Nutr Cycl Agroecosyst (2010) 88:103–109
DOI 10.1007/s10705-009-9282-7

RESEARCH ARTICLE

Interactive effects of selected nutrient resources and tied-ridging on plant growth performance in a semi-arid smallholder farming environment in central Zimbabwe

J. Nyamangara · I. Nyagumbo

Received: 5 March 2008 / Accepted: 21 April 2009 / Published online: 15 May 2009

Abstract Crop production in sub-Saharan Africa is constrained by numerous factors including frequent droughts and periods of moisture stress, low soil fertility, and restricted access to mineral fertilisers. A 2 year (2005/6 and 2006/7) field study was conducted in Shurugwi district, central Zimbabwe, to determine the effects of different nutrient resources and two tillage practices on the grain yield of maize (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr). Six nutrient resource treatments (control, pit-stored manure, leaf litter, anthill soil, mineral fertiliser, mineral fertiliser plus pit-stored manure) were combined with two tillage practices (conventional tillage and post-emergence tied ridging). Basal fertilisation was done with 0 kg ha^{-1} as control, 240 kg ha^{-1} PKS fertiliser, 18 t ha^{-1} manure, 10 t ha^{-1} manure plus 240 kg ha^{-1} PKS fertiliser, 35 t ha^{-1} leaf litter, 52 t ha^{-1} anthill soil. About 60 kg N/ha was applied to fertiliser only and fertiliser plus manure treatments as top dressing in the form of ammonium nitrate (34.5%N). A split-plot design was used with nutrient resource as the main plot and tillage practice as the subplot, and five farmers' fields were used as replicates. Grain yield was determined at physiological maturity (140 and 126 days after planting for maize and soybean, respectively) and adjusted to 12.5% moisture content for maize and 11% for soybean. In the first season (2005/06), addition of different nutrient resources under conventional tillage increased ($P < 0.05$) maize grain yield by 102–450%, with leaf litter and manure plus fertiliser treatments, giving the lowest (551 kg $ha^{-1)}$ and highest (3,032 kg ha^{-1}) increments, respectively, compared to the control. For each treatment, tied-ridging further increased maize grain yield. For example, for leaf litter, tied-ridging further increased grain yield by 96% indicating the importance of integrating nutrient and water management practices in semi-arid areas where moisture stress is frequent. Despite the low rainfall and extended dry spells in the second season, addition of the different nutrient resources still increased yield which was further increased by tied-ridging in most treatments. Besides providing grain, soybean had higher residual effects on the following maize crop compared to *Crotalaria gramiana*, a green manure. It was concluded that the highest benefits of tied-ridging, in terms of grain yield, were realised when cattle manure was combined with mineral fertiliser, both of which are available to resource-endowed households. Besides marginally increasing yield, leaf litter and anthill which represent resources that can be accessed by very poor households, have a positive effect of the soil chemical environment.

J. Nyamangara (✉) · I. Nyagumbo
Department of Soil Science & Agricultural Engineering, University of Zimbabwe, P.O. Box MP167, Mount Pleasant, Harare, Zimbabwe
e-mail: jnyamangara@yahoo.co.uk; jnyamangara@agric.uz.ac.zw

Keywords Conventional tillage · Maize · Nutrient resources · Post-emergence tied ridging · Soybean

Introduction

Soil fertility is the most important factor limiting crop productivity in sub-Saharan Africa (SSA) (Smaling et al. 1997) and this is often exacerbated by inadequate moisture content in semi-arid areas (Cleaver and Schreiber 1994). The majority of soils in SSA are light-textured and acidic, and have critically low concentrations of soil organic carbon (SOC) and nutrients (Grant 1981; Nyamangara et al. 2000) due to a combination of high rainfall that promote leaching (Kamukondiwa and Bergström 1994; Twomlow 1994; Vogel et al. 1994) and long-term cultivation with sub-optimal or no nutrient inputs (Stoorvogel and Smaling 1990). For example, in 1990 the average fertiliser use in SSA was only 8.4 kg ha^{-1} compared to 81 kg ha^{-1} in other developing countries, and 75% of the fertiliser use was limited to only six countries (Gerner and Harris 1993). In extreme cases of nutrient mining, multiple nutrient deficiencies have been reported (Mugwira and Nyamangara 1998; Mukurumbira and Nemasasi 1998), and the soils hardly respond to NPKS mineral fertiliser additions and will only respond to continual application of high rates of animal manure after several seasons (Zingore et al. 2007). The dominant smallholder cropping systems of southern and eastern and southern Africa are based on maize, the staple food, which accounts for about 50% of the calories consumed (Mugwira et al. 2002). However, soybean has also become an important source of cash income and nutritious diet with the latter being critical in reducing the negative impacts of HIV/AIDS ravaging the region.

