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Full Length Research Paper

Effects of *Faidherbia albida* on the fertility of soil in smallholder conservation agriculture systems in eastern and southern Zambia

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This study explored the benefits of *Faidherbia albida* on soil fertility in farmers' fields in areas which were suitable for Conservation Agriculture (CA) and where mature stands of *F. albida* already existed. It investigated the effects of *F. albida* on soils by testing for differences in the soil reaction (pH), total nitrogen, potassium, phosphorus and organic carbon at increasing radial distance from the tree trunk. Soil samples were collected from under and outside the canopies of 102 *F. albida* trees in four districts situated in the Southern and Eastern provinces of Zambia. The results showed evidence of a negative linear relationship between distance from *F. albida* and total nitrogen ($p = 0.003$), organic carbon ($p = 0.0001$), and potassium levels ($p = 0.0001$) but not for available phosphorus ($p = 0.708$) and soil reaction pH ($p = 0.88$). The nutrient levels were 42, 25 and 31% higher under the tree canopies than away for total nitrogen, potassium, and organic carbon respectively. *F. albida* added significant amounts of the agriculturally important nutrients which resource constrained households had difficulties replenishing to the soils through mineral fertilizer amendments because of their limited ability to purchase mineral fertilizers. It was concluded that *F. albida* improved soil fertility in farmers' fields and could be promoted in smallholder CA systems in Zambia.

Key words: *Faidherbia albida*, soil fertility, conservation agriculture, biological nitrogen fixation, Zambia.

INTRODUCTION

Soil nutrient mining is considered to be a major threat to food security and natural resource conservation in Sub-Saharan Africa (SSA). According to Bationo et al. (2006), Africa loses US$4 billion per year due to soil nutrient mining. The problem is pervasive among mixed crop and livestock farming systems of the region where competing uses for crop residues such as livestock fodder, or household fuel mean that nutrients are not sufficiently replenished into the soil. Nutrient replacement using mineral fertilizers is a limited option for many smallholder farming households of the region. At only eight kilograms per hectare, the region has the lowest mineral fertilizer application rates in the world and concomitantly, much lower crop yields than achieved in other developing regions (Morris et al., 2007). In Southern Africa, the consequent downward spiral of soil fertility has contributed to a corresponding decline in crop yields, an increase in food insecurity, food aid and environmental degradation (Mafongoya et al., 2006). In order to mitigate

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nutrient mining, agroforestry (or fertilizer tree) systems have been proposed as an innovation especially suited to resource poor farming households. Fertilizer tree systems add biologically fixed nitrogen and other agriculturally important nutrients to the soils. This is done in a way that complements the crops grown in association with the trees (Akinnifesi et al., 2010). The use of the fertilizer tree *F. albida* (Del) A. Chev has been documented in semi-arid Africa, north and south of the equator, from southern Algeria to Transvaal and from the Atlantic to the Indian Ocean (Kirmse and Norton, 1984). It has been promoted in agroforestry as its characteristic reverse phenology allows satisfactory production of crops under a full stand of the species (Roupsard et al., 1999). The leaves are shed at the onset of the rainy season which significantly reduces the shade cast beneath the trees and reduces competition for water (Kirmse and Norton, 1984), light and nutrients (Kho et al., 2001) with associated crops grown during the rainy season.

Conservation Agriculture (CA) promoters contend that integrating *F. albida* trees into CA systems based on the three principles of minimum tillage, diversified crop rotations and permanent soil surface cover enhances the soil improving benefits of CA as not only does *F. albida* fix nitrogen, it also returns other nutrients to the soil and increases Soil Organic Matter (SOM) content through the shedding of its nutrient-rich leaves and the subsequent decomposition of its leaf litter at the onset of rains (Saka et al., 1994). The increased SOM improves soil structure, enhances soil microfauna populations and minimizes excessive evapo-transpiration and soil temperatures (Mokgolodi et al., 2011).

Incorporation of *F. albida* into smallholder CA systems has been promoted in Zambia for more than 10 years. The Conservation Farming Unit (CFU) has been encouraging farmers to plant 100 of the tree per hectare as a long term means of boosting soil fertility. It has been claimed that with trees planted at this density, the nutrient-rich leaves can supply the equivalent of 300 kg ha^{-1} nitrogen and 30 kg ha^{-1} of phosphorus per year (Dancette and Poulin, 1969), a valuable asset for the many farmers who cannot afford to buy these nutrients in form of mineral fertilizers. The tree has an extensive tap root system which develops rapidly and taps groundwater at large depths in the soil (Kirmse and Norton, 1984; Roupsard et al., 1999) and brings up nutrients from deeper soil layers to surface layers which are within the crop root systems. Supplements of soil nitrogen are thus possible under *F. albida* canopy through underground release of nitrogen in decomposing roots and nodules (Mokgolodi et al., 2011). In this way, it is argued, *F. albida* reduces the requirements of externally procured mineral fertilizers. Combining *F. albida* with the three CA principles supplemented by locally adapted agronomic practices such as dry season land preparation and precision in input application is regarded as being able to improve crop yields and farmers' incomes, and to redress the soil fertility decline associated with farming as conventionally practiced by smallholders in Zambia.

