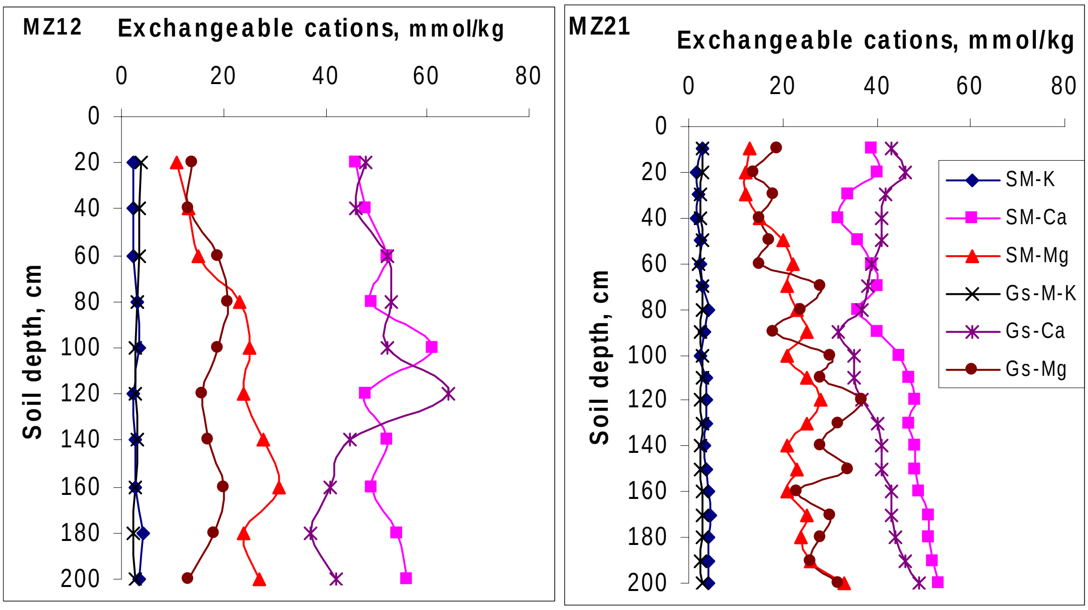

Fig. 7.4. Exchangeable cations, K, Ca and Mg levels along the soil profile in Sole-Maize (SM) and Gs-Maize (Gs) at MZ12 and MZ21.

Table 7.7. Differences in P-Olsen and in exchangeable K, Ca and Mg between Gliricida-Maize and Sole-Maize treatments at MZ12 and MZ21. Basic data are found in Appendices 7.1 and 7.2.

Depth, cm	P, mg/kg	K, mmol/kg	Ca, mmol/kg	Mg, mmol/kg
MZ12				
0-60	9.0	4	0	7
60-120	2.0	0	11	-16
120-200	-1.0	-2	-46	-42
0-200	0.1	1	-35	-52
MZ21				
0-60	-23.7	3	32	4
60-120	-17.9	-4	-42	22
120-200	-7.7	-10	-52	35
0-200	-49.3	-11	-62	61

7.4 Discussion

7.4.1 Carbon sequestration

At both sites organic C decreased in the topsoil of Sole-Maize during the course of the trials, despite annual additions of maize stover. A similar observation was made in an 18 year lasting experiment in Kenya where 16% of soil organic carbon was lost compared to initial soil C, despite continuous application of a combination of inorganic fertilizer, animal manure and maize stover (Kapkiyai *et al*, 1999). Incorporation of slow decomposing, low quality maize stover apparently was not enough to balance the release of soil carbon due to tillage. Many studies have shown that soil organic carbon declines in tillage systems (Hulugalle and Ndi, 1993; Salinas-Garcia *et al.*, 2001; Matsumoto *et al* 2002). In Sole-Maize, every season the preparation of land involved tillage with hand hoes whereby the old ridges were shifted into the old furrows to construct a new ridge (Section 1.3.2).