In the semi-arid areas of Zimbabwe (rainfall < 600 mm per annum) crop failure occurs in three out of every five years and poor rainfall distribution (extended dry spells) within a relatively wet season often reduces yield potential. Under such marginal agro-ecological conditions crop yields can be enhanced by harvesting the rain which is often in the form of high intensity storms. However, some studies have shown that sandy soils may not benefit from extra water supplies unless if soil nutrients are also added (Anshuttz et al. 1997).

Soil water regime represents a balance among four processes; evaporation, transpiration, infiltration and internal drainage. These processes are in turn controlled in part by water retention and transmission properties of the soil. Tillage practices such as tied-ridging affect hydraulic properties of the soil (Singh et al. 1998). Tied-ridging involves construction of mounds of soil of 15–25 cm high along crop rows using a hoe, a mouldboard plough or a locally available high-wing ox-drawn ridger (Elwell and Norton 1988). Cross ties, half to two-thirds the height of the ridges, are made in the furrows at 1.5–3 m intervals to capture run-off and enhance water infiltration. Tied-ridging increases water infiltration reduces run-off and controls soil erosion (Nyagumbo 2002). Vogel (1993) reported high soil loss (3.3 t/ha) and run-off (90.4 mm) under conventional tillage compared to only 0.7 t/ha soil erosion and 30.1 mm run-off under tied-ridging in a sub-humid area in Zimbabwe. Subsequent studies at Hatcliffe and Domboshawa in Zimbabwe also showed a 5-year mean annual run-off of 22 and 9% at Hatcliffe and 20 and 4% at Domboshawa of the seasonal rainfall from conventional tillage and tied-ridging, respectively (Nyagumbo 2002). However, the water harvesting effects of tied ridging have been reported to increase loading of nitrates and herbicides at the bottom of the root zone through increased drainage (Hatfield et al. 1998), a situation more relevant in high fertiliser input systems as opposed to the cropping systems in SSA where sub-optimal levels of fertiliser are used. Moyo and Hagmann (1994) reported a higher drainage (174 mm) and much lower run-off (22 mm) under tied-ridging compared to conventional tillage (147 and 118 mm, respectively) over a 5-year study conducted on a sandy soil in a semi-arid area in southern Zimbabwe.

Integrated tillage and nutrient resource management practices need to be developed for sustainable crop production, especially in semi-arid areas where smallholder farmers use a wide range of locally available nutrient resources and crop response to fertilisation is often limited by moisture stress. Pre-planting tied-ridging has been reported to cause poor germination and establishment (Meijer 1992; Vogel 1993). This study aimed to determine the effects of selected sources of nutrients commonly used by smallholder farmers in SSA in combination with two tillage practices, conventional and post-planting tied-ridging, on the growth and grain yield of maize and soybean. In the second season the residual effect of soybean and *Crotalaria gramiana* on maize growth and grain yield were also measured. It was hypothesized that tillage practices have no effect on maize and soybean growth, and there is no interaction between tillage practices and nutrient resources used.

Materials and methods

Site description and soil characterisation

The field experiments were conducted in Ward 5 of Shurugwi smallholder area from 2005 to 2007 in central Zimbabwe. The area is classified as semi-arid, receiving low and erratic rainfall (450–650 mm per annum). The area is covered by coarse-grained sandy soils derived from granitic parent material with low soil organic matter content (<1%), water retention capacity, and also deficient in N, P and S (Grant 1981). The dominant farming system is mixed cropping and livestock-based with maize as the staple crop. Arable fields are individually owned and cropped but grazing is communal in open-access areas, and also in arable fields during the dry season. Cattle-owners collect crop residues from their fields and store as dry season animal feed.

