SCHOOL OF AGRICULTURE

LIME AND NITROGEN OPTIONS ON MAIZE (*Zea mays L)* PRODUCTION IN SANDY TEXTURED SOILS OF MASVINGO, ZIMBABWE

by

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DECLARATION

I Steven Mdewa student number **M173459** declares that **Lime and Nitrogen options on maize (*Zea mays L*) production in sandy textured soils of Masvingo, Zimbabwe** is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete referencing.

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DEDICATION

To my spouse Alice, my children Tatenda C., Kudzai Steven junior, Anopaishe Emmanuel and my dear mum Christine.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAS - Atomic Absorption Spectrophotometer
AEC - Anion Exchange Capacity
ANOVA - Analysis of variance
BCSR - Base Cation Saturation Ratio
Ca - Calcium
CCE - Calcium Carbonate Equivalency
CEC - Cation Exchange Capacity
CV - Coefficient of Variation
D50%M - Days to 50% maturity
DVs - Dependant Variables
ENV - Effective Neutralising Value
GLM - General Linear Model
IVs - Independent Variables
K - Potassium
KFwt - Kernel Fresh Weight
LA - Leaf Area
LAI - Leaf Area Index
LL - Leaf Length
LM - Law of Minimum
MANOVA - Multivariate Analysis of Variance
MSNT - Maize Stalk Nitrate Test
Mg - Magnesium
MLH - Multiple Limitation Hypotheses
NPY kg - Net Plot Yield
NAR - Net Assimilation Rate
Na - Sodium
N - Nitrogen
NUE - Nitrogen Use Efficiency
Odswt (g) - One Thousand Dry Seed Weight

pH - Potential Hydrogen ions
SNV - Soil Neutralising Value
SPD - Split Plot Design
YPP - Yield Per Plant

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ABSTRACT

Approximately, more than 70% of arable land in Masvingo Province, Zimbabwe has a surface soil pH of ≤ 5. There has been a linear decline in maize yields in the region over the last four decades, particularly on sandy textured acidic soils. The study explored the net interactive effect of dolomitic lime and ammonium nitrate fertiliser on growth and yield parameters of maize

(*Zea mays L*) as well as their influence on soil pH. A Split plot design was used with 9 different treatment combinations of lime and nitrogen fertiliser coupled with three levels of lime (0, 1.5, and 3.0t $ha^{-1}L$) against three levels of nitrogen fertiliser (0, 0.2, and 0.4t $ha^{-1}N$). Yellow or Orange maize genotype of variety SC402 was established on two $612m^2$ plots, one site was a backup of the experimental plot. The field experimental trial spanned from the summer seasons of 2018/2019 to 2019/2020 on sandy textured soils classified as Fersiallitic Luvisols under irrigated conditions. The study was premised on three scientific theories namely, the Multiple limitation Hypothesis (MLH), the Law of the Minimum (LM) and the Law of Declining Yield Increments (LDYI). Growth and yield of maize is influenced by climatic, economic and soil factors. Soil acidity is largely caused by agronomic practices such as base uptake through crop harvests and application of fertilisers. Data was gathered over two seasons to evaluate and determine maize response to growth, yield and soil pH deviation for optimal lime and nitrogen application rates under irrigation conditions. Optimum lime and nitrogen application rates were realised as 3.0t ha^{-1} and0.2t $ha^{-1}N$ for growth, yield and soil pH parameter. There was an insignificant interactive effect of lime and nitrogen fertiliser treatment combinations on root depth. For belowground biomass index, there was $p< 0.05$ portraying a significant interaction at 95% confidence interval thus rejecting $H_{0.}$ Growth parameters of Leaf Area Index (LAI) and Plant Height (PH) were significant at $p< 0.05$ during the early growth period. The study concluded that maize growth and yield parameters are directly proportional to increase in both lime and nitrogen rates. With successive seasons of both lime and nitrogen application, cumulative residual effects of the two factors causes an average pH decline of ≤ 5 units annually.

Key words: Yellow maize, dolomitic lime, Nitrogen, Soil Acidity, Soil pH, Optimal.

CHAPTER ONE

1.1 INTRODUCTION

1.1.1 Soil Acidity and Maize Productivity

Emeades (2008) contends that maize is the main staple food crop for more than 300 million people worldwide, especially in Sub Saharan Africa (SSA) and Latin America. Manjeru (2017) citing FAO (1992) asserts that maize *(Zea mays L)* is the American – Indian word for corn, literally implying, “that which sustains life”. Globally, it is ranked third in importance in the family of gramineae crops, after wheat and rice (FAOSTAT, 2016). Soil pH is regarded as the most valuable soil chemical property (USA Department of Agriculture Cooperating, 2011). The use of nitrogen based fertilisers in arable lands has proved to have a reduction effect on soil pH. Lime, which is used to ameliorate soil pH, has economic implications to the farmer hence the need to achieve optimum lime and nitrogen combinations for boosting crop productivity whilst maintaining production costs at the lowest ebb. The study sought to evaluate the change in soil pH following different lime and nitrogen application rates.

The study assumed an experimental methodology which was both field and laboratory based. In order to conform to the requirements of any research study, ethical considerations were observed through securing an ethical clearance certificate from Great Zimbabwe University during the proposal stage of the study. Clearance was sought because the study was characterised by use of chemical substances in different environmental locations over time and also because Zimbabwe is a signatory to the Montreal Protocol (Montreal, Canada, 1987 and Chenje et al, 1998).

Growth and yield parameters in maize production were measured under sandy-textured soils in the 2018/2019 and 2019/2020 seasons in Masvingo Province of Zimbabwe. The main objectives of the study were to evaluate maize response to lime and nitrogen combinations, frequency of liming soils and determine changes in soil pH. This is critical for maximising nitrogen use efficiency (NUE) whilst guarding against the undesirable environmental catastrophe associated with heavy nitrogen regimes (Tumusiine et al, 2010).

Soil acidification or a decrease in soil pH, is a natural process but is accelerated by production practices, primarily the use of nitrogen (N) fertilizers (Christensen, 2013). As soil pH decreases, soil physical, chemical and biological reactions also change. One important chemical change is a marked rise in solubility of acid promoting cations such as manganese (Mn) and aluminium (Al) which cause toxicity to crop plants such as maize. Plants vary in their tolerance to acidifying mineral cations such as Al and Mn thereby creating crop-specific pH requirements (Christensen, 2013). This study, therefore, sought to explore the twin relationship between liming and the availability of nitrogen in the production of maize.

The world's population is increasing, so is the population of Zimbabwe. According to the Economic Research Service (1996), by 2060, it is estimated that food demand will be about 300% more than the 1980 levels. Therefore, the importance of advancing crop productivity, particularly cereals such as maize throughout the world is obvious.

1.1.2 World Distribution of Acid Soils

As much as 70% of the World arable land is affected by soil acidity (Rastija et al, 2010). About 50% of Australian Agricultural land has a surface pH of less or equal to 5.5 (Gazey, 2018). In the United Kingdom (Britain, Wales and England), 40% of arable soils are acidic whilst 57% of grass land soils have a pH below 6 (Goulding, 2016).Kenya acid soils cover 13% (over 1 million hectares) of the total land area under maize, legumes, tea and coffee and, as a result, production is declining on acid soils where fertilizers such as di–ammonium phosphate have been applied continuously Nekesa (2007) in Gitari et al (2015). In Zimbabwe, a 10 year study by Nyamangara and Mpofu (1996) revealed that the proportion of arable soils with pH less or equal to 5.5 increased from 42% to 77%.

1.1.3 Liming to Ameliorate Soil Acidity

Dhliwayo et al (1999) posit that failure to use lime together with the increased use of acidifying nitrogenous fertilizers has resulted in a marked increase in acidity of many agricultural soils. A study by Mukurumbira et al (1999) established that maize grain yield increased from 0.6t ha to 2.6t ha on unlimed and limed plots respectively due to increased stover, grain yield as well as nutrient uptake.

Dhliwayo (ibid) further argued that the apparent increase in the use of fertilizers has not been matched by an increased use of lime to ameliorate soil acidity.

Shoko and Moyo (2011) reiterate that soil acidity in communal areas has a negative impact on the yield of maize and groundnut in A1 and A2 farms. An increased understanding of the chemical, biological and physical properties as well as the interactions in the soil-plant atmosphere continuum that influence nitrogen availability is critical. This study was therefore, premised to explore how liming soils influence soil physical and chemical properties. The parameters that were investigated are maize biomass index, root biomass of maize, nitrogen uptake by maize as well as response of soil pH to different liming and nitrogen rates.

1.1.4 Liming Materials and their Effectiveness

Lime does not have primary mineral elements such as NPK, therefore, it is considered as a soil ameliorant rather than a fertiliser. There are several liming materials at the farmer's disposal. These include calcium carbonate (100% - CCE/SNV), Calcitic limestone (85 – 100% CCE/SNV), Dolomitic limestone (95 -109%CCE/SNV) burned limestone – 150- 175% and hydrated lime – 120 to 135% CCE/SNV. Basic slag has between 50 – 70% CCE/SNV while baked oyster shells have 80 -90% CCE/SNV (Havlin et al, 2005). Burnt lime with a soil neutralising value of 179.0 expressed as a weight percentage of pure lime; -136.0; dolomitic lime – 109.0; limestone; basic slag-86.0; phosphogypsum ($CaSo_4.2H_2O$ – 0.3; mined gypsum ($CaSo_4.2H_2O$ -12.4; fluegas desulphurised gypsum ($CaSo_4.2H_2O$ - 0.1 as well as coal fly ash whose SNV is variable (Bolan et al, 2003). The above are common liming materials used in agriculture although calcium carbonate which is considered as the standard agricultural lime, dolomitic limestone and chalk are the most commonly used soil ameliorates.

Chalk or calcium carbonate has the advantage that, if applied to the soil, it readily decomposes and get absorbed into the soil solution than limestone which reacts slowly, is hard and has large [article sizes (Goulding, 2016). Gypsum and pshophogypsum have the disadvantage that, their SNV is very small but their merit lies in that they are most effective. Dolomitic limestone is highly recommended for soils deficient in Mg^{2+} since in addition to neutralising acid soils, it also supplies Mg^{2+} which is deficient in most soils (Bennet et al, 2014). However, successive use of dolomitic lime induces K^+ deficiencies due to increase in magnesium indices exceeding 3. Sinclair et al (2014) recommend the application of lime about six months before planting and before phosphate fertiliser application. If phosphate fertiliser is applied concurrently, phosphorous becomes unavailable as it is locked up as calcium phosphate. Common agricultural limes are those which are derived from calcium and or magnesium, such as calcium carbonate or a blend of calcium and magnesium carbonate (Alberta Agriculture, Food and Rural Development [n.d].

Limestock of the travertine group encompass ground limestone and more or less burned limes. Travertine is limestone rich in Ca (CaO > 40%) but low in Mg (MgO <3%) (Beernaert, 1999). Beernaert (1999a) reported one drawback of limestones of the travertine category as that of possessing a high cationic ratio well above optimum (Calcium/Magnesium) ratio of 13 to 15 compared to the optimum cationic ratio of 4: 5. This induces disequilibrium in the cation balance resulting in low mineral uptake by crop plants. Kayonga and Goud (1989) Observed that, when travertine rocks were crashed and used as lime, they raised soil pH by 0.5 units, caused an increase in base saturation. Also, the travertine bearing rocks can eliminate aluminium toxicity in acidic soils but at the same time creating new problems of nutrient imbalances.

Another group of liming materials is that of the dolomite group. Dolomitic lime with a high magnesium content (CaO30%; MgO20%). The disadvantage that come along with the use of dolomitic ions is that it is very hard to grind into a fine usable powder hence need sophisticated machinery for both extraction and processing (Giller and Brougniez,1991).

1.1.5 Lime Recommendations

It is highly recommended to apply lime at a ploughing depth of 20 to 30 cm. The amount of lime applied also depends on depth of application with the amount decreasing with depth (UMass Extension Centre for Agriculture, 2011).

Lime is a chemical substance derived from rocks with a variety of applications including building construction, cement manufacture as well as an agricultural soil ameliorate among others. The degree of soil acidity, soil mineral and organic composition determines the type and amount of lime required in a given location. There are limiting factors to the widespread use of lime in many parts of Sub – Sahara Africa, which include lack of awareness among farmers regarding its application, appropriate application rates as well as knowledge of the effectiveness of lime in ameliorating soil acidity, bio- soil remediation and improvement of crop yields (Nduwumuremyi, 2013a).

The Soil Science Society of America (1997) defines lime requirements as the quantity of lime material needed to alter the volume of soil to attain a certain state with reference to pH attributed to solubility of aluminium ions. Nduwumuremyi, (2013b) views lime requirement from an economic perspective and asserts that the right amount of lime is needed to initiate maximum possible economic crop yield grown on soils that are acidic. Although there are several methods of estimating lime requirement of a given soil, the most common method is to assess the evolution of aluminium ions liable to be exchanged. There are two types of cations namely, basic cations and acidic cations. Calcium is a rich basic cation. The former, that is basic cation, entails those cations that increase the pH of a soil. Calcium (Ca^{2+}) ions fall within this group. The latter, that is, acidic cations, refer to those cations that confer acidity to a soil solution. Hydrogen ($H,^{+}$) and Aluminium (Al^{3+}) ions in lime, if applied in the soil, are capable of neutralising exchangeable aluminium (Al^{3+}) ion. Sub-Sahara Africa, Zimbabwe inclusive, capitalises the method of lime determination devised by Kamprath (1970) which has an exchangeable Al neutralising value of 85-90%.

1.1.6 Frequency of liming soils

Soil pH of the rhizosphere determines the ability of crop plants to absorb and utilise mineral elements from the soil. Aluminium is naturally found in soils in abundance than any other metal and its phytotoxicity is exacerbated by its high solubility at pH below 5.5 (Lukin and Epplin, 2002). Soil pH changes with time, following lime application depends on type of soil, lime application rate as well as the type of agricultural lime relative to its SNV (Froth and Ellis, 1997). Research data generated from lime application studies recommends that the carry over effect of liming materials should consider initial soil pH followed by gradual decline in soil pH (Black, 1992). The frequency of liming depends on soil type. Soils with higher clay and or organic contents are more liable to a low pH or high acidity owing to hydrogen ions that are adsorbed on clay or humus colloids (UMass Extension Centre for Agriculture, 2011). The same applies for areas of high precipitation intensity due to leaching of bases thus influencing soil's buffering capacity which has an impact on frequency of liming. The frequency of liming soils is also dependant on lime quality relative to its purity and particle size (Centre for

Agriculture, Food and the Environment, 2017). It is also dependent upon the desired pH level for a given crop and the soils CEC.

1.2 Statement of the problem

Despite the availability of lime at affordable retail price as a soil conditioner to raise pH and enhance optimum nutrient uptake, smallholder farmers are still unknowledgeable of the benefits associated with lime in the production of maize. Maize production in Zimbabwe has suffered a continuous decline against an annual national projected output of 2 million metric tonnes of cereal maize grain for both human and livestock consumption. Soil acidity is one of the most prevalent problems in production of food and fibre (Rastija et al (2010). Acid soils need constant liming if they are to be farmed successfully (Waugh, 1995: 248). Liming is one of the usual recommendations for improvement of acid soil (Summer, 1997). The productivity of crops depends heavily on nitrogen fertilisation (Zahir et al, 2014). Nutrient use inefficiencies result in negative effects such as soil acidity and environmental pollution as a result of release of greenhouse gasses into the atmosphere. Improved nutrient use efficiency calls for the implementation of sustainable nutrient management techniques, proper use of mineral fertilizers as well as improved exploitation of substantial inorganic and organic reserves of soil nutrients. Nitrogen use efficiency (NUE) is critical in agriculture development and protection of the environment. NUE is a complicated process which encompasses its assimilation, nitrification, remobilisation due to management factors (Zahir et al, 2014). Against this background, optimum nitrogen application to arable soils can improve its metabolism by plants and increase grain yield.

1.3 Hypotheses

1. H_0: There is no interactive effect between Factor A and Factor B.
2. H_1: There is an interactive effect between Factor A and Factor B.
3 H_0: $\mu_1 = \mu_2$; all the treatment means for Factor A levels (Lime Levels) are not different.
4. H_1: $\mu_1 \neq \mu_2$; the treatment means for Factor A levels (Lime Levels) are different.
5. H_0:$\mu_{n1;} = \mu_{n2;} = \mu_{n3;}$all the treatment means for the Factor B levels (Nitrogen Levels) are similar
6. H_1:$\mu_{n1;} \neq \mu_{n2;} \neq \mu_{n3;}$ at least one of the μ of the Factor B Levels (Nitrogen Levels) differs from those of others.

Factor A represent lime Levels

Factor B represents nitrogen levels

1.4 General Objective

The aim of the study was to evaluate the effect of nitrogen fertilisation in sandy-textured soils in maize production.

1.4.1 Specific Objectives

1. To estimate the extent to which availability of nitrogen due to liming sandy textured soils influences growth parameters of maize.

2. To determine how availability of nitrogen due to liming sandy textured soils influences root biomass development of maize.

3. To explore the effect of different lime and nitrogen treatment combinations on soil pH
4. To evaluate the effect of varying lime and nitrogen treatment combinations on the yield of maize.

1.4.2 Main research question

What is the effect of liming soils on the availability of nitrogen in relation to growth and yield of maize?

1.4.3 Sub-research questions

a) Does the availability of nitrogen due to liming sandy textured soils affect above ground maize biomass index?
b) Does the availability of nitrogen due to liming sandy textured soils affect root biomass of maize?
c) To what extent do different liming and nitrogen treatment combinations influence soil pH under irrigation conditions?
d) How do different lime and nitrogen combinations influence the yield of maize?

1.5 Significance of the study

The study assumed an experimental methodology which was both field and laboratory based. In order to conform to the requirements of any research study, ethical considerations were observed through securing an ethical clearance certificate from Great Zimbabwe University during the proposal stage of the study. Clearance was sought because the study was characterised by use of chemical substances in different environmental locations over time and also because Zimbabwe is a signatory to the Montreal Protocol (Montreal, Canada, 1987 and Chenje et al, 1998).

Nitrogen is regarded, not only as a highly mobile and indispensable nutrient but also, as one of the most expensive plant mineral elements with negative environmental effects due to leaching hence, its use should be treated with caution (Zahir, 2014). Infertility attributed to soil acidity in tropical areas has been a problem for quite a long time (Opala, 2017).The presence of essential plant nutrients in the soil on its own does not guarantee optimum plant performance. A whole range of chemical interactions take place in soils and soil pH influences nutrient levels tremendously (Participatory Agricultural Curriculum for the Environment, 2008:8). Nitrogen deficiency is probably the most common nutritional problem affecting plants worldwide (Pace, 2008:74).

Any given soil has an inherent chemistry and fertility by virtue of its formation. A soil intervention, be it natural or human, will alter the chemical and fertility characteristics of a soil. Soil chemistry and fertility change because of tillage-induced alterations which will in turn influence liming and fertiliser practices.

Maize is the staple crop of Zimbabwe whose continued cultivation has led to depleted soil nutrient content, particularly nitrogen. Continuous nitrogen application has tremendously affected the soil pH status, hence the need to examine how liming soils enhance the availability of the essential mineral. The results would benefit smallholder and commercial maize farmers as well as fertiliser companies on nitrogen soil requirements in relation to amount and frequency of liming. Government agricultural extension officers would also give informed nitrogen fertiliser and liming requirements. This is because fertiliser and lime application are soil-site specific. Although liming soils is highly recommended in a bid to improve soil quality, lime use in agricultural practice has been strongly influenced by the principles of economies of scale (Goulding et al., 2016). As a result of this, very little lime is being applied in arable soils worldwide.

1.6 Limitations

Masvingo Province has seven districts namely Chivi, Gutu, Bikita, Mwenezi, Zaka, Masvingo and Chiredzi. The study was limited to one of the seven districts namely Masvingo. It is hoped that the results of the study would apply to other districts in the province. Data collection was limited to the period of study which ranged from 2017 to 2020.

There are many liming materials with different soil neutralising values (SNVs) such as calcium carbonate, magnesium hydroxide, magnesium oxide and magnesium silicate. Choice of the liming material was based on initial soil pH as well as the neutralising the neutralising value of commercial limestone ranges between 96 – 98% while that of pure calcium carbonate ($CaCO_3$), pure limestone is regarded as the standard lime (Conveyers et al 2005).

Also, among the many nitrate fertilisers, this experiment shall focus on ammonium nitrate (34.5%N) since it is widely used in dryland or rain fed maize crops by the majority of Zimbabwean farmers.

1.7 Delimitations

The study involved evaluating the effect of liming soils on nitrogen requirements in relation to growth and kernel yield of maize in Masvingo District. Some parts of Masvingo fall under agro- ecological region1V. Nyakanda (2000) posits that Natural Region IV covers 33% of Zimbabwe’s land.

Soil acidity influences many soil physical, biological and chemical properties and the availability of many different mineral elements. This study focused on how liming soils affect the availability of nitrogen in the production of maize.

REFERENCES

Bennette, J, Greene, R.S.B, Murphy, W, Wocking, P and Tongeway, G (2014) The influence of lime and gypsum on long-term rehabilitation of a Red Sodosol, in a semi-arid environment of New South Wales. Soil Research 52.

Beernate, F.R (1999). Physibility Study of Production of Lime and or ground Travertine for Management of Acidic Soils in Rwanda: Brussels: Pro- Inter Project Consultants

Black, C.A, (1992). Soil Fertility Evaluation and Control. Lewis Publishers, Boca Raton.

Bolan, N.S, Headlay, M.J (2008). Role of Carbon Nitrogen and Sulphar Cycles in Soil Acidification. Handbook of Soil Acidity. New York

Christensen, D.A. et al (2018) Applying Lime to Raise Soil pH for Crop Production (Western Oregon) EM 9057 ppl-2 edu-em9057.

Chenje, M, Sola, Land Paleczny, D (1998). The State of Zimbabwe's Environment, 1998. Ministry of Mines, Environment and Tourism, Government of Zimbabwe , Harare.

Conyers, M.K: (2006): Liming and Lime Materials. Encyclopedia of Soil Science, Abingdom, Taylor and Francis

Dhliwayo D.K.C et al (1999) Soil Fertility network for maize – Based Cropping Systems in Malawi and Zimbabwe: A Critical Look at the Potential Recovery from Acid Sol Infertility in the Communal Areas of Zimbabwe. Working Paper Number 5 Soil Productivity Research Laboratory (CIMMYT).

Edmeades, D.C and Ridley, A.M (2008). Using Lime to Ameliorate Top Soil and Sub soil Acidity. Handbook of Soil Acidity. New York

Economic Research Service (1996)

FAO STAT (2016) Food and Agriculture Organisation. Soil Map of the World, Revised Legend, with Corrections and Updates. World Soil Resources Report No. 60. Rome

Foth, H.D and Ellis, B.G (1996). Soil Fertility. 2ed. Boka: Luwis Publishers

FAO/UNESCO (2011). Statistical Database for the Food and Agriculture Organisation of the United Nations: *http://www.fao.org*.

Gazey, C (2003). Responses of Wheat and Barley to liming on sandy soil with Sub soil Acidity: Graduate Research School.

Giller, K.E., Cadish., G and Mecddonagh, J.H (1991). Can Biological Nitrogen Fixation Sustain Agriculture in the Tropics? Soil science and Sustainable Land Management in the Tropics

Goulding, K.W.T. (2016) Soil Use and Management: Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. Department of Sustainable Grass land Systems.

Griller, Y and Brogniez, D (1991) Reference Document on Fertilizer and Calcitic Amendment in scope of Policy Definition of Agriculture inputs in Rwanda. Kigali

Lukin, V.V. and Epplin, F.M., (2002). Optimal Frequency and Quantity of Agricultural Lime Applications. Agricultural systems **76** Elsevier Science Ltd.

Kayonga, J and Goud, B (1989). Experiment for Soil Fertility Improvement in Crete Zaire. Soil Fertility Improvement Trials in Crete Zaire

Manjeru, P. (2017). The Influence of Abiotic Stress on CIMMYT ProvitaminA Elite Maize Germplasm. (Doctoral Thesis University of Free State, South Africa.