Martin *et al.* (1974) reported that recalcitrant lignin-type structures in various straws might lose as much as 65 to 84% of the total carbon as CO_2 within the first 6 months of decomposition. Yet, many researchers have reported increases of soil carbon after continued application of crop residues and tree prunings in the topsoil compared to the control (Wendt *et al.*, 1996; Kang *et al.*, 1999; Aulakh and Doran, 2002). In the current study, an overall increase of soil organic carbon in the topsoil 0-20 cm in Gs-Maize was obtained compared to the initial soil organic carbon at both sites. In addition to the applied organic materials the net increase has to be ascribed to belowground biomass, *i.e.* the roots partly sloughed off in the ridge during incorporation of prunings. The roots might add large amounts of carbon because they are woodier than the prunings and have carbon in more stable compounds. Hence roots may supply more stable carbon to the soil. Moreover, tillage management may be an important factor. The ridges in Gs-Maize were not shifted but rather half of the ridge was split open and the organic materials were incorporated while the other half remained undisturbed. This management practice could as well be described as reduced tillage.

Since the organic materials were incorporated within 0-20 cm on the ridge, carbon sequestered in the soil below 20 cm could be thought of largely being contributed by root turnover. Our results suggest that tree roots sequestered about 48 t C ha^{-1} in 20-200 cm at MZ12 and 64 t C ha^{-1} in 20-200 cm at MZ21, relative to the Sole-Maize. In the whole Gs-Maize intercropping system the apparent amount of soil carbon sequestered relative to Sole-Maize (denoted by C_1 in Table 7.3) amounted to 59 t C ha^{-1} per 200 cm at MZ12 and 72 t C ha^{-1} per 200 cm at MZ21. Although the trends in carbon sequestration are as expected, the measured amounts are unlikely high. These numbers would suggest that between 5 and 10 ton of organic C has been sequestered annually in the subsoil. There may be small analytical errors or systematic differences between soils and sites involved, although the soil textural differences between the soils seem negligibly small. Whatever the cause, our estimates of organic sequestration in the subsoil seem high, but they point at the importance of subsoil for C sequestration in gliricidia-maize systems.

Although in the standing biomass (roots and stumps) the trees contained up to 17 t C ha^{-1}, the sequestering of this carbon ends at wood harvest or when the tree dies. As gliricidia stumps can only be used as fuel wood, an important part of the biomass carbon returns rapidly to the atmosphere as CO_2.

7.4.2 Carbon evolution

Carbon dioxide efflux from the soil amended with maize was within the range reported by other researchers (Flanzluebbers *et al.*, 1994; Dao, 1998; Jocinthe *et al.*, 2002). During the peak period, CO_2 evolution, in Gs-Maize was three times as much as in Sole-Maize. The low CO_2 evolution during the first month after tree pruning incorporation into the soil is in agreement with the time lag for decomposition that is found in most experiments (Yang, 1996). The peak CO_2 evolution period overlapped with the peak N release in December (Figs. 4.3 & 5.2). At the end of the period (173 days) 2.6 and 7.8 t CO_2-C ha^{-1} had been evolved from Sole-Maize and Gs-Maize (Table 7.8). This C might have originated from the applied organic materials, from old soil organic matter and from root respiration. The simple analysis of Table 7.8 shows that 0.28 and 2.86 t CO_2-C ha^{-1} y^{-1} was to be ascribed to root respiration and decomposing tree and crop roots. The total amounts of roots (2 mm or less) were 9510 and 13860 cm dm^{-3} (Chapter 6) in Sole-Maize and Gs-Maize, respectively. These differences in roots cannot fully explain the differences in CO_2–C emission between Sole-Maize and Gs-Maize, but at least they make a substantial contribution.

7.4.3 Effect of soil organic C on some soil parameters

7.4.3.1 Soil physical properties

Increasing amounts of soil organic carbon in the topsoil reduce bulk density, increase porosity and thereby improve the infiltration capacity of the soil.

In the Gs-Maize, growing gliricidia roots also play an important role, because they may break hoe pans that might exist in the plots and also because decomposed roots leave holes in the soil through which water can easily percolate. We observed that 30 minutes after rainfall, water was still standing in the furrows in the Sole-Maize plots whereas in the Gs-Maize the water had all percolated into the soil, suggesting that the soil in the Gs-Maize plots had a higher infiltration rate. With the unreliable rainfall patterns and frequent mid season short-term droughts in the Sub-Saharan Africa the improvement of infiltration rate and soil water retention in the Gs-Maize would be very beneficial to the crops.

