Nutrient limitations for soybean on low-responsive sandy soils in Zimbabwe tested by a double pot experiment

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MSc Thesis Plant Production Systems

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Preface

Summary

This research aimed to diagnose nutrient limitations and the role of pH in availability of nutrients for soybean in sandy Zimbabwean soils that were known to give poor legume yields after recommended P fertilization and/or inoculation. To test this a double-pot experiment with soybean was performed. Soil from six fields known to give poor legume yields was collected and chemically analysed. On each soil the influence of eight nutrient treatments and a lime treatment on the growth of soybean was tested. The growth and final biomass of the plants was compared between each combination of soil, lime and nutrient treatment. After harvest shoot tissue of the soybean plants was analysed on nutrient concentration. Two farmers were interviewed about the management history of their fields.

All soils could be classified as sandy and acid soils and were low in organic C, total N and low to adequate in available P and exchangeable K, Mg and Ca. There were differences in biomass production between soils, but there was hardly any relation between the outcome of the chemical analysis and the pot experiment. Stem height and biomass were used as indicators to measure the growth of soybean, but stem height appeared not to be a suitable indicator. Application of lime increased both plant biomass and shoot N concentration, indicating that N_2 fixation was positively influenced. Probably this was caused by reducing the negative impacts of Al^{3+} and Mn^{2+} on the rhizobia. Therefore, if farmers want to grow legumes it is recommendable to apply lime on these acid soils. The experimental results were compromised because plants suffered from an excessive amount of P in the nutrient solution. However, the results suggested that K was the most limiting nutrient for production, because biomass was lowest in the treatment without K. Extremely sandy textured soils are known to lack the capacity to prevent K from leaching and to accumulate K. Therefore fertilization of K needs attention on sandy soils low in K, especially in soybean with its high demand for K.

1. Introduction

Smallholder farms in Zimbabwe are mostly located on acid sandy soils derived from granite, which are inherently infertile and poor in organic matter (Zingore et al., 2007). The productivity on these soils is limited by moisture or nutrient deficiencies in respectively dry and wet years (Carter and Murwira, 1995). The nutrients usually most limiting production on sandy soils in Zimbabwe are N and P (Nyamangara et al., 2000). A key to increase productivity on these soils is the addition of manure (Myers et al., 2004) or organic matter which: 1) adds multiple nutrients and base cations to the soil, 2) improves physical characteristics of the soil like water holding capacity and 3) sometimes improves synchrony between demand for N by crops and availability of N (Zingore et al., 2008). A problem is that most farmers in the communal areas of Zimbabwe own very few cattle. They have limited access to manure, so alternative solutions have to be found to increase productivity and soil fertility in these areas. One alternative way to improve the availability of N for plants is the growing of legumes. Their symbiosis with rhizobia enables them to access an alternative source of N, namely N_2 from the air. Legumes generally do not help to address deficiencies of nutrients other than N.

For an efficient production of legumes several factors have to be taken into account. Firstly the relationship between the legume and the *Rhizobium* strain can be very specific. Therefore farmers should grow genotypes of crops that form a symbiosis with indigenous rhizobia, or have to inoculate the legume seeds with the appropriate bacterial strain for that crop genotype. In Zimbabwe, for example, a constraint to soybean production by smallholders has been the requirement for inoculation, because most soybean genotypes did not have a good symbiosis with indigenous rhizobia (Waddington, 1999; Giller et al., 2011). Another factor is that shortage of other nutrients may limit plant growth indirectly by inhibition of the process of N_2 fixation. For instance, legumes dependent on N_2 fixation may also suffer from N deficiency when they receive an inadequate supply of P, because this element plays an important role in the process of N_2 fixation (Marschner, 1995). Finally legumes have, like other plants, specific demands for other nutrients and water and are sensitive to a whole range of other factors, like diseases, pests, weeds, toxicity of elements etc.

In the N2Africa project many field trials have shown that soybean often gives a good yield response to inoculation and P fertilizer application. However, in some trials hardly any response to P fertilization and inoculation was observed. Sometimes the productivity in treatments with P and/or inoculation even declined compared to the control treatments (Baijukya and Franke, 2010). Other soils gave a big response to inoculation and P fertilization, but yields were still so low indicating that other factors were limiting yield.

A low productivity of soybean and lack of response to inputs could be related to a range of factors including those described above. Many studies have been done on nutrient deficiencies in Zimbabwe, but not specific for soybean. A study by Nyamangara et al. (2000) concluded that K deficiency occurs in the communal areas of Zimbabwe and sometimes Mg deficiency. Mg is an element likely to become deficient when sandy soils are cropped using inorganic fertilizers alone. Rowell and Grant (1977) pointed out that S deficiency may also be a problem, because of the low organic matter content of the soils and the lack of naturally occurring sources of S. Shortage of Zn may occur when soils are limed or have been fertilized with P (Tagwira, 1995). In general, micronutrients are better available in soils with a low pH than in soils with a high pH, but the total amount of micronutrients may be low in soils with a low pH. So there may still be deficiency of micronutrients. Another problem may be Al^{3+} toxicity. To overcome this problem liming is advised to improve the ratio between Ca^{2+} and Al^{3+} and decrease the negative effects of Al.

This research aims to identify nutrient deficiencies that limit soybean productivity on soils found to give poor legume yields after recommended fertilization and inoculation. Therefore, a pot experiment has been performed with soybean (*Glycine max* (L.) Merr.) growing on soils from different areas in Zimbabwe. Different nutrient treatments and the influence of lime have been tested. Soil was collected from fields known to give poor legume yields, even with use of P and inoculum inputs. Moreover, interviews have been done with the farmers managing the fields from where soil was collected to gain knowledge about the management history of the soils. After identification of nutrient deficiencies in the pot trial, field experiments can be performed to derive specific recommendations for fertilization.

Objective research

Diagnose nutrient (P, K, Mg, S, Ca, Zn and other micronutrients) deficiencies and the role of pH in availability of nutrients for soybean grown on sandy Zimbabwean soils that are known to give poor legume yields after recommended fertilization and/or inoculation.

2. Methodology

A double pot experiment was set up to analyse the growth of soybean in Zimbabwean soils that were suspected to be deficient in nutrients. Sites were selected where legumes were grown and a poor yield was obtained after P fertilization and/or inoculation. The double pot technique was used in this experiment to identify nutrients that were in short supply in the soils tested (Janssen, 1990). Differences in growth between plants grown on a deficient and a complete solution were assumed to be caused by deficiency of the omitted nutrient.

2.1. Experimental design

Soybean plants were grown in double pots in a greenhouse. The greenhouse was located at Grasslands Research Station in Marondera (-18.18250°, 31.49843°), Zimbabwe. The seeds were sown on 17 January 2012. Approximately five weeks later, plants were harvested on 22 February. The experiment was set up in a completely randomised block design (CRBD) with four blocks (replicates). The four tables in the greenhouse were considered as blocks. The treatments were randomly assigned to the pots (experimental units). The experimental factors were soil type, nutrient treatment and lime treatment. Soil from six different sites was used, eight nutrient treatments were performed and on five of the eight nutrient treatments the influence of liming with dolomite was tested. The total of experimental units was 312 (i.e. 13 x 4 x 6). The eight nutrient treatments included one positive control with a complete nutrient solution, six treatments where one nutrient was omitted from the solution and one treatment where the micronutrient mixture was omitted from the solution. The nutrients tested were P, K, Mg, Ca, S, Zn and micronutrients (Table 1). The nutrient salts used and the composition of the nutrient solution can be found in Appendix II. The nutrient solution of Hoagland (1950) was used for the micronutrient mixture and the concentrations of the macronutrients were chosen on basis of the concentration ranges mentioned by Hewitt (1952). Around the experimental units guard pots with soybean were placed. These pots received the complete nutrient treatment.

Table 1. Treatment levels of nutrient omission trials.

Treatment	Nutrients						Other micronutrients[1]	Dolomite
	P	K	Mg	Ca	S	Zn		
1. Complete	+	+	+	+	+	+	+	-
2. P omitted	-	+	+	+	+	+	+	-
3. K omitted	+	-	+	+	+	+	+	-
4. Mg omitted	+	+	-	+	+	+	+	-

Treatment								
5. Ca omitted	+	+	+	-	+	+	+	-
6. S omitted	+	+	+	+	-	+	+	-
7. Zn omitted	+	+	+	+	+	-	+	-
8. Micronutrients omitted	+	+	+	+	+	+	-	-
9. Complete	+	+	+	+	+	+	+	+
10. P omitted	-	+	+	+	+	+	+	+
11. K omitted	+	-	+	+	+	+	+	+
12. S omitted	+	+	+	+	-	+	+	+
13. Micronutrients omitted	+	+	+	+	+	+	-	+

[1] Other micronutrients include Fe, Mn, Cl, B, Cu and Mo

The soils used in this experiment were taken from six selected sites known to give poor legume yields. Two sites in Mhondoro (-18.28135°, 30.64255° and -18.28134°, 30.64253), two sites in Wedza (-18.79546°, 31.68987° and -18.81564°, 31.71696°), and two sites in Murehwa (-17.40995°, 31.41370° and -17.72243°, 31.69840°) in Zimbabwe. The locations are shown in Fig. 1. Because the fields of farmer Mandebvu and Chikwanha were next to each other there is only one place mark visible.
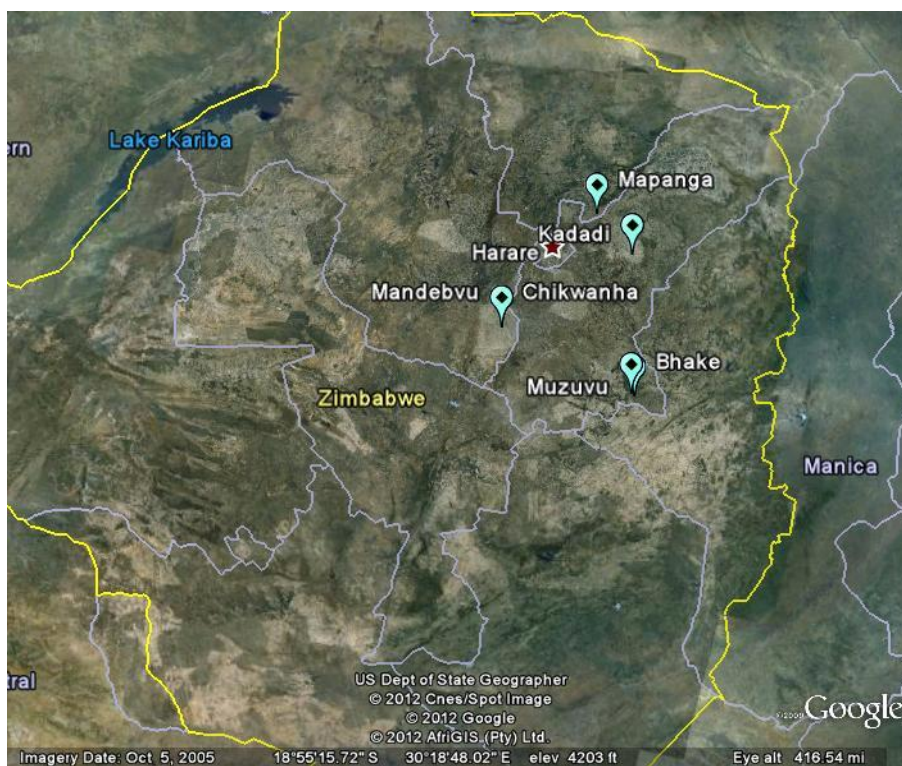
Fig. 1. Map showing the locations of the fields where soil samples were taken.

