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Water infiltration under different land use in miombo woodlands outside Morogoro, Tanzania

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Cover picture: Miombo woodland (Kitulangalo forest reserve, Tanzania).
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Abstract

Infiltration capacity is a measure of how much water that can enter the soil and hence become available to plant roots and micro organisms. A high infiltration capacity also means that less water is available for runoff and subsequent erosion. Infiltration capacity, bulk density and soil organic carbon content were measured in six land use types in miombo woodlands; natural forest, degraded forest, intensive agriculture, abandoned agriculture, degraded regenerating forest and *Albizia* plantation. The measurements were carried out in miombo woodlands about 50 km west of Morogoro, Tanzania. In the intensive agriculture and the abandoned agriculture the higher infiltration capacity was created by the mechanical disturbance and in the abandoned agricultural case also by the subsequent dense grass vegetation. The mechanical disturbance is, together with the presence of the tree roots, probably the cause of the high infiltration capacity in the *Albizia* plantation. Since the infiltration capacity increased after the establishment of an *Albizia* plantation, as well as the ability of the soil to receive high intensity rain increased when a degraded forest was left to regenerate and an *Albizia* plantation was established, this suggests that improved vegetation on a previously degraded land is positive. The mechanical disturbance created a low bulk density in the intensive agriculture and the abandoned agriculture; the dense grass may also have caused the bulk density in the abandoned agriculture to be the lowest of all land uses. Since a large number of measurements have been performed in this study it is also possible to estimate the variation within the land uses. The analysis showed that the variation within the intensive agriculture was significantly higher than in the natural forest, which may be a result of the mechanical disturbance in the intensive agriculture and a small variation in the natural forest.

Keywords*: miombo, land use, management, infiltration capacity, steady state infiltrability, bulk density, soil organic carbon, agriculture,* Albizia*, double-ring infiltrometer, wet combustion*

Sammanfattning

Infiltrationskapaciteten är ett mått på hur mycket vatten som kan tas upp av en jord och därmed bli tillgänglig för växtrötter och mikroorganismer. En god infiltrationskapacitet innebär därför att det finns mindre vatten kvar som kan orsaka ytavrinning och erosion. Infiltrationskapacitet, bulkdensitet och andel organiskt kol i marken mättes i sex markanvändningstyper: mindre störd skog, degenererad skog, intensivt jordbruk, övergivet jordbruk, degenererad återuppväxande skog samt *Albizia*-plantering. Mätningarna utfördes i miombo som är en tropisk torrskog, ca 50 km väster om Morogoro, Tanzania. Mekanisk bearbetning av jorden i det intensiva jordbruket och det övergivna jordbruket samt tätt, högväxande gräs i det övergivna jordbruket har skapat en hög infiltrationskapacitet i dessa markanvändningstyper. Den mekaniska bearbetningen av jorden är tillsammans med närvaron av trädrötter även troligtvis orsaken till den höga infiltrationskapaciteten i *Albizia*-planteringen. Då infiltrationskapaciteten var större i *Albizia*-planteringen än i den återuppväxande skogen, liksom jordens förmåga att ta emot regn av hög intensitet ökade efter att den degraderade skogen fick återuppväxa och då *Albizia* planterades, är det sannolikt att en ökad vegetation på tidigare degenererad mark är positiv. En låg bulkdensitet kan ha skapats i det intensiva jordbruket och det övergivna jordbruket på grund av den mekaniska bearbetningen av jorden. Det täta, högväxande gräset har även gjort att bulkdensiteten för det övergivna jordbruket är den lägsta. Då ett stort antal mätningar har genomförts har infiltrationskapacitetens variation inom markanvändningstyperna kunnat bedömas. Beräkningarna visade att variationen inom det intensiva jordbruket var större än variationen inom den mindre störda skogen, vilket kan bero på den mekaniska bearbetningen av jorden på det intensiva jordbruket och att variationen i den mindre störda skogen var mindre än förväntat.

Nyckelord: *miombo, markanvändning, skötsel, infiltrationskapacitet, steady state infiltrability, bulkdensitet, organiskt kol, jordbruk,* Albizia*, dubbelringinfiltrometer, våtoxidation*

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Introduction

Miombo woodlands are the largest tropical woodland in Africa and cover 2.8 million km^2 of the central and southern parts of the continent (Figure 1) (Frost, 1996) and is a part of the Zambezian phytoregion which extends over ten countries in southern Africa (White, 1983). Miombo woodlands occupy about 90 % of the forests and woodlands in Tanzania, corresponding to about 35 million ha (Campbell et al, 2007; Lulandala, 2007). The woodlands mainly consist of the genera *Brachystegia*, *Julbernardia* and *Isoberlinia* (Malaisse, 1978; Celander, 1983; White, 1983; Chidumayo, 1993; Chidumayo, 1995; Campbell et al, 2007; Lulandala, 2007) which are rarely found outside the miombo woodlands (Frost, 1996). Structurally, the woodlands have a single storey canopy layer with discontinuous understorey vegetation and grasses that can vary from dense to sparse and with fire as an important disturbance factor. The canopy coverage determines the height of the grass layer; common canopy coverage is 50 %, which enables the grass to grow to 2 m in height. Where the canopy coverage is higher, the grass layer will be shorter (Jeffers and Boaler, 1966).

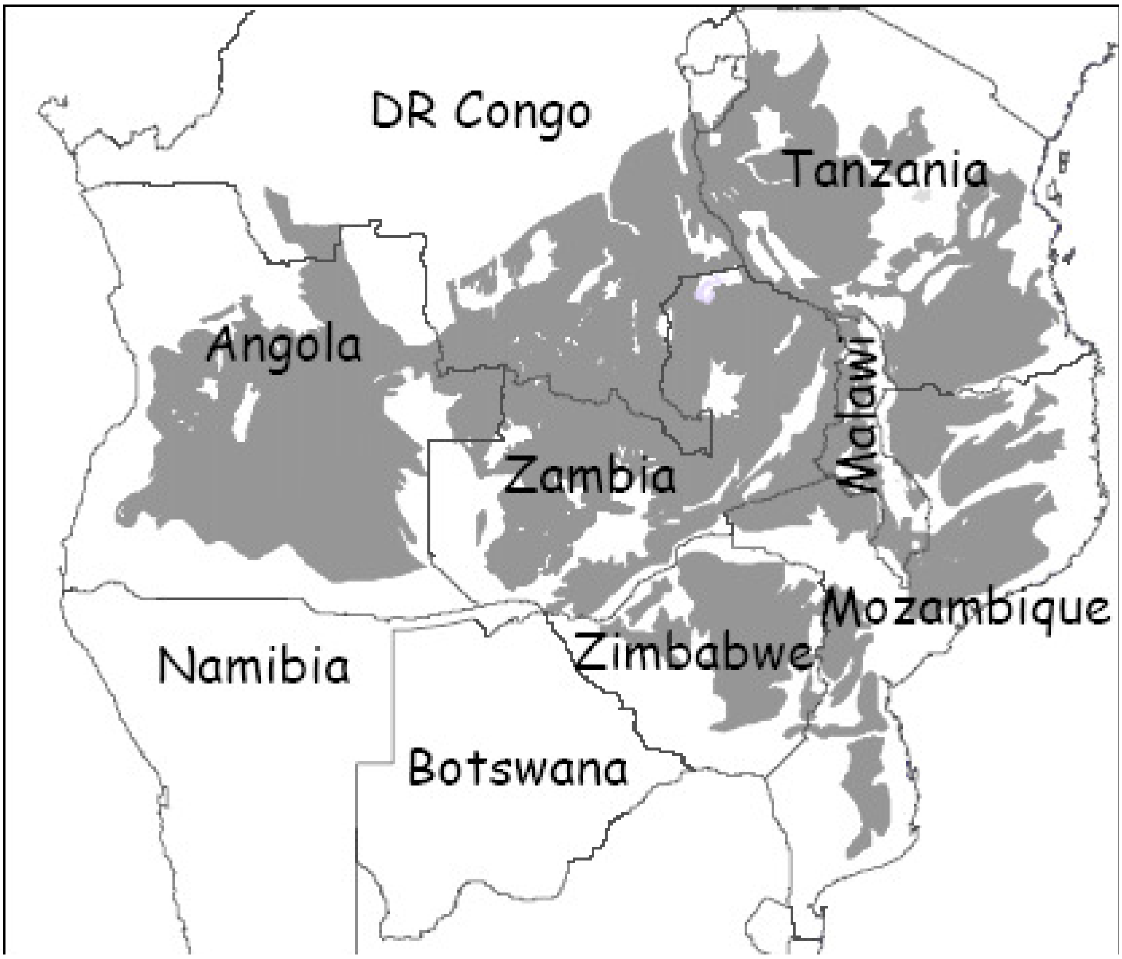

Figure 1. The distribution of the miombo woodlands. From Campbell et al, 2007.

The miombo woodlands are found on infertile soils in warm areas, 18-23 °C (Malaisse, 1978; Campbell et al, 1996; Lulandala, 2007) with an average temperature of approximately 20 ºC (Malaisse, 1978). Rainfall amounts are 700-1,400 mm during a 5-7 months wet season or seasons (Malaisse, 1978; Campbell et al, 1996; Lulandala, 2007) that extends over on average 118 days per year, one rainfall rarely exceeding 100 mm (Malaisse, 1978). The miombo woodlands are found from sea level to 1,600 m above sea level (Jeffers and Boaler, 1966). There are two types of miombo woodlands; the wetter miombo where average annual rainfall is above 1,000 mm and the drier miombo where annual rainfall is below 1,000 mm. The height of the woodland is above 15 m for wet miombo and below 15 m for dry miombo (White, 1983: Frost, 1996; Lulandala, 2007). Leaf felling occurs during August–October (Chidumayo, 1995) and over half the number of higher plants in the miombo woodlands are endemic (Rodgers et al, 1996).

More than 40 million people live in the miombo woodlands. The woodlands provides them with a variety of products, *e.g.* timber, fuel wood, medicines, mushrooms, fruits, honey, and game (Malaisse, 1978; Celander, 1983; Chidumayo, 1995; Desanker et al, 1995). The woodlands also act as hydrological control, erosion protection and climate regulation (Campbell et al, 1996). An additional 15 million people in cities depend on charcoal, fuel wood and food produced in miombo woodlands (Desanker et al, 1995).

For almost twenty years, the deforestation rate in Africa has been the highest in the world (FAO, 2007). During this time, the forests that cover 35 % of Tanzania (URT, 1998) have declined by around 1 % per year (FAO, 2007). The deforestation rate given by Moyo et al (1993) is between 300,000 and 400,000 ha per year, which is slightly below the number given by FAO (2007). Of the woodlands in Tanzania, over 40 % are protected and the rest are public land, the most of the public land being miombo woodlands. However, between 1964 and 1996, the woodland covered public lands in Tanzania declined by 50 % which corresponds to 1.6 % per year (Luoga et al, 2005).