Manure is a key source of plant nutrients although mineral fertilisers are also used by resource-endowed farmers but at low rates (<35 kg/ha N) for fear of perceived crop burn. Higher fertiliser rates are only used in vegetable gardens situated in wetlands where irrigation water is assured. However, higher N fertiliser rates (up to 100 kg N ha^{-1}) are recommended in seasons where seasonal rainfall distribution is predicted to be good.

Soil sampling and analysis

Soil samples were taken from the top 15 cm soil layer in each field (before ploughing) using a soil auger at the start of the experiment. Ten sub-samples were randomly taken from each field and thoroughly mixed to make a composite sample. After harvesting, soil samples were taken from each plot. Soil samples were taken from intra-row spaces between the planting stations. The composite samples were air-dried and passed through a 2-mm sieve before analysis. The samples were analysed for soil organic C (modified Walkely-Black), total N (micro-Kjeldahl), total P, available P (Olsen) and pH [water and 0.01 M $CaCl_2$] (Anderson and Ingram 1993).

Experimental design and planting

Five sites were selected across the ward with the participation of farmers and ploughed using an ox-drawn mouldboard plough. Two tillage treatments (conventional and post-emergence tied ridging) were used as main plots and five nutrient resource treatments as sub-plots in a split-plot design. The five experimental sites were used as replicates and each site was managed by a group of nearby farmers and each group consisted of at least ten farmers. The nutrient resource treatments were pit-stored cattle manure (18 t ha^{-1} manure), leaf litter (35 t ha^{-1}), anthill soil (52 t ha^{-1}), mineral fertiliser (240 kg ha^{-1} PKS containing 14% P 13% K 5% S + 60 kg ha^{-1} ammonium nitrate (34.5% N), mineral fertiliser plus pit-stored manure (10 t ha^{-1} manure plus 240 kg ha^{-1} PKS plus 60 kg ha^{-1} ammonium nitrate). The application rates were based on recommendations from extension agents for manure, leaf litter and mineral fertiliser, and farmer practice for anthill soil. Planting rows were marked out using ox-drawn ploughs without the mouldboard attached and nutrient resources were applied in the rows. The nutrient materials were partially covered with soil before sowing the maize to avoid seed burn. All the mineral N fertiliser was applied as top dressing at 5 weeks after planting. Post-emergence tied ridges were constructed at 4 after maize germination.

For the soybean and *Crotalaria gramiana* experiment in the first season, a similar experimental design was used but only one fertiliser treatment (240 kg ha^{-1} PKS—14% P 13% K 5% S) was used at planting. Seed for both crops was dribbled along the planting furrows, covered with soil and thinned to 10 cm intra-row spacing 2 weeks after germination. Soybean grain was harvested at its physiological maturity, and *Crotalaria* was cut after senescence, and the residues of both crops were left in the field. At the beginning of the second season, the crop residues were evenly spread in the respective plots and ploughed in. Maize was then planted in order to assess the residual effects of the legume crops.

In each case tied ridges were made on the relevant plots using a mouldboard plough followed by cross-ties using a donkey-drawn tie-maker 4 weeks after planting. In both experiments plot sizes were 100–500 m^2 depending on the size of the field and what the participating farmers at each site perceived was an adequate size to enable them objectively assess crop performance. Weeding was done by hand-hoeing when required. Grain yield was determined at physiological maturity and adjusted to 12.5% moisture content for maize and 11% for soybean.

Results

Effect of nutrient resources on soil properties

All the soil nutrient resources reduced the initial soil pH by 3.3–13.5% (Table 1). The lowest pH (pH 4.74, 0.01 M $CaCl_2$) was recorded in the fertiliser only treatment while the least reduction (0.18 units) was recorded in the anthill soil treatment. Even in the control treatment, cultivation induced the lowering of soil pH. Available soil P was only increased (5.8–40.6%) by leaf litter, manure only and manure plus fertiliser treatments when compared to the initial soil P status (Table 1). Available soil P decreased by 18.6, 7.9 and 1.9% in the control, anthill soil and fertiliser only treatments, respectively, compared to the initial status. Table 2 shows that the C-to-N ratios of the organic resources were much lower for leaf litter and anthill soil, although manure had higher N concentration. Of the three organic resources, cattle manure was a better source of P, K and Mg, and leaf litter for Ca (Table 2).