Mukurumbira (1999)

Mupepereki, S., Mafongoya, P. and Mapfumo, P. (2001). Legumes in Soil Fertility Management: The Case of Pigeon pea in Smallholder Farming systems of Zimbabwe. African Crop Science Journal. Volume 9 No.4

Nekesa, J (2007). Potential of Agricultural Lime on Improved Soil Health and Agricultural Production in Kenya. African Crop Science Journal

Nduwumuremyi, A (2013). Soil Acidification and Lime Quality: Sources of Soil Acidity, Effects of plant Nutrients, Efficiency of Lime and Liming Requirements. Journal of Agriculture and Allied Sciences. Kigali

Nyakanda, C (2000) Crop production management CRD 201. University College of Distant Education, University of Zimbabwe.

Nyamangara, J. and Mpofu, S.E (1996) Soil pH and requirement for high potential communal areas of Zimbabwe. Journal of Applies Science in Southern Africa Vol. 2 Number 2.

Opala, P.A. (2017). Influence of Lime and Phosphorous Application Rates on Growth of Maize. Advances in Agriculture. Department of Soil Science, Maseno University, Kenya

PACE (1998) Sustainable Soil Management: Participatory Agricultural Curriculum for the environment. American Journal of Botany 90(1): 143 -152

Rastija, I. et al (2010) Impacts of Liming with Dolomite on the Wheat Yield: Faculty of Agriculture, Croatia

Shoko, M.D. and Moyo, S (2011) Soil characterisation in Contrasting Cropping Systems under the fast track land reform programme in Zimbabwe Vol. 11 Number 3. African Journal of Food, Agriculture, Nutrition and Development.

Sinclair, A., Crooks, B. And Coull, M. (2014). Soils Information, Texture and Liming Recommendations. Scotland's Rural College – SRUC Technical Note TN **656.**

Soil Science Society of America (1997). Glossary of Soil Science Terms, Madison

Soil pH and Lime Management: Centre for Agriculture, Food and the Environment. Lowa State University, The Fertiliser Institute 2017. USA.

Sumner, M.E (1997): Procedures used for diagnosis and correction of soil acidity: A critical Review. Plant – Soil, Brazil

Tumuisine, E. and Brorsen, W.B.(2010) Effect of Nitrogen Fertilisation on Rye-Rye Grass Yield and Soil pH Dynamics: Agricultural and Applied Economics Association, (AAEA),CAES and WAEA Joint Annual Meeting.

UMass, Extension Centre for Agriculture (2011). Soil pH and Liming. USA Department of Agriculture cooperating.

Waugh, D (1995). Geography: An Integrated Approach. Nelson Thorns

Zahir, S. (2014). Role of Nitrogen Fertilizer in Crop Productivity and Environmental Pollution. Turkish Journal of Agriculture and Forestry. Research Gate

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Maize production

Cereal crops contribute more than 50% of the total human calories and is a reflection that cereals are a major staple food worldwide. Globally, crop production vary owing to climatic and soil factors (Chaves et al, 2003). Again, the world over maize is one of the most important crops ranked third after wheat and rice as it is used for human consumption and as animal feed (Abu et al, 2011). In South Africa, about 8.0million tonnes of the cereal maize crop is produced on annual basis on an area covering approximately 3.1 million hectares (du Pleiss, 2003). du Pleiss (2003) reiterated that maize is the most important cereal crop in South Africa and its production is done in diverse agro- ecological conditions.

Successful maize production depends on a wide range of factors that include soil tillage, fertilisation, adapted cultivars inter alia. In developing nations, maize is consumed as a staple food crop by almost 200 million people (du Pleis, 2003a). Maize production is every household's main cropping activity and is cultivated in all the agro - ecological zones of Zimbabwe (FAO, 2011). Cutts and Hassen (2002) posit that farmers in rainfall marginal zones will always attempt to cultivate maize regardless of previous failures of such attempts thus reflecting the relative importance of the crop in Zimbabwe.

2.2 Soil Reaction

2.2.1 Basic concepts of soil acidity

The problem of soil acidity is one of the major constraints to the productivity of crops in most communal areas of Zimbabwe (Dhliwayo and Mukurumbira, 1999). Soil acidity is usually experienced in sandy soils owing to their low clay content of basic minerals (Grant, Turner and Madziva, 1979). An acid is a substance which dissociates in water to liberate one or more hydrogen ions (Masaka, 2014). RoTAP (2012) postulates that soil acidification is a result of acid precipitation. The concept of soil acidity is premised on the oxygen theory. The theory postulates that oxygen is an element common to all acids and the presence of oxygen produces soil acidity (Masaka, 2014). This is against the background that oxides of some elements were true acids. Wuta and Masaka (2014), citing Lavoisier (1999) who discovered oxygen gas, reiterated that all compounds containing oxygen such as CO_2 produce carbonic acid, sulphur trioxide (SO_3) produces sulphuric acid (H_2SO_4), and phosphorous (v) oxide or phosphorous pentoxide (P_2O_5) produces phosphoric acid (H_3PO_4). Specialists concur that the acidity of a soil happens in an aqueous environment through rain or irrigation water. This occurs following the ionisation of water to result in acid formation.

The pH of a soil is regarded as a measure of the acidity or basicity of a soil solution (Masaka and Wuta, 2014). Soil pH relates to the negative logarithm (Base 10) due to the reaction of hydrogen ions (H^+) in an aqueous solution which depicts the concentration of the hydronium ion in one litre of water (Masaka, ibid). Therefore, an acid soil is one having a concentration of hydronium ions above 10^{-7} moles L^{-1} (Sinclair et al 2014). The pH of a soil is regarded as a major variable as it regulates several chemical and biological processes that happen in the soil continuum. Coull et al (2014) reiterate that both hydrogen and aluminium contribute significantly to soil acidity with hydrogen influencing the acidity of the soil directly whilst aluminium ($Al^{3+)}$ ions influence the pH of a soil indirectly. In an aqueous solution, $(Al^{3+})_{aq}$ is not a free cation, but instead, it is surrounded by six molecules of water (H_2O) to form a six or hexaquoaluminium compound thus $[Al(H_2O)_6{}^{3+}]$ (Association of Official Analytical Chemist, 1980).

Goulding, (2016) posits that hydrogen ion concentration results in loss of base cations and an increase in ($Al^{3+)}$ ion saturation. This occurs as a result of precipitation of base cations due to increased solubility of acid promoting cations, largely manganese (Mn) and aluminium ($Al^{3+)}$. The result is a condition of extreme soil acidification that leads to a non-reversible condition of clay mineral dissolution as well as reduced cat ion exchange capacity (CEC).

2.2.2 Soil pH And Factors influencing it

The letters pH denotes potential hydrogen ions. The inherent soil pH status depends largely on parent material from which soil was derived (Crooks et al. 2014). Most of the soil pH values range from 4; which is deemed too acidic for most crops and most crops cannot withstand this pH value, to pH 8; for those soils whose chief mineral is either calcium or magnesium carbonate. Soil acidifying processes include precipitation intensity, crop growth, leaching of bases as well as farming practices that use nitrogen based fertilisers (Sinclair et al, 2014). These processes that induce soil acidity can cause alkaline soils to decline very quickly to assume an acid status particularly in sandy textured soils where leaching of bases is rife.

Continuous tillage of arable soils result in a progressive decline in soil pH leading to soil acidity mainly due to losses in soil nutrients (Mukurumbira and Dhliwayo, 1999). Should nitrates get taken up by crop plants, soil acidification is not obvious, the same applies to urea, elemental sulphur fertiliser and leguminous plants (Bolan and Hedley, 2003). This is so because nitrates take up protons with them. Acidification is only imminent if urea is changed to NH_4^+ and nitrates then leached (Fertiliser Manual, RB209, 2010).

Acid precipitation is one of the prime causes of soil acidity. Rain water has a pH range of 5 to 5,6 which is classified as slightly acidic owing to the dissolution of atmospheric carbon dioxide (CO_2) in water to yield a weak acid called organic carbonic acid (H_2CO_3) (Goulding , 2016). Should a soil get exposed to this slightly acid rain, holding other acidifying agents constant and without lime application, the soil would attain an equilibrium pH range to that of rain. RoTAP (2012) reports that the contribution of human activities cannot be ignored in contributing to soil acidity. Increased acid precipitation is aggravated by the discharge of acidifying gaseous compounds such as sulphur dioxide (SO_2) and nitrogen oxides (NO_x) like nitrites (NO_2) and nitrates (NO_3^-). These emissions come from industries, automobile exhaust fumes as well as ammonia (NH_3) gas from organic and inorganic manure volatilisation.

The growth and development as well as uptake of plant mineral elements result in albeit localised soil acidification within the rhizosphere. This is attributed to root exudates containing acids (Hinsinger et al., 2003). However, soil acidification due to this source is albeit negligible in comparison to that of N and S fertilisers, almost less than 10% (Johnstone et al,. 1986). Despite its soil acidification being small, nutrient uptake and root exudates are vital in that they influence negatively the bioavailability of mineral elements needed by crop plants within the rooting zone (Marchner, 2012).

The soil biota are also important in influencing soil pH. Soil microbes through organic matter decomposition and respiration by plant roots liberate CO_2 which combines with soil water to produce H_2CO_3just as good as rain water (Goulding, 2016). The impact of such a phenomena causes a decline in soil pH of not less than 5 (Bolan et al., 2003). However, since an avalanche of processes contributes to soil acidity, the magnitude of soil biota in combination to other processes cannot be ignored. It is therefore worth noting that organic matter mineralisation, despite liberating the much needed nutrients, also contributes negatively to soil acidity.

2.2.3 World Distribution of Acid Soils

As much as 70% of the World's arable land is affected by soil acidity (Rastija et al, 2010). About 50% of Australian Agricultural land has a surface pH of less or equal to 5,5 (Gazey, 2018). In the United Kingdom, (Britain, Wales and England) 40% of arable soils are acidic whilst 57% of grass land soils have a pH below 6 (Goulding, 2016). In the United Kingdom, the use of lime is still low since the soil pH of both arable and grasslands is below the optimum (Goulding, 2016). The United Kingdom arable soils have a pH as low as 2 when peat is removed and contain pyrites, pH less than 4 in peats, 5 to 7,5 in calcareous derived soils (limestones) and pH of more than 8 in sodic (Sodium rich) soils leading to preferential nutrient uptake. This phenomenon is obtaining in Zimbabwe (South Eastern Lowveld soils) where more than 30 000 hectares of sugarcane land has been abandoned due to the problem of sodium salt accumulation owing to high temperature which brings bases to the surface through capillary attraction. In the past, soil acidity was not a problem in USA but for the past decades, continuous tillage for crop production led to a marked decline in soil pH due to use of nitrogen containing fertilisers (Zhang and Raun, 2006). In 1985 the Oklahoma Cooperative Extension Department USA reported a 30% acidity in 17000 soil samples studied with below 5.5 pH value. Ten years later, in 1995 another similar study revealed a 39% level of acidity in 3709 soil samples tested with below 5.5 pH value (Zhang et al., 1998).Kenya acid soils cover 13% (over 1 million hectares) of the total land area under maize, legumes, tea and coffee and as a result production is declining on acid soils where fertilizers such as di-ammonium phosphate have been applied continuously (Nekesa, 2007) in Gitari et al (2015).

In Zimbabwe, a 10 year study by Nyamangara and Mpofu (1996) reveals that the proportion of arable soils with pH less or equal to 5.5 increased from 42% to 77%. Soil acidity has become problematic as it brings about biophysical constraints in the productivity of staple crops, such as maize in Zimbabwe. In Chinamora communal areas a high potential maize area, 43% of the arable

soils had pH value of between 4,0 to 4,5 using a 0.01 M $CaCl_2$ scale in the 1992/1994 season . During the same period, there was a marked decline in soil pH by as much as 35% from the pH range causing problems such as poor NUE in 77% of the arable soils (Dhliwayo et al 1999). The problem was widespread across all the granite derived soils of the sandveld nationwide in Zimbabwe.

Dhliwayo et al (1999) posit that failure to use lime together with the increased use of acidifying nitrogenous fertilizers has resulted in a marked increase in acidity of many agricultural soils. A study by Mukurumbira et al (1999) established that maize grain yield increased from 0.6t ha to 2.6t ha on unlimed and limed plots respectively due to increased stover, grain yield as well as nutrient uptake. Dhliwayo (ibid) further argues that the apparent increase in the use of fertilizers has not been matched by an increased use of lime to ameliorate soil acidity.

Shoko and Moyo (2011) reiterate that soil acidity in communal areas impacted negatively on the yield of maize and groundnut in A1 and A2 farms. An increased understanding of the chemical, biological and physical properties as well as the interactions in the soil-plant atmosphere continuum that influences nitrogen availability is critical. This study was therefore premised to explore how liming soils influences soil physical and chemical properties. The parameters that were investigated are maize biomass index, root biomass of maize, nitrogen uptake by maize as well as response of soil pH to different liming and nitrogen rates.

2.3 Nitrogen (N)

Nitrogen is one of the main macro – nutrient influencing plant growth. Mineral fertilizers are the major source of nitrogen applied to crops (Robertson and Vitousek, 2009; Zahoor, 2014). Although higher nitrogen application promote better crop yields, there is no linear relationship but instead, optimum nitrogen application is essential since the high cost of nitrogen and its negative soil effects offset yield increments (King et al, 2003). Optimum nitrogen amounts need to be determined for individual crop requirements. In order to maximise NUE in cereal crop production , a compound array of mitigating solutions are required since nitrogen is lost in several ways such as leaching , de nitrification, erosion and crop harvest (Ercoli et al, 2012) . These losses are prevalent in light textured soils such as sandy –soils.

In plants, nitrogen is found in chlorophyll and plays the role of enhancing vegetative growth. If leaves of crop plants of crop plants contain enough nitrogen, they assume a dark, blue-green colouration which is a raw material for photosynthesis (Glass, 2003). Nitrogen is the main normally deficient but most important mineral in crop production since its uptake by plants is done at different growth stages particularly in cereals. For the past five decades, there has been consideration to increase the use of nitrogen fertilizers in order to boost agriculture productivity (Hirel et al, 2007)

2.4 Nitrogen Use Efficiency (NUE)

Nitrogen is regarded not only as one of the moist expensive but also a highly mobile element that is very susceptible to leaching (Shimono and Bruce, 2009). Moll et al (1982) reiterated that some progress have been made to produce nitrogen efficient cultivars that reduce nitrogen fertilizer inputs and environmental contamination. Nitrogen - fertilizer management takes into account all processes that account for atmospheric nitrogen system and nitrogen losses (Foulkes et al, (2010). Genetic altered genotypes containing glutein properties and high protein content with the proper amount of fertilizer dressings were needed to transport more nitrogen to the grain and reduce nitrogen atmospheric loses (Wu et al, 2000)

2.5 The Concept of Biomass

The biomass of an organism is the total mass of the organism at each given time (Greens et al (1990). Dry masses should be considered in usual cases through distractive methods. The biomass at the time of sampling at a given moment in time is referred to as the standing crop biomass (Greens et al 1990). Dry crop biomass are preferred to wet biomasses as fluctuations in water content due to climatic variables at different periods and growth stages would give false results. The sampled plants are oven dried at a temperature of 110℃ until a constant temperature is achieved. The growth rate parameters can be measured thus:

Growth rate (G) $= \frac{X_2}{t_2} - \frac{X_1}{t_1} g\ day^{-1}$

Where $x_1 g$ = average dry mass of plant from first sample taken at t_1 days
$x_2 g$ = average dry mass of plant from second sample taken at t_2 days

The whole plant biomass reflects the crop plant's biological yield or the economic yield where as when only the part of the plant with a commercial value is considered it is called the economic yield (Larkcom and Miller, sic). The biomass of an organism is calculated by multiplying the number of sampled organisms by their average weight (Mader, 2006)

2.6 Effect of pH on Frequency of Liming Soils

Kovacevic and Rastija (2010) said liming raised the soil pH by 2.62 units and increased the crop yields in all years following liming in soils under maize and barley in 2003 -2005, 2006 as well as in 2007.

The rise in both soil pH and yield in successive years could suggest a yearly or seasonal lime application.

Liming with dolomite (dolomitic lime) significantly influenced the pH by raising its initial very acid reaction using the control experiment making phosphorous more available. Since the study was conducted using dolomitic lime it creates a resource or materials gap.

Okalebo et al (2009) reiterated that the practice of liming acid soils is not common in Sub Sahara Africa (SSA) because of limited knowledge on lime usage, effectiveness and availability. Therefore, there is need to unlock the knowledge gap inherent in lime use.

2.7 Effect of liming sandy soils on nitrogen availability in maize production

Unlike fertilisers which are used to supply plant nutrients in relatively small amounts for plant nutrition, liming materials are used to change the chemical makeup of a substantial part of a root zone (Brady and Weil, 2014 p344). This could imply that addition of soil nutrients through fertilisation is not the last option to improve crop productivity.

The study by Brady and Weil (2014) posits that the pH range of 5.5 to 7.0 may provide the most satisfactory plant nutrient level. This generalisation may not be valid for all soil plant combinations as certain manganese deficiencies are common in some plants when sandy utisols are limited to pH values of only 6.5 to 7.0. The study, therefore, wants to explore the effect of liming as it results in exchange of calcium and or magnesium ions with those that cause soil acidity.

Studies by Marcelis et al (2015) show an increase in phosphorous movement towards roots at a rate of 2 cm per day. However, very little research was done on impact of liming on nitrogen availability and uptake, hence creating a knowledge gap to be filled through this study.

Hussein (1994) corroborates that liming soils decreases hydrogen ions (H^+) and increases hydroxyl ions (OH^-) as well as increasing phosphorous and molybdenum. Hussein (ibid) further reiterates that liming soils also promotes nodule formation in legumes. Maize is usually grown in rotation with a legume which biologically fixes nitrogen in a symbiotic manner in association with the Rhizobia bacteria. Non – liming of acid soils inhibits the nitrification processes and nitrogen fixation by legumes unless the rhizobium is acid tolerant (Larkcom and Miller, 1994).

2.7.1The effect of liming soils on root biomass

Root phenotyping and root density studies have shown that the root system is crucial for plant functioning as 20 – 50% of the total fixed carbon is translocated to the root system (Lynch and Whipps, 199, Kuzyakov and Domanski, 2000). Fenta et al (2018) conducted root architecture studies to determine its correlation with shoot parameters in soy bean cultivars called AS409RG, Jackson and Prima 2000 cultivars. Morphology parameters were used to classify the cultivars into different root phenotypes that could be important in conferring drought tolerance traits.

A positive correlation was observed between nodule size, above ground biomass and seed yield. The strong association between root parameters and whole plant productivity reveals significance of the source to sink phenomenon. Following liming, there was increased root surface area (density) and an increase in the plant’s absorptive capacity thus culminating to improved crop development. This is because water and minerals are the raw materials or sine qua non (Wilkes and Krebs, 2001) of crop development.

2.8 Root Phenotyping

Phenotypic characterisation of root traits has suffered a great drawback as a result of the complex nature of accessing the rhizosphere (Kuijken et al., 2015). The phenotyping of plant roots has a correlation with traits of agronomic importance. Root traits are influenced by environmental conditions which could be soil based or climate related. This is critical in exploring how the root system functions and for the future plant breeding programmes. Promoting plants that exhibit robust growth and high productivity in nutrient marginal soils is important in crop production. Modification of the root structure aids in optimising water and nutrient utilisation (Marcelis et al., 2015). Root morphological characterisation also compounds our understanding of how different plant species respond to abiotic soil factors and how they eventually impact on crop’s final yield. Root length, root branching and formation of root hairs is partly genetic and partly influenced by root phenes. Phenotypic root characterisation is crucial in order to boost crop productivity through enhanced water and mineral uptake through manipulating crop growing conditions (Monteros et al., 2015).

Plant roots are critical as they perform overwhelming functions as metabolic sources and sinks. Root plasticity in terms of growth in response to changes in soil pH status provides a spectrum for exploring root traits in order to boost productivity of crops. Monteros et al, (2015) asserts that distribution of parts of roots within a given environment is better known as root system architecture. Dynamism of the root system is influenced by both external and internal environment that include soil moisture, ambient temperature, nutrient status, soil pH and soil biota. Variations in root characteristics encourage plants to adapt to a variety of biotic and abiotic stresses for effective and efficient soil nutrient use. Many studies have revealed strong relations between different root traits and productivity of crops and kernel yield even under rainfall marginal conditions (Uga et al., 2013; Narayanani et al, 2014).

A good knowledge of root phenes enables agronomists to boost crop yield under severe stress conditions (Meister et al., 2014). The various functions played by roots in plant growth and developments have generated renewed interest (Meister et al., 2014; Furbank and Tester, 2011; Rascher et al. 2011). Root architecture is significant in soil health that considers root system to act as a functional living ecosystem component (Matsubara et al, 2011). In nutrient marginal soils, heavy fertilisation is critical to promote above ground and below ground plant biomass and yield(Matsubara et al, 2011). Shallow roots are effective in foraging for phosphorus since it is an immobile element. Plant roots are sensitive and respond promptly to biotic and abiotic soil and environmental stresses and convey these signals through transduction pathways (Mooney et al, 2012). Rooting depth determines the extent to which plants grow in an attempt to forage for stored water and mobile nutrients like nitrogen that are susceptible to leaching in deeper horizons of the soil (Kano et al 2011). Crop rooting depth is significantly influenced by soil chemical properties. By nature, roots are positively chemotropic and geotropic. Lateral roots contribute positively to total biomass (Gartia et al, 2015). A study by Robbins and Dinney (2015) contends that plants with dense lateral roots are associated with greater nutrient and water uptake. Maize genotype with long and few adventitious roots from soils that have a low nitrogen content, show a 30% higher yield compared to those with dense but short lateral or adventitious root (Hufnagel et al., 2014)

2.9 The effect of liming on nutrient uptake

Studies by Marcelis et al (2015) using cereal crops have shown an increase in phosphorous movement towards roots at a rate of 2 cm per day. Very little research was done on the impact of liming on nitrogen availability and uptake, hence creating a knowledge gap to be filled through this study.

Hussein (1994) corroborates that liming soils decreases hydrogen ions (H^+) and increases hydroxyl ions (OH^-) as well as phosphorous and molybdenum. Hussein (ibid) further reiterates that liming soils also promotes nodule formation in legumes. Maize is usually grown in rotation with a legume which biologically fix nitrogen in a symbiotic manner in association with the Rhizobia bacteria. Non-liming of acid soils inhibits the nitrification processes and nitrogen fixation by legumes unless the rhizobium is acid tolerant (Larkcom and Miller, 1994).

2.10 Nitrogen fertilizers and lime interactions

Liming soils has been seen to mitigate the emissions of soil N_2O provided soil moisture regimes are kept at field capacity (Nduwumuremyi, 2013). N_2O produces Nitrous acid (HNO_2) commonly known as dioxonitric (III) acid which is a weak monobasic acid which is only known in solution or aqueous form and in the form of nitrite (NO_2) salts. Soil microbes responsible for biological nitrogen fixation (BNF) can act as an indicator of soil quality. Low soil pH (acidity) inhibits the activities of free living nitrogen fixers within the rhizosphere. The soil pH categories ultra-acidity <3.5, extremely acidic 3.5 - 4.4, very strongly acidic 4.5 - 5.0 and strongly acidic 5.1 – 5.5 affect nitrogen availability within the soil continuum (USDA,1999). This is attributed to reduced survival of the Rhizobia bacteria and their effectiveness in causing infection of legume roots thus culminating to reduced nitrogen fixation due to poor nodulation. Maize is usually grown in rotation with legumes which are deemed to be bio fertilizers for nitrogen fixation.

The study by Upjohn et al (2005) showed that fertilizers with nitrogen in ammonium form such as ammonium sulphate ($NH_4^+ SO^-_4$) confer soil acidity within a period of a few weeks upon application. Contrary to other nitrogen fertilizers, calcium nitrate ($Ca(NO_3^-)$ as well as sodium nitrate ($Na^+No_3^-$) result in soil neutralisation though they are expensive and restricted to high value horticultural crops. Removal of crops by burning does not alter the acid/alkali but instead confers redistribution, resulting in the soil surface being furnished with minerals which have a neutralising effect (Conyers and Fenton, 2005).