Analysis of soils from under *F. albida* in Senegal indicated a remarkable fertility gradient from bare soils to soils under the canopy and yields of millet near trees increased two to four folds (Charreau and Vidal, 1965). Studies by Dougain (1960) in Niger indicated that on a 10 cm depth basis, which represented about 1500 tons of soil ha^{-1}, the nutrient increases due to the presence of *F. albida* were equivalent to 300 kg nitrogen, 31 kg phosphorus as P_2O_5 and 24 kg Magnesium. Soil water retention also increased under the canopy of *F. albida* (Radwanski and Wickens, 1967; Kamara and Haque, 1992) with increases of as much as 43% reported (Charreau and Vidal, 1965). On-station research in Malawi showed that mature trees could sustain unfertilized maize yields of 2.5 to 4 tons ha^{-1}, 200 to 400% more than the national averages (New Agriculturalist, 2010). Research station trials conducted in Zambia on nine year old *F. albida* trees concluded that the tree supplied 150 kg ha^{-1} of nutrients and 100 kg ha^{-1} of lime to the soil (GART, 2007).

F. albida is widely distributed in the southern half of Zambia particularly the semi-arid valley areas. It is locally known as *Musangu* and is increasingly being appreciated by smallholder farmers for its fertilizing effects on crops grown under its canopy and for its nutritious pods that serve as fodder during the dry season. The CFU has been promoting the tree through demonstrations of the yield effects of the tree on crops by conducting on-farm trials under and outside the canopies and holding field days where the results are publicized. CFU also distributes free *F. albida* seeds to CA farmers on its Conservation Agriculture Programme (CAP) and conducts training sessions with them on how to plant and look after *F. albida*. CFU had a goal of providing 120 000 farmers with starter packs of seed and sleeves and training them on how to raise and transplant seedlings into crop fields at a density of 100 plants ha^{-1} throughout its project areas in Southern, Central, Lusaka and Eastern Provinces of Zambia (CFU, 2006).

Although a lot of research has been conducted on *F. albida* in the Sahel, there is a paucity of on-station and on-farm studies on the effects of *F. albida* on soil fertility in the Zambian and regional context. A deeper understanding of the supply of nutrients by *F. albida* is important in the development of crop - tree systems that suit the needs of smallholder farmers. The objective of this study was, therefore, to explore the benefits of *F. albida* on soil fertility in farmers' fields in areas which are suitable for CA and where mature stands of *F. albida* already existed. This study investigated the effects of *F. albida* by assessing the effects of the trees on soil reaction (pH), N, K, P and soil organic carbon at increasing radial distance from the tree. We also compared the results based on district and province, whether the soils under the trees had been cultivated recently and whether livestock had deposited dung under the trees which could also contribute to the improved nutrient status of the soils. We briefly discuss some issues associated with the management of *F. albida* in this study area.

MATERIALS AND METHODS

This study was conducted between June and August 2008, and May and August 2009. Soil samples were collected from 102 *F. albida* trees in districts situated in the Southern and Eastern Provinces of Zambia. These districts were selected as they were the ones known to have *F. albida* trees among the 12 districts were CA was being promoted. The location of the sampled trees were recorded using a GPS and have been plotted on the maps presented as Figure 1a, b and c.

Description of study sites

Monze, Chipata and Petauke districts are located in Agro-Ecological Region (AER) IIa while Sinazongwe is found in AER I. AERs are categorized based on mean annual rainfall, growing season and elevation. AER IIa is characterized by mean annual rainfall of between 800 mm and 1000 mm and an average growing season of 100 to 140 days. AER I is the driest and most drought prone part of the country. It normally receives less than 700 mm of rainfall annually and has a growing season of between 80 and 120 days. Sinazongwe is located in a valley area with a mean elevation of 536 m above sea level (a.s.l). Monze is at an elevation of 1080 m a.s.l, Chipata is at 1011 m a.s.l. while Petauke is at a lower elavation of 850 m a.s.l. The climate of this study area is typified by a uni-modal rain season which usually lasts from November to April, followed by a cool and dry season lasting from May to August and a hot and dry season between September and November (GRZ, 2007). Monze, Chipata and Petauke received average annual rainfall of 732, 1033 and 932 mm respectively during the 2009/2010 farming seasons (GRZ, 2010).

Soils types in AER I range from slightly acidic Nitosols to alkaline Luvisols with pockets of Vertisols, Arenosols, Leptosols and Solonetz (MACO/JICA, 2007). The use of these soils for agricultural production is limited by lack of adequate water and high soil erosion potential. AER IIa soils are largely classified as Lixisols, Luvisols, Alisols, Acrisols and Leptosols. These are some of the best agricultural soils in Zambia and they host much of the country's commercial farming sector (MACO/JICA, 2007).

Selection of trees and measurement of dimensions

Trees were selected based on canopy size and ability to sample at three different radial distances. Very young trees (less than ten years old) were not included in the sampling frame and neither were the trees whose canopies overlapped with those of other trees. This was because the canopies were too small for the former and as we were unable to collect samples from 5 m outside the canopies for the latter. Random sampling was then used to collect the predetermined number of trees from a population of *F.albida* trees from Sinazongwe and Monze while all the trees known to exist in Chipata and Petauke Districts were included in the sample. The total sample size was 102 trees. This included 52 trees from Monze District, 35 trees from Sinazongwe District, 8 trees from Chipata District and 7 trees from Petauke District. Tree heights were estimated using clinometers while the tree circumferences were measured at breast height (137 cm) with a 10 m measuring tape. Estimations of the ages of the trees were provided by owners of the fields in which the trees were found. The canopies were determined using 30 m measuring tapes.