2.2. Cultural practices

Soil from the different sites was collected by taking subsamples from the top soil (0-20 cm) in a W pattern. A composite sample was made for each site and a subsample was taken for the chemical analysis of the soil. The chemical analysis was conducted by SPRL and included: pH (0.01 M $CaCl_2$), soil organic C (Walkley-Black), total N (Kjeldahl), available P (Olsen) and cations K, Mg and Ca (ammonium acetate). Percentages of sand, clay and silt were

Fig. 1. Illustration of the double pot experiment

determined with the Bouyoucus hydrometer method. The remainder of the soil was air-dried and sieved (<2 mm). The lime requirement was calculated with a general formula used at SPRL. First formula 1 was used to calculate per soil the required amount of lime in kg ha^{-1} to adjust the pH to 5.5. Thereafter formula 2 was used to calculate the amount of lime needed to lime 20 pots of 225 g of soil. Assumptions were an incorporation depth of 2 dm and a bulk density of 1.3 g cm^{-3}. Sandy soil usually does have a higher bulk density, but a lower value was taken to be sure to apply enough lime.

$$Lha = \Delta pH * 2000 \qquad (1)$$

$$Ltotal = \frac{Lha}{A * I * \rho * 1000} \qquad (2)$$

In which is: L_{ha} the amount of lime in kg needed to adjust the pH of a hectare of soil to 5.5, L_{total} the amount of lime in g needed to lime 20 pots with 225 g of soil, A the surface area of a hectare in dm^2, I the incorporation depth in dm and ρ the bulk density of the soil in g cm^{-3}. The pH before lime application and the amount of lime applied per pot can be found in Appendix III.

The soil that had to be treated with lime was spread well on a hard surface so that there was a thin layer of soil. The required amount of lime was spread on top and mixed very well with the soil. At SPRL liming is usually done two weeks before the start of an experiment. In this case there was not enough time to wait for two weeks and measure the change in pH. Therefore the soil was immediately used to fill the pots.

The double pot experiment was set up as described by Janssen (1990) and illustrated in Figs. 1 and 2. Pipes with gauze at the bottom were filled with 225 g of air-dried and sieved soil, which was moistened with distilled water up to field capacity. Soybean seeds, variety Serenade, were inoculated with strain MAR 1391 SPRL inoculant. Per pot two inoculated soybean seeds were sown at a depth of ca. 1.5 cm. After sowing the pots were placed on 400 cc pots with a lid on top with a hole in the middle. The 400 cc pots contained a plastic bag with the nutrient solution inside. After emergence, pots were thinned to one plant per pot. During the experiment the pots were watered daily with distilled water to keep the soil moist. The initial plan was to renew the nutrient solution each week, but this was not always possible due to a lack of distilled water.

Fig. 2. Experimental set-up in the greenhouse.

2.3. Measurements and calculations

Stem height was measured eight days after emergence (DAE) and this measurement was repeated every four days. From these data the relative growth rate (RGR) of the stem was calculated, with the formula:

$$Rs = \frac{\ln S2 - \ln S1}{t2 - t1}$$

(3)

In which Rs is the relative growth rate of the stem, S the height of the stem in mm and t the time in days. At the end of the trial, the dry weight of the shoot parts was determined. Plants were harvested and root and shoot were separated. The plant material was dried in an oven for 48 hours at 70°C to determine dry weight.

During the growing period regular visual inspections were made of the plant appearance to detect nutrient deficiency symptoms in plants. Also photographs were made. After harvest dried soybean shoots were sent to KU Leuven for the nutrient analysis of the plant tissue. The four replicates were aggregated so that no interaction effects could be tested. Total N was determined by the Kjeldahl method, while the other elements were measured with an ICP analysis.

2.4. Statistical analysis

In the statistical analysis differences in shoot dry weight and in plant nutrient concentration were tested between treatments. For all tests a univariate ANOVA was performed. The residuals of the dependent variable were checked for a normal distribution with the Kolmogorov-Smirnov test for samples sizes > 50 and with the Shapiro-Wilk test for sample sizes < 50. Distributions were significantly different from a normal distribution in two cases, namely for the test on effect of soil type and nutrient treatment on shoot dry weight (P = 0.014) and for Mg concentration in shoot tissue (P = 0.007). The outcomes of the ANOVA were still considered to be reliable, because small deviations from a normal distribution will not affect an ANOVA. Three-way interactions were not taken into account, because three-way interactions are very difficult to explain. If there was a two-way interaction a graph was made of the interacting factors to visualize the pattern of interaction. There was a blocking effect in the experiment, probably due to differences in climate within the greenhouse.

First the effect of lime treatment was tested. The overall design of the experiment was unbalanced, therefore the nutrient treatments -Mg, - Ca and –Zn were excluded from the analysis for effects of lime. The factors were lime treatment, nutrient treatment, soil type and block. Since the ANOVA was positive and there were only two categories, no post-hoc test was needed. Letters were used to indicate significant differences in figures or tables.

After the overall effect of lime was known, the treatments with lime were excluded from the data and all other nutrient treatments were included. Another univariate ANOVA was performed with factors soil type, nutrient treatment and block. No interaction was observed between soil type and nutrient treatment, but the main effects of these treatments were highly significant. LSD values were used to look which treatments differed significantly from each other. Letters were used to indicate significant differences in figures or tables.

Other univariate ANOVA's were done to test for differences in nutrient concentration of plant tissue between nutrient treatments and soils. For each of the nutrients N, P, K, Mg, Ca, S and Zn a separate test was performed with the factors nutrient treatment and soil. The effect of lime on shoot N concentration was tested by aggregating the data per soil. Nutrient treatments –Mg, -Ca and –Zn were excluded in this analysis.

There were no data for shoot weight of plants grown on soil Mhondoro Chikwanha with –Mg and –Ca treatment. After harvest the plants were put in paper bags and these bags were placed in the laboratory. During the night some plants were eaten by rats. Therefore the average shoot dry weight of soil Mhondoro Chikwanha was calculated excluding the –Mg and –Ca treatment and the average shoot dry weight for –Mg and –Ca treatments was calculated excluding soil Mhondoro Chikwanha.

The level of significance was 0.05 for all tests. The program used for the statistical analysis was IBM SPSS Statistics 19. The outcome of the ANOVA tests can be found in Appendix V.

2.5. Interviews

The initial plan was to interview all farmers whose soils were taken for the pot experiment to ask them about the management history of their plots. Soil samples were collected from six different sites, but only two farmers from Murehwa could be interviewed, because of the volatile political situation elsewhere. The soil samples from Wedza and Mhondoro were collected by field workers of CIAT and no interviews were done. The results of the interviews with the farmers from Murehwa can be found in Appendix IV.

3. Results

3.1. Relative growth rate of the stem

Fig. 3 shows the graph of the RGR of the stem for the different nutrient treatments. The shape of the graph is roughly the same for the different nutrient treatments, although the values are slightly different. It seems that the complete treatment had the highest RGR of the stem, while treatment –K the lowest RGR had, but this was not consistent over the whole period. The general pattern was first a decline in RGR of the stem, where after the RGR started increasing 18 days after emergence. However 23 days after emergence the RGR started declining again until the end of the experimental period.
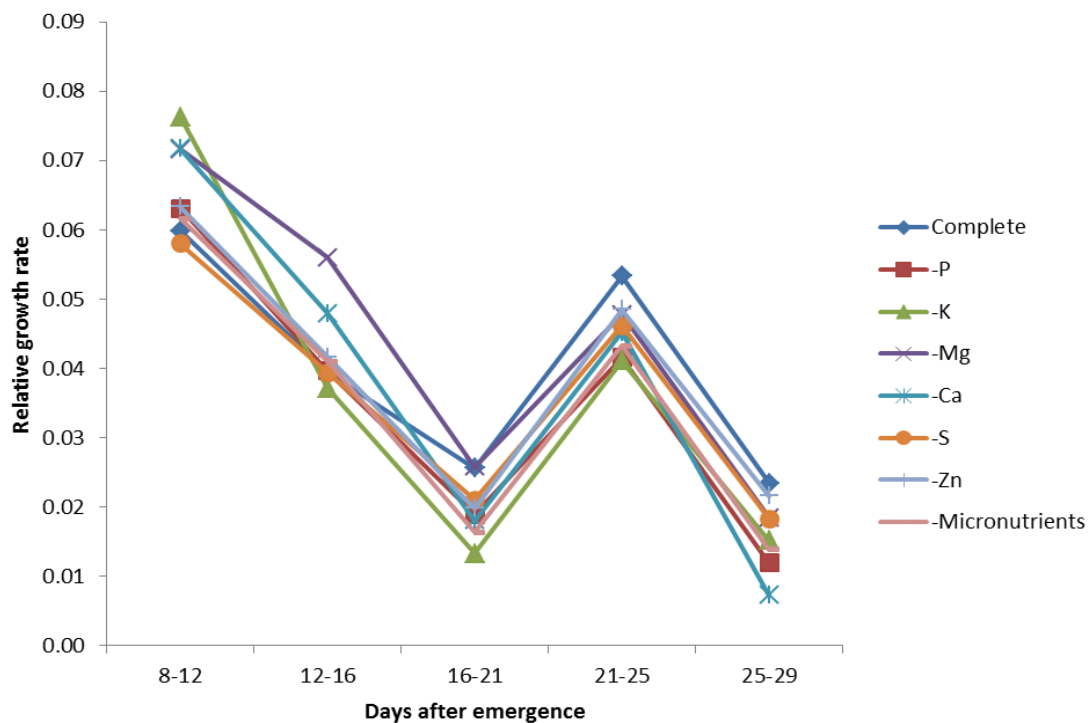
Fig. 3. Relative growth rate of soybean main stem for different nutrient treatments between 8 and 29 days after emergence.