2.11 Liming Materials

Lime is used to ameliorate the acidity of soils. The use of lime is as old as the Roman Empire since it was used by the Romans as way back as 2000 years ago (Goulding et al, 1989, Connor et al., 2011). Studies have shown that benefits of liming acid soils can be effective for many years (Tumusiine and Brorsen, 2010). There are many chemical substances used as liming materials ranging from wood ash, ground limestone, dolomitic ground limestone, chalk, ground chalk, burnt lime as well as hydrated lime (Goulding, 2016). Liming materials are bought basing on price in combination to its soil neutralising value (Sinclair et al., 2014). The SNV of a liming material is defined as the total acidic value the material can bring to neutrality when based on its laboratory reaction with hydrochloric acid (Goulding, 2016). Gypsum (calcium sulphate) [$CaSO_4$] and wood ash have low SNVs of 12 .4 and 25 respectively (Borlan et al., 2003).

Waste paper if ground into a powder, can be used as a liming material with a liming value that can raise the pH between 0.1 to 0.7 units per 100t/hectare of waste paper (Gibbs et al., 2005). Different liming materials have different SNVs but calcium carbonate is considered as a standard liming material with an SNV of 100. Bolan et al (2003) evaluated the variations in SNVs of different materials as follows: Burnt lime (CaO) 179.0, calcium hydroxide/ slacked lime ($Ca(OH)_2$ 136.0 , dolomitic lime /calcium magnesium carbonate ($CaMg(CO_3)_2$ 109.0, Slag (Ca SiO_3) 86.0 and mind gypsum ($CaSO_4 . 2H_2O$ - 12.4). Calcium based liming materials are important in the improvement of soil structure since they cause soil aggregates to move away from each other, thus improving aeration, drainage and ease of root development. On the contrary, magnesium rich limes caused soil particles to stick together promoting flocculation hence lime recommendations should rely on soil factors (Crookes et al., 2014).

2.11.1 Benefits of Liming Soils

Liming arable soils influences several chemical, biological and physical processes. Liming arable soils reduces the possibility of Mn^{2+} and Al^{3+} toxicity, improves microbial activity since most microbes except fungi and Actinomycetes thrives best in slightly acidic to alkaline soils of pH 6.0 -8 (Donahue and Auburn, 1999). Also, liming improves soils structure by inducing flocculation particularly in heavy textured soils, improves symbiotic nitrogen fixation by legumes, improves palatability of forages, provides an inexpensive source of $Ca^{2+}$and Mg^{2+} when the two named elements are deficient in soils particularly at lower pH conditions (Donahue and Auburn, 1999a). When soils are limed, the availability of nutrients particularly P and Mo is enhanced is soil pH ranges between 6.0 -7.0. However, on the contrary, the availability of other micronutrients increases with a decrease in soil pH. Hussein (1997) contends that applying agricultural lime result in a decline in solubility of acid promoting cations such as Fe, $Al^{3+.}$and Mn, increases percentage base saturation as well as promoting nodulation in legumes.

2.11.2 Lime Recommendations

Lime is a chemical substance derived from rocks with a variety of applications including building construction, cement manufacture as well as an agricultural soil ameliorate among others. The degree of soil acidity, soil mineral and organic composition determines the type and amount of lime requirement in a given location. There are limiting factors to the widespread use of lime in many parts of Sub-Saharan Africa, these include lack of awareness among farmers regarding its application, lack of appropriate application rates as well as lack of knowledge on the effectiveness of lime in ameliorating soil acidity, bio-soil remediation and improvement of crop yields (Nduwumuremyi, 2013).

The Soil Science Society of America (1997) defines lime requirements as the quantity of lime material needed to alter a volume of soil to attain a certain state with reference to pH attributed to solubility of aluminium ions. Nduwumuremyi, (ibid) views lime requirement from an economic perspective when he vowed that it is the right amount of lime needed to initiate maximum possible economic crop yield grown on soils that are acidic. Although there are several methods of estimating lime requirement of a given soil, the most common method is to assess the evolution of aluminium ions liable to be exchanged. There are two types of cations namely, basic cations and acidic cations. Calcium is a rich basic cat ion. The former, that is, basic cat ion entails those cations that increase the pH of a soil. Calcium (Ca^{2+}) ions fall within this group. The latter, that is, acidic cations refer to those cations that confer acidity to a soil solution. This shows that, if applied in the soil, hydrogen (H,$^{+}$) and Aluminium (Al^{3+}) ions in lime are capable of neutralising exchangeable aluminium (Al^{3+}) ion. Sub-Saharan Africa, Zimbabwe included, need to capitalise the method of lime determination devised by Kamprath (1970) which has an exchangeable Al neutralising value of 85-90%.

Lime requirement is also a function of the soil organic matter content, clay content and texture pH, among others summarised in a functional notation thus

$LR = f(pH+ cl+t_1+0+t_2+ p+s...)$
Where:
LR – refers to Lime Rate;
f - refers to function of;
pH– refers to potential hydrogen ions;
cl – refers to clay content of soil;
t_1– refers to texture of soil
o-soil organic content and
t_2 – refers to time of lime application.
p – refers to parent material
s – refers to soil type

If a soil organic matter content ranges between 4-5%, lime requirement by an arable soil should be increased by 20%. Nduwumuremyi (2013) posits that an increase in soil clay content and organic matter content increases its resistance to change in pH (buffering capacity) requires a greater amount of lime to raise the soil pH compared to sandy textured soils with low organic content (poor buffering capacity) hence, it is important to determine the soil organic content and textural class before determining liming requirements of an arable land.

Lime application should not be haphazard. A study by Dhliwayo et al. (1999) recommends that lime application should take into account factors such as amount of lime, time of application, depth of incorporation, frequency of lime application, importance in rotational practices as well as type of liming materials. Optimal lime rates should be based on initial soil pH. study by Brorsen and Tumusiine (2010) showed that in support of the above assertion, the rate of lime that gave optimum yield of rye grass was 1.45t/acre. This, however, is independent of other confounding soil factors that include soil type, soil organic content, texture, depth and type of lime, irrigation or dryland inter alia. Using a 4.8 initial soil pH and lime rate of 1.45t/acre applied over a four year period, soil pH was raised to 6.2. The study ascertained that it would take twenty one years for the pH to decline to a pH of 5.0. It is not enough to rely on initial lime applications but instead, subsequent applications are recommended in order to keep the soil pH near the optimum yield level.

It is advised to apply agricultural liming materials about six months before planting in order to maximise pH change before planting and before phosphate fertiliser application (Coull et al., 2014) concurrent or proximity application would result in phosphorous, combining with calcium in lime to form calcium phosphate thus becoming unavailable to plants. It is crucial to determine the initial pH of soil before applying lime to avoid the danger associated with over-liming and under-liming (Nemasasi and Sithole, 1999). Under-liming is economically a mere wastage of resources. Over-liming leads to a phenomenon known as preferential nutrient uptake that results in some plant nutritional disorders such as die back due to zinc deficiency (Mukurumbira et al., 2000). With preferential nutrient uptake, plants absorb certain plant mineral elements at the expense of others. This happens when soil pH conditions are too alkaline possibly due to over-liming or other natural soil chemical compositions.

Enough lime should be applied to sandveld soils and other light coloured soils. Red soils (*terarosa*) require liming if maize is to be cultivated so that pH is kept above 5.0 so as to avoid manganese toxicity (Tagwira, 1995). In sandy soils 1 tonne of lime is enough to initiate a soil pH rise by between 0.5 to 1 unit within the ploughing depth over a one hectare plot (Hikwa and Gatsi, 1999) This is not the case with red clay soils where the rise in soil pH of 0.2 to 0.33 is possible when the same amount of lime is applied. Maize productivity in sandy textured soils is affected by deficiency in magnesium and aluminium toxicity hence, a suitable magnesium rich lime should be used to alleviate the soil pH status (Sithole and Nemasasi, 2001). Mode of lime application is more important than the amount. This is because applying it through ploughing is less effective than disking.

The frequency and amount of lime to be applied in some cases is dependent on crop under cultivation but generally a pH of 5.0 to 6.5 is desirable (Mukurumbira et al., 1999). The lower figure being applicable to most field crops like maize and tobacco whereas the higher figure is recommended for legumes and high value horticultural crops. The use of liming material is also guided by its neutralising power. Sandy textured soils constitutes 40% of Zimbabwean soils. Such soils are usually deficient in magnesium hence dolomitic lime is usually recommended (Dhliwayo et al, 1999). Soils are amphoteric in nature as they at times, assume basic properties and, in some instances, acidic properties.

2.12 Theoretical Framework

This study is guided buy three scientific theories namely, the law of minimum, the law of limitation hypotheses as well as the law of diminishing yield increments. Doing a research is an attempt at participating in the continuing conversation called science with the variables of interest examined, manipulated and explained from a set of theories, propositions or assumptions. This study is premised on three scientific theories namely, the law of minimum (LM) by Liebig (1885), Van der Ploeg, Bohm and Kirkham (1999), The law of diminishing yield increments by Mitscherlich (1909) and the multiple limitation hypothesis (MLH) of Bloom, Chapin and Mooney (1985), Chapin et al. (1987), Gleeson and Tillman (1992), Rusteller and Shever (1992) and Van der Berg (1998).

2.12.1The Law of the Minimum (Liebig and Mitscherlich, 1885; Bohm and Kirkham,1999)

The law states that growth of plants is limited by a single resource at any given time. Von Liebig (1999) reconstituted Sprengel’s work which pioneered that, the plant will not grow if one of the elements is not available in correct amounts. Bohm and Kirkham (1999) corroborate this and added that if the lacking nutrient is availed, the plant growth is attained to a point of sufficiency. Rubio et al, (2003) posit that in carbon-limited plants, a reduction in root growth limits nitrogen acquisition whilst in nitrogen limited plants, a reduction in shoot growth results in a decrease in photosynthetic carbon gain. Lynch and Gonzalez (1993) made an observation that optimum use of primary resources such as nitrogen and light automatically influence the allocation patterns of a wide array of other mineral resources such as calcium magnesium, which may conceivably have sufficient allocations. Lynch et al, (2003) conclude that plant growth and yield obey some selected nutrients obey Liebig’s (1999) law.

2.12.2 The Theory of Multiple Limitation Hypotheses (Bloom, Chapin and Mooney, 1985; Chapin et al. 1987; Gleeson and Tillman, 1992; Rusteller and Shever, 1992 and Van der Berg, 1998).

The Theory of Multiple Limitation Hypothesis (MLH) postulates that optimum plant response culminates from balancing resource costs and benefits in such a way that the entire resources limit plant growth simultaneously (Zhu et al., 2003). Lynch (ibid) found out that neither the law of minimum nor the multiple limitation hypothesis result in response to all mineral nutrients. Rubio et al (2003) proposes a "nutrient specific" analysis taking into account the biology of each individual mineral element instead of grouping responses of crop plants in a holistic manner. This is deemed more appropriate than relying on a generalised model in exploring the availability of plant nutrient in response to plant growth and development. The MLH states that crop plants adapt to optimum levels as a result of striking a balance in relation to costs and benefits in a manner that sees all resources as having an influence on plant growth at the same time (Gleeson and Tilman, 1992). Multiple limitation hypothesis plants are expected to develop a response that is positive following the addition of a single resource. The MLH concludes that availability of one resource results in the utilisation of other resources.

Rubio et al (2003) say that the multiple limitation hypotheses (MLH) is a clear empirical evidence of how plants respond to the interaction of the above ground and below ground limitations, nitrogen, carbon and water limitations. An increase in root growth following availability of a particular soil condition would promote the availability and utilisation of below ground resources and not the limiting nutrient only (Zhu and Lynch, 2003). However, one big drawback of this theory is that, mineral nutrients have specific metabolic roles in plant physiology hence, it is not sufficient to substitute one nutrient role with that of the other nutrient. Though this assertion is held true, a study by Gonsalez and Lynch (1993) reveals that optimal use of plant basic requirements such as nitrogen and light signify an automatic allocation of a wide array of subsequent mineral elements such as calcium and magnesium, among others. This way, nitrogen availability obeys the law of Multiple Limitation Hypothesis (1985).

2.12.3 The Law of Diminishing Yield Increments

The proponent of this theory was Mitscherlich (1909). The law was developed as a refinement of the (Multiple Limitation Hypothesis (MLH) and law of minimum (LM). This theory asserts that plant growth and yield increments respond to a particular resource up to an upper limit and after which it assumes an asymptotic curve. Both Liebig's law (1885) and Mitscherlich's model (1999) gained wide acceptance in modern or contemporary agronomy. In a single element experiment, the biomass accumulation following successive nitrogen application was realised. Plants attained an increase in biomass at the minimum level and a decrease in biomass at the maximum level reflecting a point of inflexion or invasion in yield response (Rubio et al, 2003).

Nitrogen was the only nutrient revealing a dominance in terms of response curve to nutrient availability, scoring 9 out of 15cases (Rubio, ibid). Surprisingly, even under the abiotic stress induced by deficit of other elements, plant growth was realised from increases in nitrogen supply (Zhu et al, 2003). This suggests that response to nitrogen increment and its availability assumes a preferential status among the 16 essential plant elements.

REFERENCES

Abu, O, Alumunku, M, Tsue, P (2011). Can Small Scale Tomato Farmers Flourish in Benue State, Nigeria. Journal of Agricultural Sciences.

Association of Official Analytical Chemists (AOAC) (1980). Washington D.C.

Bloom, A.J., Chapin, F.S, and Mooney (1987). Resource Limitation in Plants – an economic analogy. Annual Review of Ecology and Systematic.

Bohm, W. and Kirkham (1999). On the Origin of the Theory of Mineral Nutrition of Plants and the Law of the minimum Soil Science Society of America

Bolan, N.S and Hedley, M.J. (2003). Role of Carbon, Nitrogen and Sulphur Cycles in Soil Acidification: Handbook of Soil Acidity. New York

Brady, N.C and Weil.P (2014). The Nature and Properties of Soils 13th Edition New York.

Charves, M.M, Maroco, J.P and Pereirra, J.S (2003). Understanding Plant Responses to Drought: From Genes to the whole plant. Functional Plant Biology 30.

Coneyers, M., Fenton, G and Upjohn, B.A (2005). Soil Acidity and Lime Agifacts, Department of Primary Industries.

Connor, D.J., Loomies, R.J and Cassman, K.G (2011). Crop Ecology: Productivity and Management in Agricultural Systems 2nd ed. Cambridge University Press, Cambridge.

Coull, M, Sinclair, A and Crooks, B (2014). Soils Information, Texture and Liming Recommendations. Scotland's Rural College – SRUC Technical Note TN **656.**
Soil Science Society of America (1997)

Crooks, B., Sinclair, A., Coull, M (2014). Soils Information, Texture and Liming Recommendations. Technical Note.

Cutts, J.T and Hussein, M (2002). Exploration of Legume diversity Endemic to Salt Range in the Punjab. Annual Technical Report Submitted to the University of Agriculture Faisalabad.

Dhliwayo D.K.C et al (1999) Soil Fertility network for maize – Based Cropping Systems in Malawi and Zimbabwe: A Critical Look at the Potential Recovery from Acid Sol Infertility in the Communal Areas of Zimbabwe. Working Paper Number 5 Soil Productivity Research Laboratory (CIMMYT).

Dhliwayo, D.K.C and Mukurumbira, L. (1999) Liming in Zimbabwe: A Critical Look at the Potential Recovery From Acid Soil Infertility in the Communal Areas of Zimbabwe. Working Paper No 5

Donahue, S and Auburn, A.L (1999). Liming to Improve Soil Quality. Soil Quality – Agronomy Technical Note Number 8. USA Department of Agriculture.

du Pless, J (2003). Maize Production. Directorate Agricultural Information and Services. Department of Agriculture.

Ercoli, L, Arduini, I, Mariyotti, M, Lulli, L, Masoni, A. (2012). Management of Sulphur Fertilizer to Impove duram Wheat Production and Minimise Sulphur Leaching. European Journal of Agronomy

FAO/UNESCO (2011). Statistical Database for the Food and Agriculture Organisation of the United Nations: *http://www.fao.org*.

Fertiliser Manual (2010). Soil pH and Lime Management: Centre for Agriculture, Food and the Environment. Lowa State University, The Fertiliser Institute . USA.

Foulkes, M.J, Hawkesford, M.J, Barraclough, P.B, Holdsworthy, M.J and Shewry, P.R (2010). Identifying Traits to Improve the Nitrogen Economy of Wheat: Recent Advances and Future Prospects. Field Crops Research 114.

Fenta, M, Jordan, A and Mellca,Y (2018). Understanding Resilience of Pastoralists to Climate Change and Variability in the Southern Afar Region, Ethiopia. Climate Risk Management.

Furbank, R.T. and Tester, M. (2011) Phenomics –technologies to Relieve the Phenotyping Bottleneck. Trends Plant Science.

Gibbs, P., Moir, I., Richardson, S., Hickman, G. and Chambers, B (2005) Landspreading on Agricultural Land: Nature and Impact of Paper Waste Applied in England and Wales. Science Report SC030 181/sr

Gitari, H.I, Nyawadi, S.O, Kamau, S, Karanja, N.N. Gachene, C.K.K., Raza, M, Maltra, S, Schulte-Geldermann, E (2015). Revisiting Intercropping Indices with respect to Potato-Legume Intercropping Systems. Field Crops Research

Glass, A.D.M. (2003). Nitrogen Use Efficiency of Crop Plants: Physiological Constraints upon Nitrogen Absorption. *Critical Reviews in Plant Sciences**22***

Gleeson, S and Tillman, (1992). Plant Allocation and the Multiple Limitation Hypothesis American Naturalist.

Goulding, K.W.T. (2016). Soil Use and Management: Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. Department of Sustainable Grass land Systems.

Grant, P.M and Turner, P.D (1979). Soil Acidity Factors Affecting Maize Yield in Rhodesia. Fertilizer Society of South Africa Journal.

Greens, N.P.O., Taylor, D.J., Stout, G.W. (1990) Biological Science 1 and 2. Third Edition. Cambridge University Press. Cambridge

Hikwa, D and Gatsi, T (1999). Liming in Zimbabwe: A Critical Look at the Potential Recovery from Acid Soil Infertility in Communal Areas of Zimbabwe. Network Research Results Working Paper Number 5, Harare

Hinsinger, P, Plassard, C., Tung, C and Jaillard, B (2003). Origins of Root Mediated pH Changes in the Rhizosphere and their Responses to Environmental Constraints: A Review. Plant and Soil

Hirel, B., Le Gouis, J., Ney, B.and Gallais, A. (2007). The Challenge of Improving Nitrogen Use Efficiency in Crop Plants: Towards a more Central Role for Genetic Variability and Quantitative Genetics within Integrated Approaches. *Journal of Experimental Botany* **58**

Hufnagel, B., De Sousa, S.M (2015). Duplicate and Conquer: Multiple Homologues of Phosphorous Starvation Tolerance to Enhance Phosphorous Acquisition and Sorghum Performance on Law Phosphorous Soils. Plant Physiology

Hussein, J (1994). Applied Soil Science CDSL 101 Module 1 Soil, its Formation and Properties, Harare, University College of Distance Education.

Johnston, A.E, Goulding, K.W.T and Poulton, P.R (1986). Soil Acidification during more than one Hundred Years. Under Permanent Grassland and Woodland at Rothamsted. Soil Use and Management.

Kamprath, E.J., (1970). Exchangeable Aluminium as Criterion for Liming Leached Mineral Soils .Soil Sciences of America.

Kano, M., Inukai, Y., Kitano., H, Ymauch, A (2011). Root Plasticity As the Key Root Trait for Adaptation to Various Intensities of Drought Stress in Rice. Plant Soil

Kovacevic, V and Rastija, M. (2010). Impacts of Liming By Dolomitic on the Maize and Barley Grain Yields Poljoprivreda 16: 2010 (2) pp 1-2.

Kuijken, R.C.P. et al (2015) Root phenotyping: From Component trait in the lab to breeding. Journal of Experimental Botany Volume 66 Number 18 pp 5389 – 5401 jxb/erv239 Advance access publication.

Kuzyakov, Y and Domansky, G (2000). Carbon Input into the Soil. Wiley Online Library

Larkcom, E., and Miller, R (1994). Food Production: Biology – Advanced Studies, Nelson and Sons Ltd, United Kingdom

Liebig, J.V (1885). Die Grundsatze der Agricultur- Chemie Mit Rucksicht auf die in Englend Angestellten Untersuchchungen.Fredrick Viewega and Sonhn, Braunschweig, Germany

Lynch, J (1995). Root Architecture and Plant Productivity. Plant Physiology

Lynch, J.P., and Gonzalez, A. (1993) Canopy Nutrient Allocation in Relation to Incident Light in the Tropical Fruit Tree Borojoa Patinoi (Cuatar) Journal of the American Society for Horticultural Science.

Mader, S.S. (2006) Inquiry into life McGraw – Hill, New York.

Marcelis, F.M., Rene, C.P., Fred, A., Haro, J, (2015). Root Phenotyping: From Component Trait in the Lab to Breeding. Journal of Experimental Botany. Vol. 66 No: 18

Marchner, P(2012). Mineral Nutrition of Higher Plants, 3rd Edition. Academic Press, London

Masaka, J, Nyamangara, J and Wuta, M (2014). Nitrous Oxide Emissions from Wetland Soil Amended Inorganic Fertilizers. Archives of Agronomy and Soil Science

Masaka, J. (2014). The Effect of Nitrogen Fertilizer Placement and Timing on the Uptake of Nitrogen, Phosphorous and Potassium by Spring Wheat (Tritcum Aestivum L. Cv. Spectrum) at Different Phenolog. *Journal of Agronomy*

Matsubara, S., Ruscher, U., Fiorani, F., Janisen, M., Blosfeld, L., Martin., L.L, Merchant, A., and (2011) Non Evasive Approaches for Phenotyping of enhanced Performance Traits in Bean. Functional Plant Biology

Meister, R., Rajani, M., Rozika. D and Schatman, D.P (2014). Challenges of Modifying Root Traits in Crops for Agriculture. Trends Plant Science

Mitscherlich, E.A. (1999). DassGesetz des Minimums und das Gatsetz des abnehmenden Bodenertrages. Landwirtschaftliches Jarhbuch der Schweiz.

Moll, L.C, Laura, R.C and Bergmann, G (1992). The Plan Stomatal Lineage at Glance: Journal of Soil Science

Monteros, M.J., Garcia, A.P., Motes, M., Chen, R and Blancaflor, E.B (2015). Root Traits and Phenotyping Strategies for Plant Improvements

Mooney, L, Landi, M and Schepf. A (2012). Modelling the Impact of Biopress on Root Growth and Root Water Uptake. Crop Science Society of America

Narayanani, S., Mohani, A., Gill, K.S and Prasad, P.V (2014). Variability of Root Traits in Spring Wheat Germplasm

Nemasasi, H Sithole, T, and Dhliwayo, D.C.K (1998). Soil Acidity: Is it a Problem in Maize Based Production Systems of the Smallholder Areas in Zimbabwe?. CIMMYT. Zimbabwe

Nekesa, J (2007). Potential of Agricultural Lime on Improved Soil Health and Agricultural Production in Kenya. African Crop Science Journal

Nyamangara, J. and Mpofu, S.E (1996) Soil pH and requirement for high potential communal areas of Zimbabwe. Journal of Applies Science in Southern Africa Vol. 2 Number 2.
Okalebo et al (2009)

Rascher, U., Fiorani, F., Janisen, M., Blosfeld, L., Martin., L.L, Merchant, A., and Matsubara, S (2011) Non Evasive Approaches for Phenotyping of enhanced Performance Traits in Bean. Functional Plant Biology

Rastija, I. et al (2010) Impacts of Liming with Dolomite on the Wheat Yield: Faculty of Agriculture, Croatia

Robbins, N.E, and Dinney, J.R (2015). The Divining Root: Moisture Driven Responses of Roots at the Micro and Macro Scale. Journal of Experimental Botany

RoTAP (2012). Review of Transboundary Air Pollution: Acidification, Eutrophication, Ground Level Ozone and Heavy Metals in the UK. Contract Report to the Department for Environment, Food and Rural Affairs. Centre for Ecology and Hydrology

Rubio, G. and Lavado, G. (1999). Accumulation and Allocation of resources in two waterlogging tolerant grasses. New Phytologist.

Shimono, H. And Bruce, J.A (2009). Acclimation of Nitrogen uptake Capacity of Rice to Elevated Atmospheric Carbon dioxide Concentration. Ann Bot, 103.