Effect of nutrient resources and tied-ridging on maize grain yield

All nutrient resources significantly ($P < 0.05$) increased maize grain yield without tied-ridging compared to the control, and highest yields (>3 t/ha in year 1; >1.5 t/ha in year 2) were realised when manure and fertiliser were applied in combination (Figs. 1, 2). Post-emergence tied-ridging further increased maize grain yields, even in the control treatments where yield was less than 1 t/ha, but this effect was more consistent in the first year (Fig. 1). In the second year tied-ridging depressed yield in leaf litter and mineral fertiliser only treatments. Maize grain yield in the control was similar to that in the leaf litter treatment with or without tied-ridging (Fig. 2). There was no interaction between the nutrient resources and tied-ridging.

Table 2 Selected properties of the soil amendments applied to experimental field plots

	%						C-to-N ratio
	Org C	N	P	K	Ca	Mg	
Cattle manure	16.8	0.70	1.10	0.30	0.60	0.56	24.0
Leaf litter	6.90	0.49	0.47	0.13	0.79	0.47	14.1
Anthill soil	3.34	0.25	0.29	0.11	0.50	0.31	13.4

NB Org.—Organic

Table 1 Some initial soil properties of the experimental sites and after one season of application of different nutrient resources

	pH		SOC (%)	Total N (%)	Available P (mg kg^{-1})
	H_20	$CaCl_2$			
Initial	6.04	5.48	0.82	0.060	7.20
Control	5.72	5.18			5.86
240 kg PKS + 100 kg N	5.30	4.74			7.06
10 Mg manure + 240 kg PKS + 100 kg N	5.70	5.14			10.12
18 Mg manure	5.32	4.90			7.62
35 Mg leaf litter	5.64	4.96			10.12
52 Mg Anthill soil	5.86	5.30			6.63

NB Resource applications per ha; *PKS* 14% P 13% K 5% S; *N* top-dressed as ammonium nitrate at 5 weeks after planting; Soil samples taken from conventional tillage treatments

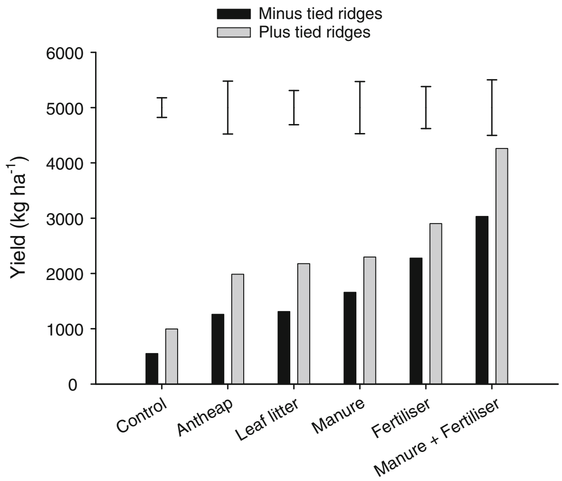

Fig. 1 Effect of different nutrient resources and tied-ridging on maize grain yield in season 1 (2005/06). Error bars represent least significant difference ($P < 0.05$)

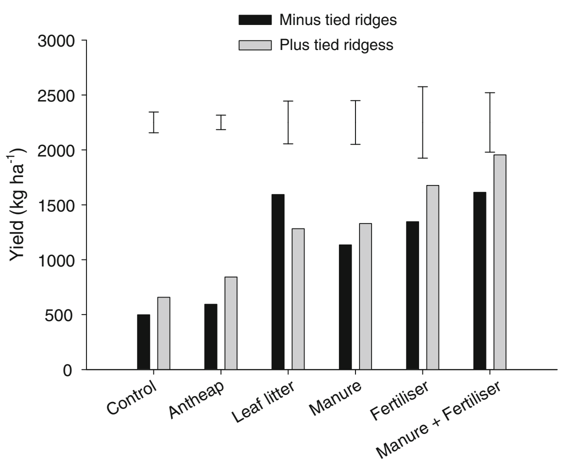

Fig. 2 Effect of different nutrient resources and tied-ridging on maize grain yield in season 2 (2006/07). Error bars represent least significant difference ($P < 0.05$)