3.2. Biomass

The statistical analysis showed that there was no interaction between nutrient treatment and lime treatment on shoot dry weight at harvest, but there was an interaction between soil type and lime treatment. Fig. 4 visualises this interaction. For soil Mhondoro Chikwanha there was no effect of lime treatment, while for soil Murehwa Kadadi there was a big difference in average dry weight between the

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treatments with and without dolomite. This strong effect of dolomite on plant growth in soil from farmer Kadadi in Murehwa may be explained by the fact that the amount of lime that was applied was estimated with a general formula. Therefore it is likely that the differences in pH adjustment are not equal between the different soils. There was not a clear relation between the amount of lime applied and the increase in biomass production. This means that no reliable conclusions can be drawn about the interaction between lime and soil, but it is still possible to draw conclusions about the overall effect of the lime treatment on plant growth.
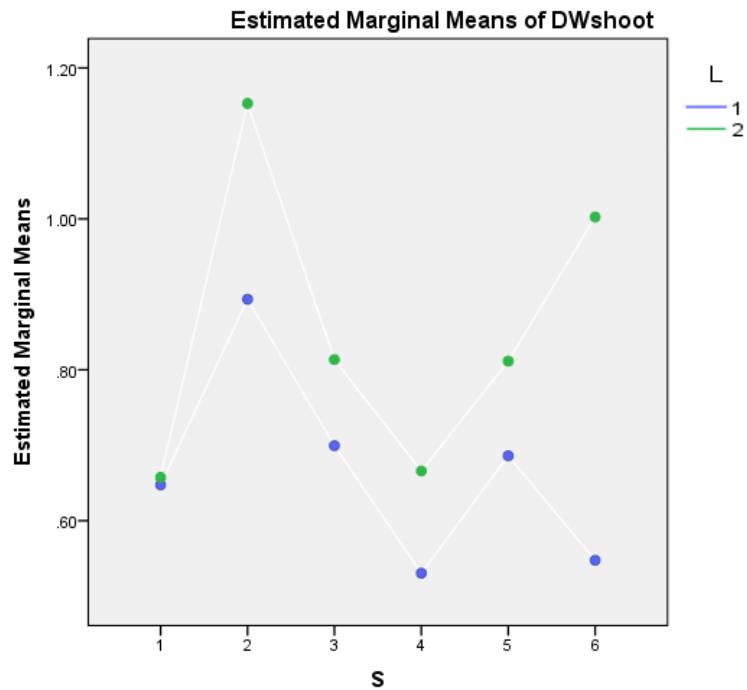
Fig. 4. Interaction between soil and lime treatment. Soil is on the x-axis with 1: Mhondoro Chikwanha, 2: Mhondoro Mandebvu, 3: Wedza Muzuvu, 4: Wedza Bhake, 5: Murehwa Mapanga and 6: Murehwa Kadadi. The blue dots represents the treatment without lime and the green dots the treatment with lime.

Fig. 5 shows the overall effect of lime treatment. The average shoot dry weight of plants without dolomite was 0.67 g against a shoot dry weight of 0.85 g for the treatment with dolomite. Shoot biomass increased significantly when dolomite was applied to the soil.
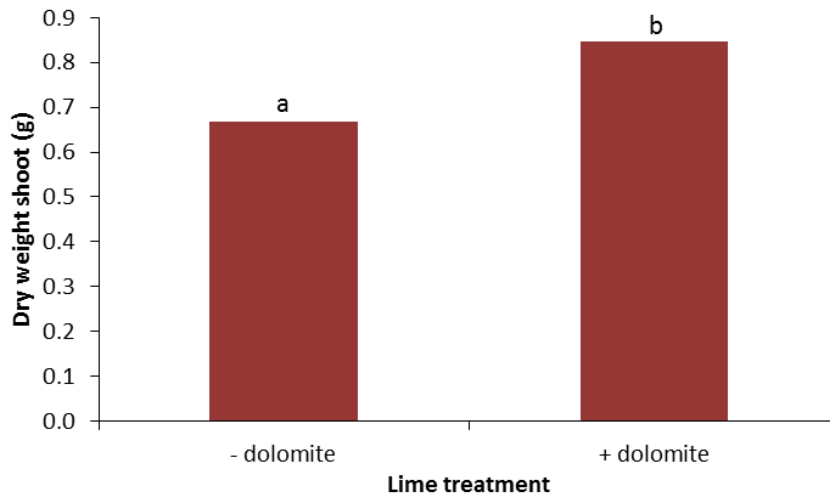
Fig. 5. Overall effect of lime treatment on dry weight shoot in g per plant. Letters a and b indicate the significant difference between the treatments.

Between the soils there were significant differences in shoot dry weight (Fig. 6). Average dry weight per soil ranged from 0.49 – 0.97 g per plant. Average dry weight on soil Mhondoro Mandebvu was significant higher than dry weight of plants grown on other soils. Plants grown on soil Wedza Bhake had a significant lower dry weight than the plants grown on other soils, except for Mhondoro Chikwanha.
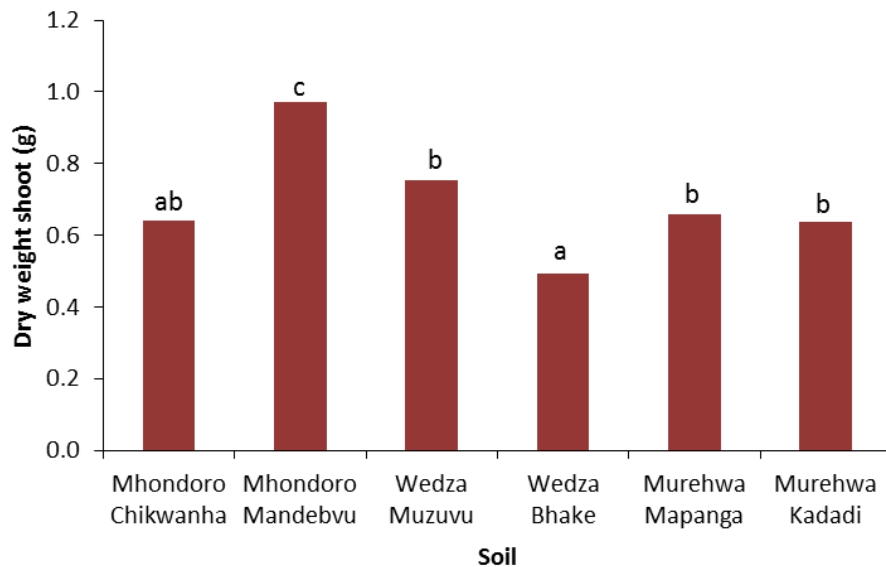
Fig. 6. Mean dry weight shoot in g per plant per soil type. Different letters indicate significant differences between soils.

Fig. 7 shows the average shoot dry weight for different nutrient treatments. The values range from 0.28 g for –K to 0.91 for the -P treatment. The –K treatment resulted in plants with a very low average dry weight. This was significant lower than the results for all other nutrient treatments. Plants grown without P in the nutrient solution had the highest shoot biomass, but this was not significantly different from the complete, -Mg and -Micronutrients treatments ($P > 0.05$).
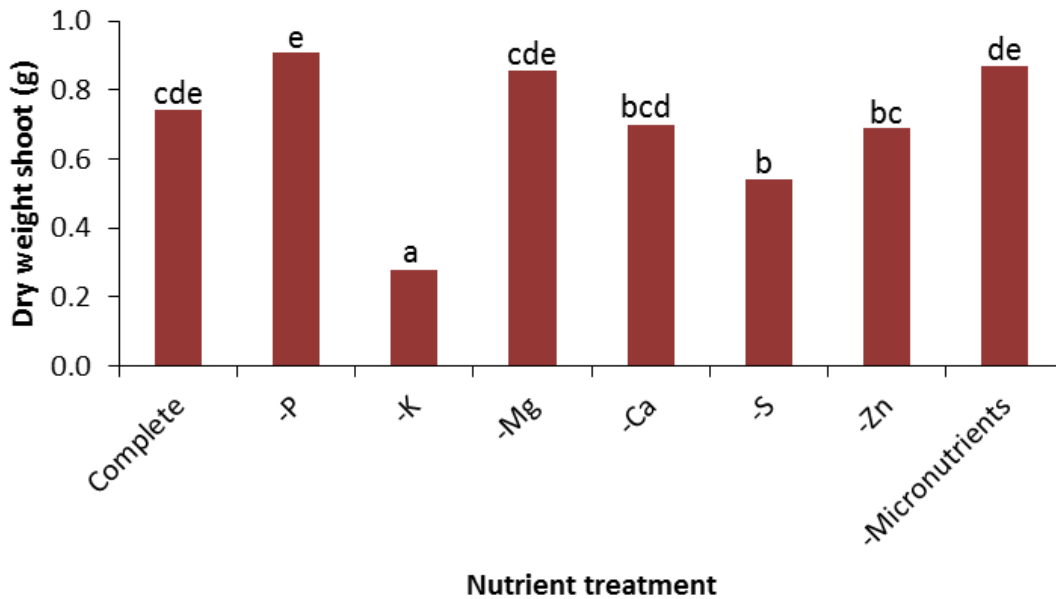
Fig. 7. Mean dry weight shoot in g per plant per nutrient treatment. Different letters indicate significant differences between nutrient treatments.

3.3. Chemical analysis soils

The texture of the soils was very similar (Table 2). All soils can be classified as sandy soils with a proportion of sand between 94 and 96% and a clay content between 4 and 6%. The soils from Mhondoro and Wedza were a bit less sandy than the soils from Murehwa, but this was only a difference of 2%.

Table 2. Proportions of sand, clay and silt in different soils.

Farmer	Area	Sand	Clay	Silt
		(%)	(%)	(%)
Chikwanha	Mhondoro	94	6	0
Mandebvu	Mhondoro	94	6	0
Muzuvu	Wedza	94	6	0
Bhake	Wedza	94	6	0
Mapanga	Murehwa	96	4	0
Kadadi	Murehwa	96	4	0

The results of the chemical analyses in Table 3 show that the pH was low in all soils. A pH of 3.8 in soil Chikwanha Mhondoro was the lowest value and the highest pH was found in soil Kadadi Murehwa, namely 4.8. This means that all soils can be classified as (strongly) acidic. The organic matter content of the soils was low and ranged from 0.39% C for Kadadi to 0.60% for Muzuvu. The total N content of the soils was low as well and ranged from 0.026% in Mapanga to 0.036% in Chikwanha. There was quite some variation in available P between soils. The highest amount was found in Muzuvu, namely 15.6 µg g^{-1}. This can be seen as a marginal concentration, while the other soils had very low or low concentrations of P (DRSS, n.d.). The lowest value was 2.5 µg P g^{-1} soil for Chikwanha. Mapanga, Mandebvu, Kadadi and Bhake had respectively 6.5, 6.7, 6.7 and 8.0 µg P g^{-1} soil. Very low K concentrations were found in the soils of farmer Kadadi and farmer Mapanga, only 0.03 and 0.05 cmol K kg^{-1} soil. This can be interpreted that these soils were deficient in K, while concentrations K in other soils were adequate (DRSS, n.d.). Muzuvu and Mandebvu had the highest values for exchangeable K with values of 0.20 and 0.19 cmol K kg^{-1} soil. The lowest value for Ca was found in soil from farmer Kadadi. Here only 0.10 cmol Ca kg^{-1} soil was measured as exchangeable Ca. The other soils had higher values, starting with 0.42 for Mapanga up to 1.76 cmol kg^{-1} for Mandebvu. Almost the same applies for Mg, although the values were different. The lowest value was 0.03 in Kadadi, followed by 0.07 in Mapanga and the highest concentration was 0.35 cmol kg^{-1} and found in Muzuvu.

Table 3. Chemical characteristics of different soils.