Shoko, M.D. and Moyo, S (2011). Soil characterisation in Contrasting Cropping Systems under the fast track land reform programme in Zimbabwe Vol. 11 Number 3. African Journal of Food, Agriculture, Nutrition and Development.

Tagwira.F (1995). Growth, Yield, Phosphorous and Zinc Uptake by Maize as affected by Lime and Phosphate. Agri-Seeds. FAO

Tumuisine, E. and Brorsen, W.B.(2010) Effect of Nitrogen Fertilisation on Rye-Rye Grass Yield and Soil pH Dynamics: Agricultural and Applied Economics Association, (AAEA),CAES and WAEA Joint Annual Meeting.

Okalebo, J.R, Othieno, C.O, Nekesa, A.O and Wairimu, K (2009) Potential for Agricultural Lime on Improved Soil Health and Agricultural Production in Kenya African Crop Science Journal.

Uga, Y., Sugimoto, K., Ogawa, S., Rane, J., Ishitane, M., Hara, N., Kitomi, Y., Inukai, Y., Ono, K, and Kano, N (2013). Control of Root System Architecture by Deeper Rooting in Increasing Rice Yield Under Drought Conditions. National Genetics

Upjohn, B., Fenton, G., Conyers, M (2005). Soil Acidity and Liming. Agifact. New South Wales Department of Primary Industries, Australia
USDA (1999)

Van Der Berg, H. (1998) Multiple Nutrient Limitation in Unicellulars: Reconstructing

Vitousek, P.M., and Robertson, G.P (2009). Nitrogen in Agriculture: Balancing the source of an Essential Resource Annu. Rev. Environ. Resource 34

Whipps, L (1990). West Africa Agricultural Productivity Programme. The World Bank. IBRD. IDA.

Wilkes, G.A and Krebs, W.A (2001). Collins Coinsise Dictionary. Harper Collins Publishers, Glasgow.

Wu, S, Jacob, D.J, Rind, D, Streets, D.G. and Mickley, L.J (2008). Effects of 2000- 2050 Global Change on Ozone Air Quality in the United States. Journal of Geophysical Research, 113 (D6)

Zahoo (2014). Influence of Integrated Use of Chemical and Organic Fertilizers on Yield and Yield Components of Wheat. International Journal of Agriculture Crop Science7 (1)

Zhang, H. and Raun, B. (2006) Oklahoma Soil Fertility Handbook. 6th Edition. Department of Plant and Soil Sciences, Oklahoma State University. OK

Zhang, H., Johnson, G., Krenzer, E.G. and Gribble, R. (1998). Soil Testing for an Economically and Environmentally Sound Wheat Production. Communications in Soil Science and Plant Analysis. 29.

ZHU, J., Rubio and Lynch, J.P. (2003) A Critical Test of the Two Prevailing Theories of Plant Response to Nutrient Availability. American Journal of Botany **90 (1)**

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Experimental Sites Description

The study was conducted during the 2018/2019 and 2019/2020 Agricultural summer seasons. Two sites both with soils classified as sandy textured soils were chosen in Masvingo District, in the Province Masvingo in Zimbabwe (Hussein et al, 1992). One site was coded as Marapira Farm Site and the other Victoria High School site both with generally initial acidic soils of $pH_{cacl}<5.1$ evaluated in the laboratory, as 4.55 Marapira Farm site and 5.1 Victoria High School site. Variations in experimental sites are important in enabling comparison of parameters over a wide spectrum and to increase the number of treatments as suggested by (Jiri and Mafongoya, 2017).

Soils at the experimental sites are classified as fersiallitic soils derived from granite rocks (Nyamapfene, 1991). The soils cover 40% of Zimbabwe's geology and have a fertility which is moderate so a wide number of crops can be successfully cultivated in them. These soils are located in rainfall marginal areas (Department of Surveyor General, 1979). According to the Central Statistical Office Digest, (2013), Masvingo lies between latitude – 21.446815 and longitude 31,838409 and an altitude of 1,075metres above sea level. The total area is 56 566 km^2 and mean daily temperature of 28 ^{o}C and frequent South Easterly winds which move at a speed of $10km/h^{-1}$.

Experimental Design

3.2.1 The Split plot design

The split plot design is an experimental arrangement that result from a specialised randomisation scheme for a factorial experiment (Ganju and Lucas, 1990). The basic split plot design involves assigning the levels of one factor to main plots arranged in either CRD, RCBD or Latin –Square and then assigning the levels of a second factor to sub plots within the main plot. In a split plot design, randomisation was done in two stages. First, the three levels of factor A (dolomitic lime were randomised over the main plots and the levels of factor B (nitrogen fertilizer) were randomised over the sub plots within each main plot. Each main plot maybe considered as a block since every sub plot has the same chance of receiving every treatment combination. There are two distinct error terms. One appropriate for the main plot that result in the testing effect of factor A and the other appropriate for sub plots in testing effect of factor B.

Generally, the error term for the main plots is larger since the main plots are larger, further apart and allow greater heterogeneity whilst the sub plots are smaller, closer to each other and allow greater homogeneity. In the split plot designs, factor interactions are compared or measured using smaller sub plots hence precision is usually increased in split plot designs than simple factorial.

3.2.2 Uses or Applicability of split plot designs

- Split plot designs are used mostly for factorial experiments in which the nature of the experimental material is involved makes it difficult to handle all factor combinations in the same manner (Fisher, 1934). It is more applicable in situations where treatment levels of one factor require larger amounts of experimental material than is demanded by other factors.

- 2. This design is also applicable when a researcher wants to increase degree of precision in estimating certain effects and strongly wishes to sacrifice precision in estimating average effects in detecting interaction of factors.

- The design is also useful when an additional factor is to be incorporated into a study or experiment to increase its scope

. 3.2.3 Advantages of the Split plot design

- Large experimental units may be utilised to compare subsidiary treatments.
- Split plot designs have higher precisions than RCD than RCBD on sub plot treatment interaction.

- The overall precision of the split plot may be increased by designing the main plot in a Latin Square design.

3.2.4 Disadvantages of the Split plot design

- Treatments in the main plots may be measured with less accuracy or precision than in RCBD.
- When missing data occur, analysis is more complex than in other designs.
- Different treatment comparisons have different error variances which makes analysis of results more complex

The Split- plot designs, despite having two or three factors are more applicable in complex situations or scenarios such as the existence of hard- to-change (HTC) factors between successive or consecutive experimental trials in agriculture field trials. Such was the case with this study since the study was conducted for two consecutive agricultural seasons (2018/2019 and 2019/2020) with fixed HTC factors such as the same sites of experimental units and treatment combinations as well as soil type, type of lime and nitrogen fertiliser.

Ganju and Lucas (1999) advocate for the Split- plot design (SPD) owing to its precision in analysing sub plot factors given the presence of extremely HTC main plot factors and its cost and time effectiveness. The SPD has as many factors as possible, so as to gain an in depth understanding of the interactive nature of factors under consideration (Gomez and Gomez, 1984). Such was the case with this study, where three factors namely dolomitic lime, nitrogen and irrigation were interacting in sandy textured soils of Masvingo Province, derived from granite and gneissic rocks.

3.2.5 Table1: Arrangement of the Split plot design

	Sub-sub/net plot								
A_0 Main Plot	A_1 B_1	$A_1 B_1 C_3$	$A_1 B_1 C_8$	$A_1 B_1 C_2$	$A_1 B_1 C_0$	$A_1 B_1 C_4$	$A_1 B_1 C_6$	$A_1 B_1 C_7$	$A_1 B_1 C_5$
A_0 Whole Plot	A_1 B_2	$A_1 B_2C_6$	$A_1 B_2C_3$	$A_1 B_2C_7$	$A_1 B_2C_2$	$A_1 B_2C_4$	$A_1 B_2C_0$	$A_1 B_2C_8$	$A_1 B_2C_1$
	A_1 B_3	$A_1 B_2C_8$	$A_1 B_2C_5$	$A_1 B_2C_3$	$A_1 B_2C_7$	$A_1 B_1 C_1$	$A_1 B_2C_4$	$A_1 B_2C_6$	$A_1 B_2C_2$

Where A_i, B_j, and C_k represent the factor levels i, j and k of the whole plot, sub-plot and sub-sub/net plots respectively for:

$("j = 1, 2, 3\ ,\quad i = 1, 2, 3\quad and\quad k = 1, 2, 3, \dots 8)$

The experiment was conducted during the seasons 2018-2019 and 2019-2020 in order to comprehensively study the effect of different levels of lime on the requirements of nitrogen (N) in the growth and yield of maize (*Zea mays L*). The levels of lime consisting of (1, 1.5, 2 and 2.5 tonnes per hectare) were arranged in a factorial combination with three replications using the Split- plot design. The statistical model of the Split- plot design (SPD) is:

$Y_{ijk} = \mu + t_i + \varepsilon_{ij} + \gamma_k + (t\gamma)_{ik} + \propto_{ij} + \beta_k + \delta_{ijk}$ *(Adapted from Ledolter, 2010)*

Where:

Y_{ijk}= is the yield of the j^{th} level of factor A, k^{th} level of factor B in the i^{th} block.

μ= is the overall mean of all observations.

t_i ($i = 1, 2, ...t$) is the main /whole plot treatment effect.

ε_{ij}($j = 1, 2, ...,r$) is the whole plot error (for example different treatment combinations assigned to each plot under the same maize genotype)

γ_k($k= 1, 2, ... , g$ represents the split plot treatment effect

$(t\gamma)_{ik}$= is the interactive effect between the main plot (MP) and Split- split plot (SSP) Treatments.

$\propto_{ij=}$is the added effect of the j^{th} level of factor A.

$\beta_k$is the added effect of the $_k{}^{th}$ level of factor B.

δ_{ijk} = is the Split plot (SSP) random error or tolerance range associated with the unit of the j^{th} observation in the $_i{}^{th}$ block.

The study assumed a Split- plot design arranged in a 2 x 3 factorial set up. The Split- plot arrangement is applicable where there are more than two factors interacting and different levels of treatments thus, resulting in a factorial experiment (Ledolter, 2010). This is the case with the experiment under investigation, as lime and nitrogen interact under both irrigation and dry land conditions. There were three ways of precision with the experimental plots, namely largest or main plot, intermediate sized plot and sub-subplot. The main plot factor receives the lowest precision whilst the sub-subplot factor is assigned the highest precision. As prescribed by Ledolter (2010), each factor was replicated 3 times.

The main plot measured 36 x 17 = 612m^2 , intermediate main plot measured 36m x 5m = 180m^2 while the net plot/sub-subplot measured 4m x 5m =20m^2 . The smaller size of the net plot induced a compromise between size of net /sub- subplots and the increased number of treatments under different agronomic conditions as prescribed by (Jiri and Mafongoya, 2018). Since there were only three 3 replicates per site, it allowed an intensive comparison of the huge number of 9 treatments.

3.3 Organic Matter Determination

Soil organic matter content was determined using the Dry ignition method by removal of organic matter from the soil mineral fraction. This resulted in a weight loss upon exposure to heat.

Procedure

A sample of air dried soil was taken and weighed to determine initial weight. The known quantity of soil sample was oven dried at a temperature of 105°C for 24 hours. Temperature was maintained at 105°C. When a constant weight was achieved, the oven temperature was adjusted to 120°C in order to burn the organic soil fraction (Sommers, 1996) as recommended by the modified classical Walkley and Black procedure (1934). This was done until a constant weight was achieved. The weight of oven dried soil at 120°C was deducted from oven dried soil at 105°C. The difference in weight loss signifies a close estimate of the soil organic fraction.

3.3.1 Soil Characterisation

Determination of soil textural class was done by randomly collecting 1 kg composite sample of soil from the two experimental sites from a 15cm depth using a soil auger. The soil sample was air dried first before sieving. Three sieve plates identified as sieve 1 9number 5) which was the longest sieve for trapping sand particles, sieve 2 (number 10) which trapped salt particles and lastly sieve 3 (number 120) which was the smallest for trapping clay particles were used. The three sieves were stacked one on one on top of the other starting with the largest sieve for sand particles. The 1kg composite soil sample was then poured into the top sieve. All the sieves were physically shaken for 20 minutes in order to allow aggregation of the different soil particles. The collected soil particles were weighed separately and each soil fraction expressed as a percentage of the total initial composite sample thus:

- % sand = mass of sand particles/ total soil mass x 100
- % silt= mass of silt particles /total soil mass x 100

- % clay= mass of clay particles / total soil mass x 100

3.3.2 Measurement of soil pH

The pH of the soil before liming and planting and after liming and crop harvesting was done in a slurry system in the ratio 1:2 for soil and distilled water respectively. The soil solution was put in a 500ml beaker and stirred thoroughly using a glass rod. The reading was then taken after dipping the digital pH metre electrode in the soil solution using a pH metre of type pH 22 LAQUAtwin Manufacturer-Thomas Scientific. The objective behind taking the soil pH status before and after liming was to establish the effect of the 9 different liming and nitrogen treatment combinations on pH rise. Differences in pH readings signified the pH unit rise.

3.3.3 Measurement of Leaf Area Index (LAI)

Leaf Area Index is a measure of the leaf area per unit of ground area at a given time. In order to calculate LAI, all sampled leaves were cut off from systematically selected maize plants in a determined ground area of $0.5m^2$ as recommended by Larkcom and Miller (1994). Since the index vary with each plant growth stage, the maize plants were measured for this parameter over a period of six weeks using the formula below devised by Larkcom and Miller (1994) (Equation 1).

$$LAI = \frac{LA}{GA} \qquad (1)$$

Where
LAI = Leaf Area Index
LA = Leaf Area
GA = Ground Area

Differences in Leaf Area from different leaf sampling units per given time signified differences in plant growth rate it is assumed that there is a linear relationship between leaf area and plant biomass. Therefore in order to determine this relationship, net assimilation rate (NAR) which is the rate at which new material was synthesised was calculated using (Equation 2) below

$$NAR = \frac{\text{Increase in plant dry mass per unit time}}{\text{Leaf Area Index}} \qquad (2)$$

The Growth rate of the crop which is an increase in crop biomass per unit area per unit time was computed as LAI x NAR (Equation 3)

Growth Rate = <u>LAI x NAR</u> (3)

In order to determine plant biomass, selected plants were harvested on a weekly interval from each of the 9 treatment plots. They were rinsed and oven dried at 65℃ and kept safely in a dry place as recommended by Masaka et al (2014), they were then measured using a sensitive digital electronic scale at designated time intervals on a weekly basis for 6 weeks.

3.3.4 Yield Evaluation

Moisture content of the seed is a very important indicator of seed physiological maturity as well as being a major determinant of the longevity if seed is to be used as grain for human and livestock consumption (Oluwaranti and Ajay, 2008) this also applies to seed used as plant propagule. Maize plants were sampled for kernel moisture determination. This was done by cross cutting the maize stalks, dehusking the cobs and sun drying them for one week. After one week, a few grains of maize were added to the cells of the moisture meter of DICKELEY-John HE 90 meter and screwed before taking the reading from the sitting glass of the moisture meter. From each of the 9 treatment plots, from the three blocks, a sample of 1000 kernels were evaluated for their thousand seed weight as recommended by Rathore (2000).

3.3.5 Table 2: Initial Experimental Sites Soil Characteristics during the 2018/2019 and 2019/2020 seasons

Site	Soil Type	Soil depth (cm)	Soil pH	Soil Colour	Organic Matter %	Area (m^2)
Marapira Farm	**Sandy loam**	**30**	**4.55**	**Brown**	**2.89**	**612**
Victoria High School	**Loam**	**30**	**5.1**	**Dark brown**	**3**	**612**

3.3.6 Table 3: Yield components of maize due to lime and nitrogen interaction during the 2019/2020 season

Treatment Number	Lime Rate (LR) t ha^{-1}	Nitrogen Rate (NR) t ha^{-1}	Shelling %	Net Plot Yield (NPY) 1000 seed weight (g)	Mean Cob Length (MCL) Mm	Mean Cob Girth /diameter (MCG/D)Mm	Bare Tips (BT)	DDR %	pH DEV
1	**0**	**0**	**84.6**	**434**	**175**	**150**	**P**	**6.9**	**0.2**

2	**0**	**0.2**	**83.7**	**454**	**230**	**158**	**P**	**6.7**	**0.6**
3	**0**	**0.4**	**81.9**	**471**	**250**	**160**	**P**	**6.6**	**0.42**
4	**1.5**	**0**	**84.1**	**360**	**210**	**158**	**N**	**6.8**	**0.48**
5	**1.5**	**0.2**	**85.1**	**585**	**240**	**170**	**N**	**5.8**	**0.65**
6	**1.5**	**0.4**	**78**	**669**	**265**	**160**	**N**	**5.6**	**0.7**
7	**3**	**0**	**91.3**	**432**	**230**	**150**	**N**	**6.6**	**0.5**
8	**3**	**0.2**	**77.8**	**663**	**230**	**175**	**N**	**6.2**	**0.4**
9	**3**	**0.4**	**79.9**	**562**	**255**	**160**	**N**	**5.5**	**0.5**

Variables: **pH - Potential Hydrogen Ions,** **S% - Shelling percentage,** **LR – Lime Rate,**
DDR% - Drying Down Rate Percentage **MCL – Mean Cob Length** **BT – Bare Tips,**
MCG/D - Mean Cob Girth/ Diameter, **P – Present,** **N – Nil,**
pH - Potential Hydrogen Ions, **NR – Nitrogen Rate,**

3.4 Ethical Considerations

The researcher abided by the rules and regulations governing any academic research. The study used chemical substances which need proper disposal. Zimbabwe is a signatory to several bio-diversity conventions (Chenje et al, 1998). Therefore, against this background, use and disposal of chemicals during and after use was done to curb eco-system disturbance in line with national and international guidelines. Although the study was conducted at Great Zimbabwe University farm and own farm trials, the protocol to use the premises was well abided by.

3.5 Data Collection

3.5.1 Soil Analysis

Ten soil samples were randomly collected from the fields for pH status. Soil was extracted using a soil auger to a 20cm depth and put in clean polythene bags that were followed by an analysis for pH and 14 days mineral nitrogen.

The growth rate of the maize crop was measured by determining the crop’s leaf area index (LAI) and multiplying it by the net assimilation rate (NAR) as recommended by Miller and Larkcom (1994). This is deemed to provide valuable information of comparing the effects of different treatments on a given crop. Also, the yield of the maize crop was assessed by determining the leaf area duration (LAD) which is indicative of a crop’s ability to photosynthesise and produce organic material during a given period.

3.6 Population, Sample and Sampling Method

Ten soil samples were drawn from two 612m^2 plots using the diagonal method. A composite sample of 1kg was taken from the mixture of ten soil samples and tested for pH and nitrogen status. The study used two hectares of land each designed to accommodate a plant population of 53333.3 plants, using a standard spacing of 750 mm inter row by 250 mm in row. A total of about 53334 plants were used for the study and a sample of 370 plants drawn using the stratified random sampling method to determine the growth and yield parameters of interest from each sub plot. The boarder effect was taken into consideration during sampling as this influences results as plants on the outside of sampling units enjoy better photosynthetic active radiation (PAR, feeding perimeter and fertility gradient) (Larkcom and Miller, 1994).

3.7 Data Analysis

Data was gathered for a period of two seasons for evaluation. It was analyzed using a statistical software package called Special Package for Social Scientists (SPSS). The statistical model used was that of the Split plot design which was as follows:

$$Y_{ijk} = \mu + t_i + \varepsilon_{ij} + \gamma_k + (t\gamma)_{ik} + \propto_{ij} + \beta_k + \delta_{ijk}$$

The analysis made use of Multivariate Analysis of Variance (MANOVA) which in simple terms is an ANOVA but with several dependent variables. Whilst ANOVA tests for the difference in means between two or more groups, MANOVA explores or tests for the difference in two or more vectors of means which would result in multivariate F values (Wilks' λ /Lambda) based on a comparison of the error variance/covariance and covariance matrix instead of the univariate F value. Although there was mention of only Wilks' Lambda, there are several other multivariate statistical tests employed that encompass Hotelling's trace, Pillay's criterion, Turkey's HSD test (honest significant difference) and Levene's Test of Equality of Error Variances inter alia. The aforesaid multivariate post hoc tests evaluate or test the multiple dependant variables (DVs) against several independent variables (IVs). In this study, dependant variables included growth parameters, yield parameters and soil pH dynamics whereas independent variables include varied lime rates, nitrogen rates and irrigation conditions. By and large, the main objective of using MANOVA was to determine if the response variables were altered or affected by the observer or researcher's manipulation of the independent variables, interactions among independent variables as well as investigating the importance of the dependant variables. Therefore, validity and reliability of the outcomes from which sound conclusions were made was premised on confirmation by post hoc MANOVA tests.

REFERENCES

Chenje, M, Sola, Land Paleczny, D (1998). The State of Zimbabwe's Environment, 1998. Ministry of Mines, Environment and Tourism, Government of Zimbabwe, Harare.

Fisher, R.A (1934). Statistical methods for Research workers, University of London.

French, A., Macedo, M., Poulsen, J., Waterson, T., and Yu, A. (1996) Multivariate Analysis of Variance (MANOVA).

Ganju, J and Lucas, J.M (1990). "Detecting Randomisation Restrictions Caused by Factors" Journal of statistical Planning and Inference Vol. 81.

Gomez, K.A. and Gomez, A.A (1984) Statistical Procedures for Agriculture Research. 2nded. New York: John Willey and Sons

Hussein, J. (1997) Applied Soil Science: Module 2. Introduction to Soil Management, University of Zimbabwe, Harare.

Hussein , J., Adey, M.A, and Ellwell, H.A. (1992). Irrigation and Dryland Cultivation Effects on the Surface Properties and Erodibility of a Zimbabwean Vertisol. Soil Use Management 8

Jiri, O. and Mafongoya, P.L. (2017) Velvet Bean and Cowpea Residual Effects on Maize Crop in Smallholder Farming Areas of Zimbabwe. Sustainable Agriculture Research Vol. 7 No.1. Canadian Centre of Science Education.

Landberg, C (2013). Soil Textures using a soil sieve: Terrestial Ecology Estension activity. Mathematics and Science Centre

Ledolter, L. (2010) Split Plot Designs: Discussion and Examples. ***International Journal of Quality Engineering and Technology, Vol. 1 No.4***: Department of Statistics and Acturial science. University of Lowa, Lowa City.

Larkcom, E., and Miller, R (1994). Food Production: Biology – Advanced Studies, Nelson and Sons Ltd, United Kingdom

Nyamapfene, K.W (1991). Soils of Zimbabwe. Harare. Nehanda Publishers (Pvt) Ltd.

Nyamangara, J and Wuta, M (2014). Nitrous Oxide Emissions from Wetland Soil Amended with Inorganic and organic Fertilizers. Archives of Agronomy and Soil Science, Taylor and Francis

Rathore, R.S (2000). Techniques and Management of Field Crop Production. Agro Bios . Jodpar.

Oluwaranti, A and Ajay, S.A (2008). Determination of soil Moisture Content of Maize Seed: Comparison of 2 Moisture Meters with the oven Method. Ife Journal of Agriculture Vol. 23 No.1

CHAPTER FOUR

4.0 EFFECT OF LIME AND NITROGEN INTERACTIONS ON EARLY STAGES OF MAIZE GROWTH

4.1 Abstract

The net interactive effects of dolomitic lime and ammonium nitrate fertiliser on early growth stages of maize in a pre - tested acid soil were evaluated using the Split- plot design with 9 treatments replicated three times comprising three levels of lime, 0, 1.5 and 3.0t ha^{-1} and three levels of nitrogen fertiliser of 0, 0.2 and 0.4t ha^{-1}. Yellow maize of variety SC402 was grown on a 612m^2 plot for two seasons namely 2018/2019 and 2019/2020 on loamy soils to evaluate the interactive effects of different lime and nitrogen combinations on below and above ground maize growth parameters. The maize plants were characterised for a period of 6 weeks for above ground and below ground growth parameters. These include Leaf Area Index (LAI), Leaf Length (LL), Plant Height(PH) as well as below ground root parameters that encompass Root Biomass (RB), Root Depth (RD), Root Diameter and Root Divergence Angle from the node. Lime and nitrogen interaction revealed a significant effect on root biomass and root angle. There was an insignificant effect on root depth on all the 9 treatments on this parameter. For root biomass, $p< 0.05$ hence it was significant at 95% confidence interval thus, rejecting H_0 . Leaf Area Index and Leaf Length as well as Plant Height were significant at $p< 0.05$ during early maize growth stages.