Soil sampling

Three composite samples were taken at three different radii (inner, middle, outer) per tree. The radial distance of the inner and middle radii depended on the canopy size of the tree while the outer radius was 5 m from the edge of the tree canopy. While the inner and middle radii fell under the tree canopies, the outer radius was outside the canopies, at an average distance of 14.5 m from the tree trunk. Ten sub-samples were taken at each radius and at soil depths of 0 to 20 cm using an auger and mixed thoroughly to obtain a composite sample. Assessments were made on the presence of dung and cultivation of crops under the sampled *F. albida* trees. Laboratory analyses were conducted on the following parameters: soil reaction (pH_{Cacl2}), total nitrogen (Kjeldahl Method, Bremner, 1965), available phosphorus (Bray 1, Bray and Kurtz, 1945), organic carbon (Walkley and Black, 1934; Walkley and Black, 1934) and potassium (Ammonium acetate buffered at pH 7 for Potassium, Chapman, 1965).

Statistical analyses

Differences in the mean nutrient levels found in the soils at the three different radii and in the four districts were tested using ANOVA and linear mixed models using the statistical software Minitab 15 (Minitab, 2009) and R Studio (R Development Core Team 2011) respectively. The linear mixed models were used as they capture and control for both fixed and random effects. The fixed effects are specific variables that are directly recorded in the course of an experiment while random effects result from repeated measurements made on the same unit. In this instance, the variations due to the trees were the random effects that were controlled for. This enhanced the probability of detecting variations that were due to the predictors, and not due to the variations between one tree and the next. Several different models were tested for each of the four nutrients. Model selection started with the inclusion of four predictors namely distance from tree, district, dung under canopy, and presence of crops under canopy. Predictors that were insignificant were dropped from the model and the final model only contained variables that were significant at the five percent level. The models were checked using the normal q-q plot and were found to be acceptable. Simple linear regressions were used to determine fertility gradients for N, P, K and OC. All the statistical analyses were conducted at probability level of $p \leq 0.05$.

RESULTS AND DISCUSSION

The sampled trees had an average height of 21.0 m and diameter at breast height of 0.99 m. The average crown diameter was 18.6 m. The age range was 25 to 150 years. The average inner, middle and outer radii for the 102 trees were 1.7, 8.7 and 14.5 m respectively. The results showed that after controlling for the variations between the trees, the radial distance from the *F. albida*

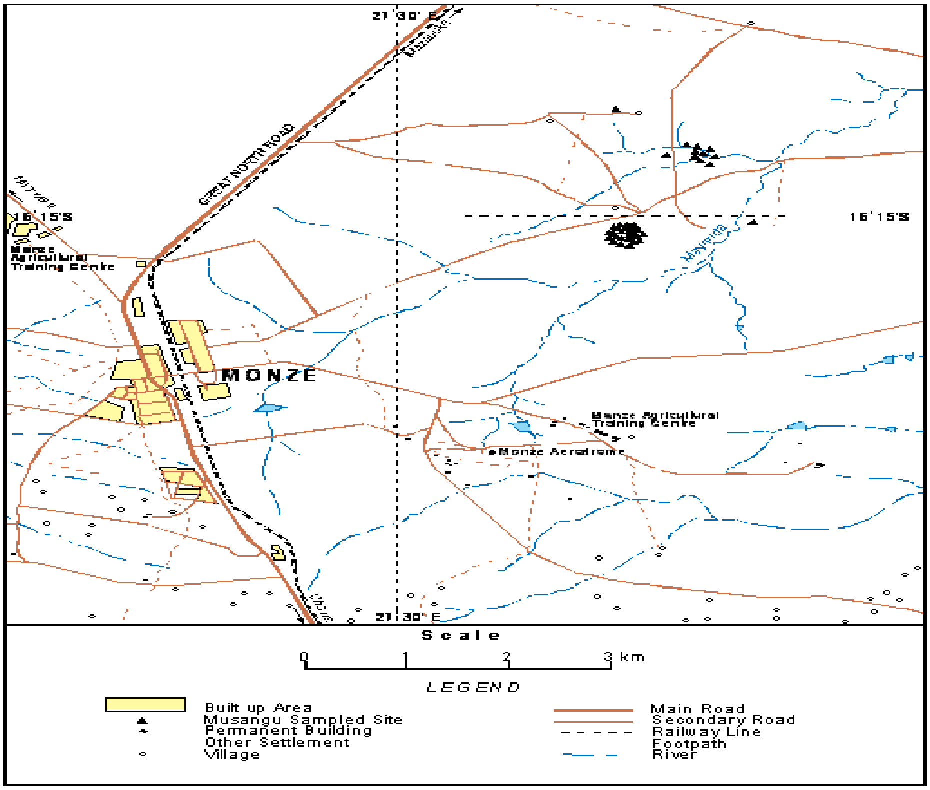

Figure 1a. Location of sampled *Faidherbia albida* trees in Monze District, Zambia.