Farmer	Area	CaCl$_2$ pH	Organic C (%)	Total N (%)	Olsen-P (μg g^{-1})	Exchangeable cations K (cmol kg^{-1})	Ca (cmol kg^{-1})	Mg (cmol kg^{-1})
Chikwanha	Mhondoro	3.8	0.41	0.036	2.5	0.11	0.87	0.16
Mandebvu	Mhondoro	4.4	0.45	0.030	6.7	0.19	1.76	0.34
Muzuvu	Wedza	4.3	0.60	0.034	15.6	0.20	1.46	0.35
Bhake	Wedza	4.7	0.44	0.030	8.0	0.12	0.43	0.09
Mapanga	Murehwa	4.3	0.50	0.026	6.5	0.05	0.42	0.07
Kadadi	Murehwa	4.8	0.39	0.027	6.7	0.03	0.10	0.03

In Table 4 the mean dry weight of the shoot is shown for each combination of nutrient treatment and soil type. These data can be used to link the results of the chemical analysis to the biomass production.

Table 4. Mean dry weight shoot in g per plant for each combination of nutrient treatment and soil.

Soil type	Mhondoro		Wedza		Murehwa	
	Chikwanha (g)	Mandebvu (g)	Muzuvu (g)	Bhake (g)	Mapanga (g)	Kadadi (g)
Nutrient treatment						
Complete	0.62	0.66	1.13	0.72	0.73	0.59
-P	0.90	1.13	0.87	0.69	0.92	0.94
-K	0.27	0.45	0.31	0.23	0.22	0.22
-Mg	n.d.[1]	0.98	1.06	0.48	0.68	1.10
-Ca	n.d.	1.21	0.74	0.45	0.50	0.60
-S	0.45	0.86	0.55	0.34	0.56	0.48
-Zn	0.61	1.12	0.73	0.37	0.67	0.66
-Micronutrients	1.01	1.38	0.65	0.68	1.00	0.52

[1] Data of shoot biomass for –Mg and –Ca treatments on soil Mhondoro Chikwanha are missing.

On average Mandebvu had the highest production compared to other soils (Fig. 6). From Table 4 can be seen that for most nutrient treatments this soil had indeed the highest production, but not for the complete nutrient treatment and the –Mg treatment. The experimental results show that even for the complete nutrient treatment, plant production depends on soil type. Yield for Muzuvu on a complete nutrient solution was 1.13 g, while the yield of Mandebvu was only 0.66 g. The higher production on

Muzuvu may be related to a higher total C content and a relatively high N concentration (Table 3). Muzuvu had also the highest concentration of Ca, which can be advantageous in case of toxicity of Al or Mn^{2+}. Compared to the other soils Mandebvu had a high concentration of exchangeable K, Ca and Mg. However the values were similar to or lower than Muzuvu for organic C, N, P, K and Mg. Only the concentration of Ca was higher in Mandebvu. K concentrations were similar in Mandebvu and Muzuvu, which explains the relatively high yields for the –K treatment. However the 0.14 g difference between these two soils cannot be explained.

In general plants in soil from Bhake performed poorly. For –P, -Mg, -Ca, -S and –Zn treatments, the yield was lowest. This is remarkable, because Kadadi had in general lower nutrient concentrations. Kadadi performed poorly as well, but better than expected on the basis of the soil chemical analysis. An example is the high yield for –Mg, while the amount of Mg in Kadadi soil was very low (0.03 cmol kg^{-1}). This may be an indication that Mg was not really a limiting factor for production. The available P in Chikwanha soil was very low (2.5 cmol kg^{-1}), but this did not result in the lowest biomass yield for the –P treatment. Bhake and Muzuvu had a lower biomass, while the P concentration was higher in both soils.

K concentrations in soils from Mapanga and Kadadi were very low compared to K concentrations in other soils. The dry weight of the shoots of the –K treatment for Mapanga and Kadadi is 0.22 g per plant, which is a lower biomass than for the other soils.

3.4. Plant nutrient concentration

For most elements there were significant differences in plant nutrient concentration between the nutrient treatments (Table 5). The percentage N in shoot tissue ranged from 2.84 to 4.62. Soybeans grown without P in the solution had a lower N concentration than the other treatments, except for the –Micronutrients treatment ($P < 0.05$). The -K treatment had the highest N concentration. There was a large variation in P concentration of the shoot tissue of different treatments. The lowest value, 0.10% P, was measured in shoot tissue of the –P treatment. The highest value, 2.14% P, is more than twenty times higher. This value was found in –S treatment. After –P the –Ca treatment had the lowest P concentration, only 0.47%. The P concentrations of the complete, -K, -Mg, -Zn and –Micronutrients treatments were all above 1.50%. The variation in K concentration was less than for P. The lowest value, 1.71%, was found in the –K treatment and the highest value, 4.03%, in the –Mg treatment. After –K the treatments –P and –Ca had the lowest K concentration of respectively 2.18 and 2.28%, followed by 3.21% for -Micronutrients. The second highest values were found in the complete, -S and –Zn treatments with respectively 3.58, 3.68 and 3.61%. The lowest concentration of Mg was found in the –Mg treatment with 0.15% and the highest value in the –K treatment with 0.43%. Except for –P, which

had a concentration of 0.23% Mg soil, all the other soils had values above 0.30%. The lowest value for Ca was 0.48% for the –Ca treatment, but this was not significantly different from the 0.61% Ca found in –P. After –Ca and –P the lowest concentration was 1.34% for the -Mg treatment and the highest value 1.61% for the treatment without S. The concentration of S ranged from 0.20% in the treatment without S to 0.49% in the –Zn treatment. The variation in Zn concentration of shoot tissue was not big. The lowest value of 21 ppm was found in –P, but this was not significantly different from the values found in –Mg, -Ca, -Zn and –Micronutrients. The highest value of 45 was found for –S, but this was not significantly different from the values for complete and -K.

Table 5. Average concentration of different elements in shoot tissue per nutrient treatment. Letters indicate significance classes within a column.

Nutrient treatment	N (%)	P (%)	K (%)	Mg (%)	Ca (%)	S (%)	Zn (ppm)
Complete	3.89 d	1.70 c	3.58 d	0.31 cd	1.35 bc	0.47 de	41 b
-P	2.84 a	0.10 a	2.18 b	0.23 b	0.61 a	0.39 cd	21 a
-K	4.62 e	1.61 c	1.71 a	0.43 e	1.56 cd	0.38 cd	40 b
-Mg	3.38 bc	1.93 d	4.03 e	0.15 a	1.34 bc	0.36 bc	29 a
-Ca	3.75 cd	0.47 b	2.28 b	0.35 d	0.48 a	0.27 ab	22 a
-S	3.63 cd	2.14 d	3.68 d	0.34 cd	1.61 d	0.20 a	45 b
-Zn	3.81 d	1.97 d	3.61 d	0.35 cd	1.45 c	0.49 e	22 a
-Micronutrients	3.19 ab	1.58 c	3.21 c	0.30 c	1.26 b	0.30 bc	27 a

Not only the nutrient treatment affected the concentration of elements in the shoots, the different soils resulted in different concentrations as well (Table 6). The lowest value for the percentage N, namely 3.34, was found in Muzuvu, while the highest value 3.88 was found in Mandebvu. Soybean shoots growing on soil from Chikwanha had a P concentration of 1.35%. The highest value was 1.55% on Kadadi soil, but the differences in P concentration were not significant. The lowest K concentration was found in Chikwanha as well, 2.89%, and this was significant lower than shoot K concentration of plants grown on soil from Bhake and Kadadi. For Mg the lowest concentration was 0.28% and found for Muzuvu. Only a significant difference was found with Mandebvu, which had a concentration of 0.34% cmol Mg kg^{-1} soil. The lowest Ca concentration was found for Muzuvu, namely 1.11%. This was significantly lower than the values found for Mandebvu and Bhake, which were 1.28% and 1.30%. The only significant difference in S concentration is between Muzuvu and Kadadi. Muzuvu had a lower concentration, 0.31% and Kadadi a higher concentration of 0.41%. Zn values range from 25 ppm for Muzuvu to 36 ppm in Kadadi.

Table 6. Average concentration of different elements in shoot tissue per soil. Letters indicate significance classes within a column.

Soil	N (%)	P (%)	K (%)	Mg (%)	Ca (%)	S (%)	Zn (ppm)
Chikwanha	3.57 abc	1.35 a	2.89 a	0.32 a	1.23 abc	0.33 a	28 ab
Mandebvu	3.88 c	1.45 a	3.06 ab	0.34 a	1.28 bc	0.37 a	35 c
Bhake	3.48 ab	1.53 a	3.21 b	0.32 a	1.30 c	0.39 a	33 bc
Muzuvu	3.34 a	1.36 a	2.93 a	0.28 a	1.11 a	0.31 a	25 a
Mapanga	3.80 c	1.39 a	2.92 a	0.29 a	1.17 ab	0.34 a	27 ab
Kadadi	3.77 bc	1.55 a	3.20 b	0.30 a	1.14 a	0.41 a	36 c

The lime treatment had a significant effect on the N concentration of the shoot. The average N concentration in the treatment without lime was 3.63% and the N concentration in the treatment with lime 3.84%.

3.5. Observations

During the growing period the appearance of the plants was regularly visually inspected. Even before the shoots emerged the roots grew through the gauze in the plastic bag with the nutrient solution. In general root development was very good; the only exception was the –Ca treatment, where root growth was retarded. This was clearer in the beginning of the growing period, but at the moment of harvest the root systems were still less developed (Fig. 8).

Fig. 8. Soybean plants at day of harvest. Root system of –Ca (left picture) is less extensive than root system of –S (right picture). Both pictures were from plants grown on soil from farmer Mandebvu in Mhondoro and were without dolomite.

After two weeks some extra pots were harvested to check for nodule formation and nodules were already clearly visible on the crown root of the soybean plants. After harvest the root systems of all plants were checked for nodulation. There were no plants without nodules. Some nodules were dissected and were found to be reddish inside (Fig. 9). By visual observation no clear differences in nodulation between treatments was found.

Fig. 9. Nodules on crown root and a cross section of a nodule at the right.

The first symptoms that could indicate nutrient deficiency appeared in the –K treatment. Already 10 days after emergence leaves were discolouring into brown and yellow. In a later stadium the plants started shedding off older leaves. Growth of the main stem and appearance of new leaves continued for

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some time as can be seen in Fig. 3. Plants grown without P or Ca were darker green than plants from the other nutrient treatments. As already mentioned, the –Ca treatment had a less developed root system and showed stunted growth of the shoot as well. The growth of the stem was also a bit stunted in plants without P in the nutrient solution, but those plants grew very well in terms of biomass production as can be seen in Figs. 3 and 7.

Fig. 10. Pictures of soybean plants at day of harvest. From left to right: Complete, -P, -K and –S treatment. All plants were from soil of farmer Kadadi in Murehwa and without dolomite.

All other nutrient treatments, namely complete, -Mg, -S, -Zn and -Micronutrients had pale green leaves. At harvest time older leaves were yellow green and small brown spots were visible on many leaves (Fig. 10).

