African Journal of Biotechnology Vol. 6 (13), pp. 1503-1508, 4 July 2007
Available online at http://www.academicjournals.org/AJB
ISSN 1684–5315 © 2007 Academic Journals

Full Length Research Paper

Nitrogen effects on maize yield following groundnut in rotation on smallholder farms in sub-humid Zimbabwe

Peter Jeranyama[1*], Stephen. R. Waddington[2], Oran. B. Hesterman[3] and Richard. R. Harwood[4]

[1]South Dakota State University, 224 SAG, Plant Science Department, Box 2207A Brookings, SD 57007;
[2]ICIMMYT, P.O. Box 6057, Gulshan, Dhaka 1212, Bangladesh.
[3]W.K. Kellogg Foundation, One Michigan Ave. East, Battle Creek, MI 49017.
[4]Department of Crop and Soil Sciences, Michigan State Univ., East Lansing, MI 48824 USA.

Accepted 10 April, 2007

Rotating maize (*Zea mays* L.) with groundnut (*Arachis hypogaea* L.) has been proposed as a way to maintain soil fertility and prevent maize productivity declines in the smallholder cropping systems of sub-humid Zimbabwe. Field experiments with fertilizer-N on maize in rotation with groundnut were conducted at three locations with sandy typic Kandiustalf soils. The specific objectives were to (i) evaluate the response to fertilizer-N of maize in rotation with groundnut compared with continuous maize and, (ii) determine the fertilizer-N replacement value of groundnut. Maize grain yields were increased up to 0.7 tha^{-1} following groundnut compared with continuous maize when no fertilizer was applied to both cropping systems. Maize yield response to fertilizer-N was higher after groundnut than continuous maize. The small groundnut yields were associated with little yield improvement for a subsequent maize crop. Fertilizer needs on maize were reduced by 0 - 64 kgNha^{-1} when maize followed groundnut.

Keywords: Maize, groundnut, smallholder cropping system, fertilizer-N replacement value.

INTRODUCTION

Declining soil fertility and crop productivity in the smallholder farms of sub-humid Zimbabwe is partly a result of continuous maize (*Zea mays* L.) production and partly due to inadequate nutrient inputs and management, exacerbated by unreliable rainfall distribution and marginal economics. Traditionally, African agricultural systems restored soil fertility lost during cropping by extended fallows with natural vegetation (Araki, 1993; Blackie and Jones, 1993). Increasing human population pressure on limited agricultural land has rendered fallowing to restore soil fertility a non-viable option, while continuous maize has become common on smallholder farms in Zimbabwe (Kumwenda et al., 1996, 1997). When cropped to sole maize, the sandy soils in these smallholder systems in Zimbabwe can supply only about 30 kgNha^{-1} per cropping season because of critically low levels of soil organic matter (Mapfumo and Mtambanengwe, 1999). Further N mineralization is dependent on annual organic inputs produced in crop residues (mainly groundnut and maize) and retained on the field or cycled through animals (as cattle manure). Continuous cropping of maize at a grain yield above 1 tha^{-1}yr^{-1} can not be sustained without frequent and substantial additions of mineral nutrients (Grant, 1970; MacColl, 1989), but the high cost and low availability of these inputs means that smallholders now use little. One alternative to reduce over-dependence on mineral fertilizers is to grow maize in rotation with a legume such as groundnut (*A. hypogaea* L). After maize, groundnut is the second most important crop for small-holder farmers in sub-humid parts of Zimbabwe and is widely recognized for its nutritive value, particularly for young children.

Legume-cereal rotations have long been recognized in southern Africa for restoring soil fertility and increasing crop productivity (MacColl, 1989; Mukurumbira, 1985). Rotations shift the biological balance in the soil, reducing build-up of pests and diseases and sustain productivity of the cropping system (Kumwenda et al., 1996). In a long-

*Corresponding author. E-mail: ngwevu38@yahoo.com. Tel: (1) 605-688-4754. Fax: (1) 605-688-4602.

Table 1. Soil properties at the beginning of the study at Chiduku, Chinyika and Domboshava, Zimbabwe, 1994.