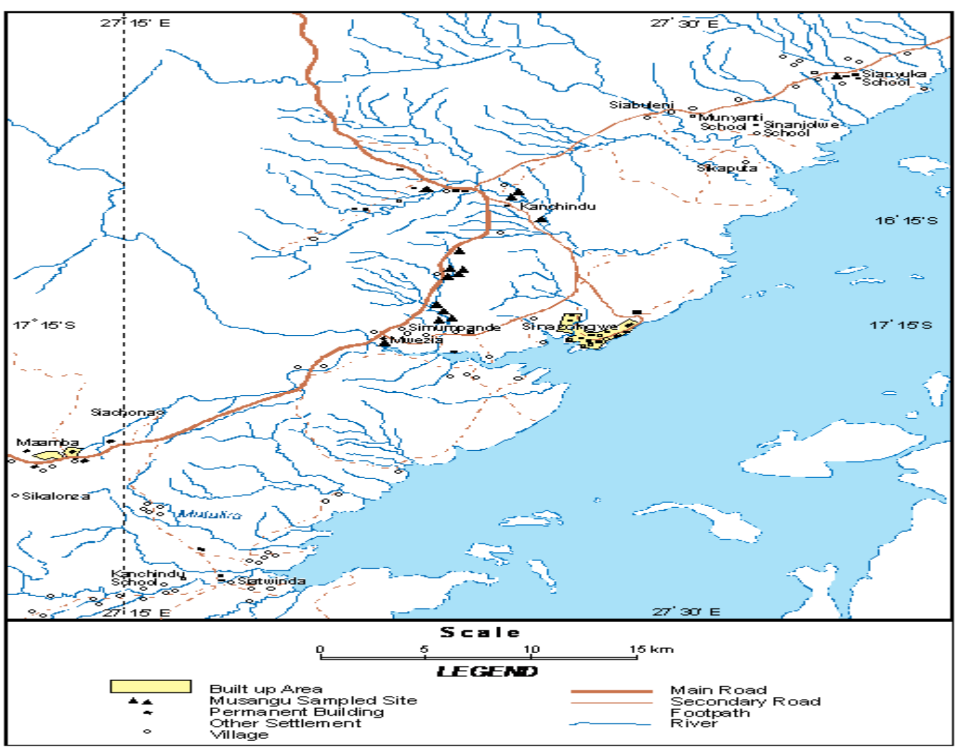

Figure 1b. Location of sampled *F. albida* trees in Sinazongwe District, Zambia.

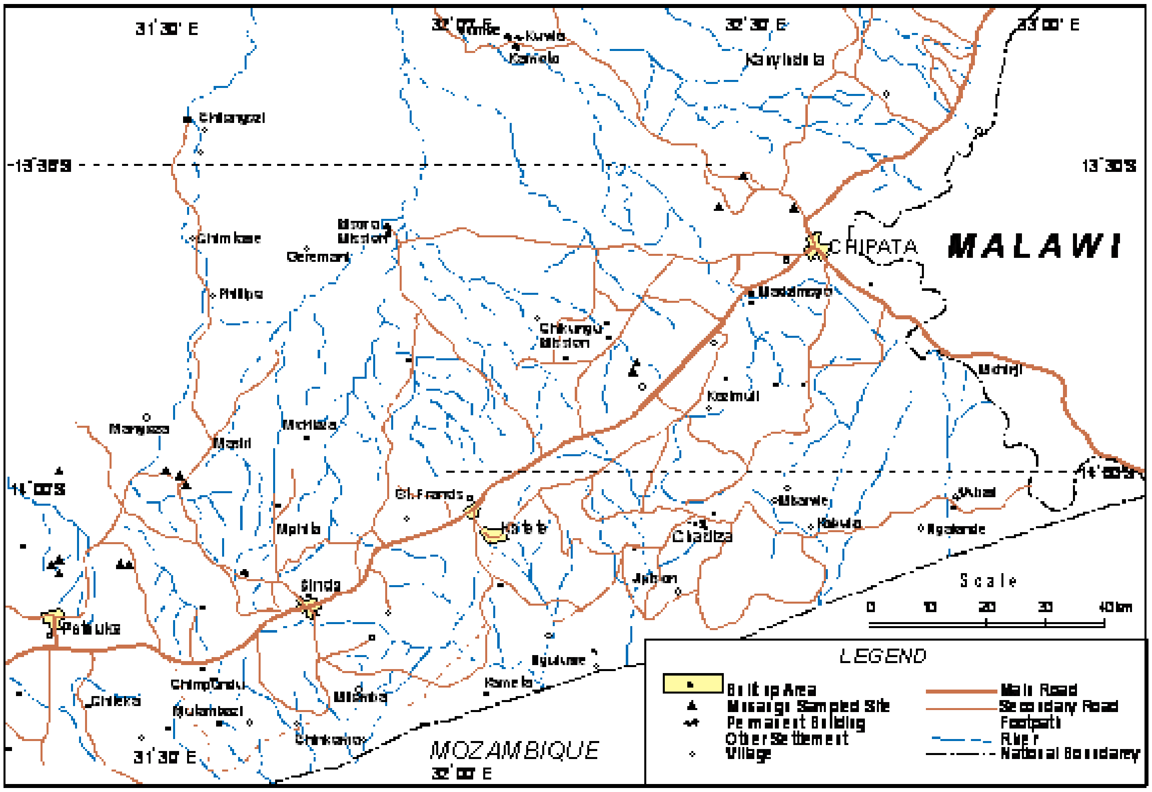

Figure 1c. Location of sampled *F. albida* trees in Eastern Zambia.

tree and the district in which the tree was located were important in determining the levels of organic carbon, total nitrogen, and potassium ($p \leq 0.05$). The model used was: Nutrient level ~Distance from tree + District + 1(1| Tree). For phosphorus, only the effect of district was significant ($p \leq 0.05$).

Effect of radius

The levels of organic carbon, total nitrogen, potassium and phosphorus reduced with increasing radial distance from the *F .albida* tree. Radial distance of 1 m from the tree resulted in a decrease of 0.3% for organic carbon, 0.003% for total nitrogen, and 0.015 cmol kg^{-1} of potassium (Table 1).

The random effects variance showed that there were large variations between and within the trees as evidenced by the large tree variance compared to the residual variance for organic carbon, potassium and phosphorus (Table 1).