Much of the miombo woodlands have been subjected to intensive use, so that there is very little unmodified miombo woodland remaining (Misana et al, 1996). The cutting of trees, mainly for charcoal and timber production as well as the need for agricultural land, is the main reason for the decline (Moyo et al, 1993; Misana et al, 1996; Campbell et al, 2007). Other reasons are grazing, brick making, fires, and the need for industrial wood as well as reducing the tse-tse fly infection of livestock and humans by clearing the vegetation in tse-tse fly habitats (Moyo et al, 1993). Nduwamungu (1996) estimated that 20 % of the largest trees were cut every year and if continued at the same rate, this could degrade all the miombo woodlands in a very short time, especially since the nutrient-poor soils causes a slow growth-rate (Campbell et al, 2007). Luoga et al (2002) also concludes that the present harvesting of trees in public miombo woodlands is unsustainable.

Soils of the miombo woodlands are usually poor with low cation exchange capacity and low contents of nitrogen and extractable phosphorous (Frost, 1996). Clearing of miombo woodlands probably has a decreasing effect on soil organic carbon, and when the clearing is followed by cultivation the amount of soil organic carbon is significantly decreased in most cases (Chidumayo and Kwibisa, 2003). The relatively poor soils are unsuitable for permanent agriculture and require a considerable vegetation cover to avoid erosion and degradation (Malaisse, 1978).

The miombo woodland soils may be stony, dominated by loamy sand, sandy loam, and sandy clay loam (Susswein et al, 2001), but is often clayish (Malaisse, 1978; Celander, 1983). They are also highly weathered and with a limited rooting depth because of stones, laterite, or gley horizons (White, 1983). The infiltration capacity is usually sufficient (Malaisse, 1978; Susswein et al, 2001) because of micro-aggregation of clay particles. Factors influencing the infiltration capacity are the amount of soil organic carbon, the soil surface structure as well as the plant and litter cover extent (Susswein et al, 2001). Too high clay content may, however, decrease the infiltration capacity and thereby increase surface runoff (Plantinga and Wu, 2003).

Planting trees in tropic agricultural land can two- to five-fold the infiltration capacity due to improvement of the soil physical properties (Ilstedt et al, 2007). Plantations of pine and eucalyptus in miombo woodlands in Zimbabwe have been shown to increase the soil organic carbon compared to grassland, although not to the levels that occur in the natural miombo woodlands (King and Campbell, 1994). Mapa (1995) showed that the infiltration capacity was larger in a teak plantation than in agricultural land, partly due to the larger amount of soil organic carbon in the teak plantation.

The infiltration capacity, the bulk density and the water holding capacity of the soil is related to the amount of soil organic carbon in the upper horizon litter layers (Susswein et al, 2001). A litter layer reduces overland flow by maintaining macroporosity which increases the infiltration capacity (van Noordwijk, 2003) and also protects the soil from splash erosion created by raindrops (Susswein et al, 2001). Fine textured soil generally contains more soil organic carbon than coarser soils (Anderson et al, 1981; Jobbágy and Jackson, 2000), although the texture alone leads to a decreased infiltration capacity (Plantinga and Wu, 2003).

When a forest is being cleared the amount of soil organic carbon has been found to decrease since the litterfall to the ground almost or completely stops. In combination with increased temperature (Allen, 1985; Sombroek et al, 1993), as well as increased aeration and moisture (Schlesinger, 1986) which increases the decomposition speed, clearing reduces the amount of soil organic carbon (Allen, 1985; Schlesinger, 1986; Sombroek et al, 1993). Decreased soil organic carbon may also be a result of increased decomposition and erosion (Tate, 1987; Sombroek et al, 1993) as well as interactions of the physical, chemical and biological processes in the soil (Solomon et al, 2000) and a reduction of the easily metabolized soil organic carbon (Tate, 1987).

When the soil is being cultivated, it often loses 20-40 % of its carbon to a depth of at least 30 cm, the largest part of the loss occurs within the first 5 years (Davison and Ackerman, 1993); Williams et al (2008) estimated the carbon losses to be 23 % at the same depth in miombo woodland. In some cases the topsoil organic carbon losses the first years after clearing can be as large as 54 % (Schlesinger, 1986) or 57 % (Tate, 1987). The soil organic carbon is important in the soil since it determines how easily nutrients, water, and air are being supplied (Dalal and Mayer, 1986; Sombroek et al, 1993; Mariscal et al, 2007). This is of particular importance in nutrient-poor soils (Walker and Desanker, 2004) such as the miombo woodland soils.

The total soil organic carbon pool changes more slowly with respect to difference in land use depending on the slow turnover rates. This is supported by Williams et al (2008) that found that in miombo woodland, the soil organic carbon content had not risen still 20-30 years after the agriculture was abandoned and the land was allowed to regenerate. Reduction of soil organic carbon in turn increases the bulk density of the soil (Allen, 1985), which is not unusual to rise during cultivation and forest clearance (Allen 1985; Davison and Ackerman, 1993; McDonald et al, 2002).

Soil organic carbon increases with increased amounts of clay and silt, the highest amounts of soil organic carbon are found in low-density soils with high clay content (Walker and Desanker, 2004). Chidumayo (1993) reported the amount of soil organic carbon to be 1.94-3.76 % in the top 10 cm and Desanker et al (1995) reported a value of 1.40 % in the A-horizon, both in miombo soils. In the tropics, the soils usually have a low amount of soil organic carbon, even in the topsoil, which is often dominated by coarse materials (Salako, 2001). The soil organic carbon has been shown to decrease when the miombo woodland becomes less dense (Kirchmann and Eklund, 1994).

The aim of this study is to examine whether the infiltration capacity, the bulk density and the soil organic carbon content varies when the land use changes from natural miombo woodland to degraded forest, intensive agriculture, abandoned agriculture, and then back towards a more continuous forest cover in degraded regenerating forest and *Albizia* plantation.

Material and methods

The study was performed at six land uses approximately 50 km east of Morogoro, Tanzania.

The area

Air temperature was 18-33 ºC and precipitation 880 mm during 2007 (Tanzania Meteorological Agency, 2008). The type of miombo woodland in this area is the dry miombo woodland (Lulanadala, *pers comm.,* 2008). Msanya et al (1995) determined the soil types as Lixisol, Cambisol, and Phaeozem and the soil textures has been identified as sandy loam, sandy clay loam, and sandy clay by Msanya et al (1995) and Nduwamungu (1996). The bulk density of the area was determined as 1.1-1.6 g/cm^3 in the top 20 cm and the soil organic carbon content in the topsoil to 0.41-3.14 % (Msanya et al, 1995). Also, the area is being regularly affected by fire (Lovett and Pócs, 1993). Dominating species are *Julbenardia globiflora, Brachystegia spp.* and *Pterocarpus rotundifolia* as overstorey vegetation, *e.g. Diplorhynchus candylocarpon, Combretum zeyheri, C. apiculatum* as understorey vegetation and *Themeda triandra* grass (Zahabu, 2001).

The land uses

Inside the Kitulangalo forest reserve is the natural forest land use, whereas the other land uses are outside the reserve, but within 10 km distance from the Kitulangalo forest reserve.

1. Natural forest

The natural forest is found within the Kitulangalo forest reserve (Figure 2), which has been protected by the Tanzanian government since 1955, covering an area of 2,637.8 ha (Lovett and Pócs, 1993). Until 1985 the reserve was a productive reserve, where it was possible to get license to cut trees (Luoga et al, 2005). The Kitulangalo forest reserve nowadays consists of around 2,000 ha after allocation of about 600 ha to Sokoine University of Agriculture (SUA) in 1995 (Malimbwi and Mugasha, 2001), thereby creating the Kitulangalo SUA Training Forest Reserve. Two guards were employed to prevent illegal cutting which is prohibited in the reserve (Zahabu, 2001), and after the guards were employed the illegal cutting decreased. However, some illegal cutting still exists and the forest is also grazed by cattle, sheep, goats and some donkeys (Menduwa, *pers comm.*, 2008). Vegetation coverage was 20 % trees, 25 % bushes and 55 % grass with a crown coverage of 60 %. Soil texture was determined as clay with patches of sand in the surface.

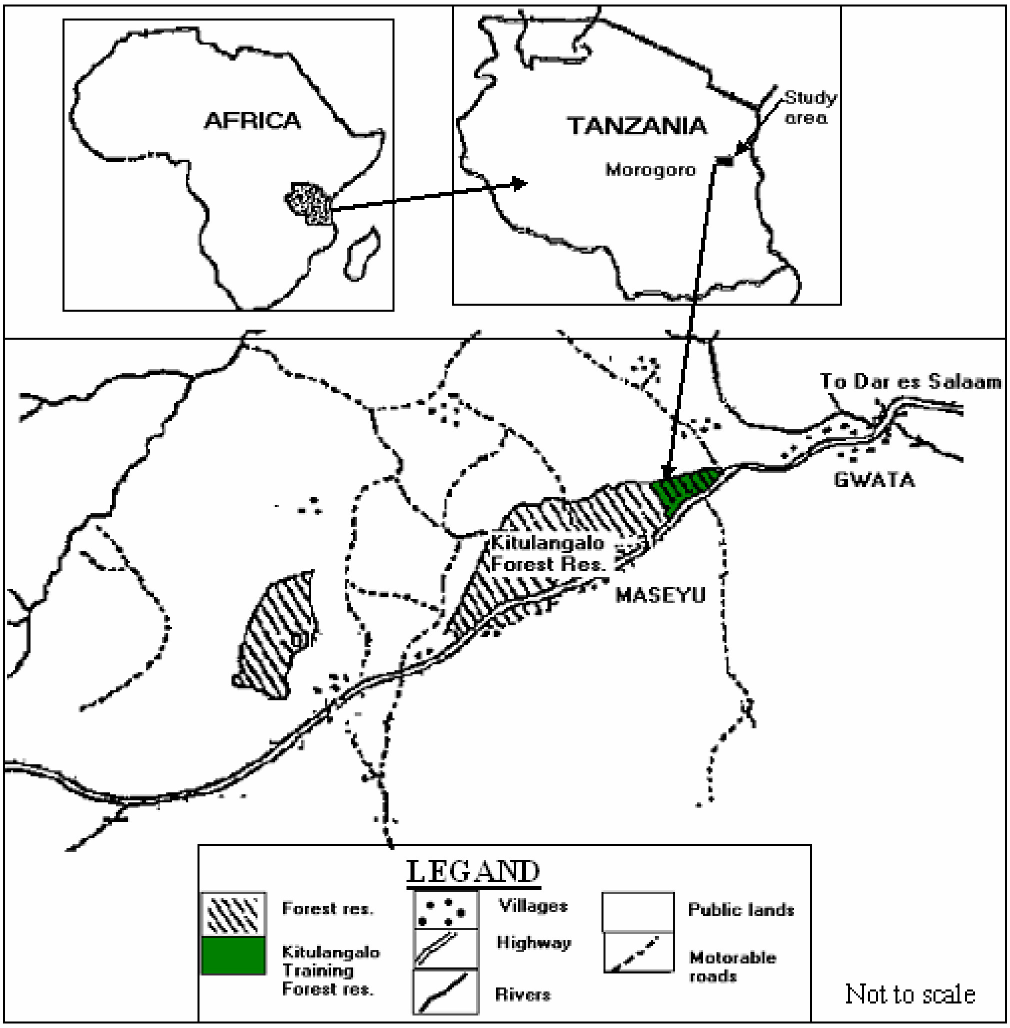

Figure 2. The location of the Kitulangalo forest reserve. From Zahabu, 2001.