Characteristic	Chinyika	Chiduku	Domboshava
Soil texture	**Sand clay loam**	**Loamy sand**	**Loamy sand**
pH ($CaCl_2$)	4.7	4.3	4.5
C (g kg^{-1})	13.5	5.2	4.6
Mineralizable N (mg kg^{-1})	41.6	18.6	24.1
P (micro g g^{-1})	3.6	4.2	4.0
K (micro g g^{-1})	8.3	3.0	-
CEC† (cmol kg^{-1})	8.3	3.1	1.9
TEB‡ (cmol kg^{-1})	8.5	6.4	5.2

†Cation exchange capacity.
‡Total exchangeable bases.

term maize-legume rotation trial in South Africa, unfertilized maize grain yields were improved by 2 tha^{-1} in rotation with field pea (*Pisum arvense* Poir) compared with unfertilized continuous maize (Nel et al., 1996). Groundnut in rotation can double the grain yield of the following maize crop under favourable management when groundnut residues are incorporated into the soil (Mukurumbira, 1985; McDonaugh et al., 1993), but benefits are far less in most farm situations. In small-holder farm experiments in Zimbabwe using low levels of inputs and management that represent farmer practice, Waddington and Karigwindi (2001, 2004) measured 44 - 48% maize grain yield increases in two cycles of a groundnut-maize-maize rotation.

Since the 1992/93 cropping season, the CIMMYT Maize Program in Harare has conducted a set of long-term experiments on crop productivity and soil fertility trends in maize-groundnut systems under current small-holder management (Waddington and Karigwindi, 2001, 2004).Two distinct agro-ecological zones, natural regions (NR) II and III (Vincent and Thomas, 1961), were chosen (A broad classification of Natural Regions is based on rainfall: NR I 900-1200 mm p.a NR II 750-900 mm p.a; NR III 650-750 mm p.a; NR IV 450-650 mm p.a and NR V < 450 mm p.a.). In our study we superimposed several N rates on the maize following groundnut and continuous maize in those experiments to (i) Evaluate the response to fertilizer-N of maize in rotation with groundnut compared with continuous maize, and (ii) determine the fertilizer-N replacement value of groundnut.

MATERIALS AND METHODS

Location and treatments

This experiment was established at Chinyika and Domboshava (both NR II), and Chiduku (NR III) smallholder areas. These represent sub-humid unimodal rainfall (800 - 900 mm in 5 months, 1300 - 1500 masl) maize cropping areas of east central Zimbabwe and have predominantly sandy loam and sandy clay loam soils derived from granite, classified as typic Kandiustalf. The sites have been cropped for various lengths of time, ranging from 14 years at Chinyika to over 70 years in Chiduku. Trophic soil properties were characterized at the beginning of the study in 1994 at each site (Table 1).

The experimental treatments (and cropping systems) in this study were; continuous maize with fertilizer, continuous maize without fertilizer, maize(Mz)-maize-groundnut(Gn)-maize rotation with fertilizer applied to maize only, and Mz-Mz-Gn-Mz rotation without fertilizer, and were fully described in Waddington and Karigwindi (2001). Fertilizer was applied at a rate of 275 $kgha^{-1}$ Compound D (8-14-7 N-P-K) as basal and a side dress of 70 kg N ha^{-1} as NH_4NO_3 so that total N-P-K applied was 92, 38.5 and 19.3 $kgha^{-1}$, respectively in all fertilizer treatments. In year four (when maize followed groundnut; 1996/97) the continuous maize with fertilizer and Mz-Mz-Gn-Mz with fertilizer cropping systems were further split into sub-plots and subjected to fertilizer applications of 0, 46, 92 or 138 $kgNha^{-1}$ as NH_4NO_3.

Maize 3-way cross hybrid 'R215' was hand-planted at two seeds per planting station on plots that had been mouldboard ploughed. Each sub-plot was 5 x 5.4 m with 6 rows of maize, planted at 0.9 m between rows and 0.5 m within rows, giving a plant population density of 44, 440 plants ha^{-1}. Basal fertilizer was applied at about one week after plant emergence (corresponding to farmer practice). Additional N fertilizer was applied as a surface dollop next to each plant station at V6 maize growth stage (Ritchie et al., 1993) when the soil moisture approximated field capacity.

Groundnut (*A. hypogaea* var. 'Spanish') was planted in rows 0.45 m apart and 0.25 m between planting stations in a row in the previous season. They were planted at two seeds per station, giving approxi-mately 160, 000 plants ha^{-1}. Because the 'Spanish' cultivars exhibit promiscuous nodulation in the soils under study and because small-holder farmers do not inoculate, seeds were not inoculated with rhizobia before planting.