3.6. Interviews

To get insight in the management history of the fields the initial plan was to interview all farmers whose land was sampled for the trials. Soil samples were collected from six sites, but only two farmers from Murehwa were interviewed, because of the volatile political situation elsewhere. The soil samples from Wedza and Mhondoro were collected by field workers of CIAT and no interviews were done. The results of the interviews with the farmers from Murehwa can be found in Appendix III.

The names of the interviewed farmers are Kadadi and Mapanga. Both farmers were solely dependent on farming for their income. Their farms were of comparable size, respectively 3 and 2.4 ha. Farmer Kadadi had considerably more livestock than farmer Mapanga. He owned 9 cows, of which 2 oxen, while farmer Mapanga had 2 oxen in total. Land preparation was done by ploughing by oxen. A common practice for the farmers was to collect crop residues and to put them in the kraal. During the dry season the fields were grazed by livestock. With regard to the application of fertilizer they were used to apply compound D, Single Super Phosphate (SSP) and lime before planting and ammonium nitrate (AN) after planting. Both farmers got advice by agricultural extension workers.

The fields of which a soil sample was taken were situated respectively 100 and 60 m from the homestead and had an area of respectively 0.4 and 0.05 ha. The infertile field made up a large proportion of the total available land of farmer Kadadi. Both farmers described the fertility and texture of the fields as poor. The water holding capacity of the soil was described as poor by farmer Kadadi, while farmer Mapanga described the water holding capacity of the soil as good.

The cropping history of the fields for the last four years was recorded (Table 7). All the numbers for yield and fertilization given by the farmers were converted to a per hectare basis. Last year both farmers had grown legumes under the N2Africa project. Farmer Kadadi did not fertilize his field and obtained a poor yield for sugarbean and no yield at all for soybean, because the crop performed very poorly. Farmer Mapanga grew groundnut and applied 100 kg SSP and 100 kg lime. He obtained a yield of 1500 kg groundnut ha^{-1}. It is obvious that most fertilizer was used for maize. Farmer Kadadi applied 500 kg compound D and 500 kg ammonium nitrate (AN) to maize, while he applied 375 kg compound D and 250 kg AN in sweet potato. The same is true for farmer Mapanga who applied 200 kg compound D and 500 kg AN for maize, while he applied only 200 kg compound D for sweet potato.

Table 7. Cropping and fertilization history over the last four years of the fields of farmers Kadadi and Mapanga. Numbers are calculated on a hectare basis.

	Kadadi			Mapanga		
Year	Crop	Yield (ha^{-1})	Fertilization (ha^{-1})	Crop	Yield (ha^{-1})	Fertilization (ha^{-1})
2011	Sugarbean Soybean	383 kg no yield	No	Groundnut	1500 kg	100 kg SSP 100 kg lime
2010	Fallow	No	No	Maize	3000 kg	200 kg compound D 500 kg AN
2009	Sweet potato	n.d.	375 kg compound D 250 kg AN	Sweet potato	3000 kg	200 kg compound D
2008	Maize	1500 kg	500 kg compound D 500 kg AN	Groundnut	700 kg	No

The farmers had different preferences for fertilizer type. Farmer Kadadi preferred urea and lime and would apply this to maize on the homefields. Farmer Mapanga preferred AN and compound D. For him maize was the most important crop to apply fertilizer on as well, but he would fertilize the midfields in the first place. To the question about changes in soil fertility over time both farmers answered that they observe a decline in soil fertility. According to farmer Kadadi the colour of the soil had changed from black to dark brown over the past years, indicating a decrease in organic matter content. In his view two factors were responsible for the decline in soil fertility, namely a problem of manure and fertiliser availability and shortage of land. A shortage of land means that the land has to be cultivated every year. Farmer Mapanga mentioned the same problem. He said that the land had to be ploughed year after year, without the application of basal fertilizers, resulting in a lower soil fertility.

4. Discussion

4.1. Indicator for growth

Two indicators have been used to determine the growth of the plants. The first one was stem height and the second indicator was final biomass of the shoot after harvest. First the suitability of these indicators will be discussed. The advantage of stem height as indicator is that the growth of each plant can be followed during the growing period by regular non-destructive measurements, unlike biomass. Janssen (1990) used total leaf length of maize as indicator for growth. With those data he calculated the relative growth rate (RGR) and the sufficiency quotient (SQ) of maize plants for different nutrient treatments. A comparison of the SQ's for the different nutrient treatments would give information about the extent in which a nutrient is limiting plant growth. Janssen (1970) proved there is an almost linear relationship between total leaf length and dry weight of maize. The increase in total leaf length of maize was exponential in the beginning and started decreasing after factors became limiting. Because soybean is a dicot the plant has a very different growth pattern than maize. Therefore stem height was used as parameter instead of total leaf length. It was supposed that the RGR and SQ for soybean could be calculated from measurements of the growth rate of the stem.

Fig. 2 shows the curve of the relative growth rate of the main stem for the different nutrient treatments. Instead of a constant RGR that starts declining after some time, the shape of the curve is more like a W. Therefore it is not possible to calculate the average RGR and the SQ. The reason that the growth of the soybean main stem has a different pattern than total leaf length in maize can be attributed to the fact that soybean produces branches as well. If much more replicates were used in the experiment it would have been possible to measure biomass each 4 days instead of stem height. Probably this would have resulted in the expected graph of the relative growth rate of soybean. Another option would be the use of mathematical growth analysis techniques to calculate the net assimilation rate (NAR) and the leaf area duration (LAD). The product of these two equals the dry matter production (Monks et al., 1988). It may be that total leaf area would be a suitable indicator for growth (Bouma, 1965), but it would be very laborious to do all the measurements.

The observations showed as well that stem height was not always a good indicator of biomass accumulation. The plants grown on a complete nutrient solution were expected to have the highest growth. When stem height was taken as indicator this was indeed the case, but it did not result in the highest final biomass of the shoot (Fig. 7). Plants grown without K in the solution still increased their stem height, while the plants looked very poor and had shed off almost all their leaves. Therefore shoot dry weight or total leaf area would be a more suitable indicator for soybean growth than stem height.

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4.2. Lime treatment

There was no interaction between lime and nutrient treatment. Between lime and soil type there was interaction, but the pH after liming was not similar between the soils. Therefore it is not possible to draw reliable conclusions about differences in soil or nutrient treatment in response to liming. The overall effect of lime on shoot dry weight was significant. Fig. 5 shows that on average shoot dry weight of the soybean plants increased from 0.67 to 0.85 g per plant if lime was applied to the soil. Positive effects of lime on production are usually caused by several factors, including: reduced levels of Al^{3+} and Mn^{2+}, an increase in N_2 fixation legumes, extra supply of Ca and an improved availability of nutrients. There might have been a small positive effect of reduced toxicity of Al^{3+} and Mn^{2+} for the roots, but there was only a minor part of the root system in the soil. It is also possible that the increase in pH improved the availability of nutrients in the soil, but the plants were provided with sufficient nutrients in the solution, except for N. The most likely explanation in this case is an increased fixation of N_2, because both total dry weight and shoot N concentration increased with lime application. pH is an important determinant for rhizobia growth. The high concentrations of Al^{3+} and Mn^{2+} at a low pH have negative effect on soybean, but even more on the growth of rhizobia. It has been observed that nodulated legumes are more sensitive to Al^{3+} and Mn^{2+} toxicity than plants receiving mineral N (Hungria and Vargas, 2000). The optimal pH (in H_2O) in solution for rhizobia ranges between 6.0 and 7.0 (Jordan, 1984) and relatively few rhizobia strains grow well at a pH less than 5.0 (Graham et al., 1994). Because the pH of the soils used in this experiment was low, an improved nodulation of rhizobia is expected after liming. Therefore it will be useful to examine the effects of lime in these soils on rhizobia in a field experiment.

Maize, which is the staple crop in Zimbabwe, has a lower threshold pH than soybean. Grant (1981) reported that field trials and wide experience have shown that on sandy soils there is little chance of maize responding to liming unless the soil is very strongly acidic with a pH value of 4.3 or less (in 0.1 M $CaCl_2$). The pH of the soils used in the experiment ranged from 3.8 – 4.8 and three of the six soils had a pH of 4.3 or less. This would mean that for these soils even for maize production a positive response can be expected when lime is applied.

4.3. Soils

There were significant differences between soils and average dry weight of shoots ranged from 0.49 – 0.97 per plant per soil (Fig. 6). However, it is difficult to relate the outcome of the pot experiment to the chemical and physical properties of the soil. This can be illustrated with the soils from Wedza Bhake and Murehwa Kadadi. The worst performing soil in terms of biomass production was Bhake, but on the basis

of the soil chemical analysis Kadadi would be expected to perform worse, because the organic C content, total N, available P and exchangeable K, Ca and Mg were lower in this soil. Only the pH was 0.1 higher in soil from Kadadi, but this cannot explain why plants grew better on Kadadi than on Bhake. The differences in chemical properties of the soils did hardly result in differences in plant nutrient concentration between Bhake and Kadadi. The concentration of Ca in the shoot was significant higher in plants grown on soil from Bhake, but this did not result in a higher biomass. Plant N concentration tended to be higher in Kadadi, which would not be expected because the total N content in the soil was lower in Kadadi. One explanation may be that soil concentrations of Al^{3+} or Mn^{2+} were higher in Bhake, having a negative effect on the rhizobia. However, data to prove this are lacking, because Al and Mn were not included in the soil chemical analysis. It is not likely that deficiencies of other nutrients than N can explain the low biomass production of Bhake compared to other soils, because shoot nutrient concentrations of plants grown on soil from Bhake were relatively high compared to the plants grown on other soils.

Although it seems there was hardly a relation between the differences in soil chemical and physical properties and the outcome of the pot experiment it can still be concluded that all the soils were acid to strongly acid and low in organic C, total N and other elements. Next to that was the biomass produced in the −K treatment lowest on the soils Kadadi and Mapanga, which soils were lowest in soil K concentration.

4.4. Nutrient treatment

It was expected that the complete nutrient treatment would result in the highest biomass production, but the −P treatment resulted in the highest biomass of all the nutrient treatments. Although the differences with the complete, -Mg and −Micronutrients treatments were not significant (Fig. 6), the plants grown without P appeared healthier. They did not show the symptoms of pale green leaves and brown discolouring the other plants showed. The cause of the poor performance of plants on the complete nutrient solution and other nutrient solutions was due to excessive amounts of P in the solution. The concentration of P was 3 mM, instead of the usual 0.7 - 1.3 mM (Hewitt, 1952) and this was the result of a miscalculation. In soils situations of P toxicity are very rare, but in hydroponics the concentration of P can be too high. Many plant species exhibit a decreased growth rate and necrosis of leaves and cotyledons when the concentration of P in these tissues exceeds 1% of dry weight (Asher and Loneragan, 1967). P tissue concentrations in the soybean shoots exceeded 1% for all nutrient treatments, except for the −P and −Ca treatment. Tagliavini et al. (1991) reported a shoot P concentration of 0.35 - 0.52% in peach seedlings grown at 5 mM P in the nutrient solution at different

root zone temperatures. This shows that there is difference in P uptake or allocation between plant species and probably soybean is much more sensitive to high concentrations of P. In general nutrient concentrations should not be high for soybean. Legget and Frere (1971) observed toxic symptoms when growing soybeans in a full strength Hoagland solution.