Table 7.8. Simple analysis of CO_2–C emissions (kg C per ha per year) from treatments Sole Maize and Gliricidia-maize, at MZ21 in 2002.

		Sole-Maize	Gs-Maize
1	CO_2–C emission	2.58	7.80
2	C from added Organic material	0.70	2.70
1-2	C from SOM and root respiration and decomposition	1.88	5.10
3	C from SOM (0-40 cm) decomposition	1.60	2.24
1-2-3	Apparent CO_2–C from root respiration and decomposition	0.28	2.86

[a] C from SOM is the carbon converted from soil organic matter estimated at conversion rates of 4% and 2% for 0-20 cm and 20-40 cm soil layer, respectively.

7.4.3.2 Soil chemical properties

The increase of exchangeable cations in the topsoil between 0-20 cm was ascribed to the addition of tree prunings. The increase of cations was within the soil in the top ridge where organic materials were incorporated. Mendham *et al*. (2003) observed that exchangeable cations, especially K decreased during the first 4 years during which the trees were still establishing but thereafter, started to increase in *Eucalyptus globus*. The authors suggested that the increase of exchangeable cations was due to decomposing tree litter. In the deeper soil generally quantities of exchangeable cations were lower in Gs-Maize than in Sole-Maize, suggesting that the roots were taking up the exchangeable cations from the sub soil and were being recycled into the topsoil via the prunings.

7.5 Conclusions

Our data suggests that Gs-Maize sequestered about 1 t C ha^{-1} y^{-1} in the topsoil (0-20 cm) via applications of prunings and crop residues, and 5-9 t C ha^{-1} y^{-1} via root turnover. These data clearly show the importance of C sequestration in agroforestry systems, though our absolute estimates for the subsoil may be too high.

Increased levels of soil organic carbon increased the water infiltration and water storage in the soil and also reduced soil bulk density in Gs-Maize. Repeated application of the prunings increased exchangeable cations in the topsoil a little but mining of nutrients from the subsoil by the tree roots was also evident. The nutrient stock of the 0-200 cm decreased as a result of extra nutrient export by the extra maize yields.

Appendix 7.1. MZ12, soil chemical and physical characteristics along the soil profile wall under sole maize and Gliricidia-maize.

Soil depth	pH (H_2O)	Org. C (mg/g)	Extract. P (mg/kg)	Exchangeable Cations ------(mmol/kg)-------			Soil Texture ------------(%)--------			Bulk density (g/cm^3)
				K	Ca	Mg	Clay	Silt	Sand	
Baseline data (taken in 1992)[a]										
0-20 cm	5.9	8.8	26	3.0	44	16	42	12	46	1.42
Sole maize										
0-20	5.7	6.6	20	2.3	46	11	48	8	44	1.44
20-40	5.6	6.3	23	2.3	48	13	49	8	43	1.45
40-60	5.8	4.0	19	2.2	52	15	43	8	49	1.47
60-80	5.9	2.3	14	2.9	49	23	41	8	51	1.31
80-100	6.1	2.2	12	3.3	61	25	48	10	42	1.42
100-120	6.3	1.1	6	2.2	48	24	45	10	45	1.38
120-140	6.2	trace	5	2.8	52	28	43	10	47	1.32
140-160	6.4	trace	4	2.8	49	31	36	8	56	1.30
160-180	6.3	trace	4	4.3	54	24	33	8	59	1.31
180-200	5.9	trace	3	3.3	56	27	30	8	62	1.31
Gliricidia										
0-20		10.9	26	3.7	48	14	45	13	48	1.38
20-40	6.0	8.2	25	3.5	46	13	41	10	49	1.33
40-60	5.9	6.9	20	3.5	52	19	42	12	46	1.29
60-80	5.6	5.1	14	2.9	53	21	39	10	51	1.28
80-100	5.9	4.4	10	2.7	52	19	44	11	45	1.27
100-120	5.8	3.6	10	2.8	64	16	37	14	48	1.26
120-140	5.7	3.7	6	2.9	45	17	38	13	48	1.25
140-160	6.0	1.9	3	2.7	41	20	41	12	47	1.27
160-180	6.3	2.4	3	2.5	37	18	39	12	48	1.28
180-200	6.2	1.2	3	2.6	42	13	33	11	57	1.24
	6.4									

[a] Source: SADC-ICRAF, Makoka-Malawi data base reference no. MZ\12\92

Appendix 7.2. MZ21, soil chemical and physical characteristics along the soil profile wall under sole maize and Gliricidia-maize.