2. Degraded forest

In the degraded forest area the miombo woodlands started to be cut by the public for fuel and charcoal production after the creation of the Kitulangalo forest reserve in 1955 (Hussein, *pers comm.*, 2008). The vegetation coverage was determined as 20 % bushes and 80 % grass with a soil texture of sandy clay.

3. Intensive agriculture

The intensive agriculture was cultivated for the fifth year with millet (*Pennisetum glaucum*) and simsim (*Sesamum indicum*) as crops. Neither fertilizers nor manure have been used but there have been burning of plant residues in the fields. The mechanical treatment of the soil is performed by hand. Before the cultivation started the area was covered by miombo woodlands until the Kitulangalo forest reserve was created. The area was then cut and left at a degraded state for 48 years until the agriculture began (Hussein, *pers comm.*, 2008). A part of the area was planted with millet and the soil texture was sandy clay.

4. Abandoned agriculture

In the abandoned agriculture the history is the same as for the intensive agriculture, although the area was abandoned in 2007 after five years of cultivation (Hussein, *pers comm.*, 2008). The abandoned agriculture now has a vegetation cover mainly consisting of high, dense grass, 80 %, with 20 % bushes and a soil texture of sandy clay.

5. Degraded regenerating forest

Cutting in the degraded regenerating forest area started when a part of the Kitulangalo forest reserve was taken over by SUA in 1995. When the village government of Maseyu took over the management of the general land that belonged to the village in 2003, the cutting for firewood and charcoal stopped and the forest was left to regenerate (Vyamana, *pers comm.,* 2008). The vegetation coverage was determined as 10 % trees, 20 % bushes and 70 % grass with a crown coverage of 20 %. Soil texture was determined as sandy clay.

6. *Albizia* plantation

The cutting of trees for firewood and charcoal production in this area also started in 1995 when a part of the Kitulangalo forest reserve was taken over by SUA. In 2003, a plantation of *Albizia vesicolor* was established. Prior to the plantation of trees, the land was plowed once with a tractor (Vyamana, *pers comm.,* 2008). The area has a vegetation cover of 5 % trees, 15 % bushes, 80 % grass and the soil texture is sandy clay.

Methods

Infiltration refers to the vertical percolation of water into a soil (Landon, 1991) and infiltration capacity measurements were performed in accordance with the widely used double-ring infiltration methodology (Wood, 1977; Malmer and Grip, 1990; Mapa, 1995; Lal, 1996). Water was poured into two rings inserted into the soil, the outer ring 30 cm and the inner ring 20 centimetres in diameter. In the inner ring, the water table was measured for four minutes every twenty minutes during three hours. The theory is that the outer ring ensures that all the divergent water movements are taking place within that ring, and the water level is therefore only measured in the inner ring where the infiltration is vertical (Bouwer, 1986; Brady and Weil, 2002). Lateral movement of water is considerably less, and therefore also the error, if a double-ring infiltrometer is used instead of a single-ring infiltrometer (Landon, 1991; Chowdary et al, 2006). The infiltration rate in the inner ring decreases with time to stabilize at the soils' minimum infiltration rate's (Bouwer, 1963).

A constant head of four centimetres of water were held in the rings during the measurements. Measurements were made at eight plots per land use and six replicates per plot. The plots were randomly selected within the land uses and the infiltration rings were placed in a 20*30 m plot with ten metres between each pair of rings and ten metres between the two rings in one pair (Figure 3).

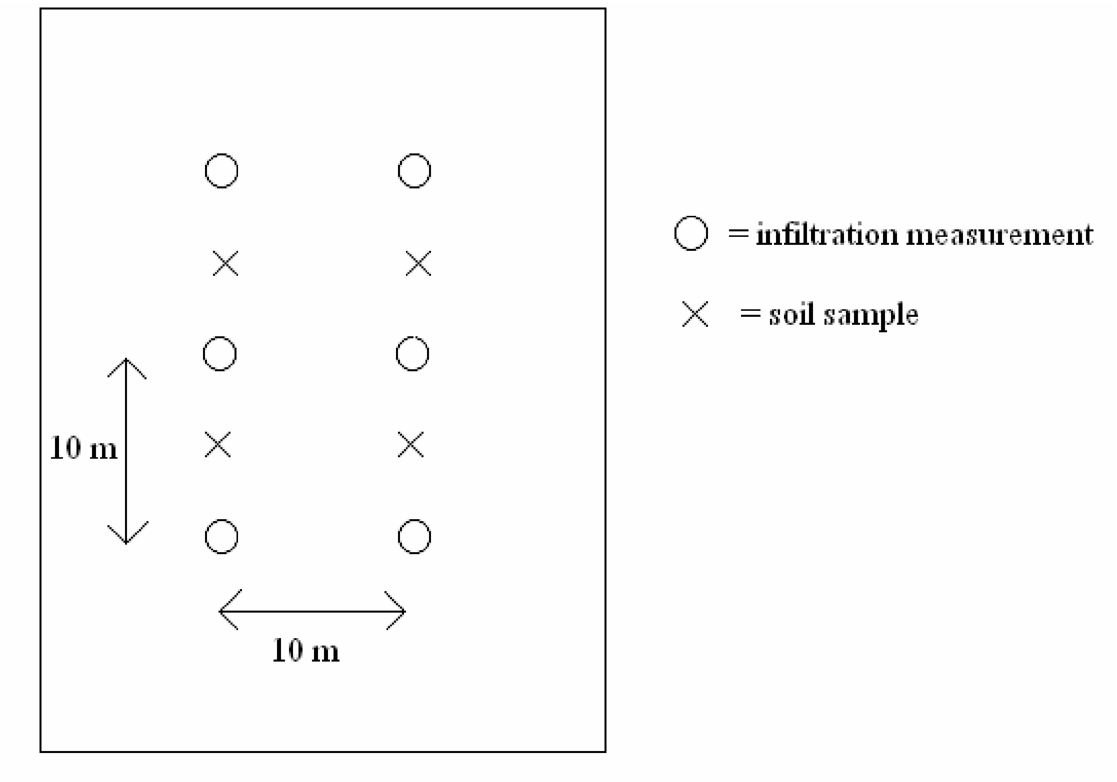

Figure 3. Schematic image over the plot settings.

Undisturbed soil samples were taken at four places per plot (Figure 3) in the top 5 centimetres, the soil sample being 5 cm in diameter. The soil samples were analyzed for water content, bulk density (dried in 105 °C) and soil organic carbon content. For the soil organic carbon content analysis the Walkley and Black method was used, which oxidizes the soil organic carbon during wet combustion (Black et al, 1965). Anderson et al (1981) used the same method for soil organic carbon analysis as well as Allen (1985), Dalal and Mayer (1986), Chidumayo (1993), King and Campbell (1994), Kirchmann and Eklund, (1994) Msanya et al (1995) and Chidumayo and Kwibisa (2003).

The steady state infiltrability was calculated using the equation (Equation 1, Equation 2) developed by Philip (1957)

$$I = st^{1/2} + At \tag{1}$$

$$I = \frac{\partial I}{\partial t} = \frac{s}{2} t^{-1/2} + A \tag{2}$$

where *i* is the infiltration rate at time *t*, *s* is the sorptivity of the soil and *A* is the transmissivity of the soil. The constants i_c and s were solved using the Excel Solver.. Philip's equation has also been used by Lal (1996), Salako and Kirchhof (2003) as well as Zomboudré et al (*submitted manuscript*).

For all land uses, steady state infiltrability, bulk density, and soil organic carbon content were measured and calculated. Standard deviation (SD) of the mean values and coefficient of variation (CV) were calculated for each parameter. CV (%) is a measurement of a proportion of the average value in percent, so that it is possible to compare values of different size and is calculated by using the standard deviation values. Percentages of the Philip's equation values equal to or above 40 mm/h were also calculated (Zomboudré et al, *submitted manuscript*). Statistical analysis was performed in SPSS 16.0 using one-way ANOVA and Tukey's test and statistical significance refers to the 5 % confidence level.

Results

The steady state infiltrability measurements (Figure 4, Table 1, Appendix 1) show that the steady state infiltrability was significantly larger in the abandoned agriculture than in the natural forest as well as in the degraded regenerating forest and in the degraded forest. The lowest steady state infiltrability was measured in the degraded forest which is significantly lower than the intensive agriculture and the *Albizia* plantation as well as the abandoned agriculture. The highest steady state infiltrabilities were measured in the abandoned agriculture followed by the *Albizia* plantation and the intensive agriculture.

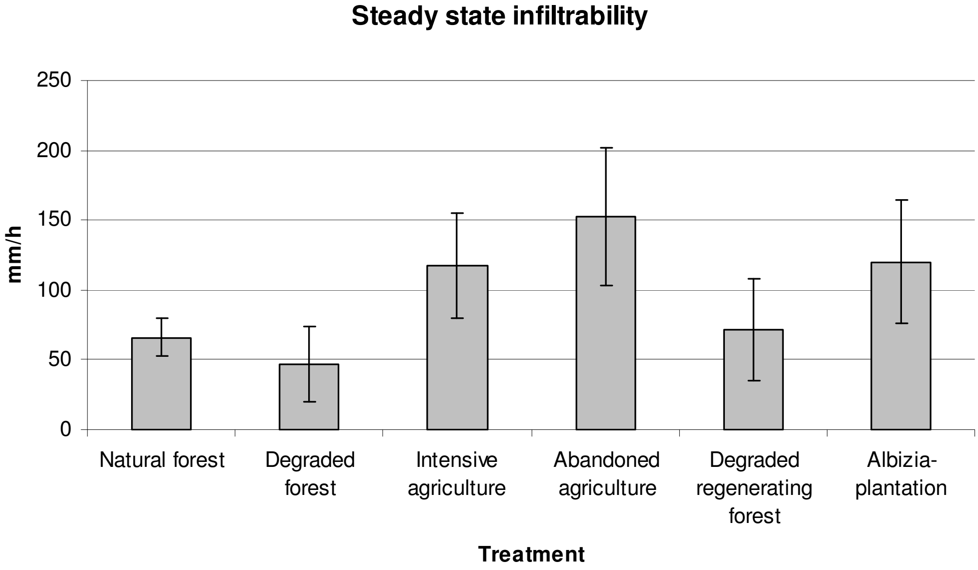

Figure 4. Measured steady state infiltrability (mm/h) for each land use. The error bars represent SD.

Table 1. The significant differences (*) in steady state infiltrability (mm/h).

	Natural forest	**Degraded forest**	**Intensive agriculture**	**Abandoned agriculture**	**Degraded regenerating forest**	***Albizia*-plantation**
Natural forest	-			*		
Degraded forest		-	*	*		*
Intensive agriculture		*	-			
Abandoned agriculture	*	*		-	*	
Degraded regenerating forest				*	-	
***Albizia*-plantation**		*				-

Among the land uses, the variation in steady state infiltrability within each land use was significantly differentiated only between the natural forest and the intensive agriculture, where the natural forest had a lower variation in steady state infiltrability than the intensive agriculture.

