International Journal of Agriculture Innovations and Research
Volume 4, Issue 5, ISSN (Online) 2319-1473

Nutrient Availability Following Planted Tree Fallows and Benefits to Subsequent Maize Crops

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***Abstract* – The effect of a two-year Sesbania and Tephrosia fallow on soil properties and growth of subsequent maize was examined in Zambia. The study was conducted on 18 sites laid in a randomized complete block design with farmers as replicates. The treatments were: Sesbania fallow, Tephrosia fallow, grass fallow, maize with and without fertilizer. Standing biomass plus litter after two years ranged from 5 to 49 mgha^{-1} for Sesbania and from 3 to 16 mgha^{-1} for Tephrosia. Both trees increased topsoil inorganic N and anaerobic N mineralisation, as compared to a two-year uncultivated fallow with regrowth of native vegetation and unfertilised maize monoculture. Topsoil inorganic N after Sesbania was directly related to Sesbania biomass (r^2=0.80). The yield of unfertilised maize was increased an average of 75% in the season after harvest of Sesbania and 43% in the season after Tephrosia. The residual benefit to maize generally lasted for two cropping seasons after Sesbania and one cropping season after Tephrosia. The magnitude and duration of the residual benefit from Sesbania was directly related to biomass at harvest. We conclude that farmers can use N_2-fixing trees to enhance soil properties and improve maize yield in the subsequent season.**

***Keywords* – Tree Fallows, Nutrient Availability, Maize Yield.**

I. INTRODUCTION

Producing more food for a growing population in the coming decades while at the same time compacting hunger and poverty is a huge challenge facing African agriculture [1]. Crop yields in Africa have been increasing, but largely driven by expansion of cultivated land (extensification) rather than by increasing yield per hectare (intensification). The average grain yields of major crops in sub-Saharan Africa (SSA) have been around 1 ton per hectare since the 1960s compared with an average yield of 2.5 tons hectare in Asian and 4.5 tons per hectare in East Asia [2].

The uncertainty of obtaining higher crop yields is further threatened by climate change and vulnerability [3]. Many farmers grow the same crops year after year on the same plot of land without adequate fertilization or soil replenishment measurements [1], [4]. Fertilizers are very expensive, unavailable and unaffordable to smallholder throughout SSA and use is very low around 8-13 kg/ha in most countries [5]. Commercial fertilisers have been widely used as external nutrients in Asia, and on commercial farms in SSA. However, very small amounts have been used by small-scale farmers. With removal of subsidies on fertilisers, small-scale farmers cannot afford inorganic fertilisers. Other problems associated with low fertiliser use by farmers are untimely delivery, high transport costs and unavailability in most cases. Currently, SSA accounts for less than one percent of global fertilizer consumption. The use of fertilizers by smallholder farmers is not economically feasible due to high prices and supply logistics. The consequences of this are land degradation, low yields, persistent poverty and wild spread malnutrition [6]. Hundreds of thousands of rainfed farmers in Zambia, Malawi, Niger and Burkina Faso have been shifting to farming systems that are restoring exhausted soils and increasing crop yields, household food security and incomes using what is called evergreen agriculture or agroforestry practices [1]. Evergreen agriculture is defined as the integration of particular tree species into annual food crop systems [1]. This approach increases food security and environmental resilience.

Cultivation with long duration fallow periods sustained low but relatively stable production of food crops in Africa. Shifting cultivation in Zambia have disappeared as increasing population density and pressure for land use led to intensive, sedentary agriculture on small-scale land holding and expansion of agriculture into marginal areas.

One promising system for the improvement of soil fertility is by the use of short duration tree fallows planted with fast growing N_2 fixing trees [7]. These trees improve soil fertility through biological nitrogen fixation [8], by recycling nutrients from the subsoil [9], [10]. Reference [11] showed that tree fallows planted with Sesbania sesban (L) Merr and other tree legumes increased soil inorganic N and N mineralisation. Sesbania fallows of two years duration increased maize grain yield by 3.8 tha^{-1} on N-depleted soils in Zambia. Nitrogen is the most limiting nutrient to maize productivity in southern Africa.

This study was done to determine the effect of two perennials, Sesbania and Tephrosia, grown for two years on diverse soils, on biomass production, available soil nutrients and yield of subsequent maize crops. It also tested the relationships between tree biomass production and changes in soil nutrients and yield of maize.