Soil depth	pH (H_2O)	Org. C (mg/g)	P (mg/kg)	Exchangeable Cations ------(mmol/kg)--------			Soil Texture -----------(%)---------			Bulk density (g/cm^3)
				K	Ca	Mg	Clay	Silt	Sand	
Baseline data (taken in 1996)[a]										
0-20 cm	5.6	9.3	10.3	3.7	37	14	38	8	54	1.55
Sole maize										
0-10	5.3	8.1	9.3	2.9	39	13	37	9	54	1.47
1-20	5.4	7.2	8.9	1.8	40	12	41	8	51	1.40
20-30	5.3	6.8	9.2	1.9	34	12	46	10	44	1.39
30-40	5.2	6.6	8.8	1.8	32	15	48	8	44	1.37
40-50	5.1	5.1	7.5	2.7	36	20	41	8	51	1.41
50-60	5.1	4.9	6.5	2.5	39	22	42	9	49	1.29
60-70	5.1	3.2	5.8	2.9	40	21	29	6	65	1.28
70-80	5.1	2.4	5.0	4.2	36	23	57	10	33	1.33
80-90	5.0	2.0	5.2	3.4	40	25	57	8	35	1.36
90-100	5.2	1.9	4.3	2.6	45	21	53	10	37	1.37
100-110	5.4	1.7	4.2	3.7	47	25	53	12	35	1.37
110-120	5.3	1.6	3.6	3.8	48	28	51	12	37	1.61
120-130	5.2	1.5	3.6	3.6	47	25	51	8	41	1.53
130-140	5.3	trace	3.3	3.4	48	21	57	8	35	1.45
140-150	5.1	trace	3.3	3.7	48	23	47	9	44	1.47
150-160	5.2	trace	2.3	4.2	49	21	30	6	64	1.35
160-170	5.4	trace	2.3	4.4	51	25	29	6	65	1.36
170-180	5.3	trace	1.9	4.3	51	24	47	6	47	1.37
180-190	5.2	trace	1.9	4.2	52	26	49	6	45	1.39
190-200	5.2	trace	1.8	4.3	53	33	45	6	49	1.33
Gliricidia										
0-10	6.1	12.7	7.0	3.1	43	19	31	16	53	1.23
10-20	5.8	11.3	6.3	2.8	46	14	44	14	42	1.24
20-30	5.9	10.5	6.4	2.5	42	18	53	12	35	1.28
30-40	5.7	9.8	2.8	2.6	41	15	51	10	39	1.29
40-50	5.6	7.8	2.2	3.1	41	17	48	9	43	1.26
50-60	5.6	6.9	1.8	2.2	39	15	51	9	40	1.29
60-70	5.7	6.1	1.7	3.0	38	28	51	10	39	1.29
70-80	5.5	5.6	1.3	2.9	37	24	53	10	37	1.33
80-90	5.4	5.2	1.7	2.6	32	18	51	11	38	1.30
90-100	5.4	5.0	1.7	2.9	35	30	57	12	31	1.37
100-110	5.3	4.4	1.9	3.0	35	28	47	8	45	1.37
110-120	5.2	4.1	1.9	2.7	37	37	51	10	39	1.40
120-130	5.2	3.6	1.6	2.8	40	32	53	12	35	1.47
130-140	5.3	3.2	1.3	2.7	41	28	53	10	37	1.43
140-150	5.2	3.3	1.8	2.6	41	34	52	9	39	1.44
150-160	5.1	3.3	1.6	2.8	43	23	54	8	38	1.39
160-170	5.2	2.8	1.8	3.1	43	30	54	8	38	1.38
170-180	5.0	2.6	1.8	2.9	44	28	53	8	39	1.29
180-190	5.1	2.7	1.2	2.5	46	26	53	8	39	1.33
190-200	5.1	2.6	1.6	2.9	49	32	52	8	40	1.32

[a] Source: SADC-ICRAF, Makoka-Malawi data base reference no. MZ\21\95