The natural forest had the highest bulk density (Figure 5, Table 2, Appendix 2), followed by the degraded regenerating forest and the *Albizia* plantation. However, these land uses were not significantly differentiated from each other. In the degraded forest a significantly higher bulk density was found than in the intensive agriculture and the abandoned agriculture. The degraded forest is also significantly lower in bulk density than the natural forest and the degraded regenerating forest. In the abandoned agriculture the lowest bulk density is found, the second lowest is the intensive agriculture. The two intensive agriculture and the abandoned agriculture are each significant different from all other land uses.

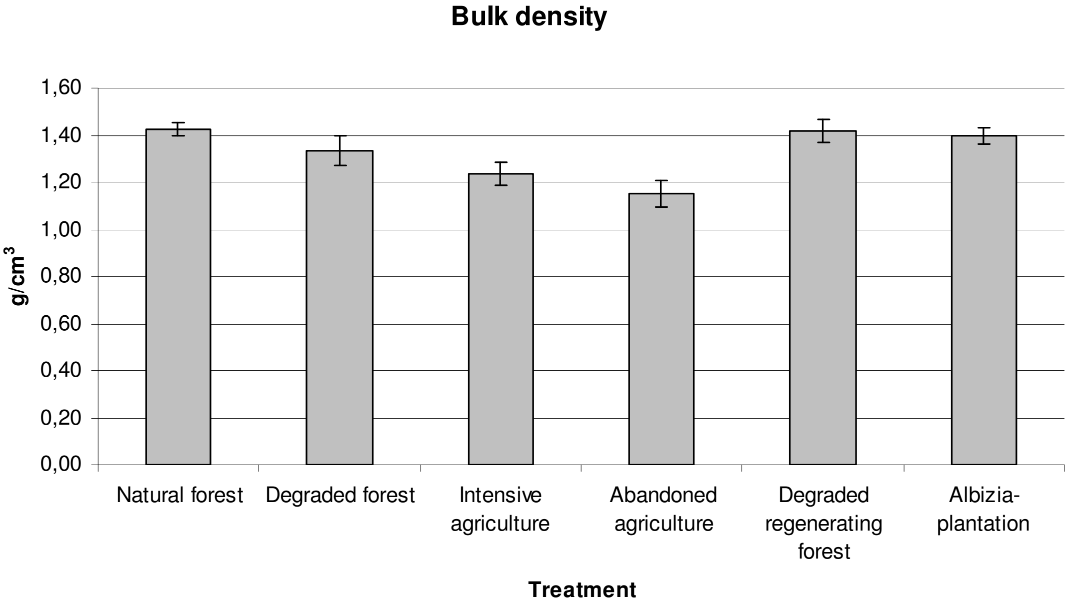

Figure 5. Measured bulk density (g/cm^3) for each land use. The error bars represent SD.

Table 2. The significant differences (*) in bulk density (g/cm^3).

	Natural forest	**Degraded forest**	**Intensive agriculture**	**Abandoned agriculture**	**Degraded regenerating forest**	***Albizia* plantation**
Natural forest	-	*	*	*		
Degraded forest	*	-	*	*	*	
Intensive agriculture	*	*	-	*	*	*
Abandoned agriculture	*	*	*	-	*	*
Degraded regenerating forest		*	*	*	-	
***Albizia* plantation**			*	*		

Soil organic carbon content (Figure 6, Table 3, Appendix 3) was highest at the intensive agriculture, which was significantly higher than at all the other land uses.

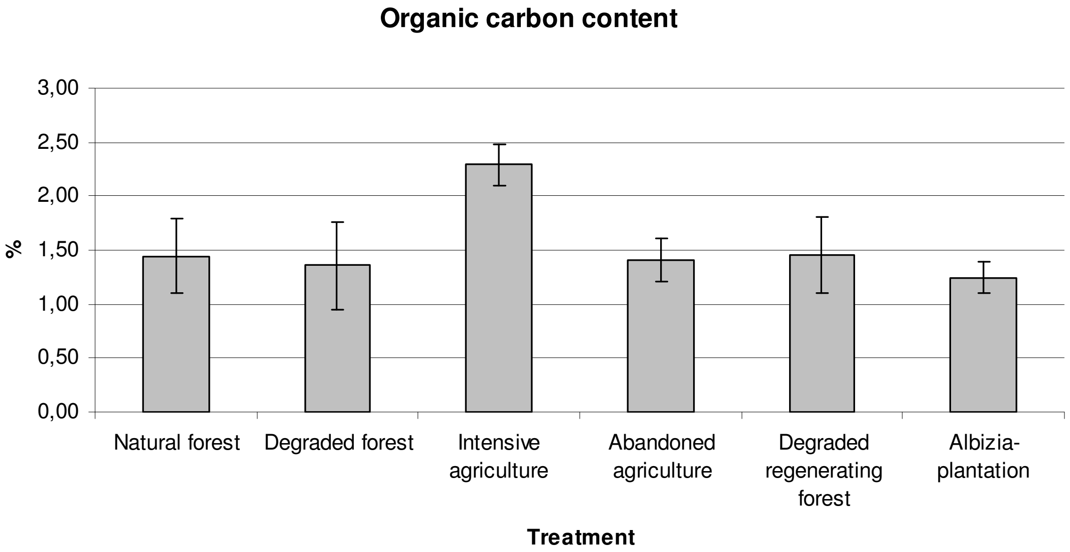

Figure 6. Measured soil organic carbon content (%) for each land use. The error bars represent SD.

Table 3. The significant differences (*) in organic carbon content (%).

	Natural forest	**Degraded forest**	**Intensive agriculture**	**Abandoned agriculture**	**Degraded regenerating forest**	***Albizia* plantation**
Natural forest	-		*			
Degraded forest		-	*			
Intensive agriculture	*	*	-	*	*	*
Abandoned agriculture			*	-		
Degraded regenerating forest			*		-	
***Albizia* plantation**			*			-

Within the land uses, the variation (Figure 7), expressed as CV, was generally high. For both the steady state infiltrability and the bulk density measurements, the CV of the natural forest was the lowest of all the land uses. Within the organic carbon content, the intensive agriculture, the abandoned agriculture and the *Albizia* plantation had a lower variation than the natural forest.

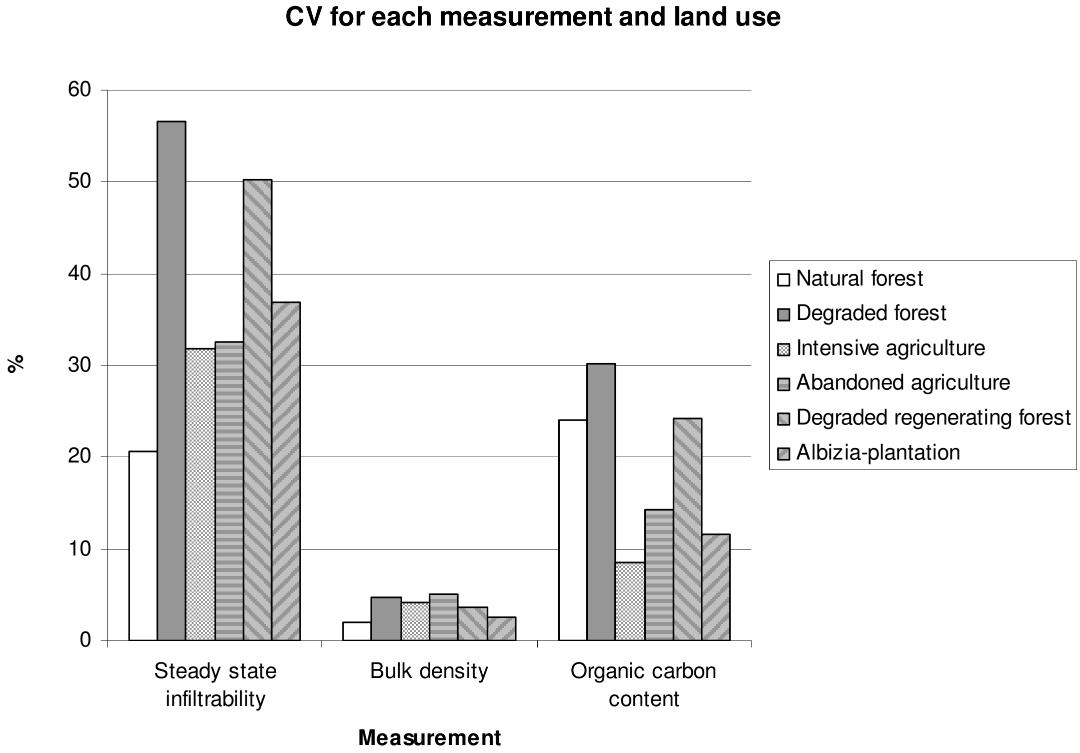

Figure 7. CV (%) for the bulk density, the soil organic carbon content and the steady state infiltrability for the different land uses.

The proportion of the measured steady state infiltrability values (Figure 8) that are at least 40 mm/h were above 80 % in the abandoned agriculture, the natural forest, the intensive agriculture and the *Albizia* plantation (100 %). However, it was below 70 % in the degraded regenerating forest and below 50 % in the degraded forest.

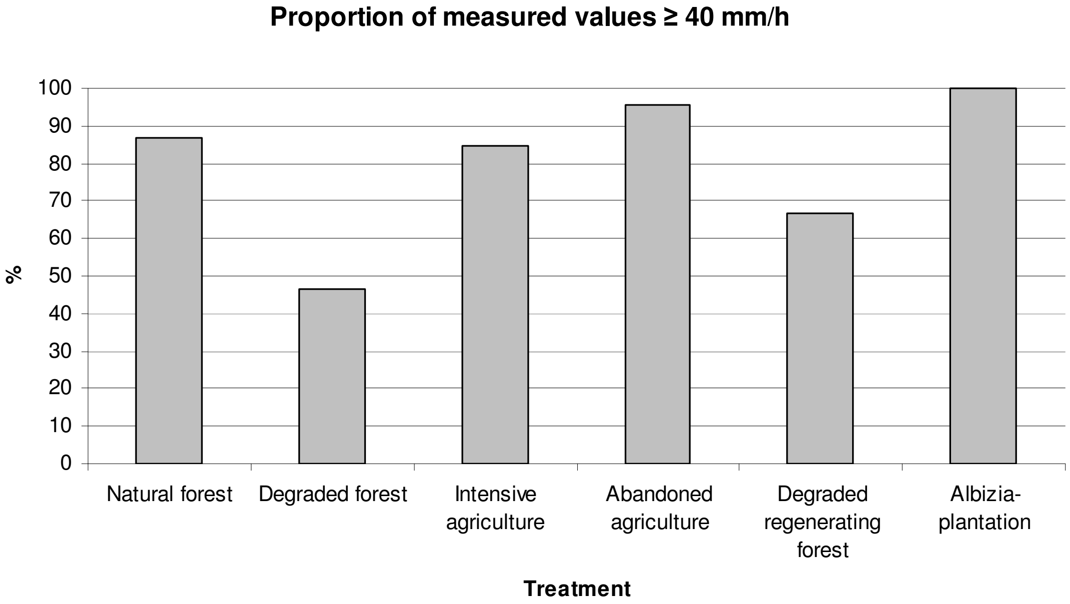

Figure 8. The proportion (%) of the measured steady state infiltrability values per land use that is equal or larger than 40 mm/h.