The results showed evidence of a negative linear relationship and existence of a fertility gradient between radial distance from *F. albida* and N, OC, and K, but not for P and soil reaction (pH) (Figure 2 and Table 2). The N, OC and K levels were significantly higher under the *F. albida* canopies than 5 m from the edge of the canopies (Table 3). The N levels were 0.17% in the inner radius and 0.12% in the outer radius. Soil N levels were 42% higher under the canopies than outside. Assuming a density of 100 mature *F. albida* trees per hectare, this would be equivalent to 4420 kg N ha^{-1} compared to 3120 kg N ha^{-1} for a field of the same area without the trees. N levels would be 1300 kg ha^{-1} higher in the field with *F. albida* compared to that without. Using a decomposition constant of 0.03 as for soils in Savanna areas (Young, 1989), this would give an annual mineralization due to the presence of *F. Albida* of 39 kg N ha^{-1}. This is equivalent to the N content in 390 kg of D- Compound fertilizer (N: P_2O_5: K_2O, 10:20:10). The C: N ratio was 11 under the canopies and 14 outside the canopies' edges, and reflected the higher N levels under the canopies. This shows that the nitrogen is more readily available under the canopy than outside. The OC level was 1.58% in the inner radius and 1.21% in the outer radius. Organic carbon was therefore 30.5% higher under the canopy as compared to outside the canopy. This would be equivalent to 41080 kg OC in a 1 hectare field with a 100 mature *F. albida* trees compared to 31460 kg OC for a similar field without the trees. These results were similar to those obtained by Charreau and Vidal (1965) who reported a remarkable fertility gradient from bare soil to

Table 1. Estimates for effect of radial distance from tree for four types of nutrients using linear mixed model.

Organic C/ nutrient	Fixed effects			Random effects variance	
	Estimate	Standard error	P-value	Tree (intercept)	Residual
Organic carbon	-0.2985	0.0032	<0.0001	0.2305	0.0938
Nitrogen	-0.003033	0.001028	0.0032	0.005	0.01
Potassium	-0.015573	0.001389	<0.0001	0.0375	0.0178
Phosphorus	-0.04577	0.1221	0.7077	429.29	136.43

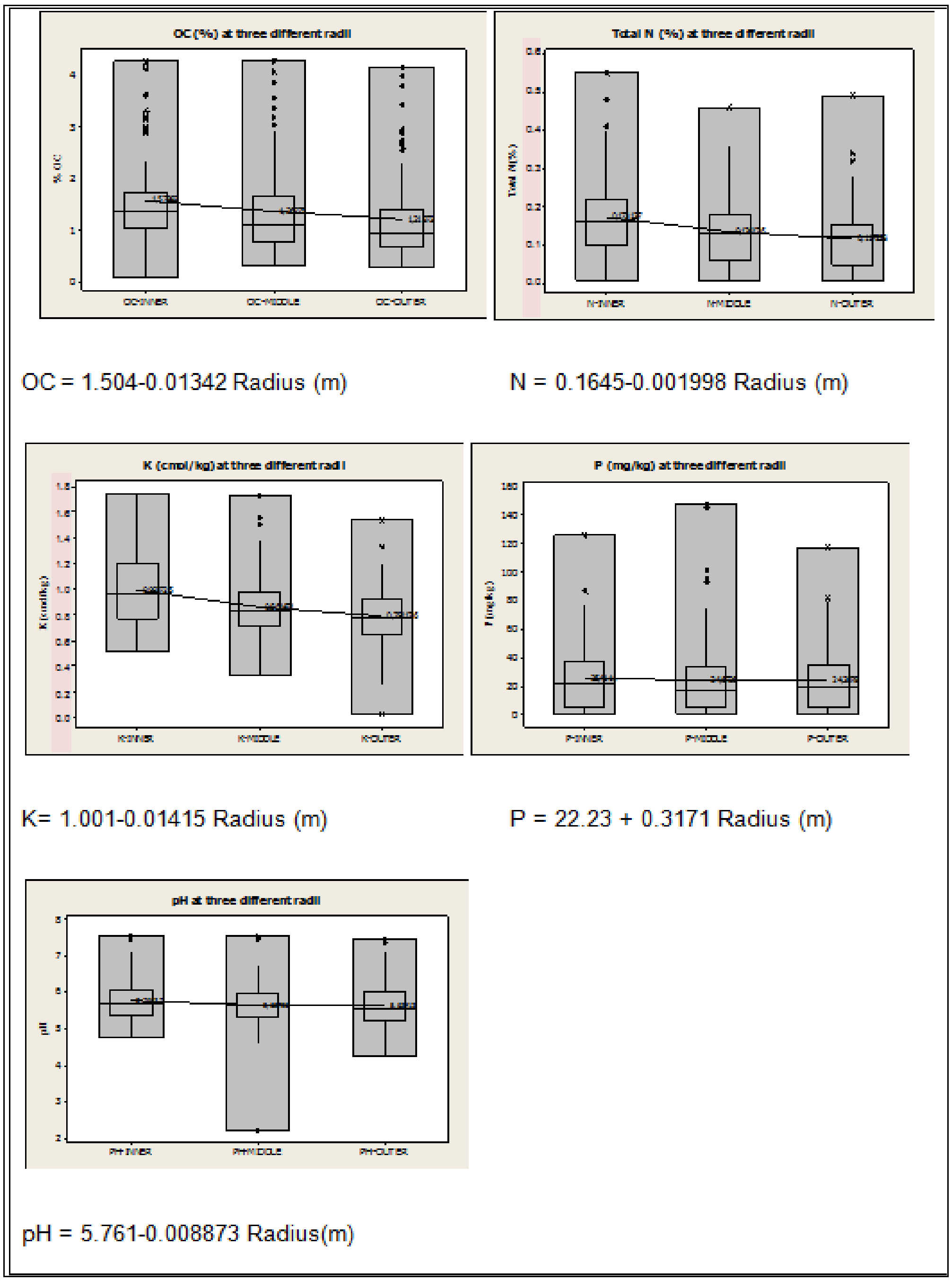

Figure 2. Box plots for P, K, OC, N and pH showing mean levels and distribution.