Effect of tied-ridging on legume growth and effect of legume residue on maize grain yield

Tied-ridging increased soybean grain yield by up to 35% over the conventional tillage in the first season but the difference was not significant (data not shown). There was evidence of Zn, Mn and Mg deficiency (interveinal chlorosis, necrotic lesions on older leaves and chlorotic spotting) during the vegetative stage at all the five sites. Dry matter yield and N content of *Crotalaria gramiana* was not determined.

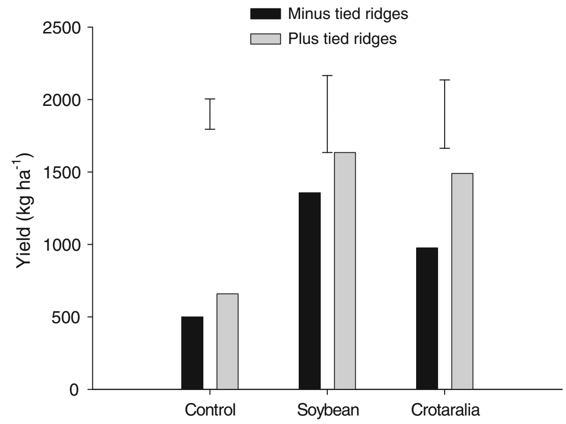

Fig. 3 Effects of soybean and *Crotalaria gramiana* residues on maize grain yield. Error bars represent least significant difference ($P < 0.05$)

Both legumes had a significant ($P < 0.05$) residual soil fertility effect on the yield of maize grown in the second year without tied-ridging (Fig. 3). Tied-ridging further enhanced the residual effect of both legumes, and the higher enhancement (500 kg/ha) was by *Crotalaria gramiana* (Fig. 3). Soybean had a higher residual effect than *Crotalaria gramiana*.

Statistical analysis

Comparisons on the effect of the different fertility treatments on grain yield were carried out using analysis of variance (ANOVA) (Genstat 2002). Separation of means were done using the least significant difference procedure ($P < 0.05$).

Discussion

Sandy soils in Zimbabwe are inherently deficient in N, P, S and also low in organic C (Grant 1981; Nyamangara et al. 2000), and therefore yields in control treatments were expected to be low (<500 kg ha^{-1}) (Figs. 1–3). The apparent lowering of pH (acidification) after just one year of cultivation, especially in mineral fertiliser treatments, indicates the poor buffering capacity of these largely sandy soils (Grant 1981). However, the decrease did not affect yield because the pH was still above threshold limits below which is reduced (Nyamangara et al. 2000). Though conducted in a semi-arid area, the study underscores the need for periodic liming if acidifying nitrogenous fertilisers are continually applied at similar (35 kg/ha) or higher rates in poorly buffered soils. Soil acidification due to the use of nitrogenous fertilisers has been reported in higher rainfall areas where lime application is recommended approximately every third year (Nyamangara et al. 2000). The frequency of application would be lower in semi arid areas where leaching of basic cations is relatively low and also as farmers apply lower fertiliser rates for fear of crop burn. The pH changes observed also seem to suggest that organic fertilisers buffer soils from acidification better than mineral fertilisers, and anthill soil had the highest pH buffering effect. Although the nutrient value of anthill soil was very low, farmers who use it would benefit from the pH moderation effect which will in turn ensure the availability of nutrients like P that become locked up when the soil becomes acidic. Organic fertilisers also improve the soil physical environment, especially the water-holding capacity which is key in semi arid areas (Nyamangara et al. 2001).