Discussion

The high steady state infiltrability (Figure 4) in the intensive agriculture (118 mm/h), the abandoned agriculture (153 mm/h) and the *Albizia* plantation (120 mm/h) may be a cause of mechanical disturbance of the soil. One reason in may the intensive agriculture and the abandoned agriculture be that a soil crust that reduces the steady state infiltrability (Mapa, 1995) has not been created. In the abandoned agriculture also the effect of the high grass now growing there can be a reason for the high steady state infiltrability.

In the *Albizia* plantation the high steady state infiltrability may be an effect from plowing before the trees were planted as well as the presence of tree roots that increases the soil organic carbon and also improves the steady state infiltrability by root channels through which water can infiltrate into the soil (van Noordwijk et al, 2004). Breaking up a soil crust that was created during the degraded state of the forest could also be a reason for the high steady state infiltrability. The lowest steady state infiltrability was measured in the degraded forest (47 mm/h) and was lower, although not significantly, than in the natural forest (66 mm/h) and the degraded regenerating forest (72 mm/h), probably as a cause of at least partial soil crusting and erosion of some topsoil material. Furthermore, the steady state infiltrability rates in the degraded regenerating forest and the *Albizia* plantation suggest that a regrowth of the forest increases the steady state infiltrability at least to the level that occurred before the degradation.

The high number of steady state infiltrability measurements per land use (48) allows an evaluation and a comparison of the steady state infiltrability variations within land uses. Other authors have done 10 (Malmer and Grip, 1990; Lal, 1996) or 15 measurements per land use (Mapa, 1995) as the most. The variation within the intensive agriculture and the abandoned agriculture can be explained by the mechanical disturbance of the soil during agriculture which created a high heterogeneity that is also caused by the grass roots in the abandoned agriculture. In the *Albizia* plantation, the heterogeneity may be due to the plowing prior to the plantation of the trees and to water following roots and root channels when infiltrating (van Noordwijk et al, 2004). The variation in the degraded forest may be explained by the large number of small values, since the variation is larger than in the natural forest and the average steady state infiltrability value is lower, *i.e.* a large proportion of the soil in the degraded forest have steady state infiltrabilities close to zero, which results in an increased risk of runoff and erosion (Zomboudré et al, *submitted manuscript*). In the natural forest and the degraded regenerating forest the variation is caused by the bushes and the trees that are growing there and causing heterogeneity with their roots (van Noordwijk et al, 2004). However, in this case, the variation within the natural forest was smaller than expected.

Although the amount of steady state infiltrability measurements is large, a significant difference of the variation within the land uses could only be found in one case, between the natural forest and the intensive agriculture. One reason for this could be that the mechanical disturbance of the soil in the intensive agriculture has created a large variation in steady state infiltrability and at the same time the spatial heterogeneity in the forest was smaller than expected. However, there is also a large natural variation within the field (Reynolds et al, 2002) which makes it difficult to statistically separate the variation within different land uses. Therefore, to obtain clearer results even more measurements need to be made since the natural variation in steady state infiltrability is so high.

The bulk density (Figure 5) measured in the natural forest (1.45 g/cm^3) is within the range of 1.1-1.6 g/cm^3 reported from Kitulangalo Forest Reserve Area by Msanya (1995), and close to the 1.29 g/cm^3 reported from miombo woodlands by King and Campbell (1994). Also the bulk density values of the degraded forest (1.33 g/cm^3), the degraded regenerating forest (1.42 g/cm^3) and the *Albizia* plantation (1.40 g/cm^3) are within the range of the values presented by Msanya (1995) but higher than the range from miombo woodlands presented by Walker and Desanker (2004) (1.08-1.30 g/cm^3). In the abandoned agriculture the bulk density (1.15 g/cm^3) was significantly lower than in the intensive agriculture (1.23 g/cm^3). However, the bulk density of the intensive agriculture is within the same range as the bulk density in miombo woodlands agriculture presented by Walker and Desanker (2004) (1.18-1.44 g/cm^3). The low bulk density in the agricultural land uses can be a cause of the mechanical disturbance of the soil, together with the short time after abandonment and the high grass now growing at the abandoned agriculture which further lowered the bulk density.

There is a significant decrease in bulk density from 1.45 g/cm^3 in the natural forest to 1.23 g/cm^3 in the intensive agriculture, which may be a result of the mechanic disturbance of the soil as well as the lack of crusting in the intensive agriculture. These results are inconsistent with the results of Lal (1996) that suggests the topsoil bulk density rises when a forest is cleared and the land is being used for agriculture. Wood (1977), as well as King and Campbell (1994) who have studied miombo woodlands, found that the bulk density increases with conversion from natural forest to agriculture. However, Walker and Desanker (2004) did not find any significant differences between the bulk density of the miombo woodlands and the agriculture.

The soil organic carbon content in the natural forest (1.44 %) and the degraded regenerating forest (1.49 %) presented here is close to the 1.40 % in miombo soils reported by Desanker et al (1995). It is also within the ranges of 0.41-3.14 % and 1.26-3.36 % that has been reported by Msanya et al (1995) and Walker and Desanker (2004), both in miombo woodlands. However, it is lower than the 1.94-3.76 % from dry miombo woodland presented by Chidumayo (1993). The organic carbon content in the *Albizia* plantation (1.24 %) and the degraded forest (1.36 %) are in the same range as the values presented by King and Campbell (1994) that reported 0.62-1.02 % in plantations and 1.04-1.62 % in a degraded forest in miombo woodland, and are not significantly different from the natural forest.

Since there has been neither fertilizer nor manure added to the intensive agriculture and the abandoned agriculture, the significantly higher soil organic carbon content in the intensive agriculture (2.29 %) than in all the other land uses is in contrary to the expectations. The elevated amounts are inconsistent with the results from miombo woodlands presented by Walker and Desanker (2004) who found that the carbon content was 0.87 % in an agricultural field. King and Campbell (1994) presented a value of 0.47 % in agriculture in miombo woodland, a result that is close to the soil organic carbon content measured in the abandoned agriculture (1.40 %). The reason for the high soil organic carbon content in the intensive agriculture may be that there is decomposing soil organic material as well as coal residues from the burning of organic plant residues in the field. Another reason could be that the intensive agriculture as well as the abandoned agriculture consists of a different soil type than the other land uses. If this soil type contains more soil organic carbon than the soil type in the other land uses, the intensive agriculture could be in the upper range and the abandoned agriculture in the lower range of the soil organic carbon content in that soil type. This could also explain the abandonment of the abandoned agriculture, since a lower soil organic carbon results in a lower nutrient status of the soil and therefore a lower crop yield.

The soil organic carbon content has been shown to increase with time after abandonment of agriculture in miombo woodlands (Williams et al, 2008). However, Walker and Desanker (2004) did not find any evidence of the soil organic carbon content rising after abandonment of agriculture in miombo woodlands. This is also contradictory to the results presented here, which showed a significant decrease in soil organic carbon content after abandonment. One reason for this may be the result of decomposition of soil organic material and the coal residues from burning of organic plant residues that the carbon content in the intensive agricultural plot high. The natural forest and the abandoned agriculture have significantly lower soil organic carbon content levels than the intensive agriculture, but are not different from each other, which suggests that the proposed reason for the high soil organic carbon content in the intensive agriculture is for some reason no longer present in the abandoned agriculture. One reason could also be that the intensive agriculture naturally is in the higher range of the soil organic carbon content than the abandoned agriculture.

The CV's (Figure 7) for the steady state infiltrabilities are high and the highest values are found in the degraded forest and the degraded regenerating forest since those treatments had many small- and zero measured values. For the bulk density, CV (Figure 7) is low for all land uses, with only a small variation between the land uses which is an indication of low variation and precise measurements.

A soils' vulnerability to erosion can be expressed as the proportion of the measured steady state infiltrability values that are equal to or exceed 40 mm/h, a rain intensity that is common in this area. The rain that is not infiltrating will form runoff on the surface and thereby create erosion. Therefore, the more rain that falls with an intensity of at least 40 mm/h that can infiltrate into the soil, the lesser the risk for erosion. The results presented here (Figure 8) shows that the land uses that are most susceptible to runoff are the degraded forest (47 %) and the degraded regenerating forest (67 %). This is probably a cause of the many zero and low-measured values in those two land uses as well as the partial crusting and erosion of some topsoil material (Mapa, 1995) in the degraded forest that lowers the capacity of the soil to receive water. However, the degraded regenerating forest has a larger proportion of the values equal to or lager than 40 mm/h than the degraded forest although not as large as the natural forest (87 %). This implies that when the vegetation of a prior degraded forest is improving the risk of surface runoff and erosion will decrease.

What can be seen from the results presented here is that the steady state infiltrability (Figure 4) in the natural forest and the degraded regenerating forest are larger, although not significantly larger, than the degraded forest. The steady state infiltrability increases significantly when an *Albizia* plantation is established compared to the degraded forest. This implies that planting trees or allowing the degenerated forest to grow back is positive considering the steady state infiltrability and is an indication that the steady state infiltrability can be restored to the levels prior to the degradation when a forest is allowed to grow back.

It can also be added that the regeneration of the forest started when the village government took over the management of the land that belonged to the village. This therefore seems to be one way to allow regeneration of degraded land so that the forest can be used sustainable in the future.

The double-ring infiltrometer is highly varying measuring method; however, the very high number of steady state infiltrability measurements in this study made it possible to assess the variation within the land uses (Figure 7). The fact that there was only one significant variation within the land uses which suggests that the variation is naturally large.

There is a large lack of studies regarding infiltration capacity, bulk density, and soil organic carbon in miombo woodlands, especially when combining several land use types. Usually, the studies are regarding agriculture (Chidumayo, 1993; King and Campbell, 1994; Kirchmann and Eklund, 1994; Msanya et al, 1995; Walker and Desanker, 2004; Williams et al, 2008) or tree plantation (King and Campbell, 1994). However, King and Campbell (1994) as well as Walker and Desanker (2004) have studied more than two land use types, although none of these studies is concerning the infiltration capacity. More research is needed since the miombo woodlands are being rapidly deforested and it is therefore important to know how the infiltration capacity, the bulk density, and the soil organic carbon content changes with changed land use so that is will be possible to preserve and sustainably use the miombo woodlands in the future.

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Appendix 1

Data for the steady state infiltrability measurements.

Table 4. Measured infiltration values from the natural forest. The difference in water levels (mm) for each measuring period (min).