II. METHODOLOGY

A. Site Description

The study was conducted on 18 sites in eastern and central Zambia. These sites were chosen based on soil types, texture and rainfall amounts. The amount of rainfall received ranged from 550 mm to 1500 mm across the three seasons. The rainfall at these sites is unimodal, most of it coming between December and March.

B. Experimental Design and Management

The study was initiated in 1993. The experimental design used was a randomised complete block design with farmers as replicates. The treatments were: Sesbania (provenance Kakamega) fallow, Tephrosia (provenance Misamfu) fallow, grass fallow, maize with fertiliser and maize without fertiliser. Tephrosia fallows were established by direct seeding while Sesbania fallows were established using 8 weeks old seedlings. The spacing of trees in the fallows was 1 x 1 m. Weeding was done in the first year of establishment at all sites. The fallow trees grew for two years before clearance of the fallows was done in November 2005 by cutting trees at ground level. The trees were left in the plot for two weeks to shed remaining leaves. Wood from the plots was removed and used by the farmers.

C. *Plant Sampling for Trees*

A net plot of 32 m^2 with 32 trees was used. Six representative trees were taken to measure leaf and wood biomass. Plant sub-samples of 500 g and 1 kg were taken to determine leaf and stem dry matter at fallow clearance surface litter using 3 quadrants of 2 m x 1 m. Sub samples of 1 kg were also taken for drying at 65^{o}C for dry matter determination. Leaf and litter biomass of tree fallows were incorporated into the soil at land preparation for cropping.

D. *Soil Sampling and Analyses*

Initial soil samples were collected in October 1993. Further samples were collected two years later at fallow clearance and one year during the cropped phase in October. The soil samples were collected with an Edelman auger from a depth of 0 – 15 cm. In each plot, soil was collected and bulked from 20 locations sub samples were taken to the laboratory and stored at 4^{o}C prior to extraction. About 20 g soil was extracted with 100 m L of 2 mKcl. The samples were shaken on a horizontal shaker at 250 oscillations min^{-1}, filtered through the Whitman No. 5 filter paper and frozen until analysis. A second subsample of soil was dried at 105^{o}C for 24 hours to determine the dry weight of extracted soil. All results were expressed on an oven dry weight soil basis.

Ammonium-N was determined on the extracts by salicylate-hypochlorite calorimetric method [12]. Nitrate-N was determined by cadmium reduction [13] and subsequent calorimetric analysis of nitrate. The sum of ammonium nitrate and nitrate-N is referred as total inorganic N in the text.

Anaerobic N mineralisation potential was determined by a 7-day incubation of flooded soils at 40^{o}C, as described by [14]. Anaerobic N mineralisation was calculated as the difference between the ammonium extracted from incubated and non-incubated samples, expressed as mgN 1 kg^{-1} dry soil.

E. *Maize Crop Management*

The fallow plots were cropped for 3 years using a maize hybrid MM604 at a spacing of 75 cm x 30 cm. Maize was planted on ridges at all sites except at Masumba where it was planted on flat. Ridging was done at planting and re-ridged at weeding time. Compound D (10: 20: 10 – N: P: K) was applied at the rate of 250 kgha^{-1} as basal dressing fertiliser in the fertilised plot only. Urea (46% N) was applied to fertilised maize at the rate of 168 kgha^{-1}. Maize was grown for 2 seasons at all sites and 3 seasons at selected sites which showed residual potential after the second season. Maize stover was always removed from the plots to avoid livestock interference with the plots. The plots were left undisturbed until November when they were prepared for maize planting.

A net plot of 2013.5 m^2 was used to measure maize yield components. A representative sample of 20 cobs was taken to determine maize grain yield which was expressed at 13% moisture content.

F. *Statistical Analyses*

Analyses of variance were conducted using Genstat version 5 [15]. Simple correlation's coefficient based on plot data were determined for linear relationship between soil N, tree biomass and maize yield. Results are considered statistically to be significant when $P \leq 0.05$.

III. RESULTS

The 18 sites in Zambia represented a range of soil textures. Eight of the 18 sites had exchangeable K below the critical value of 0.15 cmol$_c$ kg^{-1}. Based on work in western Kenya the site with 0.04 cmol$_c$ kg^{-1} (Chipata 5) was probably K limiting. At the other sites with K between 0.10 and 0.15 cmol$_c$ kg^{-1}, K would likely not be limiting yield until the N and P deficiencies were totally eliminated. The results in 5 highlight that K could become limiting at many locations, and fallows could play an important role in alleviating potential K problems and N deficiency is overcome.