The reduction in available P concentration in just one season shows the inherent low status of the nutrient, and thus the soils are vulnerable to nutrient mining when rainfall is adequate. Soil nutrient mining has been widely reported in smallholder areas in SSA (Smaling et al. 1997). However, the decrease in soil pH due to cultivation and mineral fertiliser application could have also contributed to the reduction in the soil available P.

Besides supplying N, P, K and S, anthill soil, leaf litter and cattle manure also supply Ca, Mg and micronutrients to crops. These extra nutrients, which were not contained in NPKS fertiliser, could have had some growth effect in the manure, leaf litter and anthill soil treatments. However, Ca, Mg and micronutrient deficiencies have been reported on maize in high rainfall areas where leaching under acid soil conditions is high (Mugwira and Nyamangara 1998).

Increase in yield induced by all nutrient resources compared to the control treatment implied that smallholder farmers can apply any of these resources available to them in order to enhance yield and improve food security as well as to counter nutrient mining. Although the yield increases were small for anthill soil and leaf litter, these resources are often used by the most resource-poor farmers who do not have access to any other better sources of nutrients. However, the results showed that highest yields, and hence food security, can be achieved through combined application of cattle manure and mineral fertiliser. The higher residual fertility of soybean than *Crotalaria gramiana* suggested that incorporation of soybean into the cropping system will be relatively more attractive to farmers given its dual role.

The enhanced yield under tied-ridging compared to conventional tillage, especially in the first year, implied that tied-ridging can increase rain water use efficiency. When rainfall is low, as in year 2, the benefits are diminished or absent due to extended dry spells. Lack of interaction between soil nutrient resources and tillage practices implied that these treatments acted independent of each other. Besides moisture conservation, the practice of constructing post-emergence tied-ridges has also been found to enhance weed control (Nyagumbo 1993). The benefits of tied-ridging were also evident on soybean yield and on maize grown on legume residual fertility implying that the practice can be applied to legume-maize-based cropping systems.

Conclusions

The integration of soil fertility with moisture conserving techniques such as tied-ridging can potentially increase productivity under semi-arid conditions, suggesting increased water use efficiency. The highest yield benefits occur when livestock manure and mineral fertilisers are applied in combination but such benefits are diminished when prolonged dry spell conditions occur. Nutrient-poor fertility resources such as leaf litter and anthill soil are worthwhile investments for resource-constrained farmers as they also improve the soil chemical and possibly physical, environment. Inclusion of soybean in farming systems can enhance crop productivity through its residual fertility effects though its yield remains low.

Acknowledgments We thank the Rockefeller Foundation for funding this work through the Soil Fertility Consortium for Southern Africa (SOFECSA).

References

Anderson JM, Ingram JSI (1993) Tropical soil biology and fertility: a hand book of methods. CAB International, Wallingford

Anshuttz J, Kome A, Nederlof M, de Neef R (1997) Water harvesting and soil moisture retention. Agrodok series 13, CTA, Agromisa, Wageningen, The Netherlands

Cleaver K, Schreiber G (1994) Reversing the spiral: the population, agriculture and environment nexus in sub-Saharan Africa. World Bank, Washington

Elwell HA, Norton AJ (1988) No-till tied ridging: a recommended sustainable crop production system. Institute of Agricultural Engineering, Ministry of Agriculture, Harare 85pp

Genstat (2002) Genstat release 6.1. VSN International Ltd, Oxford

Gerner H, Harris G (1993) The use and supply of fertilisers in sub-Saharan Africa. In: van Reuler H, Prins WH (eds) The role of plant nutrients for sustainable food crop production in sub-Saharan Africa. Dutch Association of Fertiliser Producers (VKP), The Netherlands, pp 107–125

Grant PM (1981) The fertilisation of sandy soils in peasant agriculture. Zim Agric J 78:169–175

Hatfield JL, Allmaras RR, Rehm GW, Lowery B (1998) Ridge tillage for corn and soybean production: environmental quality impacts. Soil Tillage Res 48:145–154. doi:10.1016/S0167-1987(98)00141-X

Kamukondiwa W, Bergström L (1994) Nitrate leaching in field at an agricultural site in Zimbabwe. Soil Use Manage 10:118–124. doi:10.1111/j.1475-2743.1994.tb00471.x