Plot 1	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	5	7	5	7	4	4	6	5
Ring 2	5	13	8	5	5	6	6	8
Ring 3	20	5	8		7	15	0	6
Ring 4	8	7	7		8	5	10	7
Ring 5	5	14	11	19	7	9	6	
Ring 6	14	3			8	4	1	

Plot 2	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	5	3	2	12	3	5	7	1
Ring 2	4	2	6	6	8	3	4	3
Ring 3	2	9	8	2	6	5	5	4
Ring 4	4	6	5	5	4	3	2	3
Ring 5	5	7	4	4	3	5	6	3
Ring 6	5	15	11	5	8	10	3	6

Plot 3	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	4	13	14	7	5	4	5	3
Ring 2	9	9	5	8	5	6	5	3
Ring 3	1	8	11	5	18	6	3	5
Ring 4	22	15	7	14	4	6	8	4
Ring 5	36	24	10	16	17	3	15	5
Ring 6	10	15	8	4	6	5	9	5

Plot 4	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	14	21	17	14	8	10	13	10
Ring 2	4	5	10	3	6	6	5	6
Ring 3	7	9	8	5	12	6	6	2
Ring 4	13	17	10	9	7	8	9	9
Ring 5	8	6	6	8	3	6	7	5
Ring 6	3	10	20	5	6	6	4	4

Plot 5	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	14	11	9	7	6	7	6	7
Ring 2	6	11	5	9	3	7	8	6
Ring 3	8	6	8	5	5	9	5	
Ring 4	4	5	3	3	3	1	1	1
Ring 5	9	7	7	7	5	5	6	6
Ring 6	5	4	4	6	5	1	6	5

Plot 6	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	8	5	5	4	4	6	6	5
Ring 2	13	15	13	10	3	10	5	12
Ring 3	5	6	4	5	6	3	2	2
Ring 4	8	8	11	5	11	10	7	2
Ring 5	6	9	4	3	10	4	3	5
Ring 6	7	8	11	6	3	8	3	6

Plot 7	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	5	8	7	5	7		7	5
Ring 2	11	6	7	5	6		3	6
Ring 3	11	9	8	8	7	5	6	3
Ring 4	12	11	11	8	10	9	10	10
Ring 5	4	9	7	7	6	10	6	5
Ring 6	7	7		5	5	0	4	2

Plot 8	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	4	6	3	5	7	5	3	6
Ring 2	3	4	4	3	2	7	5	2
Ring 3	8	4	4	2	2	4	3	4
Ring 4	3	4	3	2	4	4	4	4
Ring 5	3	2	5	4	2	3	1	4
Ring 6	4	3	3	6	4	9	15	3

Table 5. Measured infiltration values from the degraded forest. The difference in water levels (mm) for each measuring period (min).

Plot 1	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	8	3	3	8	4	1	6	5
Ring 2	2	1	1	1	0	0	2	2
Ring 3	6	4	6	6	5		3	4
Ring 4	0	0	2	1	1	0	1	1
Ring 5	2	1	4	1	0	0	1	0
Ring 6			1	1	2	2	2	1

Plot 2	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	6	15	9	5	9	4	3	5
Ring 2	12	22	6	21	13	10	4	10
Ring 3	4	3	4	3	2	9	2	3
Ring 4	6	8	18	7	5	2	2	2
Ring 5	10	15	14	13	10	9	9	6
Ring 6	5	3	3	3	2	5	3	2

Plot 3	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	6	8	6	6	5	3	4	3
Ring 2	3	2	1	3	2	2	3	2
Ring 3	1	0	0	1	1	3	0	0
Ring 4	0	1	0	1	1	0	0	0
Ring 5	0	4		3	4		1	1
Ring 6	1	2		1	2	0	1	2

Plot 4	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	11	6	6	3	9	2	5	2
Ring 2	18	7	5	6	4	12	6	7
Ring 3	10	5	10	10	7	7	4	4
Ring 4	6	5	6	6	13	3	5	9
Ring 5	1	6	4	3	6	8	8	5
Ring 6	6	4	4	2	2	8	2	4

Plot 5	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	4	3	1	1	0	1	0	0
Ring 2	9	1	0	2	2	2	2	1
Ring 3	6	2	2	0	2	2	2	3
Ring 4	6	2	2	1	1	2	2	3
Ring 5	3	0	1	1	1	2	2	2
Ring 6	6	2	1	2	3	2	3	3

Plot 6	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	6	4	6	2	4	3	7	3
Ring 2	18	10	11	11	6	7	7	2
Ring 3	11	3	4	8	6	3	7	7
Ring 4	8	3	7	5	3	5	4	5
Ring 5	9	8	10	5	10	13	2	3
Ring 6	5	6	3	13	9	6	3	2

Plot 7	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	1	1	1	0	0	1		3
Ring 2	0	1	0	1	0	1	0	2
Ring 3	0	0	0	1	2	0	1	0
Ring 4	1	2	0	1	1	1	2	1
Ring 5	3	3	4	3		3	5	1
Ring 6		4	5	4	6	5	6	5

Plot 8	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	5	7	14	12	4	6	4	8
Ring 2	4	4	11	7	5	7	8	7
Ring 3	4	2	4	4	3	8	5	2
Ring 4	7	3	2	3	4	8	3	2
Ring 5	4	6	6	5	2	4	5	3
Ring 6	9	8	11	13	10	8	11	4

Table 6. Measured infiltration values from the intensive agriculture. The difference in water levels (mm) for each measuring period (min).

Plot 1	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	5	6	5		6		2	
Ring 2	13	14	11	13	13	9	13	8
Ring 3	8	2	6		6	10	9	9
Ring 4	18	15	15	9	3	14	14	12
Ring 5	12	3	10	0	9	10	9	11
Ring 6	11	11	6	8	6	5	7	9

Plot 2	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	12	13	6	11	6	6	10	7
Ring 2	16	15	13	21	12	15	20	9
Ring 3	14	8	9	8	7	11	7	7
Ring 4	18	10	15	14	20	13	10	10
Ring 5	35	33	9	30	17	26	16	11
Ring 6	22	22	11	11	12	20	4	5

Plot 3	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	5	2			8	6		
Ring 2	19	5			12	11	11	8
Ring 3	33	34	33	28	27	19	17	21
Ring 4	18	18	17	2	18	12	11	16
Ring 5	18	16	15	16	10	13	15	14
Ring 6	12	11	12	12	11	12	11	10

Plot 4	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	1	1	1	1	1	3		3
Ring 2	10		8	6	7	8	8	7
Ring 3	2	2	3	1	1	0	2	2
Ring 4	16	13	15	14	11	13	13	3
Ring 5	6	4	4	3	2	6	3	5
Ring 6	5	3	3	4	3	1	5	6

Plot 5	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	15	13	9	9	7	14	8	12
Ring 2	12	11	12	12	8	15	11	15
Ring 3	29	19	25	9	18	13	18	7
Ring 4	22	14	18	11	14	13	15	13
Ring 5	18	22	21	14	26	13	13	22
Ring 6	22	16	18	20	25	11	14	19

Plot 6	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	6	4	6	2	4	3	7	3
Ring 2	18	10	11	11	6	7	7	2
Ring 3	11	3	4	8	6	3	7	7
Ring 4	8	3	7	5	3	5	4	5
Ring 5	9	8	10	5	10	13	2	3
Ring 6	5	6	3	13	9	6	3	2

Plot 7	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	3		5	2	4	5	3	3
Ring 2	14	12	11	12	15	14	10	10
Ring 3	16	11	13	11	12	23	9	10
Ring 4	22	17	17	17	15		13	14
Ring 5	7	6	6	6	5	6	7	7
Ring 6	9	7	10	8	8	6	7	8

Plot 8	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	30	30	32	16	17	16	15	9
Ring 2	11	7	19	14	10	10	18	11
Ring 3	16	10	10	14	8	6	19	6
Ring 4	26	17	11	14	8	7	17	10
Ring 5	12	16	13	20	10	17	15	12
Ring 6	13	14	14	18	18	5	5	11

Table 7. Measured infiltration values from the abandoned agriculture. The difference in water levels (mm) for each measuring period (min).

Plot 1	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	7	7	6		7	5	4	
Ring 2	14	14	14		12	9	13	5
Ring 3	16	11	15	14	14		11	10
Ring 4	10	8	7	8	10	8	8	7
Ring 5	18	15	16	18	13		11	14
Ring 6	23	21	19	14	21	21	19	17

Plot 2	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	20	30	29	30	25	20	28	6
Ring 2	18	30	17	13	29	14	5	19
Ring 3	48	34	31	27	32	31	25	24
Ring 4	30	40	13	15	19	19	13	12
Ring 5	13	29	25	18	23	21	18	22
Ring 6	21	22	8	6	13	11	7	21

Plot 3	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	25	21	22	18	18	9	13	12
Ring 2	19		18	11	14	14		12
Ring 3	17		13	16	17	16	16	14
Ring 4	4	11		16	17	14	15	16
Ring 5	17	15	16	13	14	12	12	11
Ring 6	19	18	16	16	14	12	11	13

Plot 4	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	30	14	8	15	6	13	5	6
Ring 2	19	19	7	14	15	14	10	15
Ring 3	15	6	16	13	27	9	16	12
Ring 4	30	19	22	13	13	17	17	14
Ring 5	20	6	16	8	15	20	5	19
Ring 6	17	8	8	15	9	14	20	5

Plot 5	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	31	24	27	23	15	15	13	20
Ring 2		15	16	15	15	13	14	15
Ring 3	29	13	11	6		17	13	15
Ring 4		28	27	22	18	14	19	21
Ring 5	14		4	12	10	8	8	8
Ring 6	14	16	20	10	8	9	10	10

Plot 6	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	7	26	19		9	6	13	12
Ring 2	17	14	29		4	17	9	10
Ring 3	22	10	3	4	8	9	7	8
Ring 4	11	9	22	20	7	4	5	7
Ring 5	24	23	10	9	4	5	21	10
Ring 6	10	9	10	3	4	9	15	4

Plot 7	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	12	10	7		9	9	8	9
Ring 2	4	5	4	6	6	3	4	3
Ring 3	17	8	12	10	9	10	10	11
Ring 4	14	9	9	7	5	8	6	7
Ring 5	17	12	10	10	11	7	6	7
Ring 6	16	10	11	12	12	9	11	10

Plot 8	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	13	4	5	4	4	4	3	5
Ring 2	4	4	11	8	8	8	7	6
Ring 3	20	21	16	4	2	8	9	15
Ring 4	10	8	13	12	15	14	16	16
Ring 5	3	25	17	21	25	22	20	13
Ring 6	28	12	15	21	12	12	6	7

Table 8. Measured infiltration values from the degraded regenerating forest. The difference in water levels (mm) for each measuring period (min).