The P concentration in the shoot for the –P treatment was on average 0.10%, which is below the critical value of 0.30% P in soybean tissue (Sabbe et al., 2000). The plants of the –P treatment showed indeed symptoms of P deficiency; dark green leaves and stunted growth (Mengel and Kirkby, 1987). The concentration of N was also significant lower than in other treatments, except compared to the –Micronutrients treatment. For K, Mg, Ca and Zn the concentrations in –P treatment were second lowest. These nutrients were only found in lower concentrations in the treatments where the concerning element was omitted. Because the –P treatment performed best in terms of biomass production the relatively low concentrations of the other elements were not caused by deficiency. It is likely that in other treatments there was accumulation of elements due to other limitations, while in the –P treatment the concentration of elements was more diluted. The growth of plants of the –P treatment was probably limited either by P or N. If P is in short supply plants dependent on N_2 fixation may be limited in their production, because P is an important element for N_2 fixation. The concentration of N was below the critical value for soybean (Sabbe et al., 2000), but the observed symptoms could be associated with P deficiency, rather than N deficiency. For a next experiment it is advisable to have a control treatment with N in the solution. In that situation it is possible to conclude whether the effect of an omitted nutrient was due to deficiency of that nutrient or that plant growth was limited by N shortage. Another reason to include N in the complete nutrient treatment is that N_2 fixation starts at the earliest between 10 and 21 days after inoculation (Marschner, 1995). Kouchi et al. (1989) reported nitrogenase activity in soybean at 13 days after inoculation and substantial amounts of N_2 are fixed approximately 4 weeks after germination (Imas and Magen, 2008).

The –K treatment resulted in the lowest biomass production and was the first treatment showing symptoms that could indicate nutrient deficiency. Most elements were found in relatively high shoot concentrations in this treatment. For instance the concentration of N and Mg was highest of all nutrient treatments and the other elements were also found in relatively high concentrations. Only the concentration of K was significant lower than all the other treatments. The K concentration was on average 1.71% and this is around the critical value of K for early growth of soybean (Sabbe et al., 2000). Because the produced biomass was very low in the -K treatment, this may indicate that K was limiting production. If K was limiting other elements were in sufficient amounts and were accumulating in the plant tissue. This would explain the low biomass production and high concentrations of other elements in the plant tissue, but the symptoms of the plants did not look like K deficiency symptoms. Sinclair

(1993) describes K deficiency symptoms as follows: 'Symptoms appear first on the older leaves and in early stages of growth an irregular yellow mottling appears around leaflet margins. This symptom often is followed by necrosis of chlorotic areas and downward cupping of leaf margins. Dead tissues then drop away so that the leaves appear ragged. Chlorosis and necrosis may spread inward to include half or more of the leaflet, but the basal portions remain green.' Fig. 11 shows the shoot of a soybean plant with discoloured leaves. The basal portions did not remain green and there were no ragged leaves. If K was not the limiting factor it is possible that the poor growth was caused by a higher uptake of P.

Research showed that a decreasing concentration of K in the nutrient solution has an increasing effect on the uptake of P (Fageria, 2001). If this would have been the case this should translate in higher shoot P concentrations in the –K treatments, but P concentrations were equal or lower than in most nutrient treatments. It is not possible to draw a clear conclusion, because it seems that K was the limiting factor for production, but the symptoms did not correspond with the described symptoms for K deficiency. Yet K fertilization needs special attention in the sandy soils of Zimbabwe (Nyamangara, 2000). Soil K status in the analysed soils ranged from deficient to adequate and soybean is known to require a large amount of K. Dry matter yield, nodule number, nodule weight per plant and total N accumulation in soybean increase with increasing K-supply (Premaratne and Oertli, 1994).

Fig. 11. Plant –K treatment with brown leaves.

Furthermore K can have positive effects on production in times of drought. Many sandy soils have little water holding capacity. Crops on these soils suffer more rapidly from drought stress than crops on clayish soils. Although soybean can stand water stress to a great extent yield reduction caused by drought can be minimized if adequate K is supplied (Joshi, 2008). Rainfall in Zimbabwe is often erratic. There are periods of drought and periods of heavy rainfall. According to Tucker (1997) extremely sandy-textured soils do lack the capacity to hold K against leaching and show little or no accumulation from long-term K applications. Therefore annual applications of K are the best way to supply enough K to sustain good soybean production.

The –Mg treatment did not result in a lower production than the complete treatment. The concentration of Mg was 0.15% in this treatment. Sabbe et al. (2000) reported 0.03-0.6% as critical value. Apparently the plant got sufficient Mg from the seed or the soil. The concentration of K was highest in this treatment compared to the other treatment and this was probably due to a lack of competition in nutrient uptake between Mg and K, because usually high concentrations of one element inhibit the uptake of the other element.

The -Ca treatment resulted in reduced root growth (Fig. 8). Ca is immobile in plants and essential for root development (Bangerth, 1979; Marschner, 1995). Therefore a small amount of Ca in the nutrient solution is needed for good root development. The lower root volume may have caused a reduced uptake of other nutrients as well and in particular P and K, because these concentrations in the plant were low compared to other treatments. The –Ca treatment was the only treatment for which the P concentration in plant tissue fell in the normal range. The colour of the leaves in the –Ca treatment was darker green than in the other treatments, except for –P, but the biomass produced was less than in the –P treatment. Probably this was caused by a reduced uptake of nutrients by the lower root volume.

After the –K treatment the lowest biomass production was obtained for the nutrient treatment –S. The concentration of S in the soybean shoot in the –S treatment was 0.20%. This is slightly lower than the critical value of 0.25% S for soybean (Sabbe et al., 2000). This value was reported for soybean at flowering stage, so the critical value for early growth may deviate from this 0.25%.

The –Zn and –Micronutrients treatments were not significant different from the complete treatment in terms of biomass production. However the average biomass of –Zn was significantly lower than for –Micronutrients. This result is unexpected because in the –Micronutrients treatment all the micronutrients were omitted including Zn. Probably the plants were able to take up sufficient micronutrients from the soil and the treatments with micronutrients may have suffered also a bit from too high concentrations of micronutrients in the Hoagland solution (Legget and Frere, 1971).

4.5. Management

In the first place it should be noted that with only two farmers interviewed no conclusions can be drawn about common practices or preferences of Zimbabwean farmers. Next to that are the quantitative data given by the farmers on yield and fertilization not reliable, because they were based on a rough estimation of the area of the fields. Therefore, fertilizer rates and yields cannot be compared with values reported in literature. Types of fertilizer and application times mentioned by the farmers in this research were in agreement with the fertilizer recommendations of the Zimbabwe Fertilizer Company (FAO, 2006). Both farmers declared to have a preference to apply fertilizer or manure to the maize crop, as could be expected because maize is the staple food in Zimbabwe. The farmers did not always use fertilizer when they grow legumes. Probably this is caused by their preferences for other crops or other fields, but it may be that farmers have the idea that legumes can be grown without fertilization. The farmers described their fields as having a poor soil fertility and observed a decline in soil fertility. They attributed that to limited access to manure and fertilizer and shortage of land. If more land would be available, farmers could open new outfields in the case soil fertility declines. This occurs for instance in

Gokwe (Masvaya et al., 2010), another area in Zimbabwe, but apparently this is not the case in Murehwa. This means that farmers should try to improve the soil fertility of their poor fields or should invest their resources in more fertile fields. It depends on the situation what is wise to do. However, it was notable that the two farmers rarely applied lime on the poor fields, while the pH was very low. Lime application and a low fertilization dose will probably increase legume yields on poor fields.

5. Conclusions

- The soils used in this experiment could all be classified as sandy and acid soils. All the soils were low to very low in organic C, total N, Olsen-P and exchangeable K, Mg and Ca.

- The results of the experiment show that K was the most limiting nutrient for production and S was the second limiting nutrient. However, it was not possible to draw clear conclusions about nutrient limitations, because results were compromised due to excessive amounts of P in the nutrient solution. Despite of the problems with P the experimental results suggest that K availability on these poor sandy soils needs attention. From literature is known that extremely sandy textured soils lack the capacity to prevent K from leaching and do not accumulate K from long-term K applications. It is also known that soybean requires a large amount of K. Therefore the effect of annual K applications to soybean should be investigated in field experiments.

- The use of lime increased biomass production of soybean and shoot N concentration. Although the optimal pH for soybean is higher than the pH in the non-responsive soils used, it is likely that the primary cause for this increase was due to the positive effect on the rhizobia. Rhizobia are more sensitive than soybean to Al^{3+} and Mg^{2+} which concentrations are higher at low pH. Therefore it is recommendable for farmers to apply lime on their acid soils to obtain a better production of legumes. For maize in Zimbabwe it is known that a response to liming is only expected if the pH < 4.3 ($CaCl_2$).

- Stem height was not a suitable indicator for the growth rate in biomass of soybean. A suitable alternative non-destructive indicator could be total leaf area, but is laborious to measure.

- For a next pot experiment it is recommended to include N in the nutrient solution. This makes it possible to distinguish whether growth is limited by N deficiency or deficiency of another nutrient. If soybean is grown a half strength Hoagland solution should be used to avoid toxic concentrations of elements.

- The double pot technique is not suitable to test the effect of omitting Ca, because that element is needed for good root development.

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Appendix I – Brief experimental plan

Thesis Plant Production Systems

A double-pot experiment with soybean to test for nutrient limitations in sandy Zimbabwean soils responding poorly to fertilization and inoculation

Contact persons: W.J. (Wietske) van der Starre, tel. 0681916902

                             A.C. (Linus) Franke, tel. 0317481376

Factors and levels

Block (B):   B1 = Block 1

                             B2 = Block 2

                             B3 = Block 3

                             B4 = Block 4

Soil type (S):   S1 = Mhondoro Chikwanha

                             S2 = Mhondoro Mandebvu

                             S3 = Wedza Muzuvu

                             S4 = Wedza Bhake

                             S5 = Murehwa Mapanga

                             S6 = Murehwa Kadadi

Nutrient treatment (N):   N1 = Complete nutrient solution

                             N2 = P omitted from solution

                             N3 = K omitted from solution

                             N4 = Mg omitted from solution

                             N5 = Ca omitted from solution

                             N6 = S omitted from solution

                             N7 = Zn omitted from solution

                             N8 = Micronutrients omitted from solution

Lime treatment (D)   D1 = Without dolomite

                             D2 = With dolomite

Further specifications

Location: Greenhouse SPRL, Marondera, Zimbabwe

Crop type: Soybean (*Glycine max L.*)

Sowing date: 17 January 2012

Harvesting date: 21 February 2012

Sowing density: Two seeds per pot. After emergence pots are thinned to one seed per pot.

Fertilization: According to nutrient treatment.