Six of the 18 sites had extractible P below the critical value of 5 mg kg^{-1}. This is not nearly as severe as a P deficiency in western Kenya, and it does not contradict earlier conclusions that N is the most limiting nutrient in eastern Zambia. It does, however, suggest that P could become a problem when N deficiencies are overcome. Hence, we need to know whether fallows can contribute to increasing P availability by increasing the P in labile fractions of soil organic matter.

Tree Biomass

There was large variability in biomass production of Sesbania and Tephrosia across sites (Table 1). Sesbania produced twice the amount of leaf biomass compared to that of Tephrosia. However, there were no significant differences between the two species on the litterfall at fallow clearance.

Total standing biomass at fallow clearance of Sesbania was four times that of Tephrosia (Table 1). Sesbania standing biomass was directly related in clay content (R^2 = 0.50, Fig 1). Higher tree biomass was obtained on soils with higher clay content (Fig 1). However, this relationship did not hold for Tephrosia (r^2 = 0.00).

Table 1. Standing biomass of fallows after two years (18 locations in Zambia)

Treatment	Standing biomass (t ha^{-1})		
	Average	Minimum	Maximum
Sesbania fallow	13	3.9	43
Tephrosia fallow	3.9	1.5	9.0
Grass fallow	5.3	2.9	9.5

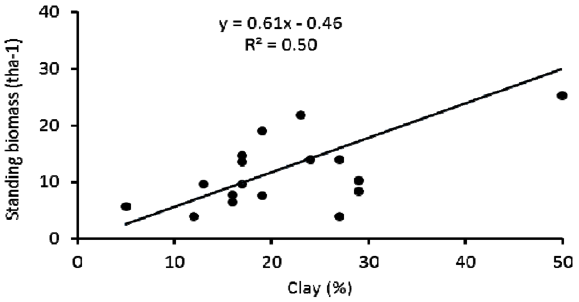

Fig. 1. Relationship between topsoil clay content and Sesbania standing biomass (Zambia, 95/96 season)

Maize Grain Yields After Fallows

The fallows had significant effect on maize grain yield during the cropping phase (Table 2). In the first cropping of Sesbania significantly higher maize yields were obtained compared to Tephrosia. Tephrosia gave higher maize grain yields compared to grass fallow. There was no significant yield differences between grass fallow and unfertilised maize grain yield. In the second and third year of cropping maize grain was in this order: Sesbania > Tephrosia = grass fallow = unfertilised maize. There were no significant differences among treatments in the third year of cropping. Maize grain yield was directly correlated to tree biomass in N (Table 2) and preseason inorganic N (Figure 3) in Sesbania fallows. However, this relationship was not observed in Tephrosia fallows.

Table 2. Effect of fallows on maize grain yield (18 locations in Zambia)

Land use	Maize grain yield (t ha^{-1})		
	Fallow harvest	1 year	2 years
Sesbania fallow	3.9	1.7	1.1
Tephrosia fallow	2.4	0.8	0.9
Grass fallow	1.1	0.7	0.7
Unfertilized maize	1.0	0.7	0.6
LSD (0.05)	0.8	0.6	0.6

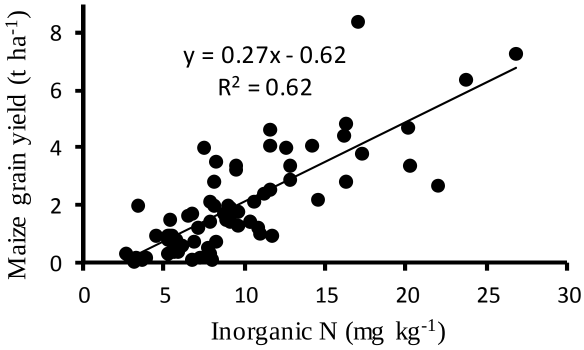

Fig. 2. Relationship between preseason topsoil inorganic N and maize yield (18 locations in Zambia, 95/96 season)

Effects of Fallows on Soil Inorganic N and Potassium

Sesbania and Tephrosia fallow plots had significantly higher amounts of ammonium N compared to grass fallow and unfertilised plot at fallow clearance (Table 3). The same trend was observed in the first year of cropping. The trend was: Sesbania > Tephrosia = grass fallow > unfertilised plots. In the third year of cropping Sesbania has the significantly higher amount of ammonium – N than the other treatments. Nitrate N was in the order of Sesbania = Tephrosia = unfertilised > grass fallow at fallow clearance. Sesbania had significantly higher nitrate N than the rest of the treatments in the first cropping (Table 3).