Maize grain yield was harvested from a 2.7 x 3 m section of the three centre rows of each sub-plot, so that the area harvested was 8.1 m^2 and grain yield was adjusted to 125 gkg^{-1} moisture content. Total aboveground biomass of maize was measured from two adjacent middle rows from an area of 2.7 m^2 and dried at 60°C for at least 48 h to obtain dry matter yields.

Plant and chemical analysis

Total N in maize grain was determined by a modified micro-Kjeldahl method. Dry maize grains were ground in a Wiley mill (Thomas Scientific, Swedesboro, NJ) to pass through a 2 mm screen. Ground maize grain samples of 0.1 g were digested in 4 ml of 18 M H_2SO_4 with 1.5 g K_2SO_4 and 0.075 g Se catalyst. Following diges-

Table 2. Effect of cropping system on unfertilized maize grain yield at three locations in northern Zimbabwe.

Cropping system†	Maize grain yield (t ha^{-1})		
	Chiduku	Chinyika	Domboshava
Mz-Mz-Mz-Mz	0.71	0.39	1.62
Mz-Mz-Gn-Mz	0.77	0.68	2.36
CV (%)	4	26	20
Contrast			
Mz-Mz-Mz-Mz vs Mz-Mz-Gn-Mz	NS	*	*
Percent increase‡	8	74	46

†Underlined letter indicates year for yield. Mz = maize, Gn = groundnut.
*Significance at $P \leq 0.05$. NS = non significant at $P \geq 0.05$.
‡Refers to increase due to rotation over continuous maize.

Table 3. Fitted regression equations for maize grain yield (GR), grain N uptake (GRN) and total aboveground biomass (TDM) in two cropping systems as a function of fertilizer N applied (x).

Cropping System	Equation	R^2	Signif.
Chinyika			
Mz-Mz-Mz-Mz	GR = 0.38 + 0.05 (x) - 0.0003 (x^2)	0.62	0.05
	GRN = 3.80 + 0.15 (x)	0.89	0.001
	TDM = 2.74 + 0.02 (x)	0.46	0.06
Mz-Mz-Gn-Mz	GR = 0.56 + 0.01 (x)	0.84	0.05
	GRN = 2.87 + 0.12 (x)	0.87	0.001
	TDM = 2.76 + 0.03 (x)	0.79	0.003
Domboshava			
Mz-Mz-Mz-Mz	GR = 1.56 + 0.01 (x)	0.82	0.002
	GRN = 13.96 + 0.18 (x)	0.72	0.01
	TDM = 3.93 + 0.03 (x)	0.65	0.02
Mz-Mz-Gn-Mz	GR = 2.14 + 0.01 (x)	0.80	0.003
	GRN = 19.68 + 0.18 (x)	0.83	0.002
	TDM = 5.75 + 0.02 (x)	0.48	0.05

Mz = maize, Gn = groundnut.

tion, total NH_4^+ was determined by spectrophotometry. Maize grain N uptake was calculated as the product of dry matter yield and nitrogen concentration.

Statistical analysis

The experiment was a RCBD with treatments arranged in a split plot replicated three times. Cropping systems were main plots and fertilizer-N rates subplots. Analysis of variance in Proc GLM (SAS, 1997) was used to analyze treatment effects with respect to maize grain yield, grain N uptake and total aboveground biomass in the fourth year. Cropping systems were also compared using orthogonal contrasts. Subsequent linear and quadratic maize responses to fertilizer-N rates within a cropping system were also evaluated. Whenever trends were significant, regression equations were calculated to determine fertilizer N replacement values (FRV) of groundnut in rotation with maize.

RESULTS

Maize yields following groundnut (no fertilizer)

Groundnut kernel yields for the three locations ranged from 0.16 to 0.34 tha^{-1} and the vegetative biomass ranged from 0.65 to 1.6 tha^{-1}. The plough down was between 16 and 40 $kgNha^{-1}$.