Layout pot experiment

G	G	G	G	G	G	G	G
G	1	14	27	40	53	66	G
G	2	15	28	41	54	67	G
G	3	16	29	42	55	68	G
G	4	17	30	43	56	69	G
G	5	18	31	44	57	70	G
G	6	19	32	45	58	71	G
G	7	20	33	46	59	72	G
G	8	21	34	47	60	73	G
G	9	22	35	48	61	74	G
G	10	23	36	49	62	75	G
G	11	24	37	50	63	76	G
G	12	25	38	51	64	77	G
G	13	26	39	52	65	78	G
G	G	G	G	G	G	G	G

G	G	G	G	G	G	G	G
G	79	92	105	118	131	144	G
G	80	93	106	119	132	145	G
G	81	94	107	120	133	146	G
G	82	95	108	121	134	147	G
G	83	96	109	122	135	148	G
G	84	97	110	123	136	149	G
G	85	98	111	124	137	150	G
G	86	99	112	125	138	151	G
G	87	100	113	126	139	152	G
G	88	101	114	127	140	153	G
G	89	102	115	128	141	154	G
G	90	103	116	129	142	155	G
G	91	104	117	130	143	156	G
G	G	G	G	G	G	G	G

G	G	G	G	G	G	G	G
G	157	170	183	196	209	222	G
G	158	171	184	197	210	223	G
G	159	172	185	198	211	224	G
G	160	173	186	199	212	225	G
G	161	174	187	200	213	226	G
G	162	175	188	201	214	227	G
G	163	176	189	202	215	228	G
G	164	177	190	203	216	229	G
G	165	178	191	204	217	230	G
G	166	179	192	205	218	231	G
G	167	180	193	206	219	232	G
G	168	181	194	207	220	233	G
G	169	182	195	208	221	234	G
G	G	G	G	G	G	G	G

G	G	G	G	G	G	G	G
G	235	248	261	274	287	300	G
G	236	249	262	275	288	301	G
G	237	250	263	276	289	302	G
G	238	251	264	277	290	303	G
G	239	252	265	278	291	304	G
G	240	253	266	279	292	305	G
G	241	254	267	280	293	306	G
G	242	255	268	281	294	307	G
G	243	256	269	282	295	308	G
G	244	257	270	283	296	309	G
G	245	258	271	284	297	310	G
G	246	259	272	285	298	311	G
G	247	260	273	286	299	312	G
G	G	G	G	G	G	G	G

G = guard pots

Appendix II – Composition of nutrient solutions

The pH of the nutrient solutions ranged between 6.0 – 6.5. NaOH and HCl were used to adjust the pH.

Complete solution

Nutrient salts	H_3PO_4, KCl, K_2SO_4, $CaCl_2$, $MgSO_4$
Micronutrient mixture	$ZnSO_4$, FeCl, $MnCl_2$, H_3Bo_3, $(NH_4)_6Mo_7O_{24}$, $CuSO_4$

Cations	meq	Anions	meq
H	9	PO_4	9
K	5	Cl	10
Ca	8	SO_4	5.5
Mg	2.5		
Total	24.5	Total	24.5

Solution without P

Nutrient salts	KCl, K_2SO_4, $CaCl_2$, $MgSO_4$
Micronutrient mixture	$ZnSO_4$, FeCl, $MnCl_2$, H_3Bo_3, $(NH_4)_6Mo_7O_{24}$, $CuSO_4$

Cations	meq	Anions	meq
K	5	Cl	10
Ca	8	SO_4	5.5
Mg	2.5		
Total	15.5	Total	15.5

Solution without K

Nutrient salts	H_3PO_4, $CaCl_2$, $MgSO_4$
Micronutrient mixture	$ZnSO_4$, FeCl, $MnCl_2$, H_3Bo_3, $(NH_4)_6Mo_7O_{24}$, $CuSO_4$

Cations	meq	Anions	meq
H	9	PO_4	9
Ca	8	Cl	8
Mg	2.5	SO_4	2.5
Total	19.5	Total	19.5

Solution without Mg

Nutrient salts	H_3PO_4, K_2SO_4, $CaCl_2$
Micronutrient mixture	$ZnSO_4$, FeCl, $MnCl_2$, H_3Bo_3, $(NH_4)_6Mo_7O_{24}$, $CuSO_4$

Cations	meq	Anions	meq
H	9	PO_4	9

Cations		Anions	
K	6	SO_4	6
Ca	8	Cl	8
Total	17	Total	17

Solution without Ca

Nutrient salts H_3PO_4, KCl, K_2SO_4, $MgSO_4$

Micronutrient mixture $ZnSO_4$, FeCl, $MnCl_2$, H_3Bo_3, $(NH_4)_6Mo_7O_{24}$, $CuSO_4$

Cations	meq	Anions	meq
H	9	PO_4	9
K	5	Cl	2
Mg	2.5	SO_4	5.5
Total	10.5	Total	10.5

Solution without S

Nutrient salts H_3PO_4, KCl, $CaCl_2$, $MgCl_2$

Micronutrient mixture $ZnSO_4$, FeCl, $MnCl_2$, H_3Bo_3, $(NH_4)_6Mo_7O_{24}$, $CuSO_4$

Cations	meq	Anions	meq
H	9	PO_4	9
K	4	Cl	14.5
Ca	8		
Mg	2.5		
Total	17.5	Total	17.5

Solution without Zn

Nutrient salts H_3PO_4, KCl, K_2SO_4, $CaCl_2$, $MgSO_4$

Micronutrient mixture   FeCl, $MnCl_2$, H_3Bo_3, $(NH_4)_6Mo_7O_{24}$, $CuSO_4$

Cations	meq	Anions	meq
H	9	PO_4	9
K	5	Cl	10
Ca	8	SO_4	5.5
Mg	2.5		
Total	18.5	Total	18.5

Solution without micronutrients

Nutrient salts H_3PO_4, KCl, K_2SO_4, $CaCl_2$, $MgSO_4$, $ZnSO_4$

Micronutrient mixture   -

Cations	meq	Anions	meq

H	9	PO_4	9
K	5	Cl	10
Ca	8	SO_4	5.5
Mg	2.5		
Total	18.5	Total	18.5

Appendix III – Calculations lime requirement

Soil	pH	Lime (kg ha^{-1})	Lime (g pot^{-1})
Mhondoro Chikwanha	3,8	3460	0,30
Mhondoro Mandebvu	4,4	2240	0,19
Wedza Muzuvu	4,3	2420	0,21
Wedza Bhake	4,7	1700	0,15
Murehwa Mapanga	4,3	2600	0,23
Murehwa Kadadi	4,8	1460	0,13

Appendix IV – Questionnaire

Farmer Kadadi (Murehwa)

Household

- What is the size of the household?
  4 people
- Age and gender of head
  Male (52 yrs.)
- Do you own cattle? Small livestock? Draught power?
  9 cows of which 2 oxen
- What is the area of your land?
  3 ha
- Who earns cash? From which activities?
  No other activities than farming

Field

- Area field
  0.4 ha
- Distance from homestead
  100 m
- How do you describe your soil in terms of texture, color, moisture holding properties?
  Poor texture, color has changed from black to dark brown, poor water holding capacity
- How do you describe the fertility of the soil?
  Poor
- What is the cropping history of the field?
  1) Soybean and sugarbean, 2) fallow, 3) sweet potatoes, 4) maize
- Was there a crop rotation or intercropping?
  No
- What happens to crop residues?
  They are put in the kraal
- Grazing in dry season?
  Yes
- What were the yields?
  1) Soybean very poor, 9 buckets sugarbeans, 2) no yield, 3) unknown, 4) 600 kg maize
- Have yields changed for the crops you grow? How? Why?
  Yes, soil fertility is decreasing. There is a problem of access to manure and fertilizer and there is shortage of land so land has to be cultivated every year.

Soil management

- How do you prepare your land? Did you change methods over the years?
  Ploughing. No.
- What fertilizers are used (inorganic fertilizer, manure, leaf litter, compost, spread ant heap)? And in which quantity?
- No fertilizer, 2) no fertilizer, 3) 100 kg AN and 150 kg compound D, 4) 200 kg AN and 200 kg compound D.
- Have fertilizers type or quantity changed over the years?
  No.
- When do you apply inputs in the season?
  Three weeks after planting first dose AN, after six weeks second dose AN.
- Do you have preferences which fertilizer to use? Which crops to receive them? Amongst fields?
  Yes, lime and urea. Maize. Homefields.
- Do you get advice from somebody how to manage your land?
  Yes, from extension workers

Farmer Mapanga (Murehwa)

Household

- What is the size of the household?
  4 people
- Age and gender of head
  Male (58 yrs.)
- Do you own cattle? Small livestock? Draught power?
  2 oxen
- What is the area of your land?
  2.4 ha

Field

- Area field
  0.05 ha
- Distance from homestead
  60 m
- How do you describe your soil in terms of texture, color, moisture holding properties?
  Loose soil, good moisture holding capacity, light brown, poor texture.
- What is the cropping history of the field?
  1) Groundnuts, 2) maize, 3) sweet potatoes, 4) groundnuts
- Was there a crop rotation or intercropping?
  No specific crop rotation and no intercropping
- What happens to crop residues?
  They are put in the cattle kraal
- Grazing in dry season?
  Yes
- What were the yields?
  1) 75 kg groundnuts, 2) 150 kg maize, 3) 150 kg sweet potatoes, 4) 2 buckets groundnuts
- Have yields changed for the crops you grow? How? Why?
  There is a decline in soil fertility on that field. The cause is ploughing of field year after year without applying basal fertilizers.

Soil management

- How do you prepare your land? Did you change methods over the years?
  Ploughing by oxen.
- What fertilizers are used (inorganic fertilizer, manure, leaf litter, compost, spread ant heap)? And in which quantity?
  1) 5 kg SSP and 5 kg lime, 2) 10 kg compound D and 25 kg AN, 3) 10 kg compound D, 4) No
- Have fertilizers type or quantity changed over the years?

No
- When do you apply inputs in the season?

  Compound D, SSP and lime before planting. AN 3 weeks after planting.
- Do you have preferences which fertilizer to use? Which crops to receive them? Amongst fields?

  Preference for AN and compound D. Maize. Midfields.
- Do you get advice from somebody how to manage your land?

  Yeas, from extension workers

Appendix V – SPSS output

Effect of lime treatment

Tests of Between-Subjects Effects

Dependent Variable:DWshoot

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	34.362[a]	92	.373	4.339	.000
Intercept	138.275	1	138.275	1606.433	.000
S * N * L	2.884	20	.144	1.675	.044
B * S	1.547	15	.103	1.198	.279
B * N	2.967	12	.247	2.873	.001
B * L	.144	3	.048	.557	.644
S * N	2.839	20	.142	1.649	.049
S * L	1.201	5	.240	2.790	.019
N * L	.319	4	.080	.928	.450
B	3.334	3	1.111	12.913	.000
N	12.816	4	3.204	37.223	.000
S	4.295	5	.859	9.980	.000
L	2.015	1	2.015	23.408	.000
Error	12.653	147	.086		
Total	185.290	240			
Corrected Total	47.015	239			

a. R Squared = .731 (Adjusted R Squared = .562)

Estimates

Dependent Variable:DWshoot

L	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	.667	.027	.614	.720
2	.851	.027	.798	.904

Effect of nutrient treatment (N), soil (S) and block (B).