Key words: Lime, Nitrogen, Root Biomass, Root Depth, Plant Height, Above Ground Biomass, Maize

4.2 Introduction

Maize is a cereal crop ranked as the third most popular, worldwide after rice and wheat because of its wide range of uses and high carbohydrate content (FAOSTAT, 2016).Maize and its variants such as the yellow (orange) variety is rich in carotenoids which are precursors to vitamin A synthesis with nutritional and health benefits(Manjeru,2017).The above ground maize plant organs can be processed into silage for dairy animal feeds whilst, the kernels (grain) have domestic and industrial uses. However, growth and productivity of maize has been adversely affected by severe mineral depletions and low soil pH (Nyamangara and Mpofu,1996).Cereal crops contribute more than 50 percent of human calories globally (Zahoor et al,.2014).Nitrogen occurs in plant green pigments called chlorophyll a and chlorophyll b and the nitrogen element promotes plant vegetative growth. Plant leaves with adequate nitrogen develop a dark or blue - green colouration which is a raw material for photosynthesis through enhanced solar radiation interception. Nitrogen is by far the most valuable nutrient for diverse plant growth phases. However, nitrogen because of its high mobility through volatilisation and leaching is usually scarce hence, its availability to crops, such as maize, becomes a major limiting factor (Glass, 2003). Despite the important role of nitrogen in crop production, its use in improving crop production whilst at the same time guarding against contamination of the biosphere should be treated with caution (Hirel et al, 2007). This is against the background that fertilisers that contain significant amounts of ammonium (NH_4^+) and amine ($R\text{-}NH_2$ or $C\text{-}NH_2$) have more chances of inducing acidity to the soil (Cassman, 1999). Thus, the study sought to explore the interactive effect of varying lime and nitrogen rates in the early growth of maize grown in acidic sandy soils.

4.3 Materials and Methods

4.3.1 Field Study Site:

The two- year study was conducted in Masvingo Province in two experimental own-farm field trials. The sites are located in Masvingo District The soil organic matter content of the two sites were 2.89% and 3% respectively, determined using the dry ignition /weight loss method. Two sites were used so that one would act as a backup in the event of any negative eventualities. The type of soil at both experimental sites were loam soils of pH 4.6 and 5.1. The sites are located in an area that experiences distinct cold winters and hot summers with a minimum temperature of 5°C and maximum temperature of 29°C.

4.3.2 Treatments

The study was conducted in field experiments which were done in two consecutive agricultural summer seasons 1 and 2. Soils were first of all tested in the laboratory for pH status, organic matter content and textural class. Maize seed was sown in rows after thorough land preparation which included digging to 25 to 30 cm depth, lime application 5 weeks prior to planting and marking of main plots, sub-plots and sub-sub/net plots. Inter-row spacing was 750mm whilst in-row spacing was 250mm. The summer maize was largely grown under irrigation, although natural rains supplemented the crop's water requirements. There were 9 treatments. Treatment 1 (T_1) acted as the control as no lime and top dressing fertiliser was used whilst the rest of the 8 treatments had three varying levels of lime and nitrogen application regimes (see table 1 for treatment combinations). Lime was applied through broadcasting after partitioning the plots into homogenous units for even distribution of lime with three replicates.

Nitrogen was applied four weeks after crop emergence in the form of ammonium nitrate ($NH_4^+N0_3^-$) through the hill placement method excluding the control plots.

4.3.3 Table 4: Varying lime and nitrogen treatment combinations for season 1(2018/2019) and Season 2 (2019/2020

Treatment	**Independent Variables**							
Rep 1	**Lime t ha^{-1}**	**N t ha^{-1}**	**Rep 2**	**Lime t ha^{-1}**	**N t ha^{-1}**	**Rep 3**	**Lime t ha^{-1}**	**N t ha^{-1}**
T_1	0	0	T_5	1.5	0.2	T_9	3.0	0.4
T_2	0	0.2	T_8	3.0	0.2	T_4	1.5	0
T_3	0	0.4	T_2	0	0.2	T_6	1.5	0.4
T_4	1.5	0	T_1	0	0	T_7	3.0	0
T_5	1.5	0.2	T_3	0	0.4	T_5	1.5	0.2
T_6	1.5	0.4	T_6	1.5	0.4	T_2	0	0.2
T_7	3.0	0	T_7	3.0	0	T_8	3.0	0.2
T_8	3.0	0.2	T_9	3.0	0.4	T_3	0	0.4
T_9	3.0	0.4	T_4	1.5	0	T_1	0	0

4.3.4 Measurement of aboveground and belowground parameters of maize

Aboveground (vegetative) and belowground (root) growth parameters were measured for a period of six weeks after crop emergence to determine variability due to different lime and nitrogen application rates. Aboveground maize growth parameters were determined by measuring plant biomass, Leaf Area Index (LAI) and Leaf Length (LL) on a weekly basis for six weeks. Plant Biomass was determined by oven drying the aboveground plant organs 70°C for 72 hours until a constant weight was achieved from the control plot and eight treatment plots. The plant samples were collected from the sub-sub/net plots excluding boarder row plants which were affected by the boarder effect. This is termed the Net assimilation Rate (NAR) as it considers increase in plant biomass divided by the leaf area as shown below.

$$\text{NAR} = \frac{\text{Increase in plant biomass unit time}}{\text{Leaf Area (LA)}}$$

In order to complement the weaknesses of growth determination through biomass increment, the study, alongside the above method, used the Leaf Area Index (LAI) method. This was done by a destructive method through cutting off all the leaves of the sampled plants and dividing their LA by ground area per unit time.

$\text{LAI} = \frac{\text{LA}}{\text{GA}}(\text{time})$ (*adapted from Larckom and Miller, 1994)*

Where: LAI is Leaf Area Index
LA is Leaf Area
GA is Ground Area

Belowground (root) biomass and depth/length were also measured weekly for 6 weeks from one week, post emergence. This involved a careful excavation of the root system after irrigating the plants to field capacity in order to remove all the roots. The plants were washed thoroughly using tap water to remove soil. Root depth /length was achieved by measuring the length of central roots using a 30cm ruler. Route diameter was measured using a micro-meter screw gauge at the same time starting from the last internode. Root biomass was done following the aboveground biomass oven drying procedure as prescribed by Masaka (2005).

4.4 Results

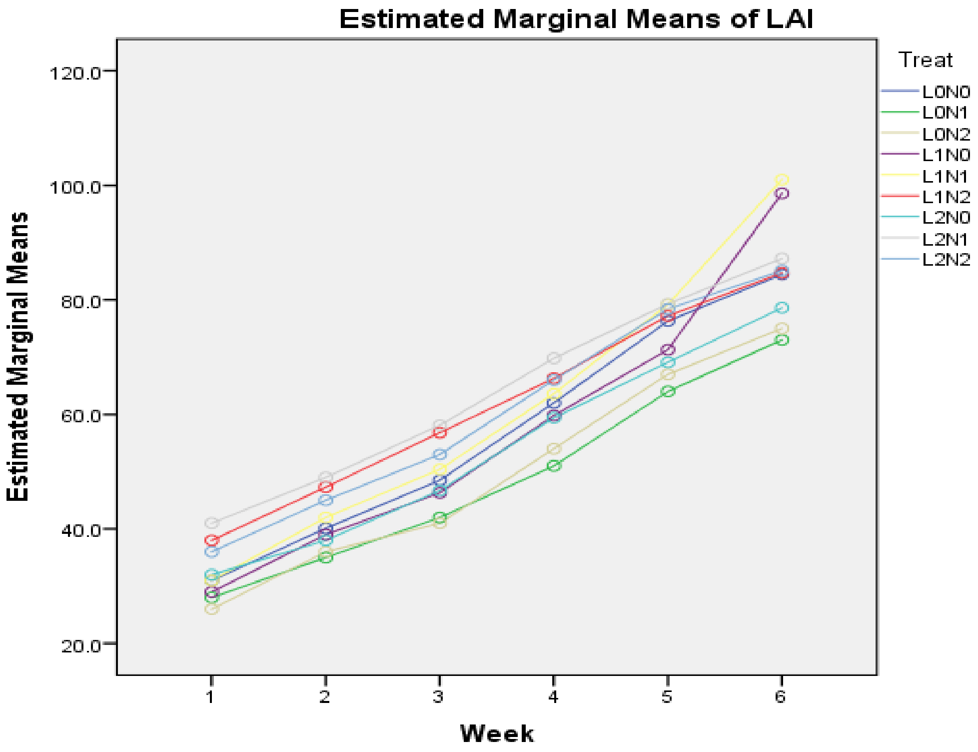
4.5 Leaf Area Index (LAI)

Leaf Area Index was measured for a period of six weeks from the nine different treatment combinations of dolomitic lime and ammonium nitrate fertilizer. The treatment combinations were L0N0 (zero lime and zero nitrogen), L0N1 (No lime application and 0.2t ha^{-1}N) , L0N2 (no lime and 0.4kgs ha^{-1}N), L1N0, L1N1, L1N2, L2N0, L2N1 as well as L2N2. From the three sampled plants evaluated for Leaf Area Index, the highest mean score was recorded in treatment L2N1 (2t ha^{-1}L) versus 0.2t ha^{-1}N) at the end of the six week period. The Significant increase in Leaf Area Index following optimum levels of dolomitic lime and a moderate nitrogen application regime. This resonates well with the utterances by Hussein (1997) when she says that raising soil pH through liming increases P and Mo availability as well as increasing percentage base saturation. The bases include Mg which is an essential element in chlorophyll formation, thus increasing solar energy interception as shown by results in table 5 and line graph below..

4.5.1 Table: 5 Descriptive Statistics for Leaf Are Index

Dependent Variable: LAI

Treat	Week	Mean	Std. Deviation	N
Total	1	32.444	4.9272	9
	2	41.267	4.9353	9
	3	49.200	5.9904	9
	4	61.322	6.0245	9
	5	73.533	5.7918	9
	6	85.294	9.5550	9
	Total	57.177	19.4253	54



4.5.2 Figure 1: Estimated Marginal Means for Leaf Area Index

Generally, statistical methods are not a guarantee that a factor has an effect but instead, provides a fertile ground from which reliable and valid conclusions and recommendations can be inferred. These results suggest that, minimum levels of both nitrogen and lime rates are essential but, for optimum net assimilation rate (NAR) which signifies growth rate, a lime rate of 3t ha^{-1} L against a nitrogen rate 0.2t ha^{-1} N gives the best results in relation to both root and aboveground biomass accumulation as a parameter of growth rate. Going beyond the lime rate of 3.0t ha^{-1} L against a nitrogen application rate of 0.4t ha^{-1}N, obeys Liebig-Mitsherlich (1909) model as postulated by Rubio (2003). This could be linked to the preferential nutrient uptake phenomenon where the plant takes up certain nutrients at the neglect of trace elements like boron and zinc. The study revealed that, an interactive effect of lime and nitrogen in growth of maize, yields positive results as was confirmed by post hoc statistical tests such as the Turkey's HSD Test and the Bonferroni Test when the study was assigned an Alpha error ($\propto$ = 0.05%) or 95% C.I. When all lime and nitrogen rates were considered for the growth parameter, the optimum aboveground and belowground biomass accumulation was realised at 3.0t ha^{-1} L and 0.2t ha^{-}

^{1} N and declined when 3.0t ha^{-1} L and 0.4t ha^{-1} N were applied due to induced trace elements deficiency as corroborated by Miller et al, (1994) and Fageria et al (n.d).

In both season, 1 (2018/2019) and Season 2 (2019/2020), treatment 2 (T_2) had no effect on root length thereby implying a higher treatment that would result in significant root length. The sample mean (μ) for root biomass for season 1 ranged from 37.3g for T_1 to 39.3g for T_8. The coefficient of variation (C.V.) for root biomass for season 1 and 2 were computed thus:

C.V = $\frac{SD}{\mu} \times 100 \left(\frac{6.0024}{39.519} X\ 100\right)$ C.V = $\frac{SD}{\mu} \times 100 \left(\frac{4.7824}{40.556} X\ 100\right)$

= 15.18% Season **1 (2018/2019)** = 11.79% Season **2 (2019/2020)**

The summative coefficient of variation (C.V.) for Leaf Area Index for season 1 and 2 were also computed thus:

C.V = $\frac{SD}{\mu} \times 100 \left(\frac{9.5550}{85.294} X\ 100\right)$

= 11.20% Season1 and 2 **(2018/2019 and 2019/2020)**

Hence the C.V. of field crops such as maize, soy bean, wheat and cotton, among others, should not exceed 15. The results of root biomass and aboveground biomass were both ≤ 15 thus, making the outcomes valid and reliable as also confirmed by the Turkey's HSD Test and the Bonferroni Test.

T_8 and T_9 recorded the highest root biomass. Treatment 2 (T_2) and T_3 results showed no /little relationship between nitrogen and root development as there was a greater plant height and LAI as well as kernel yield with no lime application but increasing plant susceptibility to lodging.

Treatment L1N2 and L2N1 had large LAI with L2N1 recording a mean of 64.1 over a period of six weeks. The two treatments were therefore effective in solar radiation interception or harvesting.

4.6 Plant Height

During the sixth week of height measurement, treatments L1N1, L2N1 and L2N2 recorded the highest plant heights of ≥ 100cm. Although the eventual maize plant height averaged 205cm, the most favourable lime and nitrogen treatment combinations emerged as L2N1 (3t ha^{-1}L and 0.2t ha^{-1}N). Thereafter, L2N1 3t ha^{-1}L and 0.4t ha^{-1}N revealed the maximum plant height and it is at this height that the plateau growth pattern postulated by Rubio (2003) was noted. The L2N1 treatment combination showed a significant lime and nitrogen interaction in influencing plant height. In the L0N0 (control plot) maize plant height at the same sixth week terminal period of height measurement, height was > 85cm. Plant height influences plant dry weight (biomass) accumulation and the overall solar radiation interception which has a bearing on 1000 seed weight (harvestable index). Also, where premature harvesting of maize for silage as a biological yield is critical, height of crops matters most. As indicated below in tables 6a and 6b, and further referenced through figures 2 and 3 for different treatment combinations and maize response to top dressing over a six week duration, respectively. Results of this parameter were confirmed satisfactory by two statistical post hoc diagnostic tests such as the Turkey's HSD Test and the Levene's Test of Equality of Error Variances.

4.6.1 Table 6a: Estimated Marginal Means for Plant Height Treatment Combinations

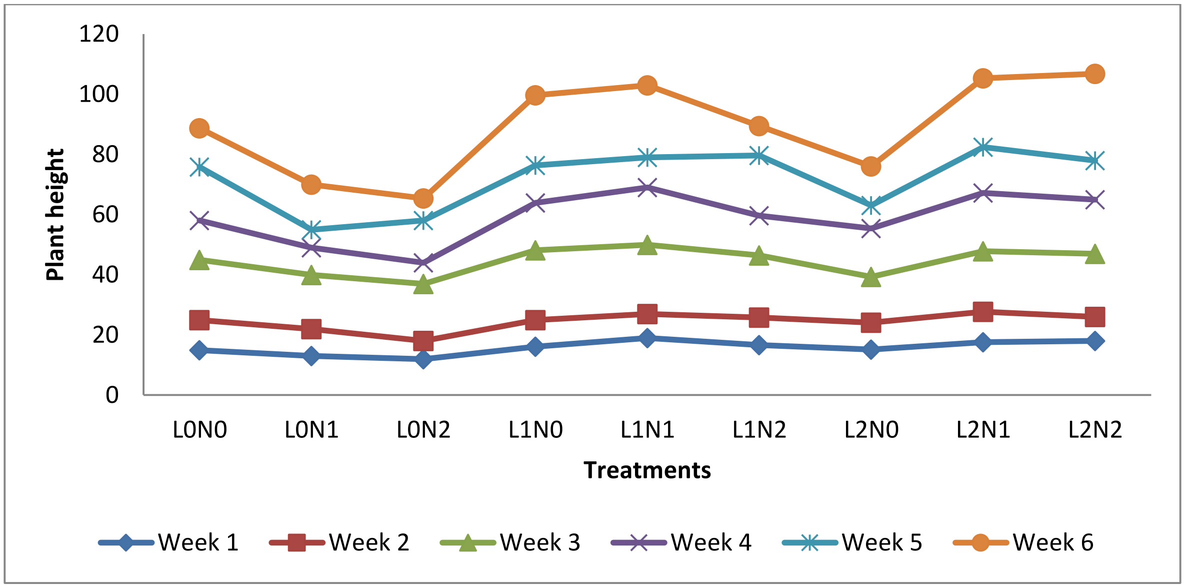
Dependent Variable: Plant Height

Treat	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
L0N0	51.250	2.248	46.707	55.793
L0N1	41.500	2.248	36.957	46.043
L0N2	39.067	2.248	34.523	43.610
L1N0	54.883	2.248	50.340	59.427
L1N1	57.833	2.248	53.290	62.377
L1N2	52.917	2.248	48.373	57.460
L2N0	45.500	2.248	40.957	50.043
L2N1	58.000	2.248	53.457	62.543
L2N2	56.800	2.248	52.257	61.343

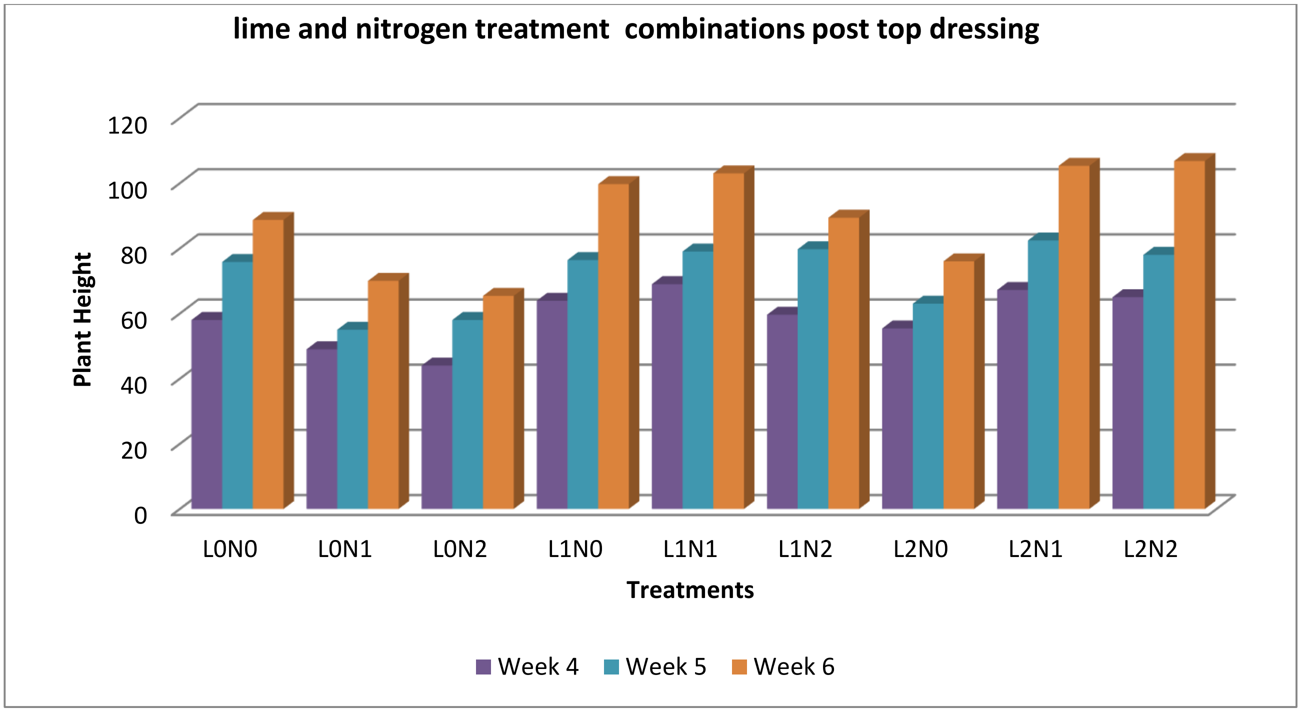
4.6.2 Table 6b for weekly Interval Height Measurement

Dependent Variable: Plant Height

Week	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	15.833	1.836	12.124	19.543
2	24.511	1.836	20.801	28.221
3	44.522	1.836	40.813	48.232
4	59.011	1.836	55.301	62.721
5	71.922	1.836	68.213	75.632
6	89.367	1.836	85.657	93.076



4.6.3 Figure 2: Different lime and nitrogen treatment combinations over a six week period



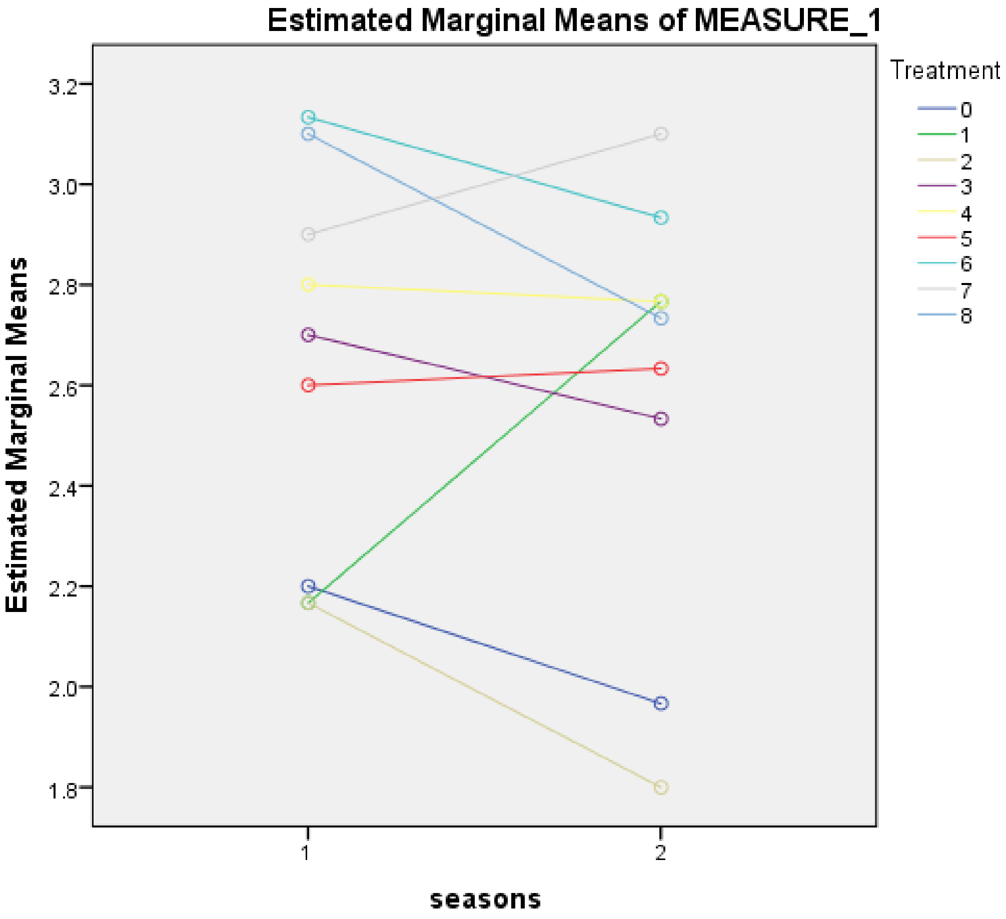
4.6.4 Figure 3: Interactive effect of lime and nitrogen treatment combinations post top dressing (Nitrogen treatment)

4.7 Root Diameter

As with root diameter, only the control, L0N0 and the two treatments L0N1 and L2N1 had significant effects in influencing root diameter. This is most likely to have been influenced by optimal soil -lime chemical reaction over seasons as opposed to one growing season. That was confirmed by the post hoc Levene's Test of Equality of Error Variances and Huynh-Feldt Test among others.