Because of significant ($P \leq 0.05$) treatment x location interactions, data are presented as treatment effects with-

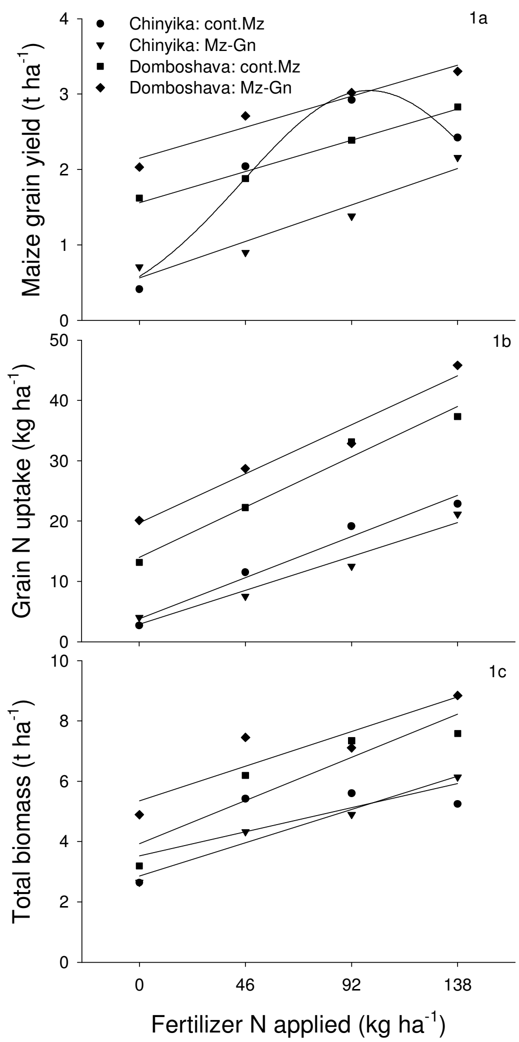

Figure 1a. Effect of fertilizer N application on maize grain yield in continuous maize (Mz-Mz-Mz-Mz) and maize in rotation with groundnut (Mz-Mz-Gn-Mz) cropping systems at Chinyika and Domboshava in 1997. 1. Effect of fertilizer N application on maize grain N uptake in continuous maize (Mz-Mz-Mz-Mz) and maize in rotation with groundnut (Mz-Mz-Gn-Mz) cropping systems at Chinyika and Domboshava in 1997. 1. Effect of fertilizer N application on total aboveground maize biomass in continuous maize (Mz-Mz-Mz-Mz) and maize in rotation with groundnut (Mz-Mz-Gn-Mz) cropping systems at Chinyika and Domboshava in 1997.

in location (Table 2). Unfertilized maize grain yields following groundnut were increased by 0.7 tha^{-1} at Domboshava, 0.4 tha^{-1} at Chinyika and less than 0.1 tha^{-1}, at Chiduku (Table 2). However, maize grain yields after groundnut at Chiduku were not significantly (P ≥ 0.05) better than unfertilized continuous maize.

Maize yields following groundnut (variable N applied)

Linear and quadratic equations were calculated within the split-plot model for Domboshava and Chinyika. For each cropping system, regression equations were obtained for maize grain yield (GR), grain N uptake (GRN) and total aboveground biomass (TDM) as a function of fertilizer N applied (Table 3).

At Chiduku, maize grain yield did not significantly respond to N applied. Maize grain yield following groundnut was only numerically larger than continuous maize without fertilizer N applied. Therefore no regression equations were calculated for Chiduku.

At Chinyika, continuous maize showed a quadratic response while maize following groundnut responded linearly to increasing N rates. At N 30 kgNha^{-1}, continuous maize was always associated with a yield higher than that of maize following a groundnut crop (Figure 1a).

Maize grain yields following both groundnut and continuous maize linearly responded to increasing N rates at Domboshava (Figure 1a). At all N rates, yields were significantly (P̣ 0.05) higher following groundnut than following maize. Maize grain N uptake for the two cropping systems linearly responded to increasing N rates at Domboshava (Figure 1b).

Total aboveground biomass of maize following groundnut at Domboshava was 2 tha^{-1} higher than continuous maize when no fertilizer N was applied. Differences in total aboveground biomass for the two cropping systems were not found at higher rates of fertilizer N (Figure 1c). At Chinyika, total aboveground biomass for both cropping systems responded linearly to increasing N rates (Figure 1c). Continuous maize produced signifycantly (P̣≤ 0.05) higher biomass yields than maize following groundnut at all N rates except at 138 kgNha^{-1}.