Tests of Between-Subjects Effects

Dependent Variable:DWshoot

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	22.234[a]	84	.265	3.156	.000
Intercept	87.667	1	87.667	1045.322	.000
B * S	1.683	15	.112	1.337	.195
B * N	3.109	21	.148	1.765	.033
S * N	3.771	33	.114	1.362	.124
B	2.209	3	.736	8.778	.000
S	4.019	5	.804	9.584	.000
N	7.060	7	1.009	12.026	.000
Error	8.303	99	.084		
Total	119.232	184			
Corrected Total	30.536	183			

a. R Squared = .728 (Adjusted R Squared = .497)

Estimates

Dependent Variable:DWshoot

			95% Confidence Interval	
S	Mean	Std. Error	Lower Bound	Upper Bound
1	.640[a]	.059	.523	.758
2	.971	.051	.869	1.073
3	.753	.051	.651	.854
4	.493	.051	.392	.595
5	.659	.051	.557	.760
6	.636	.051	.535	.738

a. Based on modified population marginal mean.

Estimates

Dependent Variable:DWshoot

N	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	.741	.059	.624	.859
2	.907	.059	.790	1.024
3	.280	.059	.162	.397
4	.857[a]	.065	.728	.985
5	.698[a]	.065	.569	.826
6	.539	.059	.422	.656
7	.691	.059	.574	.808
8	.870	.059	.753	.987

a. Based on modified population marginal mean.

Normal Q-Q Plot of Residual for DWshoot
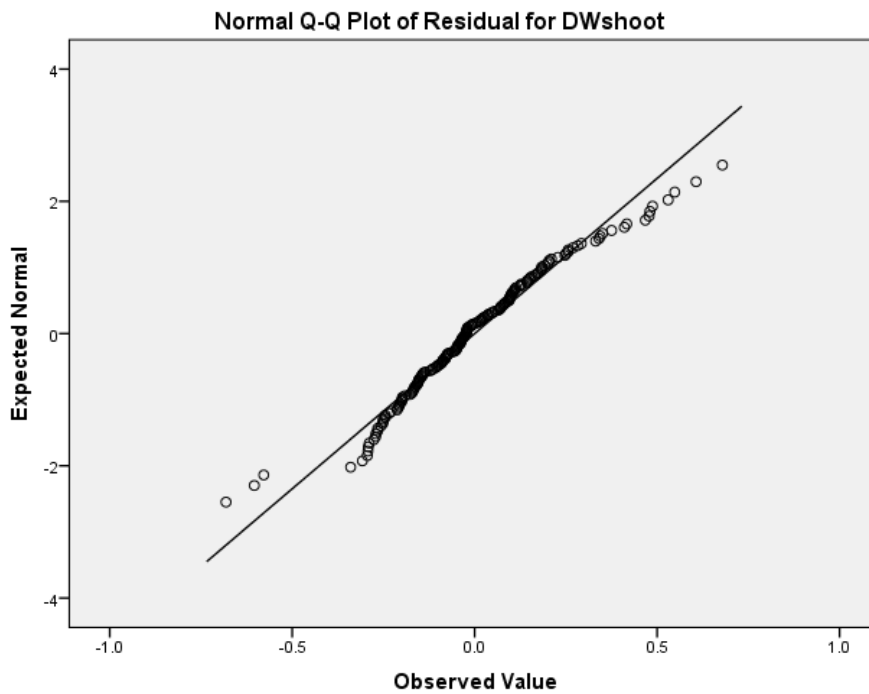
Nutrient concentration shoot tissue

Nitrogen

Tests of Between-Subjects Effects

Dependent Variable:N

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	13.367[a]	12	1.114	12.138	.000
Intercept	595.827	1	595.827	6492.475	.000
Soil	1.719	5	.344	3.746	.009
Nutrient	11.666	7	1.667	18.160	.000
Error	3.028	33	.092		
Total	627.604	46			
Corrected Total	16.396	45			

a. R Squared = .815 (Adjusted R Squared = .748)

Estimates

Dependent Variable:N

Nutrient	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1.00	3.885	.124	3.633	4.137
2.00	2.845	.124	2.593	3.096
3.00	4.620	.124	4.368	4.871
4.00	3.384	.137	3.104	3.663
5.00	3.747	.137	3.467	4.026
6.00	3.627	.124	3.376	3.879
7.00	3.809	.124	3.558	4.061
8.00	3.194	.124	2.942	3.445

Phosphorus

Tests of Between-Subjects Effects

Dependent Variable:P

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2.213E9	12	1.844E8	56.215	.000
Intercept	9.283E9	1	9.283E9	2829.417	.000
Soil	29230352.356	5	5846070.471	1.782	.144
Nutrient	2.189E9	7	3.128E8	95.329	.000
Error	1.083E8	33	3280771.264		
Total	1.200E10	46			
Corrected Total	2.321E9	45			

a. R Squared = .953 (Adjusted R Squared = .936)

Estimates

Dependent Variable:P

Nutrient	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1.00	17022.167	739.456	15517.732	18526.601
2.00	1001.667	739.456	-502.768	2506.101
3.00	16057.167	739.456	14552.732	17561.601
4.00	19284.956	821.207	17614.198	20955.714
5.00	4723.756	821.207	3052.998	6394.514
6.00	21397.000	739.456	19892.565	22901.435
7.00	19652.667	739.456	18148.232	21157.101
8.00	15760.667	739.456	14256.232	17265.101

Potassium

Tests of Between-Subjects Effects

Dependent Variable:K

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2.998E9	12	2.499E8	68.145	.000
Intercept	4.147E10	1	4.147E10	11310.478	.000
Soil	79660452.150	5	15932090.430	4.345	.004
Nutrient	2.910E9	7	4.157E8	113.375	.000
Error	1.210E8	33	3666570.134		
Total	4.555E10	46			
Corrected Total	3.119E9	45			

a. R Squared = .961 (Adjusted R Squared = .947)

Estimates

Dependent Variable:K

Nutrient	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1.00	35794.167	781.726	34203.734	37384.599
2.00	21819.500	781.726	20229.067	23409.933
3.00	17136.833	781.726	15546.401	18727.266
4.00	40260.750	868.150	38494.486	42027.014
5.00	22771.750	868.150	21005.486	24538.014
6.00	36832.167	781.726	35241.734	38422.599
7.00	36115.167	781.726	34524.734	37705.599
8.00	32128.667	781.726	30538.234	33719.099

Magnesium

Tests of Between-Subjects Effects

Dependent Variable:Mg

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	29516559.395[a]	12	2459713.283	10.281	.000
Intercept	4.255E8	1	4.255E8	1778.544	.000
Nutrient	27172501.314	7	3881785.902	16.225	.000
Soil	1962181.872	5	392436.374	1.640	.177
Error	7895327.561	33	239252.350		
Total	4.784E8	46			
Corrected Total	37411886.957	45			

a. R Squared = .789 (Adjusted R Squared = .712)

Estimates

Dependent Variable:Mg

Nutrient	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1.00	3125.833	199.688	2719.565	3532.102
2.00	2322.000	199.688	1915.731	2728.269
3.00	4250.000	199.688	3843.731	4656.269
4.00	1459.839	221.765	1008.655	1911.023
5.00	3548.839	221.765	3097.655	4000.023
6.00	3398.833	199.688	2992.565	3805.102
7.00	3458.833	199.688	3052.565	3865.102
8.00	3036.333	199.688	2630.065	3442.602

Calcium

Tests of Between-Subjects Effects

Dependent Variable:Ca

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	7.322E8	12	61019811.124	48.673	.000
Intercept	6.550E9	1	6.550E9	5224.932	.000
Nutrient	7.014E8	7	1.002E8	79.920	.000
Soil	22894462.900	5	4578892.580	3.652	.010
Error	41370849.733	33	1253662.113		
Total	7.602E9	46			
Corrected Total	7.736E8	45			

a. R Squared = .947 (Adjusted R Squared = .927)

Estimates

Dependent Variable:Ca

Nutrient	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1.00	13485.667	457.104	12555.682	14415.651
2.00	6089.333	457.104	5159.349	7019.318
3.00	15555.000	457.104	14625.016	16484.984
4.00	13402.317	507.639	12369.518	14435.116
5.00	4792.517	507.639	3759.718	5825.316
6.00	16089.833	457.104	15159.849	17019.818
7.00	14494.500	457.104	13564.516	15424.484
8.00	12610.167	457.104	11680.182	13540.151

Sulphur

Tests of Between-Subjects Effects

Dependent Variable:S

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	44062001.590[a]	12	3671833.466	6.000	.000
Intercept	5.738E8	1	5.738E8	937.623	.000
Soil	5695077.656	5	1139015.531	1.861	.128
Nutrient	38739015.239	7	5534145.034	9.043	.000
Error	20195508.844	33	611985.116		
Total	6.610E8	46			
Corrected Total	64257510.435	45			

a. R Squared = .686 (Adjusted R Squared = .571)

Estimates

Dependent Variable:S

Nutrient	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1.00	4688.000	319.371	4038.236	5337.764
2.00	3865.500	319.371	3215.736	4515.264
3.00	3773.333	319.371	3123.569	4423.098
4.00	3550.506	354.679	2828.906	4272.105
5.00	2743.906	354.679	2022.306	3465.505
6.00	2035.167	319.371	1385.402	2684.931
7.00	4924.000	319.371	4274.236	5573.764
8.00	2986.833	319.371	2337.069	3636.598

Zinc

Tests of Between-Subjects Effects

Dependent Variable:Zn

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4689.937[a]	12	390.828	8.705	.000
Intercept	42662.932	1	42662.932	950.240	.000
Nutrient	3832.495	7	547.499	12.195	.000
Soil	903.551	5	180.710	4.025	.006
Error	1481.601	33	44.897		
Total	50802.635	46			
Corrected Total	6171.538	45			

a. R Squared = .760 (Adjusted R Squared = .673)

Estimates

Dependent Variable:Zn

Nutrient	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1.00	40.858	2.735	35.293	46.424
2.00	20.770	2.735	15.205	26.335
3.00	40.262	2.735	34.696	45.827
4.00	29.045	3.038	22.864	35.225
5.00	21.961	3.038	15.780	28.141
6.00	44.567	2.735	39.001	50.132
7.00	21.960	2.735	16.395	27.525
8.00	26.903	2.735	21.338	32.469

Effect of lime treatment on shoot N concentration.

Tests of Between-Subjects Effects

Dependent Variable:N

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	21.732[a]	9	2.415	18.795	.000
Intercept	836.961	1	836.961	6514.845	.000
Lime	.609	1	.609	4.744	.034
Nutrient	21.076	4	5.269	41.014	.000
Lime * Nutrient	.046	4	.012	.090	.985
Error	6.423	50	.128		
Total	865.117	60			
Corrected Total	28.155	59			

a. R Squared = .772 (Adjusted R Squared = .731)

Estimates

Dependent Variable:N

Lime	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1.00	3.634	.065	3.503	3.766
2.00	3.836	.065	3.704	3.967