4.7.1 Table 7 Descriptive Statistics for Root Diameter

	Treatment	Mean	Std. Deviation	N
Root Diameter 1	0	2.200	.1732	3
	1	2.167	.3215	3
	2	2.167	.1528	3
	3	2.700	.6083	3
	4	2.800	.2000	3
	5	2.600	.3606	3
	6	3.133	.3786	3
	7	2.900	.3606	3
	8	3.100	.1000	3
	Total	2.641	.4618	27
Root Diameter 2	0	1.967	.1528	3
	1	2.767	.2082	3
	2	1.800	.2000	3
	3	2.533	.0577	3
	4	2.767	.3055	3
	5	2.633	.5686	3
	6	2.933	.3055	3
	7	3.100	.1000	3
	8	2.733	.1528	3
	Total	2.581	.4699	27

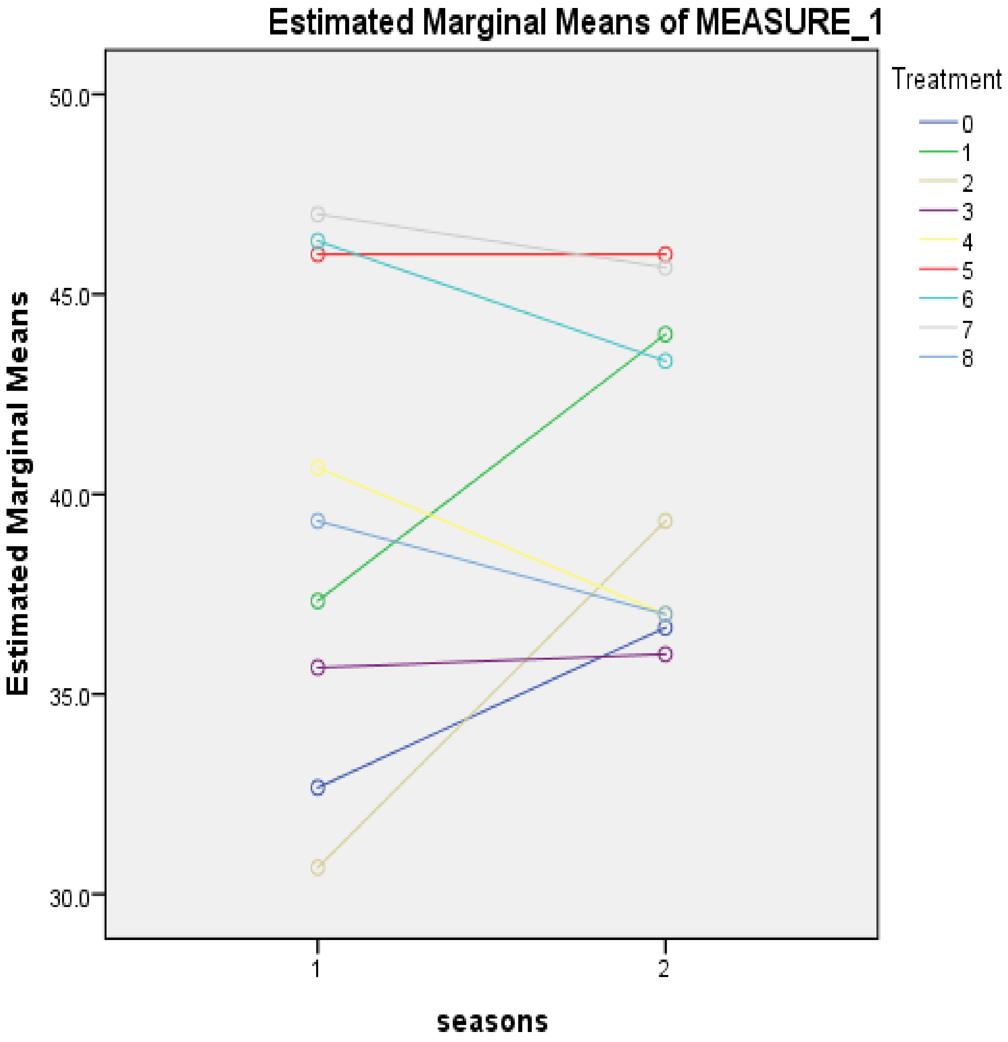


4.7.3 Figure 4: Estimated Marginal Means for Root Diameter for Seasons 1 and 2

Tables 6a, 6b and 7 show the effect of lime and nitrogen interaction on early growth stages of aboveground and belowground maize growth parameters. Results indicate that there was a distinct pattern of treatment combination effect on both aboveground and belowground biomass and length of maize organs.

4.8 Discussion

Both above and below ground biomass are critical as they determine the crop's biological yield which influences the economic yield. This is very critical because in this case, the kernel or thousand seed weight is only a proportion of the biological yield as corroborated by Larkcom and Miller (1994). Season 2 recorded a slightly higher biomass and root depth as well as leaf length. The difference could be attributed to the residual effects of lime whose effects can go up to 20 years with continuous cropping and liming (Lukin and Epplin, 2002).



4.8.1 Figure 5: Estimated Marginal Means for Root Biomass

Treatment 2 (T_2) and treatment 3 (T_3) results showed no or little relationship between nitrogen and root development as there was a greater plant height and LAI as well as kernel yield with no lime application but increasing plant susceptibility to lodging hence the findings of the study resonates with the (Matsubara et al, 2011; Mooney et al, 2012; and Robbins and Dinney, 2015) studies which postulate that shallow roots are effective in scavenging for nutrients. Generally, the usual growth pattern of slow growth rate at first growth phase of one to two weeks, attaining an exponential (rapid) growth phase and eventually assuming a plateau was realised. The sigmoid flexure or **S** shape was the resultant pattern across all treatment regardless of variations in lime and nitrogen treatment combinations.

The study made use of the relative growth rate as compared to the absolute growth rate. The former is a much better indicator or method of growth rate determination as it is capable of comparing different sized plants at different growth stages under varied conditions in different environments (Larkcom and Miller, 1994). The latter, absolute growth rate which refers to the mean increase in plant biomass per unit time measured by sampling plants from a given population at timed periodic intervals is considered for computing plant biomass per unit time.

Despite variability in relation to lime and nitrogen treatments, all treatments including the control showed an increase in LAI with stage of maize growth particularly during weeks 4 to 6 of the exponential growth phase. This growth pattern following the uptake of primary elements, namely N, P and K in plant biomass was consistent with the findings by (Masaka, 2005, and Ellen and Spiertz, 1990). This study attributed the exponential growth to rapid stem elongation towards and during silking and anthesis in the tropics. Results of this study show that liming and nitrogen combinations of 3.0t ha^{-1} lime and 0.2t ha^{-1} nitrogen have significant effect on aboveground and belowground maize biomass.

4.9 Conclusions

Results of different lime and nitrogen combinations had a significant effect on root biomass and an insignificant effect on root length. Averaged across the entire lime and nitrogen treatment combinations, the highest aboveground biomass of 87.3g for L2N1 (3t ha^{-1}) Lime (L) and 0.2t ha^{-1}) Nitrogen (N) was obtained. Increasing nitrogen rates whilst holding lime rate constant at 3.0t ha^{-1} (L2N2) led to a decrease in aboveground biomass following a reduction in net assimilation rate (NAR). These results suggest that minimum levels of both nitrogen and lime rates of 1.5t ha^{-1} (L) and 0.2t ha^{-1} (N) are essential for optimum NAR which boosts growth rate, a lime rate of 3t ha^{-1} against a nitrogen rate of 0.2t ha^{-1} (N) give the best biomass accumulation as a parameter of growth rate. Sandy textured soils are prone to leaching of mobile N hence require high application rates coupled with increased lime rates as well. The vegetative stage of maize growth is associated with higher nitrogen uptake and assimilation rates. Optimum lime and nitrogen combinations result in development of brace or pop roots, adventitious and dense root hairs improving maize abiotic stress tolerance.

REFERENCES

Cassman, K.G. (1999). Ecological Intensification of Cereal Production Systems: Yield Potential, Soil Quality and Precision Agriculture. *Proceedings of the National Academy of Sciences of the United States of America* **96**

Davies, D.B., Vaidyanathan, L.V., Rule, J.S. and Jarris, R.H. (1979) Effect of Sowing Date and Timing and Level of Nitrogen Application to Direct Drilled Winter Wheat. Exp. Husb.**35**

Ellen, J. and Spiertz, J.H.J. (1980). Effect of Rate and Timing of Nitrogen Dressings on Green Yield Formation of Winter Wheat. Fert. Research1

Fageria, N.L., Zimmermann, F.J.P. and Baligar, V.C., (n.d). Lime and Phosphorous Interactions in Wheat, Common Bean and Corn in an Oxisol. *Journal of Plant Nutrition, Vol.18*

FAO/UNESCO (1998). World Reference Base for Soil Resources (http://en.FAOSoilclassification).

FAO/UNESCO (2015) Statistical Database for the Food and Agriculture Organisation of the United Nations: *http://www.fao.org*.

Friesen, D.K., Juo, A.S. and Miller, M.H., (1980). Lime and Lime – Phosphorous- Zinc Interactions in Soil. *Soil Science Society of America Journal: Vol. 44No.6*

Glass, A.D.M. (2003). Nitrogen Use Efficiency of Crop Plants: Physiological Constraints Upon Nitrogen Absorption. *Critical Reviews in Plant Sciences**22***

Gomez, K.A. and Gomez, A.A (1984) Statistical Procedures for Agriculture Research. 2nd ed. New York: John Willey and Sons

Hirel, B., Le Gouis, J., Ney, B.and Gallais, A. (2007). The Challenge of Improving Nitrogen Use Efficiency in Crop Plants: Towards a more Central Role for Genetic Variability and Quantitative Genetics within Integrated Approaches. *Journal of Experimental Botany* **58**

Larkcom, E., and Miller, R (1994). Food Production: Biology – Advanced Studies, Nelson and Sons Ltd, United Kingdom

Liebig, J.V. and Mitscherlich, E.A. (1909). Die Grundsatze der Agricultur-Chemie mit Rucksicht auf die in England angestellten Untersuchxhungen. Fredrick V ieweg and Sohn, Braunschweig, Germany.

Lukin, V.V and Epplin, F.M. (2002). Frequency and Quantity of Agricultural Lime Applications. Department of Agriculture Economics. Oklahoma State University.

Masaka, J. (2005). The Effect of Nitrogen Fertilizer Placement and Timing on the Uptake of Nitrogen, Phosphorous and Potassium by Spring Wheat (Tritcum Aestivum L. Cv. Spectrum) at Different Phenolog. *Journal of Agronomy*

Montgomery, D.C. (2013) Design and Analysis of Experiments 8thed.New York, Willay and Sons

Nyamangara, J and Mpofu, S.E (1996). Soil pH and Requirement for high Potential Communal Areas of Zimbabwe. Journal of Applied Science in Southern Africa. Vol. 2 No.2

Manjeru, P. (2017) The Influence of Abiotic Stress on CIMMYT Provitamin A Elite Maize Germplasm. (Doctoral Thesis University of the Free State, South Africa.

Nyamasoka, B., Nyamugafata, P., Madyiwa, S., and Nyamangara, J. (2014). Urban Farmer Practices in Soil Fertility and Water Management and the Influence of Gender in Harare and Chitungwiza, Zimbabwe. African Journal of Agriculture Journal Research.

Opala, P.A. (2017). Influence of Lime and Phosphorous Application Rates on Growth of Maize. Advances in Agriculture. Department of Soil Science, Maseno University, Kenya

Robbins, N.E and Dinney, J.R (2015). The Divining Root: Moisture –driven Responses of Roots at the Micro-and Marcro- Scale. Journal of Experimental Botany.

Rubio, G., Zhu, J and Lynch, J.P (2003). A critical GTest of the Two Revealing Theories of Plant Response to Nutrient Availability. America Journal of Botany 90 (1)

Zahir, S. (2014). Role of Nitrogen Fertilizer in Crop Productivity and Environmental Pollution. Turkish Journal of Agriculture and Forestry. Research Gate

CHAPTER FIVE

5.0 EFFECT OF LIME AND NITROGEN INTERACTION ON MAIZE (*Zea mays L)* YIELD PARAMETERS

5.1 Abstract

The yield of maize (Zea mays L) is governed by several factors which can either be climatic, economic or soil oriented. Top dressing nitrogen based fertilisers have dual effects that can be both positive and detrimental. They increase the productivity of crops through enhanced crop growth and production while, at the same time, inducing a decline in soil pH. The study was conducted to determine the best lime and nitrogen combinations that guarantee optimal maize yields at the same time preventing nitrate induced soil acidity. Data was gathered from field experimental trials of the 2018 to 2019 and 2019 to 2020 agricultural seasons. A maize (Zea mays L) kernel yield response and pH functions were evaluated and estimated in order to determine optimal lime and nitrogen fertiliser treatment combinations in sandy textured soils, under irrigation conditions. The optimum application rates of lime and nitrogen were realised for maize under sandy textured soils without compromising soil pH. The study adopted a split plot experimental design with two factors namely dolomitic lime (Calcium-magnesium carbonate) interacting with ammonium nitrate fertilizer with three levels of both dolomitic lime and ammonium nitrate fertilizer replicated three times thus the three levels, three replicates and two factors resulted in a 2x3x3 factorial set up within a split plot design. Results of the field trial revealed a very significant effect of dolomitic lime and nitrogen fertilizer interaction in boosting yield parameters of maize namely thousand seed weight, cob length, cob girth and shelling percentage all whose p-value was ($p < 0.03$) in all the three parameters evaluated.

Keywords: Dolomitic Lime, Soil pH, maize, Optimal, Yield

5.2 Introduction

For almost five decades, Zimbabwe experienced vast phases in the production of the staple maize crop (Food and Agriculture Organisation, 2015). In the 1986/1987 Agricultural season, Zimbabwe recorded a peak in maize production of 2.229.000 metric tonnes which made her food secure for both livestock and humans. This is contrary to the only 360 000 tonnes recorded in the 1991/1992 agricultural season and other later years. The decline in maize yield was partly due to climatic conditions, land reform and notably soil fertility or pH decline. Top dressing nitrogen containing fertilizers in monocropping cereal crop production increases H+ ion concentration in the soil. Tumusiine et al (2010) identify three primary factors that lead to a decline in soil pH. These include the removal of bases like Mg^{2+} and Ca^{2+} during harvesting of crop plants. Secondly, the application of nitrogen rich fertilisers such as those of the ammonium ((NH^+_4) and amine (R-NH_2 OR C-NH_2) group and the eventual nitrification transformation process yield hydrogen ions (H^+).Aluminium is also implicated in the soil pH decline (Tabitha et al, 2008, Cassman, 1999). The other cause of soil pH decline emanates from residual nitrates (NO^-_3) that remain from those taken up by crop plants. The high solubility of nitrates causes them to be leached from the rhizosphere to deeper soil horizons. These illuviation and eluviation processes carry with them basic cations, notably Ca and Mg. This leaching of bases as well as crop uptake confers the amphoteric nature of arable soils. Thus at one point, arable soils can be basic and at times acidic.

Back then, acid soils in arable lands in Zimbabwe communal areas used not to be a problem owing to the widespread use of organic animal manures in maize production. Though maize is considered as tolerant to acid soils, for optimum yields, chronic and ultra-acidity will reduce maize growth and potential optimal yield. Tembo et al (2008) and Tumuisiime et al (2010) conducted studies using data from long experiments using wheat and Rye grass and found that, other than causing yield reduction due to pH decline, the profit margin is also reduced. This study sought to determine the optimal lime and nitrogen rates in boosting maize production without compromising input cost and soil pH through lime and nitrogen interactions under irrigation conditions.

5.3 Materials and Methods

5.3.1 Experimental site characterisation

A two year field experiment was conducted on two own-farm field trials in Masvingo District in Zimbabwe. Zimbabwe is located is Sub- Saharan Africa with a geographical position that lies between latitudes 15° and 22 ° S and longitudes 26° and 34° E (FAO sub- Regional Office for East and Southern Africa, 2000). Basing on precipitation intensity and Agricultural productivity, Masvingo, which was the study site, is located in Agro-Ecological zone 5 (Mugandani et al, 2012). The study site altitude is

1.075m above sea level and latitude -21.446815 and longitude 31.838409 (Central Statistical Digest, 2013). The type of soil at the experimental site are sandy loam soils grouped as Fersiallitic Luvisols of the G6 classification category derived from granites and gneissic granites (Hussein et al, 1992 and Nyamapfene, 1991). Experimental sites were coded as Marapira site and Victoria High School site, both with initial acidic soils of $pH_{cacl} \leq 5.1$

5.3.2 Experimental Design and Routine Agronomic Practices

The yellow or orange maize genotype SC402 was planted in the early summer seasons of 2018/2019 and 2019/2020. That was done to allow the maize crop to acquire more heat units. The crop was sown at a seeding rate of 20kg/ha at an inter row spacing of 750mm and in row spacing of 250mm to give a plant population of 53333 plants per hectare. A Split- plot design (SPD) with three replicate ions per treatment was put into effect. In an SPD, a third factor is included. Similarly, this study employed three factors viz lime, nitrogen and irrigation factor in order to satisfy the experimental dictates of the SPD.

Levels of the sub plots are as well assigned the sub-sub plots to the sub-sub plots or net plots. Three treatment levels of lime and nitrogen were administered in the ratios 0, 1.5 and 3.0t $ha^{-1}L$ and 0, 0.2 and 0.4t $ha^{-1}N$ respectively. Dolomitic lime ($CaMg(CO_3)_2$ with an SNV /CCE of 95-109 was applied 5 weeks prior to planting and incorporated into the soil to the 25-30cm conventional ploughing depth followed by light irrigation to allow soil lime chemical reaction to partake. Nitrogen was applied in the form of ammonium nitrate (34.5%N) ($NH_4N_3^-$) during week four through the hill placement method $^{\pm}$5cm away from each maize plant. Top dressing using ammonium nitrate was done 24 hours after irrigating the soil to field capacity to allow quick dissolution of nitrate ions thus, reducing losses through volatilization.

The pH of the top soil was evaluated twice during each growing season. It was measured at the beginning and post harvesting of the experimental maize crop. Soil pH determination was done in a 1:2 soil/distilled water solution using a digital pH meter .Variations in soil pH for lime – nitrogen treated plots and control plots were taken as shown in Table 8 below.

5.3.3 Table 8 Soil pH Change and Yield Variability Due to Lime and Nitrogen Interaction

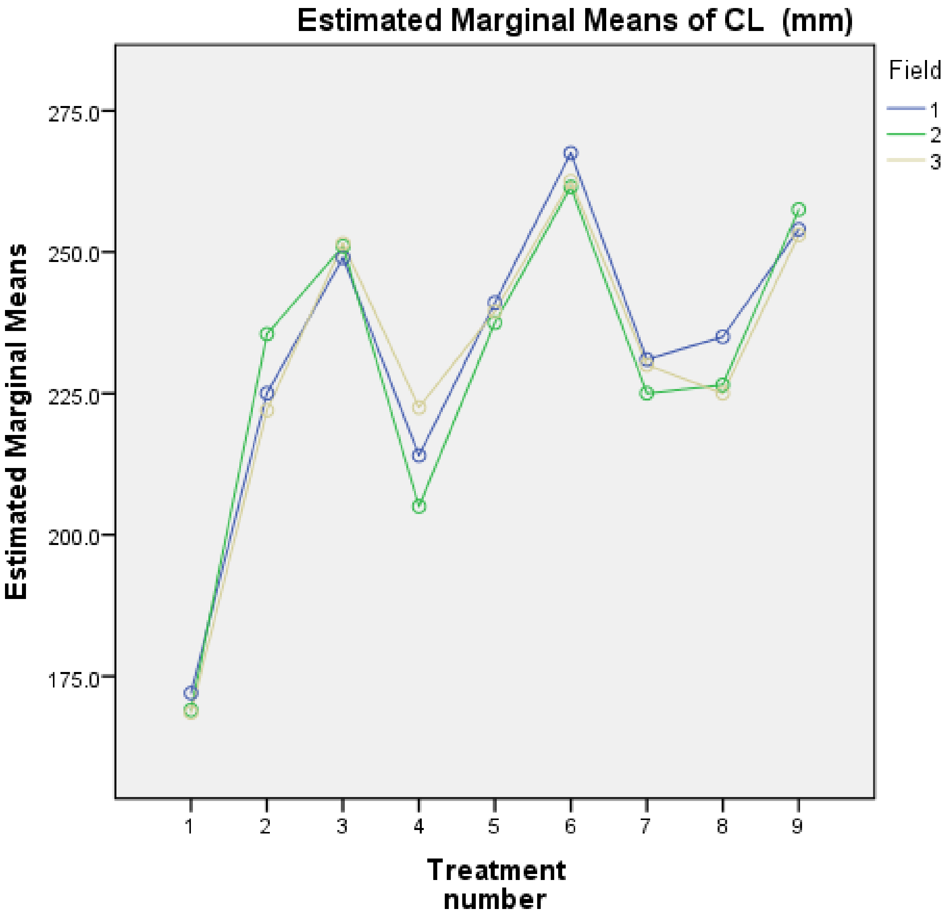
Treatment Number	**Lime Rate (LR) t ha^{-1}**	**Nitrogen Rate (NR) t ha^{-1}**	**Shelling %**	**Net Plot Yield (NPY) 1000 seed weight (g)**	**Mean Cob Length (MCL) Mm**	**Mean Cob Girth /diameter (MCG/D)Mm**	**Bare Tips (BT)**	**DDR %**	**pH DEV**
1	**0**	**0**	**84.6**	**434**	**175**	**150**	**P**	**6.9**	**0.2**
2	**0**	**0.2**	**83.7**	**454**	**230**	**158**	**P**	**6.7**	**0.6**
3	**0**	**0.4**	**81.9**	**471**	**250**	**160**	**P**	**6.6**	**0.42**
4	**1.5**	**0**	**84.1**	**360**	**210**	**158**	**N**	**6.8**	**0.48**
5	**1.5**	**0.2**	**85.1**	**585**	**240**	**170**	**N**	**5.8**	**0.65**
6	**1.5**	**0.4**	**78**	**669**	**265**	**160**	**N**	**5.6**	**0.7**
7	**3**	**0**	**91.3**	**432**	**230**	**150**	**N**	**6.6**	**0.5**
8	**3**	**0.2**	**77.8**	**663**	**230**	**175**	**N**	**6.2**	**0.4**
9	**3**	**0.4**	**79.9**	**562**	**255**	**160**	**N**	**5.5**	**0.5**

5.4 Results

5.5 Cob Length (CL)

5.5.1 Table 9: Dependent Variable: CL (mm)

Treatment Number	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	169.833	2.317	165.158	174.508
2	227.500	2.317	222.825	232.175
3	250.500	2.317	245.825	255.175
4	213.833	2.317	209.158	218.508
5	239.333	2.317	234.658	244.008
6	263.833	2.317	259.158	268.508
7	228.667	2.317	223.992	233.342
8	228.833	2.317	224.158	233.508
9	254.833	2.317	250.158	259.508



5.5.2 Figure 6: Estimated Marginal Means for Cob Length

The control/check (T_0) has an SED of 2.313 and a μ (mean) of 169.833: the C.V. for the check/ control was calculates as:

$$C.V = \frac{SED}{\mu} \times 100 = \left(\frac{2.317}{169.833}\ X\ 100\right)$$

= 1.36% (C.V) for control plot cob length

Treatment 5 (T_5 with 1.5t ha^{-1} L and 0.4t ha^{-1} N) recorded the highest μ (mean) cob length of 263mm with a C.V. of :

$$C.V = \frac{SED}{\mu} \times 100 = \left(\frac{2.317}{263}\ X\ 100\right)$$

= 0.88% (C.V) for treatment 5

Treatment 3(T_3 with 0t ha^{-1} L and 0.4t ha^{-1} N) decreased following a treatment combination of no lime and 0.4t ha^{-1} N giving a cob length C.V. of:

$$\text{C.V} = \frac{SED}{\mu} \times 100 = \left(\frac{2.317}{213.833}\ X\ 100\right)$$

= 1.08% (C.V) for treatment 3(T_3)

Treatments6 and 8 (T_6 and T_8)with 3.0t ha^{-1} L and 0t ha^{-1} N and 3.0t ha^{-1} L and 0.4t ha^{-1} N were similar in terms of mean cob length hence, had the same C.V. of :

$$\text{C.V} = \frac{SED}{\mu} \times 100 = \left(\frac{2.317}{228.667}\ X\ 100\right)$$

= 1.0% (C.V) for treatments 6 and 8 (T_6 and T_8).