Table 2. Nutrient levels at different radii from *F. albida.*

Parameter	Inner radius (N=102)	Middle radius (N=102)	Outer radius (N=102)	p - value
pH ($Cacl_2$)	5.77[a] (0.095)	5.66 [a](0.126)	5.63[a] (0.128)	0.283
Nitrogen (%)	0.17[a] (0.014)	0.14[b] (0.009)	0.12[b] (0.009)	0.0001
Organic carbon (%)	1.58[a] (0.074)	1.36[ab] (0.061)	1.21[b] (0.057)	0.009
C:N ratio	10.95[a] (1.38)	12.92[ab] (1.20)	13.84[b] (1.76)	0.031
Phosphorus (mg/kg)	25.41[a] (3.80)	24.67[a] (5.24)	24.31[a] (3.82)	0.944
Potassium (cmol/kg)	0.99[a] (0.041)	0.86[b] (0.030)	0.79[c] (0.028)	0.0001

The values in parentheses are standard errors. [a,b] means in the same column followed by the same letter were not significantly different at p≤ 0.05.

Table 3. Nutrient levels under *F. albida* based on district.

Parameter	Radius	Chipata (N= 24)	Petauke (N=21)	Monze (N=156)	Sinazongwe (N= 105)	p- value
pH ($Cacl_2$)	Inner	5.76	5.85	5.70	5.75	0.884
	Middle	5.79	5.74	5.58	5.64	
	Outer	5.65	5.82	5.57	5.63	
	P- Value	*0.174*	*0.816*	*0.596*	*0.429*	
Organic Carbon (%)	Inner	2.78	3.62	1.28	1.35	0.0001
	Middle	2.61	3.37	1.14	1.0	
	Outer	2.15	3.39	0.94	0.94	
	P- Value	*0.111*	*0.993*	*0.001*	*0.007*	
Phosphorus (mg/kg)	Inner	22.19	31.06	18.9	30.12	0.260
	Middle	21.1	35.06	22.23	24.55	
	Outer	21.1	33.56	19.14	27.67	
	P- Value	*0.615*	*0.929*	*0.879*	*0.255*	
Potassium (cmol/kg)	Inner	0.81	1.11	0.10	0.95	0.002
	Middle	0.73	0.90	0.85	0.85	
	Outer	0.62	0.88	0.79	0.79	
	P- Value	*0.056*	*0.136*	*0.0001*	*0.003*	
Nitrogen (%)	Inner	0.22	0.29	0.15	0.17	0.0001
	Middle	0.17	0.25	0.12	0.12	
	Outer	0.15	0.26	0.10	0.10	
	P- Value	*0.008*	*0.819*	*0.555*	*0.012*	

The vertical p values are from comparisons among the four districts for the listed parameters while the horizontal ones are from the mean separation of the nutrient levels for each district.

soils under the canopies of *F. albida* in Senegal. OC improves the water holding capacity of the soil (Katyal et al., 2001; GART, 2008). A study conducted in the low rainfall areas of Monze and Lisutu of Southern Zambia reported organic matter levels that were on average 1% higher under the canopies than outside (GART, 2008). The N levels were 43% higher under the canopies than outside. The authors argued that this contributed to improved productivity under the canopies.

Soil organic matter (SOM) improves water holding capacity, increases plant nutrient and moisture availability and reduces soil erosion (Woomer and Swift, 1994; Lal 2006). Continuous cropping, crop residue removal and tillage reduce SOM. In light of the challenges associated with crop residue retention reported in smallholder farming systems in SSA (Giller et al., 2009; Lal, 2006;

Chivenge et al., 2007) and Zambia in particular (Umar et al., 2011), incorporation of *F. albida* into CA could go a long way in increasing SOM through leaf and pod litter. SOM content of 3.2 and 2.4% under and outside the canopies respectively reported during this current study were higher than what has generally been reported in Zambian soils (Stromgaard, 1984; Lungu and Chinene, 1999). GART (2008) reported SOM levels of 2.2% under *F. albida* canopies and 1.1% at 5 m outside the canopies. Such high SOM levels coupled with the low C: N ratio under the canopies would significantly improve crop yields under the canopies by making N more available and improving soil moisture retention. This would help resource constrained smallholder farmers to increase their crop production while reducing dependency on externally procured mineral fertilizers.

In a study of *F. albida* and its effects on Ethiopian Highland Vertisols, Kamara and Haque (1992) found a significant inverse relationship between SOM, N, P, K concentration and distance from the tree. The *F. albida* did not seem to influence soil reaction (pH) and the exchangeable cations Na, Ca and Mg. The build-up of SOM, N, P and K under the tree canopies was attributed to the *F. albida* litter fall and accumulation. They found N and P contents in the fresh leaves and twigs to be 3.85% N and 0.3% P for the leaves and 1.27% N and 0.2% P for twigs. Hadgu et al. (2009) found clear differences in total nitrogen, SOM and available phosphorus under and away from the canopy in their study of traditional *F. albida* based land use systems of northern Ethiopia. GART (2008) reported similar N content (3.6%) in *F. albida* leaves. GART (2007) estimated that a six year old tree was capable of shedding off 500 kg of leaf dry matter and equated this to the application of 18 kg nitrogen per hectare. The trees in this study were older with much larger canopies and shed off more leaves than the trees reported on by GART (2008). This coupled with the biological nitrogen fixation in the roots resulted in the higher value of 39 kg N ha^{-1} attributed to the presence of *F. albida* in this current study.