Meijer RA (1992) Ridging as a primary tillage practice, results of three years of applied research. Animal draught Power Research and Development Programme, Magoye Research Station, Magoye, Zambia 14pp

Moyo A, Hagmann J (1994) Growth-effective rainfall in maize production under different tillage systems in semi-arid conditions and granitic sands of southern Zimbabwe. Proceedings of the 13th international conference, International Soil Tillage Research Organisation (ISTRO), Aalborg, Denmark, pp 475–480

Mugwira LM, Nyamangara J (1998) Organic carbon and plant nutrients in soils under maize in Chinamhora communal area. In: Bergström L, Kirchmann H (eds) Carbon and nutrient dynamics in natural and agricultural tropical systems. CAB International, Wallingford, pp 15–21

Mugwira LM, Nyamangara J, Hikwa D (2002) Effects of manure and fertilizer on maize at a research station and in smallholder (peasant) area of Zimbabwe. Commun Soil Sci Plant Anal 33:379–402. doi:10.1081/CSS-120002752

Mukurumbira LM, Nemasasi H (1998) Micronutrient in the maize-based system of the communal areas of Zimbabwe. In: Waddington SR, Murwira HK, Kumwenda JDT, Hikwa D, Tagwira F (eds) Soil fertility research for maize-based farming systems in Malawi and Zimbabwe. CIMMYT/Soil FertNet, Harare, Zimbabwe, pp 229–232

Nyagumbo I (1993) Farmer participatory research in conservation tillage: practical experiences with no-till tied ridging in communal areas lying in the sub-humid north of Zimbabwe. Proceedings of the 4th Annual Scientific Conference, 11–14 October 1993, SADC Land and Water Management Research Programme, Gaborone, Botswana, pp 236–249

Nyagumbo I (2002) Effects of three tillage systems on seasonal water budgets and drainage of two Zimbabwean soils under maize. Doctor of Philosophy thesis, Department of Soil Science and Agricultural Engineering, University of Zimbabwe, Harare. 270pp

Nyamangara J, Mugwira LM, Mpofu SE (2000) Soil fertility status in the communal areas of Zimbabwe in relation to sustainable crop production. J Sustain Agric 16:15–29. doi:10.1300/J064v16n02_04

Nyamangara J, Gotosa J, Mpofu SE (2001) Effects of cattle manure on the structure and water retention capacity of a granitic sandy soil in Zimbabwe. J Soil Tillage Res 62:157–162. doi:10.1016/S0167-1987(01)00215-X

Singh B, Chanasyk DS, McGill WB (1998) Soil water regime under barley with long-term tillage-residue systems. Soil Tillage Res 45:59–74. doi:10.1016/S0167-1987(97)00067-6

Smaling EMA, Nandwa SM, Janssen BN (1997) Soil fertility is at stake. In: Buresh RJ, Sanchez PA, Calhoun F (eds) Replenishing soil fertility in Africa. SSSA Special Publication Number 51, Madison, WI, pp 47–61

Stoorvogel JJ, Smaling EMA (1990) Assessment of soil nutrient depletion in sub-Saharan Africa, 1983–2000. Report 28 DLO Winand Staring Ctr for Integrated Land, Soil and Water Research, Wageningen, The Netherlands

Twomlow SJ (1994) Field moisture characteristics of two fersilliatic soils in Zimbabwe. Soil Use Manage 10:168–173. doi:10.1111/j.1475-2743.1994.tb00481.x

Vogel H (1993) Evaluation of five tillage systems for smallholder agriculture in Zimbabwe. Tropenlandwirt 94:21–36

Vogel H, Nyagumbo I, Olsen K (1994) Effect of tied-ridging and mulch ripping on water conservation in maize production on sandveld soils. Tropenlandwirt 95:33–44

Zingore S, Murwira H, Delve RJ, Giller KE (2007) Soil type, historical management and current resource allocation: three dimensions regulating variability of maize yields and nutrient use efficiencies on smallholder farms. Fld Crop Res 101:296–305. doi:10.1016/j.fcr.2006.12.006