Fertilizer replacement value

Fertilizer N replacement values (FRV) of groundnut ranged from 6 to 64 kgNha^{-1} based on grain yield, 0 - 34 kgNha^{-1} based on grain N uptake and 1 - 32 kgNha^{-1} based on total aboveground biomass (Table 4).

DISCUSSION

The plough down N obtained in this study compares well with those calculated by Suwanarit et al. (1986) and Dakora et al. (1987), of 42 and 38 kgNha^{-1}, respectively. Because kernels are harvested and removed from the field, net plough down N is therefore primarily based on the haulms and fallen leaves. Plough down N values tend to underestimate the actual contribution of groundnut to soil N because only the green or intact vegetative material is measured.

Although there were positive yield increases in maize grain yield following groundnut at Chinyika and Chiduku, these yields remained small (less than 1 tha^{-1}) and were less than half of those obtained at Domboshava. Other work with the same long term maize-groundnut-maize rotation experiments using farmer inputs and manageme-

Table 4. Fertilizer N replacement value to subsequent year's maize after groundnut crop at Chinyika and Domboshava, Zimbabwe in 1997/98.

Parameter	Fertilizer N replacement value (kg N ha^{-1})	
	Chinyika	Domboshava
Grain yield	6	64
Grain N uptake	0	34
Total above ground biomass	1	32

nt on sub-humid smallholder farms in Zimbabwe has shown only small maize improvements after groundnut (Waddington and Karigwindi, 2001, 2004) and farmers in these areas often do not recognize maize-grain legume rotation as a practice that helps soil fertility (Bellon et al., 1999). This appears to be due to poor growth, low grain yield and perhaps small N input from groundnut when using farmer's practices and inputs (that include seed saved from farmer crops and no fertilizer) on farmers' fields. Causes of poor groundnut yields under these conditions in Zimbabwe include late planting and weeding, low plant densities, soil organic matter, soil pH, and deficiencies of P, K, Ca, Mg and N (Waddington and Karigwindi, 2001; Murata et al., 2002).

Our results at Chinyika and Domboshava corroborate those of Mukurumbira (1985) who evaluated maize grain yields following several food legumes (including groundnut) and fallow in central Zimbabwe. Maize grain yields were greater following groundnut (6.2 tha^{-1}) than unplanted fallow (4.3 tha^{-1}) or maize (3.9 tha^{-1}).

Results for Chiduku and Chinyika show that the common assumption that a groundnut crop improves N availability and enhances yield in a subsequent year may not always be correct on smallholder fields where soil fertility is low. Waddington and Karigwindi (2001) attributed this observation to poor growth and small N input from groundnut when grown under smallholder practices without fertilizer or lime inputs. The result was further confirmed by the maize grain N uptake following groundnut at Chinyika. Maize grain N uptake was only higher for maize following groundnut without fertilizer-N input, but at any other fertilizer rate, continuous maize had signifycantly higher N uptake (Figure 1b). Grain N uptake at Chinyika versus Domboshava was not influenced by initial mineralizable N, which was almost two fold greater at Chinyika compared with Domboshava. Nitrogen is a very mobile nutrient in sandy soils and may have been subject to more leaching at Chinyika (as the rainfall pattern seems to suggest) than at Domboshava. Mugwira (1989) working with a maize-legume-maize rotation in sub-humid smallholder areas of Zimbabwe observed that maize grain N uptake following a legume was affected by the quality (especially N content) of legume residues incorporated into the soil.

Contrary to Chiduku and Chinyika, maize grain N uptake at Domboshava following groundnut was increased by 41% at each N rate compared with continuous maize. This can be attributed to a better groundnut crop from the previous season, higher plough down N (40 $kgNha^{-1}$) than that of the two on-farm sites (mean of 19 kg Nha^{-1}) and better rainfall events.

Fertilizer replacement value (FRV) is the quantity of fertilizer N required to produce a yield in a crop that does not follow a legume that is identical to that produced by incorporation of the legume (Giller et al., 1994). Grain N uptake based FRV at Domboshava (34 $kgNha^{-1}$) was very close to the plough down N (40 Nha^{-1}) at that location. If plough down N is an indicator of FRV then in this case it represented 85% efficiency of incorporation.