Table 3. Effect of fallows on inorganic N in topsoil (18 locations in Zambia)

Land use	Maize grain yield (t ha^{-1})	
	Fallow harvest	1 year
Sesbania fallow	13.4	13.4
Tephrosia fallow	10.9	10.0
Grass fallow	6.6	8.4
Unfertilized maize	7.8	7.1
Significance level	<0.001	<0.001

In the second year of cropping Sesbania > Tephrosia = grass fallow > unfertilised maize. In the third year Sesbania > Tephrosia = grass fallow = unfertilised maize plots in terms of soil nitrate levels.

Total inorganic N was significantly higher in Sesbania > Tephrosia > grass fallow = unfertilised maize plots at fallow clearance (Table 3). The trend was this order: Sesbania > Tephrosia = grass fallow. However, Tephrosia had significantly higher total inorganic N that unfertilised maize plots. In the second year Sesbania > Tephrosia = grass fallow > unfertilised maize plots. The same trend was observed in the third year of cropping except that unfertilised maize plots had similar amounts of total inorganic N as Tephrosia.

There were no significant differences among treatments on anaerobic N mineralisation rates at fallow clearance (Table 4). In the first year of cropping Sesbania > Tephrosia = grass fallow > unfertilised maize plots. Unfertilised maize plots had significantly lower mineralisation rates than the rest of the treatments which showed no significant differences among themselves. The trend was observed in the second year of cropping. In the third year Sesbania > grass fallow > Tephrosia = unfertilised maize plot. At fallow clearance there were no significant differences among treatments on potassium in the soil (Table 5). In the first year of cropping Sesbania = grass fallow > unfertilised maize plots. The same trend was observed in the second year of cropping. In the third year Sesbania = grass fallow > unfertilised maize plots.

Table 4. Effect of fallows on anaerobic N mineralization (18 locations in Zambia)

Land use	N mineralization (mg kg^{-1} day^{-1})	
	Fallow harvest	1 year
Sesbania fallow	2.4	3.1
Tephrosia fallow	2.1	2.3
Grass fallow	2.4	2.4
Unfertilized maize	2.0	1.6
Significance level	0.29	<0.001

Table 5. Effect of fallows on exchangeable K (18 locations in Zambia)

Land use	Exchangeable K ($cmol_c$ kg^{-1})	
	Fallow harvest	1 year
Sesbania fallow	0.32	0.39
Tephrosia fallow	0.30	0.33
Grass fallow	0.34	0.40
Unfertilized maize	0.29	0.27
Significance level	0.10	<0.001

The Relationship Between Fallow Tree Biomass with Maize Grain and Soil Organic Nitrogen

The inorganic N was determined in the top 15 cm in October 1995 at the end of the fallows. The maize yield is for the next season (1995/96). Figure 3 combines data for all four treatments.

The increase in maize yield in the first season after Sesbania (Figure 3) and the second season after Sesbania (Figure 4) was directly related to the standing biomass of Sesbania at the end of the fallow. The intercept of 4.5 tha^{-1} tree biomass in Figure 4 suggests that more than 4.5 tha^{-1} of Sesbania standing biomass is required in order to obtain a residual benefit to maize in the second season after the fallow.

Maize grain yield increase is determined as the yield after Sesbania minus the yield after continuous unfertilised maize. The increases in yield with Sesbania were greater in the first season after the fallow (up to 6.6 tha^{-1}) than in the second season after the fallow.