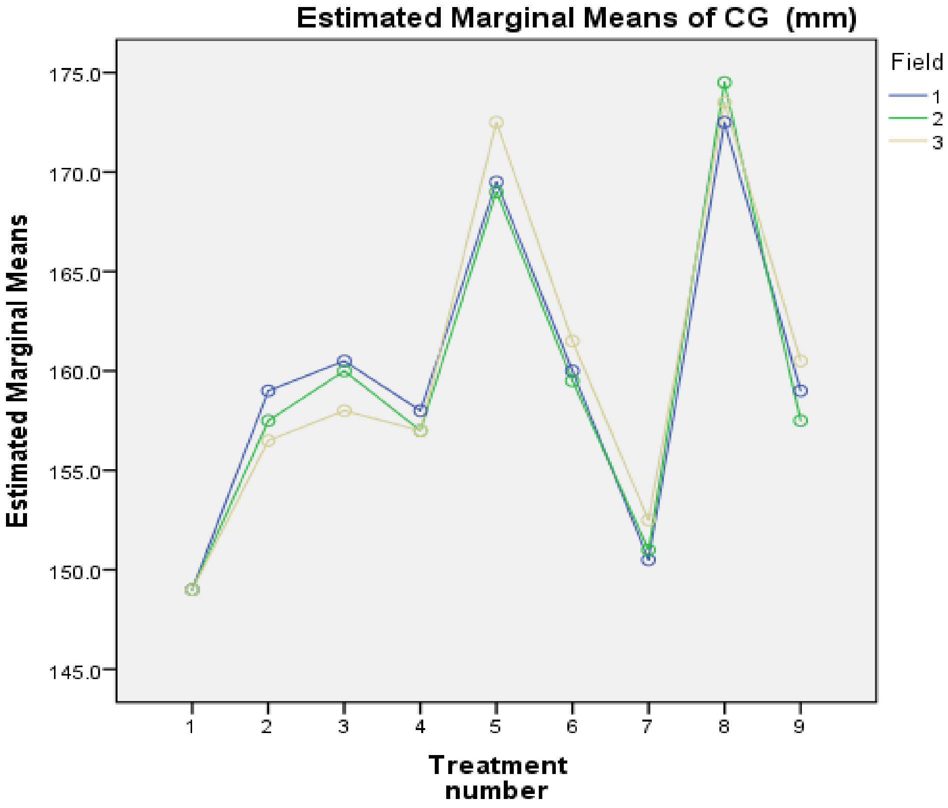
It is at this level that the optimum level for cob length (LRP) model of von Liebig and Mitschelirch-Baule is realised. There was a linear association between kernel size, cob size, number of rows with cob length and cob girth. Increased cob length and reduced cob girth gave rise to an increase in kernel size and reduction in number of rows per cob from a μ (mean) of 12 rows to 10 and 8.

Treatment 5 (T_5 with 1.5t ha^{-1} L and 0.4t ha^{-1} N) had 14 rows per cob and Treatments6 (T_6 3.0t ha^{-1} L and 0t ha^{-1} N) had 16 rows. Therefore, the number of cob rows increased with an increase in lime rates thus increasing both shelling percentage and Net Plot Yield (NPY). It is therefore, apparent that cob length (CB) is a function of nitrogen treatment and not lime application. However, increased lime rates with no nitrogen, increased cob girth (CG) and number of rows. Increase in cob girth with lime application, increased the shelling percentage. For Net Plot Yield (NPY) on the contrary, increased nitrogen rates reduced the drying down rate percentage (DDR %) known as delayed senescence. This increased thousand seed weight through prolonged translocation of photo assimilates from the source (Foliage) to the sink (Cob or grain), particularly in season 2.

5.6 Cob Girth (CG)

5.6.1 Table 10: Dependent Variable: CG (mm)

Treatment Number	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	149.000	.753	147.480	150.520
2	157.667	.753	156.146	159.187
3	159.500	.753	157.980	161.020
4	157.333	.753	155.813	158.854
5	170.333	.753	168.813	171.854
6	160.333	.753	158.813	161.854
7	151.333	.753	149.813	152.854
8	173.500	.753	171.980	175.020
9	159.000	.753	157.480	160.520

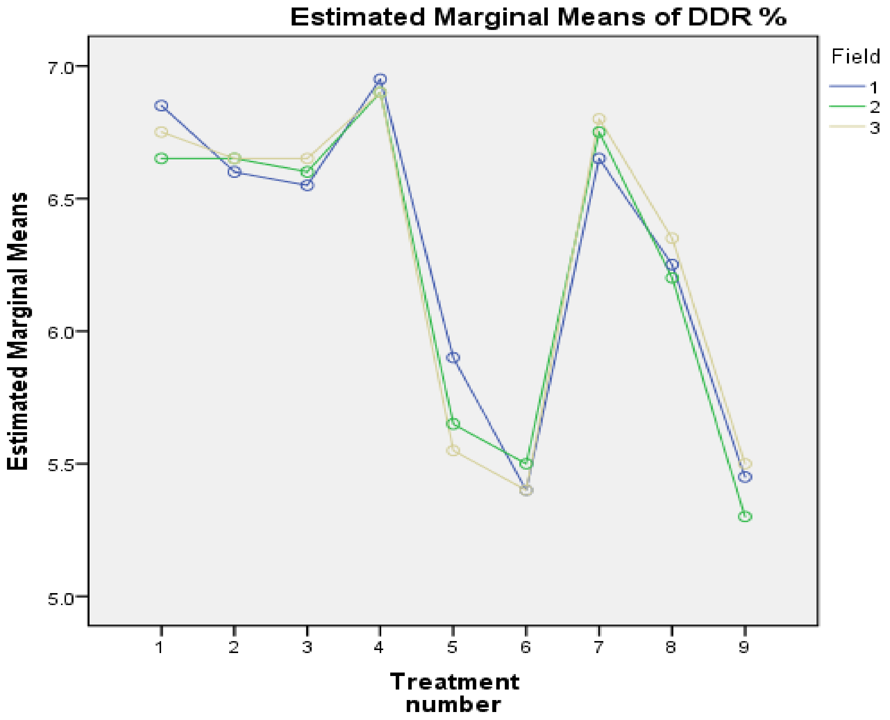


5.6.2 Figure 7: Graph showing Estimated Marginal Means of Cob Girth

5.7 Drying Down Rate Percentage (DDR%)

5.7.1 Table 11: Dependent Variable: DDR %

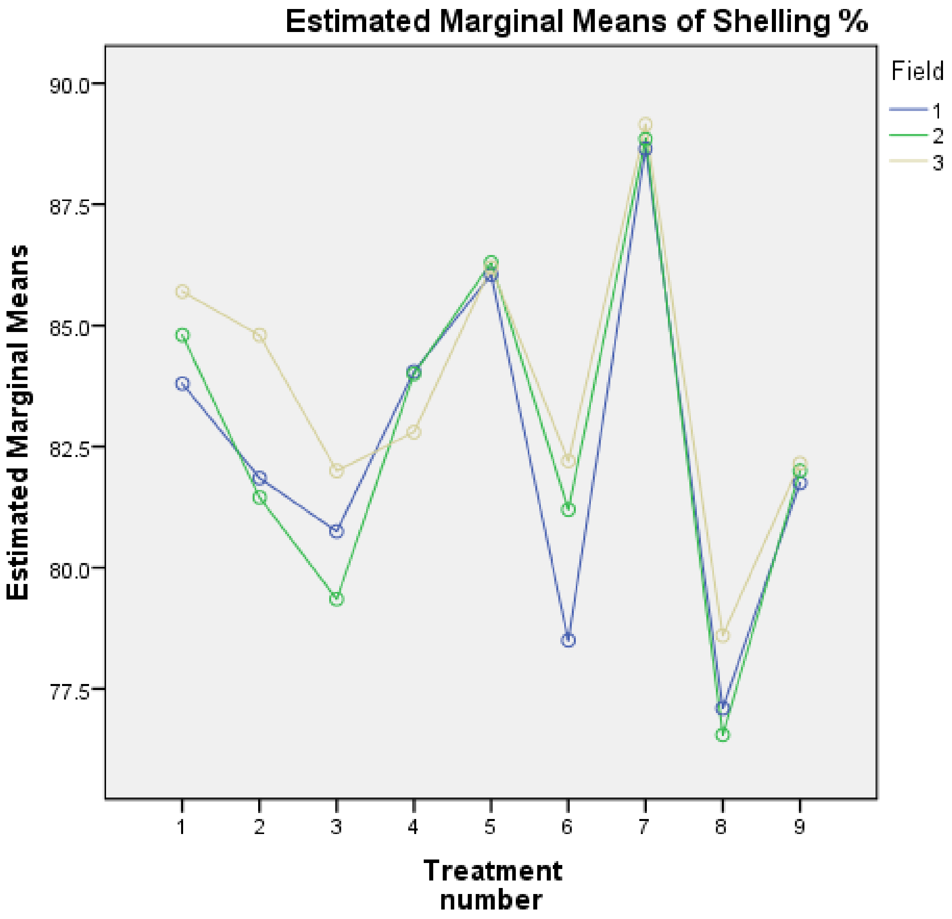
Treatment Number	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	6.750	.066	6.618	6.882
2	6.633	.066	6.501	6.766
3	6.600	.066	6.468	6.732
4	6.917	.066	6.784	7.049
5	5.700	.066	5.568	5.832
6	5.433	.066	5.301	5.566
7	6.733	.066	6.601	6.866
8	6.267	.066	6.134	6.399
9	5.417	.066	5.284	5.549



5.7.2 Figure 8: Estimated Marginal Means for Drying Down Rate %

5.8 Measurement of Yield Parameters

The objective of this study was to determine the optimal lime and nitrogen treatment combinations to which maize yield response under irrigated conditions attains an economic threshold. Maize yield can be limited by a decline in soil pH. Average kernel yield response to lime and nitrogen treatment combinations is shown in Table 10. In this study, results showed that maize kernel yield response is a function of soil pH status as well as nitrogen-lime interactive processes. Several statistical models for crop yield response to the interactive effect of nutrient and lime have been developed. The study found a significant positive yield response following a lime and nitrogen treatment combination of T$_5$ (1.5t ha^{-1}L and 0.2t ha^{-}N), T6 (1.5t ha^{-1}L and 0.4t ha^{-}N), and T$_8$ (3.0t ha^{-1}L and 0.2t ha^{-}N). All were witnessed in season 2.



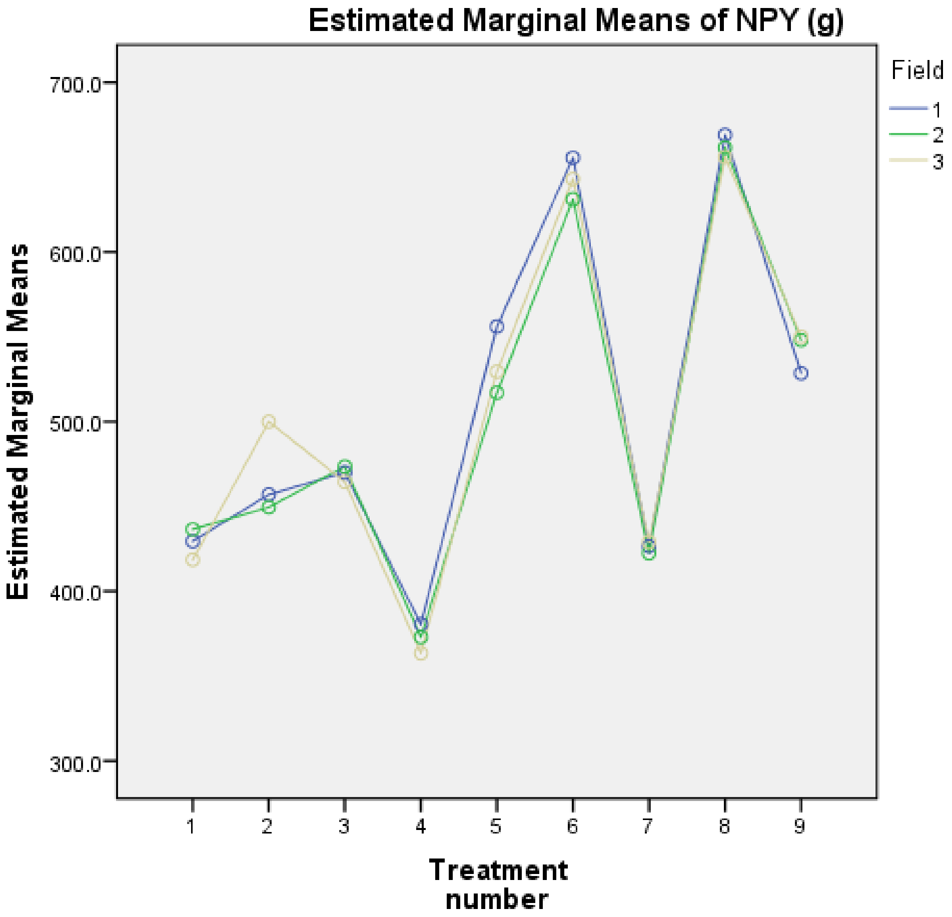
5.8.2 Figure 9: Graph showing Estimated Marginal Means for Shelling Percentage

The highest Kernel Yield was obtained with a treatment combination of T_8 (3.0t ha^{-1}L and 0.2t ha^{-}N). Cob length, cob girth and thousand seed /kernel weight increased exponentially with increase in lime and nitrogen treatment combinations. Table 9 showed a significant interaction between maize yield and lime –nitrogen rates. (F value for Shelling % (S%), Net Plot Yield (NPY), Cob Length (CL) and Drying Down Rate % (DDR%), $p \leq 0.05$) being 3.694, 6.110, 1.118 and 1.102 respectively. Generally, the maximum kernel yield was obtained at 1.5t ha^{-1}L interacting with 0.2t ha^{-}N and 3.0t ha^{-1}L interacting with 0.2t ha^{-}N treatment combinations. This could be attributed to the use of dolomitic lime which confers calcium: magnesium rich soil (increased base saturation) and improved Biological Nitrogen Fixation (BNF). The highest mean value (μ) for Net Plot Yield (NPY) was recorded for T_6 and T_8 with 643.2g and 662.2g (thousand seed weight) respectively when evaluated using the Estimated Marginal Means (EMM).

5.8.2 Table 12: Descriptive statistics for Net Plot Yield (NPY) below

Dependent Variable: NPY (g)

Field	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	508.056	5.975	495.997	520.114
2	501.389	5.975	489.330	513.447
3	506.000	5.975	493.942	518.058



5.8.3 Figure 10: Estimated Marginal Means for Net Plot Yield

Rep 1 (NPY) **Rep 2 (NPY)**

C.V = $\frac{SED}{\mu} \times 100 = \left(\frac{5.975}{508.056}\ X\ 100\right)$ C.V $= \frac{SED}{\mu} \times 100\ \left(\frac{5.975}{501.389}\ X\ 100\right)$

= 1.17% **= 1.19%**

Rep 3 (NPY)

C.V = $\frac{SED}{\mu} \times 100 = \left(\frac{5.975}{506.00}\ X\ 100\right)$

= 1.18%

Season 1 (NPY) C.V. **Season 2 (NPY) C.V.**

C.V = $\frac{SED}{\mu} \times 100 = \left(\frac{4.879}{496.852}\ X\ 100\right)$ C.V $= \frac{SED}{\mu} \times 100\ \left(\frac{4.879}{513.444}\ X\ 100\right)$

= 0.98% **= 0.95%**

All yield parameters were statistically significant. These include Shelling percentage, Net Plot Yield, Cob Length, Cob Girth and Drying Down Rate percentage with successive seasons (Season 2) compared to season 1. Yield should not be construed to mean quantitative components only but also qualitative components or organoleptic qualities such as colour. This study found out that in increased nitrogen rates with no application of lime, there was loss of yellow (orange) colour in yellow maize kernels at harvesting. This signified loss of carotenoids like β-carotene, α-carotene and β-cryptoxanthin which are converted in the intestinal lumen to produce vitamin A.

5.9 Discussion

An optimum yield in terms of Shelling Percentage, Net Plot Yield per thousand seed weight, Mean Cob Length and Cob Girthwere obtained with an application rate of 1.5t ha^{-1}L interacting with 0.4t ha^{-1}N. As fertilizer and lime quantities increase, so is the yield. Agronomic studies have revealed that crops respond to some factors provided that the input factor is limiting (Tumusiine et al, 2010). This resonates with the decreasing marginal return concept or the plateau yield pattern observed by Adam (1984) when he found out that liming is a limiting factor in crop production.

Results of the study showed a gradual increase in soil pH as well as grain yield with successive seasons of lime and nitrogen application. This confirms the assertion that lime effect has a long life span and hence, should be taken as a capital investment rather than an operating input (Lukin and Epplin, 2002). All economic yield parameters are statistically significant at 95% C.I. as confirmed by the Multivariate

Tests, namely, Pillai's Trace Test, Wilk's Lambda Test, Hotelling's Trace Test and Roy's Largest Root Test.(P-value = 0.003) across all yield parameters evaluated.

Although there are several models that have been used in agronomy, to determine crop yield response to inputs which are yield limiting, a computational pattern that favours a plateau crop response to input limiting factors such as mineral and lime effect has garnered more support in agriculture. This notion resonates with the von Liebig and Mitscherlich –Baule (1999) phenomenon as cited by Lukin and Epplin, 2002). In this study, such is the case with the L2N1 (3.0t ha^{-1}L and 0.2t ha^{-}N). However, there are critics of the Linear-Response Plateau (LRP) model. These include Hall (1983), Paris and Knapp (1989) and Frank et al (1990) who contend that the plateau functions/ model disregards errors above the maximum and optimum. Despite the weaknesses inherent in the LRP model, its estimates remain reasonable and of practical significance in modelling input-yield response.

This concurs with the findings by Fageria and Baligar (2003) and Fageria (2009) who corroborate that the increase in yield of field crops is linked to calcium and magnesium (Ca and Mg) availability following a decline in soil pH.T_9 with a treatment combination of L2N2 (3.0t ha^{-1}L versus 0.4t ha^{-}N) obeyed Mitscherlich and Rubio's Law of diminishing yield increments (point of inflexion).

As opposed to Tull and Nyamuda (2006) who said that soil acidity causes loss of colour or pigmentation in horticultural crops, this study revealed the opposite. Treatments that had higher levels of nitrogen with no lime application showed loss of the yellow or orange colouration in yellow maize thus, reducing their pro-vitamin A nutritional value under an acid stress soil environment.

5.10 Conclusion

By and large, the coefficient of variation (CV) for yield parameters, namely cob length, cob girth or diameter, and thousand seed weight all recorded coefficient of variations of well below 15%. The fact that CVs are below 15% confirms the significant interaction of factors at play in cereal crop production thus making the results significant at 95% confidence interval. The results concluded that a dual treatment combination of both lime and nitrogen fertiliser influenced all yield parameters tested. A lime and nitrogen treatment combination of 3t ha^{-1} interacting with a nitrogen rate of 0.2t ha^{-1} was found to give the optimum maize yield response in sandy textured soils cultivated under irrigation. Irrigation conditions coupled with lime and nitrogen treatment combinations resulted in a gradual increase in soil pH which concurred with the findings of other scholars. Consequently, lime and nitrogen treatment combinations using the three treatment factors of lime, nitrogen and irrigation showed positive residual lime effects over seasons.

REFERENCES

Adams, F. (1984) “Crop Response to Lime in Southern United States” In: Adams (ed) Soil Acidity and Liming, 2nd Edition. American Society of Agronomy. Madison

Cassman, K.G. (1999). Ecological Intensification of Cereal Production Systems: Yield Potential, Soil Quality and Precision Agriculture. *Proceedings of the National Academy of Sciences of the United States of America* 96

EDMEADES, D.C and Ridley, A.M. (2003) Using Lime to Ameliorate Top Soil and Sub soil Acidity. In:

FAO/UNESCO (2015) Statistical Database for the Food and Agriculture Organisation of the United Nations: *http://www.fao.org*.

Fageria, N.K. (2008) Optimum Soil Acidity Indices for Common Bean Production on an Oxisol in No-Tillage System. Com. Soil Science. Plant Anal.

Fageria, N.K. and Baligar, V.C.(2008) Ameliorating Soil Acidity of Tropical Oxisols by Liming for Sustainable Crop Production.

Fageria, N.K. and Moreira, A. (2010) Liming Influence on Soil Chemical Properties, Nutritional Status and Yield of Alfalfa (Medicago sativa L).

Fageria, N.L., Zimmermann, F.J.P. and Baligar, V.C., (n.d). Lime and Phosphorous Interactions in Wheat, Common Bean and Corn in an Oxisol. *Journal of Plant Nutrition, Vol.18*

FAO/UNESCO (2015) Statistical Database for the Food and Agriculture Organisation of the United Nations: *http://www.fao.org*.

Frank, M., Beattie, B. and Embelton, M. (1990) A Comparison of Alternative Crop Response Models. American Journal of Agricultural Economics 72

Friesen, D.K., Juo, A.S. and Miller, M.H., (1980). Lime and Lime – Phosphorous- Zinc Interactions in Soil. *Soil Science Society of America Journal: Vol. 44No.6*

Gomez, K.A. and Gomez, A.A (1984) Statistical Procedures for Agriculture Research. 2nded. New York: John Willey and Sons

Hall, H.H. (1983) Economic Evaluation of Crop Response to Lime. American Journal of Agricultural Economics **65**

Hussein, J., Adey, M.A and Elwell, H.A (1992) Irrigation and dryland Cultivation Effects on Surface Properties and Erodibility of Zimbabwe Vertisols. Soil Use Management **8**

Liebig, J.V. and Mitscherlich, E.A. (1909). Die Grundsatze der Agricultur-Chemie mit Rucksicht auf die in England angestellten Untersuchxhungen. Fredrick V ieweg and Sohn, Braunschweig, Germany.

Lukin, V.V and Epplin, F.M. (2002). Frequency and Quantity of Agricultural Lime Applications. Department of Agriculture Economics. Oklahoma State University.

Larkcom, E., and Miller, R (1994). Food Production: Biology – Advanced Studies, Nelson and Sons Ltd, United Kingdom

Montgomery, D.C. (2013) Design and Analysis of Experiments 8thed.New York, Willay and Sons
Nyamapfene, K.W (1991) Soils of Zimbabwe. Harare. Nehanda Publishers (Pvt) Ltd.

Opala, P.A. (2017). Influence of Lime and Phosphorous Application Rates on Growth of Maize. Advances in Agriculture. Department of Soil Science, Maseno University, Kenya

PACE (1998) Sustainable Soil Management: Participatory Agricultural Curriculum for the environment. American Journal of Botany 90(1): 143 -152

Paris, Q. And Knapp, K. (1989) Estimation of von Liebig Response Functions. American Journal of Agriculture Economics **71**

Rengel, Z.,ed. Handbook of Soil Acidity. New York, Marcel Dekker. 2003

Sinclair, A., Crooks, B. And Coull, M. (2014). Soils Information, Texture and Liming Recommendations.

Tabitha, T.B., Koenig, R.T., Huggins, D.R., Harsh, J.B. and Rossi, R.E. (2008) Lime Effects on Soil Acidity, Crop Yield, and Aluminium Chemistry in Direct – Seeded. Soil Science Society of America. Journal 3 (72)

Tumuisine, E. and Brorsen, W.B.(2010) Effect of Nitrogen Fertilisation on Rye-Rye Grass Yield and Soil pH Dynamics: Agricultural and Applied Economics Association, (AAEA),CAES and WAEA Joint Annual Meeting.