At several sites in Malawi, carbon and total nitrogen were from 3 to 30% and from 5 to 29% respectively higher beneath F. *albida* canopies while exchangeable K, Ca and Mg were also higher beneath tree canopies (Saka et al., 1994). In an on-farm field experiment in Niger, Kho et al. (2001) estimated the nitrogen and phosphorus availability under *F. albida* trees to be more than 200 and 30%, respectively higher under the canopies than outside.

Potassium levels in the soils under the canopies were higher than those outside the canopies by 25%. This represented levels of 1007 kg K ha^{-1} and 802 kg K ha^{-1} under and outside the canopies respectively. Under a full stand of the tree, K levels would on average be higher by 202.8 kg K ha^{-1} compared to a field without the trees. This is equivalent to the K contained in 2443 kg of D-Compound fertilizer which is the nationally recommended basal dressing fertilizer in Zambia. In a study on the ecology of *F. albida* in Sudan, Radwanski and Wickens (1967) found that the uppermost horizons of the soil profiles under *F. albida* contained more OC, N and P but less K that those outside the canopies.

In this study, the P levels were high regardless of distance from the tree (p = 0.944) and there was no clear effect of distance from the canopy and the P level in the soil. Dabin (1980) and von Uexkull (1986) contended that the nature of the parent rock, soil reaction (pH), the presence of P fixing compounds such as sesquioxides, the nature and amount of organic matter in the soil were important factors in the P available dynamics of soils. Review of the results of the on-farm trials which had been conducted by GART (2008) in Magoye and Lusitu areas of Southern Zambia during this current study found no statistically significant differences in the P levels from soils under and outside the *F. albida* canopies (p = 0.44). The P levels under and outside the canopies were as high as 27.65 and 29.54 mg kg^{-1} respectively. The authors attributed this to the increased solubility of P at high pH which at between 6 and 7 was reported to be optimal. The contrasted effects of the P in this study and those of others (for example, Radwanski and Wickens, 1967) may point to the importance of other factors in the environment which may mask the effects of the *F. albida*. For instance, no significant differences were found in the soil nutrient pools beneath and outside the *F. albida* canopies on the lakeshore plains of Malawi. This was attributed to the high natural fertility of the alluvial soils which along with the soil mixing during tillage activities may have masked the nutrient enrichment associated with the trees (Rhoades, 1995). P levels could also vary based on individual soil types although we did not analyze this aspect during this current study.

Many of the reported benefits of the nutrient accumulation and yield benefits under the canopy over *F. albida* assume that there is a complete canopy cover of the tree. This is, however, rarely the case and it is, therefore, easy to overestimate the real benefits of *F. Albida* when calculating nutrient accumulation and production benefits per unit area. For this study, the average number of *F. albida* trees per household was 18 during the 2006/2007 farming season. This figure doubled by the 2008/2009 farming season but the added trees were still too immature to contribute any significant amounts of nutrients. Thus, the estimated amounts of N, OC and K added to the soil based on the actual number of mature trees is 234 kg ha^{-1} N, 1732 kg ha^{-1} OC and 37 kg ha^{-1} K. It can thus be seen that the actual accumulated nutrients levels were less than would be expected under full canopy. The households found it challenging to achieve the recommended 100 trees per hectare due to low access to planting material (either seeds or seedlings); low survival rate and susceptibility to browsing by livestock of the young trees; and termite attacks.

Crop production in the tropics is often limited by the availability of soil P. Highly weathered soils in the tropics, such as Ferralsols, Acrisols, and Luvisols, as well as Gleysols and Vertisols are generally deficient in P. Cambisols show average P deficiency while Fluvisols and Nitosols often show low to no deficiency (Dabin, 1980). Potassium levels greater than 10 mg kg^{-1} are considered high for tropical soils (Aune and Lal, 1997). The P levels reported in this study were, therefore, relatively high. The high available P in this study may be attributed to the presence of carbonaceous minerals in the parent rock as interviews with the owners of the fields in which the trees were found revealed almost a complete lack of mineral fertilizer application under and outside the tree canopies and the high P could, therefore, not be attributed to mineral fertilizer amendments. A search of the literature on available P levels in Zambia did not reveal any results showing low available P levels. Yet numerous projects aimed at *inter alia* increasing the low levels of available P in Zambian soils have been and continue to be implemented. This alludes to the need for knowledge on local soil conditions before promotion of technologies premised on regional or national soil nutrient estimates.

The soil reaction (pH) showed insignificant variations with increasing radius from tree with an average of 5.8 under the canopy and 5.6 for outside the canopy. Since the values were higher than 5 at all radii, the soils are suitable for production of most tropical crops (Aune and Lal, 1997). These results are similar to those obtained by GART (2008) which found that soil reaction (pH) under the canopies was generally similar to that away from the canopies and ranged between 5.3 and 7.0. Kho et al. (2001) estimated that N available from the *F. albida* caused a production increase of 26% in millet while the phosphorus availability was estimated to cause a production increase of up to 13%. GART (2008) reported yield responses due to *F. albida* in groundnuts, sorghum, cowpeas and maize. Maize yields were 3 tons ha^{-1} under *F. albida* canopies and only 2 tons ha^{-1} outside the canopies. From Senegal it was reported that the yield of pearl millet was 2.5 times higher under the canopy of *F. albida* than outside the canopy (Charreau and Vidal, 1965). The N and OC additions from *F. albida* reported in this current study could result in similarly higher yields under the canopies. These yields would be higher than the average yields of only one ton ha^{-1} currently achieved by smallholder farmers without the benefits of *F. albida* and low levels of mineral fertilizer application.