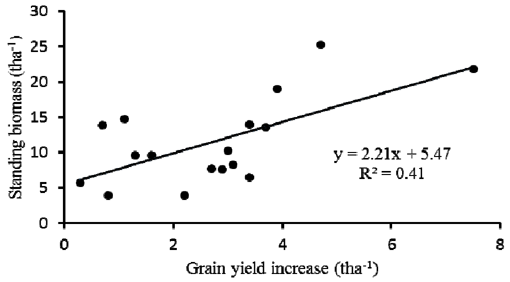

Fig. 3. Relationship of maize yield increase one season after fallow and Sesbania biomass (Zambia, 95/96 season; reference = grass fallow)

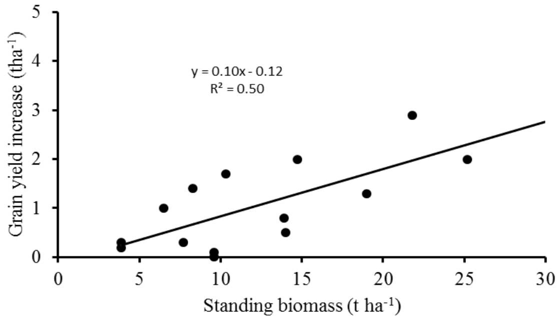

Fig. 4. Relationship of maize yield increase two seasons after fallow and Sesbania biomass (Zambia, 96/97 season; reference = grass fallow)

The results of the relationship between increase in maize yield after Sesbania and the standing biomass of Sesbania are not altered when the grass fallow rather than continuous unfertilised maize is used as the control. Figure 4 shows results for the second crop of maize after Sesbania, and can be contrasted with the results in Figure 3.

With Tephrosia, in contrast to Sesbania, there was no direct relationship between the increase in maize yield and the standing tree biomass at the end of the fallow. A number of different correlations were conducted between maize yield in the two seasons after Tephrosia and biomass of various Tephrosia plant parts at the end of the fallows. In all cases, no strong direct relationship was obtained between maize yield after Tephrosia and Tephrosia biomass (Figure 5).

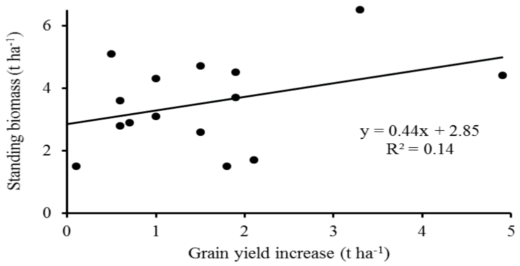

Fig. 5. Relationship of maize yield increase one season after fallow and Tephrosia biomass (Zambia, 95/96 season; reference = grass fallow)

The reason for the good relationship with Sesbania (Figures 2, 3 and 4) but not with Tephrosia (Figure 5) is not immediately evident.

Figure 6 further highlights the relationship between standing biomass at the end of a fallow and the yield of the subsequent maize crop. The relationship was good for Sesbania, suggesting that the fallow benefit of Sesbania was related to the biomass production of Sesbania. There was no comparable relationship with Tephrosia.

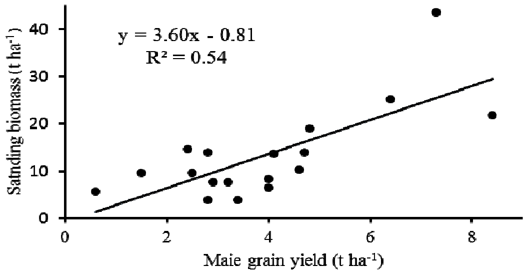

Fig. 6. Relationship between maize yield one season after fallow and Sesbania biomass (Zambia, 95/96 season)

The increase in inorganic N in the topsoil at the end of a Sesbania fallow was strongly related to the standing biomass of Sesbania at the end of the fallow (Figure 7). But soil inorganic N at the end of a Tephrosia fallow, as with maize grain yield after Tephrosia, was not directly related to the biomass of Tephrosia.

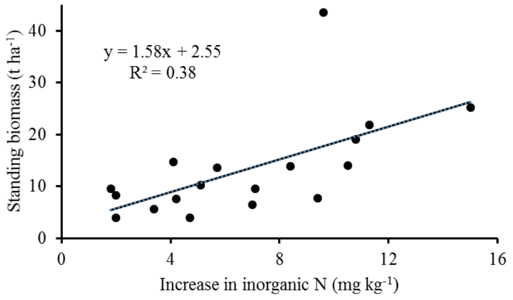

Fig. 7. Relationship between increase in topsoil inorganic N after fallow and Sesbania biomass (Zambia, October 1995; reference = grass fallow)

Tephrosia increased yield of a subsequent maize crop (Figure 8) and inorganic N (data not shown), although these increases were not as great as with Sesbania. The increases with Tephrosia, for unknown reasons, were not directly related to the standing biomass of Tephrosia at the end of the fallow. The relationship did not improve by using Tephrosia biomass after nine months rather than at the end of the two-year fallow (data not shown).