Plot 1	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	8		6	9	10	5	8	5
Ring 2	23	20	14	15	12	6	10	9
Ring 3	0	2	1	0	0	0	1	1
Ring 4	5	8	4	5		5	4	5
Ring 5	1		2	0	1	0	0	1
Ring 6	2	1	2	0	0	0	0	0

Plot 2	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	3	11	10	2	3	5	1	4
Ring 2	10	3	4	3	4	10	1	5
Ring 3	25	9	21	10	5	4	3	4
Ring 4	20	25	27	17	26	9	9	5
Ring 5	6	5	9	5	3	6	2	6
Ring 6	8	5	8	6	3	6	2	2

Plot 3	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	1	1	1	0	1	1	4	0
Ring 2	10	6	6	5	7	5	6	7
Ring 3	2	1	1	1	1	2	3	2
Ring 4	1	2	3	1	4	2	2	3
Ring 5	5	28	17	18	8	9	13	7
Ring 6	0		1	2	1	0	0	

Plot 4	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	6	3	3	4	1	1	0	2
Ring 2	4	3	2	3	4	5	6	2
Ring 3	8	2	2	3	5		1	
Ring 4	5	2	2	1	4	2	0	4
Ring 5	6	1	3	2	2		3	2
Ring 6	3	2	2	2	3		3	3

Plot 5	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	4	5	0	2	3	6	7	3
Ring 2	28	35	28	25	25	18	20	19
Ring 3	4	1	1	2	7	2	1	1
Ring 4	12	11	11	9	11	14	14	11
Ring 5	0	1	2	1	3	2	1	1
Ring 6	5	8	6	6	5	7	7	5

Plot 6	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	20	17	19	17	15	15	12	20
Ring 2	22	18	20	22	19	19	15	16
Ring 3	20	11	15	9	17	15	5	5
Ring 4	19	14	6	11	21	15	10	6
Ring 5	8	13	5	2	4	15	6	9
Ring 6	14	5	5	4	5	18	10	4

Plot 7	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	10		11	12	11	13	12	9
Ring 2	1	1	2	1	2	1	1	2
Ring 3	5	0	5	4	3	5	5	4
Ring 4	1	0	0	0	1	1		0
Ring 5	9	9	13	9	9	9	9	7
Ring 6		4	9	7	7	8	7	5

Plot 8	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1		3	4	4	2	3	9	9
Ring 2	20	15	5	7	7	11	12	13
Ring 3	9	15	19	20	18	17	19	19
Ring 4	19	14	16	8	6	5	6	7
Ring 5	2	8	3	5	4	6	6	3
Ring 6	8	10	11	12	9	8	6	5

Table 9. Measured infiltration values from the *Albizia* plantation. The difference in water levels (mm) for each measuring period (min).

Plot 1	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	7	10	6	8	9	7	9	7
Ring 2	17	15	14	15	18	15	16	11
Ring 3	10	8	9	9	8	10	9	10
Ring 4	25	33	29	20	29	28	28	28
Ring 5	19	11	18	16	17		14	9
Ring 6	22	19	23	17	26		18	24

Plot 2	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	12	11	8	16	9	15	17	13
Ring 2	13	11	13	17	10	15	24	27
Ring 3	4	22	7	6	5	3	4	19
Ring 4	18	29	29	22	10	15	6	13
Ring 5	8	8	5	5	2	4	7	6
Ring 6	6	10	3	6	4	5	4	5

Plot 3	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	15	28	16	11	10	9	11	9
Ring 2	16	15	15	14	13	12	9	9
Ring 3	11	10	9	10	10	10	7	9
Ring 4	14	15	13	13	14	11	12	12
Ring 5	10	20			15	16	15	16
Ring 6	15	16		15	15	12	11	11

Plot 4	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	30	14	2	15	10	14	12	15
Ring 2	17	8	27	14	11	9	10	8
Ring 3	9	10	4	5	3	3	5	7
Ring 4	7	14	15	2	15	6	2	4
Ring 5	4	24	6	5		3	4	5
Ring 6	5	4	8	11	7	9	10	10

Plot 5	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	10	10	12	8	8	12	8	10
Ring 2	7	6	9	6	7	7	3	7
Ring 3	4	2	4	3	3	4	4	5
Ring 4	16	13	15		13		13	14
Ring 5	4	6	2	3	6	1	4	4
Ring 6	10	10	11	8	11	10	9	10

Plot 6	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	17	13	9	34	30	12	8	12
Ring 2	20	22	12	3	2	11	4	6
Ring 3	3	3	5	7	5	5	4	8
Ring 4	10	11	14	13	5	14	11	5
Ring 5	3	9	3	5	2	2	7	6
Ring 6	4	10	4	3	4	11	6	10

Plot 7	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	7	9	6	8	8	5	6	7
Ring 2	9	8	7	7	6	5	6	8
Ring 3	6	11	14	14	12	13	12	14
Ring 4	5	1	4	4	3	3	4	4
Ring 5	22	15	14	14	12	11	12	10
Ring 6	17	17	11	10	12	9	11	10

Plot 8	14-18	34-38	54-48	74-78	94-98	114-118	134-138	154-158
Ring 1	7	3	2	3	3	5	4	4
Ring 2	5	8	3	5	9	2	1	5
Ring 3	5	2	7	3	6	2	1	4
Ring 4	11	5	2	4	5	10	14	2
Ring 5	7	9	14	11	5	10	17	11
Ring 6	7	10	12	15	9	6	4	11

Appendix 2

Data for the bulk density measurements.

Table 10. Dry weight (g) for the bulk density samples from the natural forest.

Plot	Sample	Dry weight (g)
1	1	129.34
1	2	153.22
1	3	133.63
1	4	132.60
2	1	141.99
2	2	134.99
2	3	147.10
2	4	141.76
3	1	144.14
3	2	154.47
3	3	132.19
3	4	131.10
4	1	130.54
4	2	145.65
4	3	133.19
4	4	130.99
5	1	127.32
5	2	141.70
5	3	145.26
5	4	144.80
6	1	141.10
6	2	115.58
6	3	139.37
6	4	151.64
7	1	141.33
7	2	135.98
7	3	151.95
7	4	140.52
8	1	150.40
8	2	123.63
8	3	151.37
8	4	146.34

Table 11. Dry weight (g) for the bulk density samples from the degraded forest.

Plot	Sample	Dry weight (g)
1	1	138.33
1	2	142.21
1	3	130.66
1	4	142.61
2	1	134.66
2	2	136.28
2	3	142.01
2	4	134.87
3	1	138.63
3	2	135.12
3	3	115.47
3	4	138.29
4	1	122.20
4	2	134.32
4	3	123.15
4	4	133.43
5	1	122.64
5	2	131.20
5	3	128.15
5	4	121.86
6	1	136.91
6	2	113.86
6	3	109.37
6	4	118.07
7	1	130.89
7	2	141.78
7	3	135.89
7	4	125.63
8	1	121.11
8	2	135.87
8	3	126.26
8	4	142.67

Table 12. Dry weight (g) for the bulk density samples from the intensive agriculture.

Plot	Sample	Dry weight (g)
1	1	140.85
1	2	131.40
1	3	111.39
1	4	111.36
2	1	125.42
2	2	119.61
2	3	114.66
2	4	111.40
3	1	123.56
3	2	117.64
3	3	117.79
3	4	120.38
4	1	132.65
4	2	124.34
4	3	121.28
4	4	126.19
5	1	121.38
5	2	119.26
5	3	122.14
5	4	121.23
6	1	115.36
6	2	126.45
6	3	107.02
6	4	120.40
7	1	120.50
7	2	128.21
7	3	128.64
7	4	121.93
8	1	126.61
8	2	124.08
8	3	129.62
8	4	117.27

Table 13. Dry weight (g) for the bulk density samples from the abandoned agriculture.

Plot	Sample	Dry weight (g)
1	1	119.34
1	2	130.04
1	3	96.42
1	4	98.59
2	1	108.66
2	2	100.17
2	3	102.97
2	4	109.28
3	1	118.46
3	2	112.00
3	3	109.32
3	4	99.39
4	1	104.01
4	2	112.83
4	3	125.43
4	4	113.21
5	1	107.78
5	2	107.50
5	3	114.32
5	4	99.62
6	1	123.26
6	2	128.53
6	3	99.21
6	4	117.34
7	1	116.96
7	2	119.05
7	3	118.76
7	4	133.54
8	1	122.90
8	2	109.99
8	3	120.64
8	4	114.84

Table 14. Dry weight (g) for the bulk density samples from the degraded regenerating forest.

Plot	Sample	Dry weight (g)
1	1	142.12
1	2	148.10
1	3	149.30
1	4	146.32
2	1	137.82
2	2	130.66
2	3	135.65
2	4	133.25
3	1	143.08
3	2	148.79
3	3	125.99
3	4	128.90
4	1	149.74
4	2	145.65
4	3	146.97
4	4	142.51
5	1	141.30
5	2	137.70
5	3	135.70
5	4	131.28
6	1	135.27
6	2	138.23
6	3	135.87
6	4	146.11
7	1	131.45
7	2	135.45
7	3	132.88
7	4	134.54
8	1	132.63
8	2	147.89
8	3	146.86
8	4	137.21

Table 15. Dry weight (g) for the bulk density samples from the *Albizia* plantation.

Plot	Sample	Dry weight (g)
1	1	134.89
1	2	136.74
1	3	131.96
1	4	138.87
2	1	138.99
2	2	140.59
2	3	137.18
2	4	126.08
3	1	140.74
3	2	141.95
3	3	120.40
3	4	146.86
4	1	144.86
4	2	133.89
4	3	128.80
4	4	142.15
5	1	149.49
5	2	132.30
5	3	125.57
5	4	142.43
6	1	142.37
6	2	145.85
6	3	143.25
6	4	137.26
7	1	137.90
7	2	117.72
7	3	133.36
7	4	136.34
8	1	153.69
8	2	140.20
8	3	138.92
8	4	133.39

Appendix 3

Data for the soil organic carbon measurements.

Table 16. The amounts of $FeSO_4$ added to the sample and the blank from the natural forest, two replicates for each sample.

Plot	Sample	$FeSO_4$ (ml) replicate 1	$FeSO_4$ (ml) to blank for replicate 1	$FeSO_4$ (ml) replicate 2	$FeSO_4$ (ml) to blank for replicate 2	Mean % OC
1	1	15.40	0.539	14.90	0.539	3.61
1	2	16.80	0.539	16.10	0.539	1.67
1	3	16.30	0.539	15.70	0.539	1.89
1	4	16.20	0.539	16.10	0.539	1.04
2	1	15.90	0.539	16.30	0.539	1.09
2	2	15.30	0.539	14.80	0.539	1.61
2	3	12.50	0.539	12.40	0.539	0.96
2	4	14.20	0.539	14.60	0.539	1.11
3	1	14.30	0.539	14.30	0.539	1.54
3	2	12.80	0.539	14.10	0.539	1.33
3	3	13.10	0.539	12.80	0.539	1.59
3	4	13.00	0.539	13.40	0.539	1.28
4	1	15.00	0.539	15.20	0.539	1.30
4	2	14.40	0.539	14.20	0.539	0.67
4	3	15.90	0.539	16.50	0.539	0.93
4	4	16.20	0.539	16.20	0.539	0.85
5	1	15.60	0.539	15.20	0.539	1.28
5	2	15.90	0.539	15.30	0.539	1.46
5	3	15.70	0.539	15.70	0.539	1.41
5	4	15.10	0.539	15.40	0.539	1.80
6	1	14.90	0.539	13.90	0.539	1.46
6	2	15.40	0.539	16.10	0.539	2.85
6	3	16.70	0.539	16.80	0.539	1.57
6	4	15.40	0.539	15.10	0.539	1.00
7	1	16.60	0.539	16.40	0.539	1.00
7	2	15.40	0.539	14.50	0.539	1.46
7	3	15.40	0.539	15.60	0.539	0.57
7	4	13.60	0.539	14.30	0.539	1.72
8	1	15.20	0.539	15.40	0.539	1.74
8	2	16.00	0.539	15.40	0.539	1.68
8	3	17.20	0.539	16.90	0.539	1.59
8	4	15.40	0.539	15.10	0.539	1.15

Table 17. The amounts of $FeSO_4$ added to the sample and the blank from the degraded forest, two replicates for each sample.