Effect of district

There were statistically significant differences in the N, OC, and K based on district (and province) but not for soil reaction (pH) and P. Chipata and Petauke districts (Eastern Province) had significantly higher N in soil compared to Monze and Sinazongwe (Southern Province) ($p = 0.0001$). The mean N level for Chipata and Petauke was 0.18 and 0.25% respectively while that for Monze and Sinazongwe was 0.14 and 0.13% respectively (Table 3).

The OC levels in the samples from Chipata and Petauke were significantly higher than those from Monze and Sinazongwe ($p = 0.0001$). With mean values of 2.51 and 3.31%, these soils are considered to be rich and productive. For K, Chipata had significantly lower levels than the other three districts ($p = 0.002$) while no significant differences were observed among the other districts. The higher levels of plant nutrients observed in Eastern Province could be attributed to the higher rainfall received there compared to Southern Province which promoted higher crop and biomass production and resulted in higher soil water holding capacity (GART, 2008). Moisture stress probably reduced biological N yield in Southern Province as the province is a drought prone region. It could also be possible that there were genetic differences among the trees found in the two provinces and more research on this could help better explain this observation. Values of over 20 mg/kg available P were observed in all the districts. The variations within districts were also quite large.

F. albida trees can be particularly important in the Southern Province as the soil organic carbon and N levels were the lowest here. In this Province, there is also more livestock and more competition for use of crop residues as fodder. The SOM additions from the tree are therefore more critical in enhancing soil moisture retention in this Province. Another opportunity for promotion of *F. albida* in the Southern Province is that most local communities there are already aware of its soil fertility improving benefits and as a source of dry season fodder for their livestock. This is different from the situation in the Eastern Province where it was reported that most CA farmers were unaware of the tree’s benefits and most of them had cut it down from their fields (personal communication with senior CFU staff).

Effect of cultivation and presence of dung

No significant differences in nutrient levels were observed due to cultivation under the trees ($p = 0.711$). Out of the 102 trees sampled, 97 had soils which had been cultivated under them while no evidence of cultivation was found for the soils under the remaining 5 trees. Mean values for OC, N and K for soils under *F. albida* trees where dung was observed under the tree canopies were not statistically different from the values from under the tree canopies with no visual evidence of dung at 5% level of significance ($p = 0.059$). Only 11 out of the 102 trees were observed to have dung under their canopies. The low incidence of dung found under the *F. albida* trees could have been because, in some cases, the fields in which the trees were found had been fenced off to keep livestock out, the dung may have been incorporated into the soil during tillage, or the trees were very far from homesteads and out of reach of free range livestock. Sturmheit (1990) contended that most farmers of Southern Zambia perceived leaf drop from *F. albida* less important for soil improvement compared to the effects of livestock dung which accumulated under the tree when livestock sought shade there and relished its pods during the hot dry season. However, during this study, all the farmers talked to and anecdotal evidence attributed the better performance of crops under *F. albida* to the tree itself.

In this study the results seem to show that the higher N, OC and K levels observed under the *F. albida* trees' canopies were due to the presence of the trees which improved the nutrient economy of the soils through biological nitrogen fixation and litter fall and not due to presence of dung. Similarly, Charreau and Vidal (1965) reported crop yield increase in an area from which livestock had been excluded for a number of years and attributed this to the leaf litter provided at the start of the rainy season when it could readily be decomposed or mineralized.

Conclusion

The results revealed that mature *F. albida* trees supplied significant amounts of N, OC and K to the soils under their canopies resulted in a clear fertility gradient for these nutrients. The N, OC and K levels were 42, 31 and 25% respectively higher under the canopies than outside. There were no significant differences in the P levels and soil reaction (pH) based on radius and district. The SOM addition through litter fall is an important alternative to the SOM from crop residues which are routinely removed from the fields after harvest and put to alternative uses. For these reasons, use of the tree could be promoted among smallholder conservation agriculture farmers in the areas where mature stands exist and planting of new trees in other areas could also be encouraged as is already being done by the CFU in Zambia. This would supplement the nutrient additions that are made through mineral fertilizer application and rotations with annual leguminous crops. More efforts could be expended on the promotion of *F. albida* in areas where mature stands already exist than in the promotion of new stands of *F. albida* since establishment of trees is time consuming in terms of planting and protection of new stands. In addition, it takes at least 15 to 30 years before the full benefit of new planting can be reaped. However, new planting can still be an alternative where population density of *F. albida* is low. Insecure land tenure may also discourage farmers from planting and protecting new stands of *F. albida*. Planting of *F. albida* trees is thus an option for the households that have secure tenure to their land. The existence of already mature stands would save labour and time commitments inherent in the establishment of young *F. albida* seedlings and the long time it takes for the tree to mature and provide substantial benefits to farmers that are eager for immediate gains and may not have the land tenure security to invest in soil improvements that take years to show benefits. There is also a need for more local soil analyses to have a better idea of what nutrients are in very limited supply and in need of immediate replenishment instead of relying on estimates calculated from elsewhere.

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