Fertilizer replacement values obtained in this study are similar to those reported by Jeranyama et al. (2000) working with maize + legume intercrop- maize rotations in Zimbabwe, who reported FRV values of 18 - 36 kgN ha^{-1}, and other researchers for groundnut using maize as a test crop. Mugwira (1989) in Zimbabwe reported FRVs of 30 -120 kg Nha^{-1} for groundnut and other annual food legumes in rotation with maize in NR IV and II. In northern Ghana, groundnut had FRV's of 60 $kgNha^{-1}$ (Dakora et al., 1987). Jones (1974) evaluated residual effects of groundnut on a subsequent maize crop in savannah areas of Nigeria and obtained an equivalent of 43-73 $kgNha^{-1}$ when no fertilizer N was applied to maize. Maize yields in short rotations with legumes at Bunda, Malawi were found to be better after legumes with poor grain yield but vigorous vegetative growth such as lablab (*Lablab purpureus*) and these generally left more residual N than groundnut or soybean (*Glycine max*) (MacColl, 1989). Legume equivalent values were 52, 26 and 0-14 kg N ha^{-1} for lablab, groundnut and soybean, respectively in that study.

Conclusions

This research showed that maize yields were improved in rotation with groundnut compared with continuous maize in smallholder cropping systems at two of three sites in sub-humid Zimbabwe. Unfertilized maize grain yields were improved by 0.1 - 0.7 tha^{-1} following groundnut compared with continuous maize. However, improvements over continuous maize were not observed at two of the three sites when maize was fertilized at the recommended N rate, partly due to excessive rains received at those sites.

The groundnut crop reduced fertilizer needs of a subsequent maize crop by up to 64 $kgNha^{-1}$ based on maize grain yield (representing up to a 70% saving in N fertilizer needs per hectare) and up to 32 $kgNha^{-1}$ based on maize total above-ground biomass at Domboshava, while at Chiduku and Chinyika (the on-farm sites), rotation contributed just 0 - 6 $kgNha^{-1}$.

Our results suggest that benefits of including groundnut in rotation with maize are sensitive to smallholder practices of allocating few inputs (such as fertilizer and lime) to groundnut in the smallholder farms of Zimbabwe. In conclusion, N contribution to maize from a preceding groundnut crop may often be modest on smallholder farm sandy soils under current smallholder management in Zimbabwe. To be successful, such rotations will need to be combined with support to help Zimbabwe smallholder farmers invest in fertilizer inputs.

ACKNOWLEDGEMENTS

We are very grateful to the late Johannes Karigwindi, John Chifamba and Nixon Chiworeso for field and laboratory assistance. This research was funded by the Rockefeller Foundation Predissertation Internship Programme and the CIMMYT Maize Programme.

REFERENCES

Araki S (1993). Effect on soil organic matter and soil fertility of the chitemene slash-and-burn practice used in northern Zambia. In Proceedings: Soil Organic Matter Dynamics and Sustainability of Tropical Agriculture. 367-375 (Eds Mulongoy K, Merckx R). Chichester, U.K.: Wiley-Sayce.

Bellon MR, Gambara P, Gatsi T, Machemedze TE, Maminimini O, Waddington SR (1999). Farmers' taxonomies as a participatory diagnostic tool: Soil fertility management in Chihota, Zimbabwe. CIMMYT Economics Working Paper 99-13, Mexico, D.F.:CIMMYT.

Blackie MJ, Jones RB (1993). Agronomy and increased maize productivity in southern Africa. Biol. Agric. Hortic. 9: 147-160.

Dakora FD, Aboyinga RA, Mahama Y, Apaseku J (1987). Assessment of N_2-fixation in groundnut (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculata* L.Walp) and their relative contribution to a succeeding maize crop in Northern Ghana. MIRCEN J. 3: 389-399.

Giller KE, McDonagh JF, Cadisch G (1994). Can biological nitrogen sustain agriculture in the tropics? In Soil Science and Sustainable Land Management in the Tropics, 713-191 (Eds J.K. Syers and D.L. Rimmer). Wallingford, U.K.: CAB International.

Grant PM (1970). Restoration of productivity of depleted sands. Rhodesia Agric. J. 67: 131-137.

Jeranyama P, Hesterman OB, Waddington SR, Harwood RR (2000). Relay-Intercropping of sunnhemp and cowpea into a smallholder maize system in Zimbabwe. Agron. J. 92: 239-244.