Plot	Sample	$FeSO_4$ (ml) replicate 1	$FeSO_4$ (ml) to blank for replicate 1	$FeSO_4$ (ml) replicate 2	$FeSO_4$ (ml) to blank for replicate 2	Mean % OC
1	1	15.30	0.545	15.30	0.545	1.33
1	2	14.80	0.556	14.80	0.556	1.42
1	3	13.20	0.556	15.60	0.556	1.60
1	4	15.00	0.556	15.20	0.556	1.29
2	1	15.20	0.545	15.60	0.545	1.28
2	2	15.50	0.556	15.80	0.556	1.04
2	3	14.50	0.545	15.70	0.545	1.41
2	4	15.50	0.556	15.50	0.556	1.11
3	1	15.60	0.545	15.40	0.556	1.17
3	2	15.40	0.556	15.40	0.545	1.22
3	3	18.40	0.545	17.20	0.545	0.24
3	4	13.90	0.556	14.70	0.556	1.64
4	1	17.00	0.545	14.90	0.545	1.04
4	2	15.70	0.556	15.30	0.556	1.11
4	3	16.60	0.556	15.60	0.545	0.91
4	4	17.10	0.545	16.10	0.545	0.76
5	1	13.60	0.545	15.60	0.545	1.63
5	2	15.20	0.545	15.70	0.545	1.26
5	3	18.00	0.545	15.90	0.545	0.61
5	4	16.90	0.545	15.70	0.545	0.89
6	1	12.70	0.545	12.40	0.545	2.52
6	2	14.10	0.556	14.50	0.556	1.64
6	3	11.20	0.545	11.80	0.545	2.98
6	4	14.90	0.545	15.30	0.545	1.41
7	1	15.90	0.545	18.00	0.545	0.61
7	2	15.60	0.556	16.20	0.556	0.93
7	3	14.80	0.545	15.00	0.545	1.50
7	4	14.70	0.545	14.30	0.545	1.67
8	1	14.90	0.556	15.50	0.545	1.31
8	2	13.20	0.545	13.30	0.545	2.22
8	3	15.10	0.545	13.30	0.545	1.80
8	4	13.80	0.545	14.50	0.545	1.83

Table 18. The amounts of $FeSO_4$ added to the sample and the blank from the intensive agriculture, two replicates for each sample.

Plot	Sample	$FeSO_4$ (ml) replicate 1	$FeSO_4$ (ml) to blank for replicate 1	$FeSO_4$ (ml) replicate 2	$FeSO_4$ (ml) to blank for replicate 2	Mean % OC
1	1	12.50	0.556	13.60	0.556	2.19
1	2	12.50	0.556	13.00	0.556	2.33
1	3	12.40	0.556	12.10	0.556	2.55
1	4	12.00	0.556	11.60	0.556	2.75
2	1	13.10	0.556	12.60	0.556	2.28
2	2	13.60	0.556	13.00	0.556	2.08
2	3	13.40	0.556	12.90	0.556	2.15
2	4	11.60	0.556	10.40	0.556	3.10
3	1	13.60	0.556	14.40	0.556	1.77
3	2	13.10	0.556	13.20	0.556	2.15
3	3	11.40	0.556	11.70	0.556	2.86
3	4	14.60	0.556	15.30	0.556	1.35
4	1	11.80	0.556	11.50	0.556	2.82
4	2	12.20	0.556	12.40	0.556	2.53
4	3	12.20	0.556	12.20	0.556	2.57
4	4	13.00	0.556	12.20	0.556	2.39
5	1	12.90	0.556	12.70	0.556	2.31
5	2	12.90	0.556	12.10	0.556	2.44
5	3	14.90	0.556	14.60	0.556	1.44
5	4	12.00	0.556	12.10	0.556	2.64
6	1	12.70	0.556	13.00	0.556	2.28
6	2	13.50	0.556	13.60	0.556	1.97
6	3	9.80	0.556	7.90	0.556	4.06
6	4	14.60	0.556	15.70	0.556	1.26
7	1	13.60	0.556	14.00	0.556	1.86
7	2	13.00	0.556	12.90	0.556	2.24
7	3	13.40	0.556	13.70	0.556	1.97
7	4	13.00	0.556	12.20	0.556	2.39
8	1	11.80	0.556	12.20	0.556	2.66
8	2	13.60	0.556	13.20	0.556	2.04
8	3	13.70	0.556	12.80	0.556	2.11
8	4	14.00	0.556	14.20	0.556	1.73

Table 19. The amounts of $FeSO_4$ added to the sample and the blank from the abandoned agriculture, two replicates for each sample.

Plot	Sample	$FeSO_4$ (ml) replicate 1	$FeSO_4$ (ml) to blank for replicate 1	$FeSO_4$ (ml) replicate 2	$FeSO_4$ (ml) to blank for replicate 2	Mean % OC
1	1	14.20	0.539	14.80	0.539	1.74
1	2	14.30	0.539	14.60	0.539	1.76
1	3	16.10	0.539	14.60	0.539	1.38
1	4	14.90	0.539	15.40	0.556	1.36
2	1	15.40	0.556	15.70	0.556	1.09
2	2	15.70	0.545	15.20	0.545	1.26
2	3	15.00	0.556	15.80	0.556	1.15
2	4	15.10	0.539	15.60	0.539	1.38
3	1	16.20	0.556	15.60	0.556	0.93
3	2	16.20	0.539	16.20	0.539	1.01
3	3	14.70	0.539	14.40	0.539	1.72
3	4	15.50	0.539	15.90	0.539	1.23
4	1	14.30	0.539	14.90	0.539	1.70
4	2	15.00	0.556	15.00	0.556	1.33
4	3	12.90	0.556	13.60	0.556	2.11
4	4	14.70	0.556	14.50	0.556	1.51
5	1	15.90	0.539	14.80	0.539	1.38
5	2	13.90	0.556	14.60	0.556	1.66
5	3	15.70	0.556	15.10	0.556	1.15
5	4	15.90	0.556	15.60	0.556	1.00
6	1	14.60	0.539	14.70	0.539	1.68
6	2	14.40	0.539	14.30	0.539	1.81
6	3	13.90	0.539	14.60	0.539	1.85
6	4	15.00	0.556	14.60	0.556	1.42
7	1	15.40	0.556	15.00	0.556	1.24
7	2	14.30	0.556	14.50	0.556	1.60
7	3	15.80	0.539	16.10	0.539	1.12
7	4	15.50	0.539	14.80	0.539	1.46
8	1	15.20	0.556	15.30	0.556	1.22
8	2	15.20	0.556	15.40	0.556	1.20
8	3	15.20	0.556	15.90	0.556	1.09
8	4	15.00	0.539	15.60	0.539	1.40

Table 20. The amounts of $FeSO_4$ added to the sample and the blank from the degraded regenerating forest, two replicates for each sample.

Plot	Sample	$FeSO_4$ (ml) replicate 1	$FeSO_4$ (ml) to blank for replicate 1	$FeSO_4$ (ml) replicate 2	$FeSO_4$ (ml) to blank for replicate 2	Mean % OC
1	1	15.40	0.539	14.90	0.539	1.46
1	2	16.80	0.539	16.10	0.539	0.90
1	3	16.30	0.539	15.70	0.539	1.10
1	4	16.20	0.539	16.10	0.539	1.03
2	1	15.90	0.539	16.30	0.539	1.05
2	2	15.30	0.539	14.80	0.539	1.51
2	3	12.50	0.539	12.40	0.539	2.62
2	4	14.20	0.539	14.60	0.539	1.79
3	1	14.30	0.539	14.30	0.539	1.83
3	2	12.80	0.539	14.10	0.539	2.19
3	3	13.10	0.539	12.80	0.539	2.41
3	4	13.00	0.539	13.40	0.539	2.30
4	1	15.00	0.539	15.20	0.539	1.48
4	2	14.40	0.539	14.20	0.539	1.83
4	3	15.90	0.539	16.50	0.539	1.01
4	4	16.20	0.539	16.20	0.539	1.01
5	1	15.60	0.539	15.20	0.539	1.36
5	2	15.90	0.539	15.30	0.539	1.27
5	3	15.70	0.539	15.70	0.539	1.23
5	4	15.10	0.539	15.40	0.539	1.42
6	1	14.90	0.539	13.90	0.539	1.79
6	2	15.40	0.539	16.10	0.539	1.20
6	3	16.70	0.539	16.80	0.539	0.77
6	4	15.40	0.539	15.10	0.539	1.42
7	1	16.60	0.539	16.40	0.539	0.88
7	2	15.40	0.539	14.50	0.539	1.55
7	3	15.40	0.539	15.60	0.539	1.31
7	4	13.60	0.539	14.30	0.539	1.98
8	1	15.20	0.539	15.40	0.539	1.40
8	2	16.00	0.539	15.40	0.539	1.23
8	3	17.20	0.539	16.90	0.539	0.65
8	4	15.40	0.539	15.10	0.539	1.42

Table 21. The amounts of $FeSO_4$ added to the sample and the blank from the *Albizia* plantation, two replicates for each sample.

Plot	Sample	$FeSO_4$ (ml) replicate 1	$FeSO_4$ (ml) to blank for replicate 1	$FeSO_4$ (ml) replicate 2	$FeSO_4$ (ml) to blank for replicate 2	Mean % OC
1	1	15.30	0.539	15.70	0.539	1.31
1	2	15.60	0.539	15.00	0.539	1.40
1	3	16.20	0.541	15.80	0.541	1.08
1	4	14.50	0.541	15.50	0.541	1.51
2	1	16.70	0.541	16.80	0.541	0.75
2	2	16.80	0.541	15.90	0.541	0.93
2	3	16.20	0.539	16.10	0.539	1.03
2	4	14.90	0.539	15.80	0.539	1.38
3	1	15.60	0.539	15.40	0.539	1.31
3	2	15.90	0.539	16.50	0.539	1.01
3	3	15.80	0.539	15.50	0.539	1.25
3	4	16.80	0.539	15.60	0.539	1.01
4	1	16.20	0.539	15.90	0.539	1.08
4	2	15.50	0.539	16.10	0.539	1.18
4	3	14.60	0.539	16.20	0.539	1.36
4	4	15.60	0.539	15.50	0.539	1.29
5	1	16.80	0.539	17.20	0.539	0.67
5	2	14.90	0.539	15.90	0.539	1.36
5	3	15.30	0.539	14.50	0.539	1.57
5	4	16.30	0.539	15.60	0.539	1.12
6	1	15.50	0.539	15.50	0.539	1.31
6	2	15.80	0.539	15.40	0.539	1.27
6	3	15.30	0.539	15.90	0.539	1.27
6	4	15.80	0.539	15.70	0.539	1.20
7	1	15.50	0.539	15.60	0.539	1.29
7	2	15.80	0.541	15.20	0.541	1.29
7	3	15.30	0.539	15.70	0.539	1.31
7	4	15.90	0.539	15.70	0.539	1.18
8	1	16.20	0.539	15.10	0.539	1.25
8	2	14.70	0.539	15.20	0.539	1.55
8	3	14.60	0.539	14.30	0.539	1.76
8	4	15.20	0.539	14.90	0.539	1.51

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