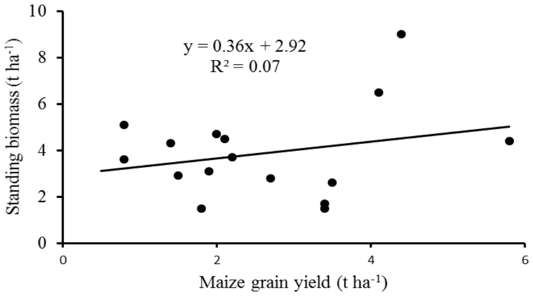

Fig. 8. Relationship between maize yield one season after fallow and Tephrosia biomass (Zambia, 95/96 season)

IV. DISCUSSION

The 18 sites in Zambia represented a range of soil textures. Eight of these sites had exchangeable K below the critical value of 0.15 $\mathrm{cmol_c\ kg^{-1}}$. This suggest that K can be limiting to maize productivity. Improved fallows would be important in regulating K in K depleted soils. Six of the 18 sites had extractable P below the critical value of 5 mg $\mathrm{kg^{-1}}$. This suggests that P could become a problem when other deficiencies are overcome. There is need to know improved fallows increase P availability by extracting P in labile fractions of soil organic P [16]. Improved fallows have been shown to overcome N deficiency [4], [17], [18]. From these results application source of organic K and P as suggested to increases maize yield after improved fallows [19], [20].

In this study the yield of maize was directly related to pre-season inorganic N in the top soil. Tephrosia increased the yield of subsequent maize crop and inorganic N. However, these increases were not as high as in Sesbania. These increases were also not related to the standing biomass of Tephrosia at the end of the fallow. This would be attributed to the low amount and low quality biomass produced by Tephrosia compared to Sesbania. These results agree with other studies from southern Africa which showed that maize yields was linearly correlated with top soil inorganic N after fallows [11]. Sesbania was more affected than Tephrosia in increasing inorganic N in the top 15 cm soil layer. This effect persisted for 2 years after fallows. The difference in the top soil N dynamics could be attributed to Sesbania producing higher amounts of high quality litter (high N, low lignin, polyphenols) compared to Tephrosia litter. This litter decomposes and mineralises rapidly to release a lot of inorganic N [21], [22].

The increase in maize yield in the first and second season after Sesbania was directly related to standing biomass at end of the fallow. From our results it can be concluded that more than 4.5 $\mathrm{tha^{-1}}$ tree biomass is needed from Sesbania in order to obtain residual benefit for maize in the second season after the fallow. The relationship between standing tree biomass and maize yield after fallows agree with results of [23]. With Tephrosia, in contrast to Sesbania, there is no direct relationship between increase in maize yield and standing tree biomass at the end of the fallow. This can be partially attributed to low amount of biomass and poor quality biomass produced by Tephrosia compared to Sesbania.

V. CONCLUSION

Both Sesbania and Tephrosia fallows increased topsoil inorganic N and mineralisation. Maize yield was directly related to preseason inorganic N. Sesbania standing biomass was directly related to topsoil inorganic N and yield of the following maize crop. Tephrosia standing biomass was not related to yield of the following maize crops. It can be concluded that 7 tha-1 of biomass will have a two year benefit on maize yield while greater than 9 tha-1 biomass will have benefit on the following maize crops for three years.

Since these fallows are providing N which is critical for plant growth in tropical soils, there is need to scale up such technologies. From these results, it can be realized that for scaling out Sesbania, clay content can be used as a biophysical indicator to map out areas where this technology can be scaled out. It would be important to map out these soils for greater impact on food security.

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Obert Jiri was born on 16 December, 1977 in Bikita, Zimbabwe. He is currently finishing his PhD in Climate Change Adaptation in Smallholder Farming Systems at the University of KwaZulu-Natal, South Africa. He holds a Masters in Agriculture (Agronomy, Soil and Forage Science) from the University of Zimbabwe as well as a BSc (Hons) Agriculture (Crop Science) from the same University. His research interests include climate change adaptation and mitigation, geotechnology, precision agriculture and integrated soil fertility management.