Jones MJ (1974). Effects of previous crop on yield and nitrogen response of maize at Samaru, Nigeria. Exp. Agric. 10: 278-279.

Kumwenda JDT, Waddington SR, Snapp SS, Jones RB, Blackie MJ (1996). Soil Fertility Management Research for Maize Cropping Systems of Smallholders in Southern Africa: A review. NRG Paper 96-02. Mexico, D.F.: CIMMYT.

Kumwenda JDT, Waddington SR, Snapp SS, Jones RB, Blackie MJ (1997). Soil fertility management in southern Africa. In Africa's Emerging Maize Revolution, 157-172 (Eds Byerlee D, Eicher CK). Boulder, CO, USA: Lynne Rienner Publishers.

MacColl D (1989). Studies on maize (*Zea mays* L.) at Bunda, Malawi. II. Yield in short rotation with legumes. Exp. Agric. 25: 367-374.

Mapfumo P, Mtambanengwe F (1999). Nutrient mining in maize-based systems of rural Zimbabwe. In Maize Production Technology for the Future: Challenges and Opportunities. Proceedings of the Sixth Eastern and Southern Africa Regional Maize Conference, 21-25 September 1998, 274-277. Addis Ababa, Ethiopia: CIMMYT and Ethiopian Agricultural Research Organization.

Matlon PJ (1984). Technology evaluation. In Coming Full Cycle: Farmers' Participation in the Development of Technology, 95-118 (Matlon PJ, Cantrell R, King D, Benoit-Cattin M (eds). Ottawa, Canada: IDRC.

McDonagh JF, Toomsan B, Limpinuntana V, Giller KE (1993). Estimates of the residual nitrogen benefits of groundnut to maize in Northeast Thailand. Plant Soil 154: 267-277.

Mugwira LM (1989). Biological nitrogen fixation in crop rotations. In Chemistry and Soil Research Institute Annual Report 1988/89. 102-110. Harare, Zimbabwe: Department of Research and Specialist Services. Ministry of Agriculture, Government of Zimbabwe.

Mukurumbira LM (1985). Effects of rate of fertilizer nitrogen and previous grain legume crop on maize yields. Zimbabwe Agric. J. 82: 177-179.

Murata MR, Hammes PS, Zharare GE (2002). Soil amelioration effects on nutrient availability and productivity of groundnut on acid sandy soils of Zimbabwe. Exp. Agric. 38: 317-331.

Nel PC, Barnard RO, Steynberg RE, de Beer JM, Groenveld HT (1996). Trends in maize grain yields in a long-term fertilizer trial. Field Crops Res. 47: 53-64.

Ritchie SW, Benson GO, Lupkes SJ, Salvador RJ (1993). How a corn plant develops. Special Report No. 48. Ames, Iowa, USA: Iowa State University Cooperative Extension Services.

SAS Institute, Inc. (1997). SAS/STAT Users Guide, Release 6.12 Ed. Cary NC., USA.

Shumba EM, Waddington SR, Rukuni M (1992). Use of tine-tillage, with atrazine weed control, to permit earlier planting of maize by smallholder farmers in Zimbabwe. Exp. Agric. 28: 443-452.

Swanarit A, Suwannarat C, Chotechanungmanirat S (1986). Quantities of fixed N and effects of grain legumes on following maize, and N and P status of soil as indicated by isotopes. Plant Soil 93: 249-258.

Vincent V, Thomas RG (1961). An agricultural survey of Southern Rhodesia. Part 1. Agroecological Survey, 41-102. Harare, Zimbabwe.

Waddington SR, Karigwindi J (2001). Productivity and profitability of maize + groundnut rotations compared with continuous maize on smallholder farms in Zimbabwe. Exp. Agric. 37:83-98.

Waddington SR, Karigwindi J (2004). Longer-term contribution of groundnut rotation and cattle manure to the sustainability of maize-legume smallholder systems in sub-humid Zimbabwe. In Integrated Approaches to Higher Maize Productivity in the New Millennium. Proceedings of the 7th Eastern and Southern Africa Regional Maize Conference, 338-342 (Eds DK Friesen, Palmer AFE). Nairobi, Kenya: CIMMYT and Kenya Agricultural Research Institute.