CHAPTER SIX

6.0 LIME AND NITROGEN FERTILIZER INTERACTION ON SOIL pH DYNAMISM IN MAIZE

6.1 Abstract

Acid soils of arable lands require liming in order to reduce the concentration of hydrogen ions that reduce crop yields. Several factors, for example crop type, type of soil and prevailing climatic conditions as well as farming system should be considered in application of lime to acid soils if crop productivity is to be achieved. While there are many causes of soil acidity, the use of nitrogen fertilisers has contributed immensely to the decline of soil pH. Crop yields are influenced greatly by the pH of the soil. The study focused on exploring soil pH deviations following different rates of lime and nitrogen fertilisers. Three levels of lime and nitrogen fertiliser were used in sandy textured soils. Data regarding deviations in soil pH were gathered from field experimental trials of yellow maize grown in sandy textured soils under irrigation conditions. A field study was conducted during the 2018/2019 and 2019/2020 summer seasons to evaluate the physiological responses of maize due to 9 different dolomitic lime and ammonium nitrate fertilizer treatment combinations. Maize of cultivar SC 402 which is a yellow/orange genotype was planted during the two seasons. After each harvesting during the two season experimental trials, soil samples were taken from the treatment plots for pH evaluation. Results of the study revealed that with zero lime and zero nitrogen (L0N0) in the control plot, a soil pH decline by 0.2 units was realised over two farming seasons. The optimum levels of 1.5t ha^{-1} lime and 0.4t ha^{-1} Nitrogen (L1N2) application rates revealed a soil pH test result of 0.7 units of acid decline ($p < 0.05$). The study concluded that, an increase in nitrogen fertilizer application rate should correspond with an increase in lime rates per given time.

Keywords: Yellow maize, Lime, Soil pH, Nitrogen, Soil Acidity

6.2 Introduction

Soil pH is regarded as the only most crucial chemical attribute of soil. The pH of a soil is a function of the proportion of acidic cations and basic cations present on soil exchange sites. Common acidic cations are hydrogen, aluminium ($A1^{3+}$), iron (11) oxide (Fe^{2+}) and iron (111) oxide (Fe^{3+}) whilst basic cations include Calcium (Ca^{2+}), magnesium (Mg^{2+}), Potassium (K^+), ammonium (NH_4^+) and Sodium (Na^+) (Mallarino, 2005). Thus a soil can either be acidic or alkaline or basic. This confers and explains the amphoteric nature of soils.

The pH of a soil relates to its degree of acidity or alkalinity when measured in a neutral solution. Soils that have pH values of less than 7.0 are considered acidic whilst those higher than 7.0 are classified as alkaline or basic. The concentration of hydrogen ions in a soil-solution is termed active acidity since it is only a small proportion of the entire hydrogen ions found in the soil (Agriculture, Food and the Environment, 2017). The bulk of hydrogen ions remain adsorbed to the soil humus and clay colloids and is referred to as reserve acidity. Here, the hydrogen ions are retained in soil exchange sites. Aluminium is the most abundant mineral in soils and is highly soluble when pH declines below 5.0 (Lukin and Epplin, 2002). Since AL^{3+} ions are ubiquitous in soils, it is considered a prime cause of soil acidity following its dissolution promoted by nitrate fertilisers. The use of lime in agriculture is a viable alternative compared to other options in promoting and restoring of soil fertility and a healthy soil ecosystem. The study sought to determine the extent to which lime and nitrogen treatment combinations influence soil pH dynamics in the growth of irrigated maize that is cultivated in sandy textured soils.

6.3 Materials and Methods

6.3.1 Site Characterisation

The field study was conducted over two farming seasons spanning from the 2018/2019 to 2019/2020 seasons. It was an own-farm field experimental trial coupled with laboratory soil tests conducted at Gary Magadzire School of Agriculture, Chemistry Laboratory of Great Zimbabwe University. The type of soil on the two experimental sites was classified as Fersiallitic Luvisols of the 5G Family (Hussein, 1992). These soils grouped as 5G are sandy in texture and are of granite rock derivation with a low nutrient status and poor water holding capacity but with the potential to become productive with good water and fertility management (Hussein, 1997). The soils are the most widespread soils in Zimbabwe and are used for cultivation of cereals such as maize despite their inherent low base saturation status and low organic contents. The soil samples were extracted from the 20cm coring depth using a soil auger from two experimental sites whose geographical locations were (Latitude –

21.446815 and longitude 31.838409 and altitude of 1.075m above sea level). Rainfall ranges between 450 and 650mm per annum with frequent SE winds that move at a velocity of 10km per hour.

Prior to planting, soil texture was determined by sifting using sieve plates of three hole diameters ≤2.0mm. Soil pH was determined using digital pH meters in the ratio 1:2 soil-distilled water solution. The pH meter used was that of the Pen Testers pocket sized pH meter of type compact water proof pH 22 LAQUAtwin Manufacturer - Thomas Scientific. It has unique feature that it includes a flat sensor that makes measurement of liquids or semi-solids easy which makes it suitable for laboratory or environmental conditions. That was done to ascertain deviation in soil pH following dolomitic lime application for two successive seasons.

6.3.2Table 13 Soil pH Change and Yield Variability Due to Lime and Nitrogen Interaction

Treatment Number	**Lime Rate (LR) t hat ha^{-1}**	**Nitrogen Rate (NR) t hat ha^{-1}**	**Shelling %**	**Net Plot Yield (NPY) 1000 seed weight (g)**	**Mean Cob Length (MCL) Mm**	**Mean Cob Girth /diameter (MCG/D)Mm**	**Bare Tips (BT)**	**DDR %**	**pH DEV**
1	**0**	**0**	**84.6**	**434**	**175**	**150**	**P**	**6.9**	**0.2**
2	**0**	**0.2**	**83.7**	**454**	**230**	**158**	**P**	**6.7**	**0.6**
3	**0**	**0.4**	**81.9**	**471**	**250**	**160**	**P**	**6.6**	**0.42**
4	**1.5**	**0**	**84.1**	**360**	**210**	**158**	**N**	**6.8**	**0.48**
5	**1.5**	**0.2**	**85.1**	**585**	**240**	**170**	**N**	**5.8**	**0.65**
6	**1.5**	**0.4**	**78**	**669**	**265**	**160**	**N**	**5.6**	**0.7**
7	**3**	**0**	**91.3**	**432**	**230**	**150**	**N**	**6.6**	**0.5**
8	**3**	**0.2**	**77.8**	**663**	**230**	**175**	**N**	**6.2**	**0.4**
9	**3**	**0.4**	**79.9**	**562**	**255**	**160**	**N**	**5.5**	**0.5**

Variables: **pH - Potential Hydrogen Ions, S% - Shelling percentage, LR – Lime Rate,**
DDR% - Drying Down Rate Percentage MCL – Mean Cob Length BT – Bare Tips,
MCG/D - Mean Cob Girth/ Diameter, P – Present, N – Nil,
pH - Potential Hydrogen Ions, NR – Nitrogen Rate,

6.3.3 Experimental Design and Reagents

The study assumed a Split- plot experimental design (SPD) (See Table 1 above). The Split- plot experimental design is an extension of the split plot design. The only difference lies in the number of factors at play. The split plot design has ≤ two factors. In this study, the factors were dolomitic lime and ammonium nitrate fertilizer. There were three factors replicated three times with three lime and nitrogen rates thus giving a 3 x 3 x 3 factorial combination. Dolomitic lime (with 30% calcium oxide and 20% magnesium oxide) with an effective SNV/CCE of 95% to 109% was applied through broadcasting and incorporated within the 200mm depth at least 5 weeks prior to planting followed by irrigation. The lime rates were 0, 1.5 and 3.0t ha^{-1}L against a nitrogen rate of 0, 0.2 and 0.4t ha^{-1}N at four week stage of crop emergence.

6.4 Planting

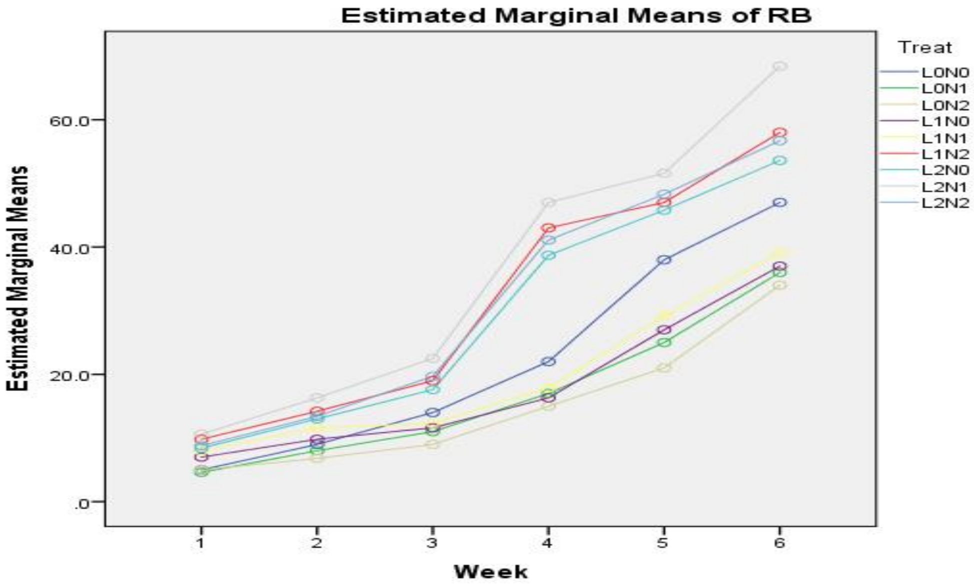
Planting commenced during the2018/2019 season and was repeated during the 2019/2020 season. A basal application of compound D fertiliser was applied to all the plots including the control at ($T_{0,}$ $T1_{,}$ T_2...T_8) at a rate of 150kg ha^{-1} through the drilling method. One maize seed was put per planting station in rows which were 20m long and 750mm wide. A yellow/Orange maize genotype SC402 was planted to a 5cm depth at an in row spacing of 250mm. The same October planting date was maintained for the two seasons to avoid variability caused by seasonal change in heat units. Overhead irrigation was done concurrently for the three replications.

6.5 Measurement of Parameters

Growth and yield parameters were evaluated to determine crop response to different levels of soil pH following different levels of nitrogen and lime rates. Growth parameters included measurement of LAI, NAR as evidenced by change in both aboveground and belowground maize biomass index on a weekly basis for six weeks (Larkcom and Miller, 1994; Taylor et al, 1997). Plant organs were oven dried to a constant weight at 70°C for 24 hours. After harvesting, soil samples were collected from each of the treatment plots for determination of soil pH_{cacl} deviation following different rates of lime and nitrogen fertiliser regimes.

6.6 Results

Results of the study revealed a increase in soil acidity by 0.2 units in the control plot (T_0, L0N0). This could suggest that with no lime application, sandy textured soils under irrigation conditions, soil acidity increased by a margin of 0.2 units. The increase in soil acidity by 0.2 units over two farming seasons could be attributed to natural causes of acidity such as acid rain, aluminium and manganese prevalence, root exudates as well as respiration from soil microbes among other factors. When 0.2t ha^{-1} N were applied consecutively over two seasons with no lime application, a threefold increase in soil acidity of 0.6 units was recorded. Conversely, a 0.48 unit of soil pH (decrease in acidity) was recorded when 1.5t ha^{-1} L against a 0t ha^{-1}N. When nitrogen fertiliser was increased from 0t ha^{-1}N to 0.2t ha^{-1}N against a lime rate of 1.5tha^{-1}, soil pH results revealed a 0.65 unit decrease in soil acidity. A 0.7 unit decrease in acidity over two farming seasons was recorded in the treatment plot where 1.5t ha^{-1}L and 0.4t ha^{-1}N were applied. That was the optimum lime and nitrogen application rate for the study which revealed a soil pH test result of 0.7 unit acidity decline. When lime rates were exponentially raised and maintained at 3t ha^{-1} with nitrogen rates staggered at 0. 0.2 and 0.4t ha^{-1}N, a decline in soil acidity of 0.5 units, 0.4 and 0.5 units respectively were obtained. This depicted an average of 0.5 unit reduction in acidity when a constant 3t ha^{-1}L was applied reflecting a Linear Response Plateau (LRP) model or sigmoid flexure.



6.6.1 Figure 11 Estimated Marginal Means for Root Biomass

6.7 Discussion

Soil acidity varies with the agronomic practice at play, whether irrigation or dryland. Dolomitic Lime is rich in Ca and Mg and with water availability, the hydrogen carbonates ($HC0_3$) in Lime consumes the H^+ ions causing a decline in soil pH (Havlin et al, 1999). The findings also concur with the outcomes of Moreira et al (2005) and Fageria (2006) who reported similar results attributed to Ca and Mg contents in dolomitic lime. Irrigation leaches bases such as calcium, magnesium, potassium as well as sodium leaving soil exchange sites vacant. This creates room for acid inducing cations like hydrogen ions (H^+) in positions previously occupied by bases. Removing weeds from arable lands carries with them as much as 40pounds (18,1kg) of calcium and 18 pounds (8.2kg) of magnesium per acre ($4900m^2$) per year (Centre for Agriculture, Food and the Environment, 2017 – University of Massachusetts's College of Natural Sciences, 2017).

So it is imperative that methods of crop harvesting be revised in order to retain nutrients particularly bases which tend to buffer soil pH decline. The study used sandy-loam soils under irrigation conditions. Results of the study revealed coarse-textured soils are prone to leaching of bases increasing the frequency and amount of amine and ammonium based fertilisers. This eventually results in heavy dressings of both liming materials and nitrogen fertilisers. At a treatment combination of L0N1 (0t ha^- L versus 0.2t ha^{-1}N), soil pH rose by 0.6 units from that of the control (L0N0). With a treatment of L2N0 (3.0t ha^-L and 0t ha^{-1}N) soil pH declined by 0.5 units. This concurs with the findings by Lukin and Epplin (2003) who postulated that on average, pH increased by 0.7 – 0.8 units when 2t/acre of lime was applied.

At L2N2 (3.0t ha^-L versus 0.4t ha^{-1}N), soil pH increased by a meagre 0.5 units over two farming seasons. This would have been linked to successive base removal by crop plants during harvesting as supported by Marchner (2012). In treatments where rates of nitrogen were high but with low or no lime rates such as 0t ha^-L versus 0.4t ha^{-1}N and 1.5t ha^-L versus 0.4t ha^{-1}N, acidity increased (low pH). The low soil pH was caused by a reduction in the buffering capacity of the soil with increased nitrogen application regimes. This is in sync with the findings by the Massachusetts University, Centre for Agriculture, Food and the Environment (2017) which contend that a more acid soil causes a depression in the buffering capacity of the soil. Eventually, this calls for huge lime rates which give a financial burden to the farmer. Although there are huge deposits of dolomitic limestone in Sub Sahara Africa (SSA), with a Ca: Mg ratio of CaO30%: MgO20%, very little is known regarding their agronomic benefits (Nduwumuremyi, 2013).

Calcium and magnesium are considered as secondary elements. Despite calcium and magnesium having several direct plant physiological functions such as acting as both constituents of organic and inorganic compounds as well as acting plant enzyme activators, they have direct soil structural functions. Calcium is critical in flocculation of clay soils whilst magnesium enhances the sticking together of single –grained sandy particles. Dolomitic lime which was used in the study contains calcium and magnesium which confer these agronomic benefits in addition to the usual soil pH amendment functions. Sinclair et al (2014) contend that sodium is lost from course textured soils like sandy soils over a period of 12 months.

Presence of sodium in the soil results in sodic soils. Sodic soils influence pH of the soil. Sodium salts changes the pH of the soil from being acidic to attain a pH > 8 which can be corrected by soil drainage through irrigation as recommended by Masaka et al (2008). The study used ammonium nitrate coupled with a base (Dolomitic lime- $CaMg(CO_3)_2$). The average increase in soil pH of 0.6 units attained in two successive seasons of both lime and nitrogen treatment combinations resonates with the findings by other researchers like Epplin and Lukin (2004).

6.7 Conclusion

The study concluded that generally, with no lime and no fertilizer application (L0N0), an average of pH decline (increased acidity) of 0.2 units was realised over two farming seasons. On a positive note, an optimal lime and nitrogen treatment combination of 1.5t ha^{-1} lime interacting with 0.4t ha^{-1} nitrogen (L1N2) has a significant effect in increasing soil pH thus ($p< 0.05$). This is contrary to the assertion that clay soil is more prone to acidity owing to multiple exchange sites. The conclusions of the study are due to the fact that sandy soils are prone to leaching of bases that leave acidic cations within the soil exchange sites. Sandy textured soils also require heavy dressings of nitrate and ammonia based fertilisers due to their CEC hence, are more vulnerable to low soil pH than heavy soils of high clay and humus contents.

REFERENCES

FAO/UNESCO (2015) Statistical Database for the Food and Agriculture Organisation of the United Nations: http://www.fao.org.

Fageria, N.K. (2006) Liming and Copper Fertilisation in Common Bean Production on an Oxisol in no Tillage System. Journal of Plant Nutrition 29.

Ganju, J., and Lucas, J.M. (1999) Detecting randomisation Restrictions caused by **Factors**. *Journal of Statistical Planning and Inference, Vol.81*

Gomez, K.A. and Gomez, A.A (1984) Statistical Procedures for Agriculture Research. 2ndед. New York: John Willey and Sons

Havlin, J. Beaton, J.D., Tisdale, S.L and Nelson, W.L (1999) Soil Fertility and Fertilisers, An Introduction to Nutrient Management. Upper Saddle River, Prentice Hall

Hussein, J, Adey, M.A. and Elwell, H.A.(1992). Irrigation and Dryland Cultivation Effects on Surface Properties and Erodibility of Zimbabwe Vertisols. Soil Use Management 8.

Hussein, J (1997). Applied Soil Science SLD102: Introduction to Soil Management. University College of Distance Education, Harare

Larkcom, E., and Miller, R (1994). Food Production: Biology – Advanced Studies, Nelson and Sons Ltd, United Kingdom

Lukin, V.V and Epplin, F.M. (2002). Frequency and Quality of Agricultural Lime Applications. Department of Agriculture Economics. Oklahoma State University.

Mallarino, A.P (2005) Module 8: Soil pH and Lime Management. Lowa State University, United States of America.

Masaka, J, Muguti, P and Chivandi, E (2008). Nutrient Deficiency Effects on the Biometric Characteristic of Tobacco Seedlings in float tray Systems. Journal of Plant Nutrition
Mukurumbira (1999)

Massachusetts College of Natural Sciences (2017). Soil pH The Centre for Agriculture, Food and the Environment.

Marschner, H (2012). Mineral Nutrition of Higher Plants, 2nd ed. Academic Press, London.

Moreira, A. and Fageria, N.K. (2009) Liming Influence on Soil Chemical Properties, Nutritional Status and Yield of Alfalfa Grown in Acid Soil.

Moreira, A. and Carvalho, J.G. and Evangelista, A.R. (2005) Calcium and Magnesium Ratio in the Fertility of a Dystrophic Dark Red Latosol Cultivated Alfalfa, Agrotec.

Nduwumuremyi, A. (2013) Soil Acidification and Lime Quality: Sources of Soil Acidity, Effects on Plant Nutrient, Efficiency of lime and Liming Requirements. Research and Reviews: Journal of Agriculture and Allied Sciences.

Tabitha, T.B., Koenig, R.T., Huggins, D.R., Harsh, J.B. and Rossi, R.E. (2008). Lime Effects on Soil Acidity, Crop Yield, and Aluminium Chemistry in Direct – Seeded. Soil Science Society of America. Journal 3 (72)

The Centre for Agriculture, Food and the Environment: (2017). Soil pH and Liming. University of Massachusetts.

CHAPTER SEVEN

7.0 GRENERAL CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The study concluded that the amount of limestone needed to adjust the pH of arable soils depends on type of soil as well as the inherent soil pH. Soils that contain high clay and or organise matter contents have a greater reserve of potential acidity therefore require large amounts of limestone to neutralise the organic acids. The study also concluded that lime application has direct and indirect agronomic benefits to the farmer. The primary or direct lime benefit is that of increasing soil pH whilst the secondary benefits emanate from the improved soil structure, improved availability of macro and some microelements. Lastly, management of soil pH is an integral component of best agronomic practices and requires knowledge of how soils become prone to acidity and the roles that liming play in influencing soil chemical, physical and biological properties.

7.2 Recommendations

Limestone recommendations in arable lands are based on several factors that rely on agronomic practices at play, soil test results, type of crop (acid tolerant or acid sensitive), soil type, soil factors such as texture, organic matter content among others. From the outcomes of this study, the following are recommended to farmers:

- Since sandy soils are prone to leaching of bases leaving acid promoting cations like Al^{3+} , Mn and H^+, farmers are encouraged to increase quantities of both lime before planting and nitrogen at top dressing stages. This is because coarse textured soils require frequent top dressing fertilization through split application which is most likely to confer acidity by leaving H^+ ions.
- An optimum lime and nitrogen treatment combinations of 1.5t ha^{-1} lime combined with 0.4t ha^{-1} (L1N2) nitrogen produced a good shelling percentage, highest net plot yield (NPY), highest mean cob length (MCL) as well as soil pH increase of 0.7 units over two farming seasons.
- If maize is to be grown in sandy soils, liming becomes a prerequisite since naturally, these soils are usually acidic. Liming would improve Mo uptake which improves N fixation.

- Dolomitic lime which is a blend of calcium and magnesium is highly recommended in acid prone soils to particularly those that lack Ca and Mg.
- Although large quantities of both lime and nitrogen are needed in sandy soils to boost maize productivity, there is need to strike a balance between economic benefits of increasing lime and nitrogen versus agronomic benefits.

7.3 Statements for further research

The study implores further research to be conducted in order to determine the residual effects of lime-nitrogen interaction since knowledge of lime residual effects exceeds 20 years which is more than the life span of most research studies. Further studies should focus on agronomic practices at play, soil type, topography, previous crops to determine how they influence soil pH dynamics. Lastly, different crops have different uptake rates of basic and acidic cations therefore researchers are needed to explore how they respond to liming and nitrogen interaction.

APPENDICES

APENDIX 1: LIST OF FIGURES

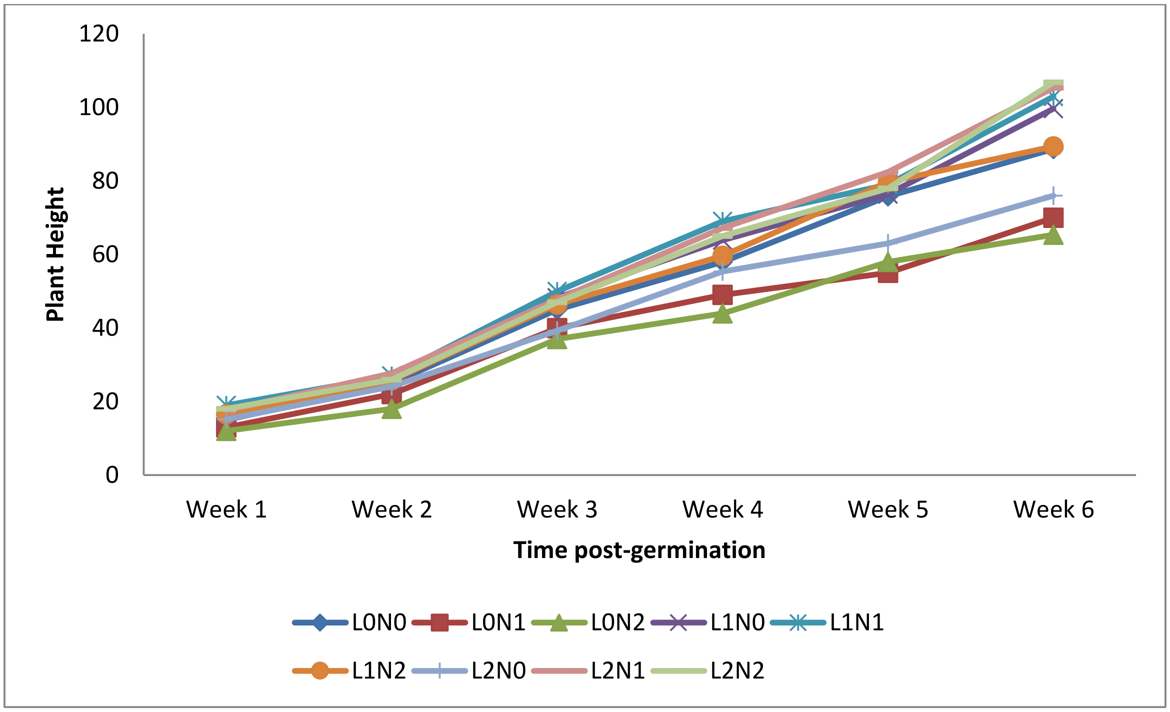


Figure12: Plant Height Post Germination

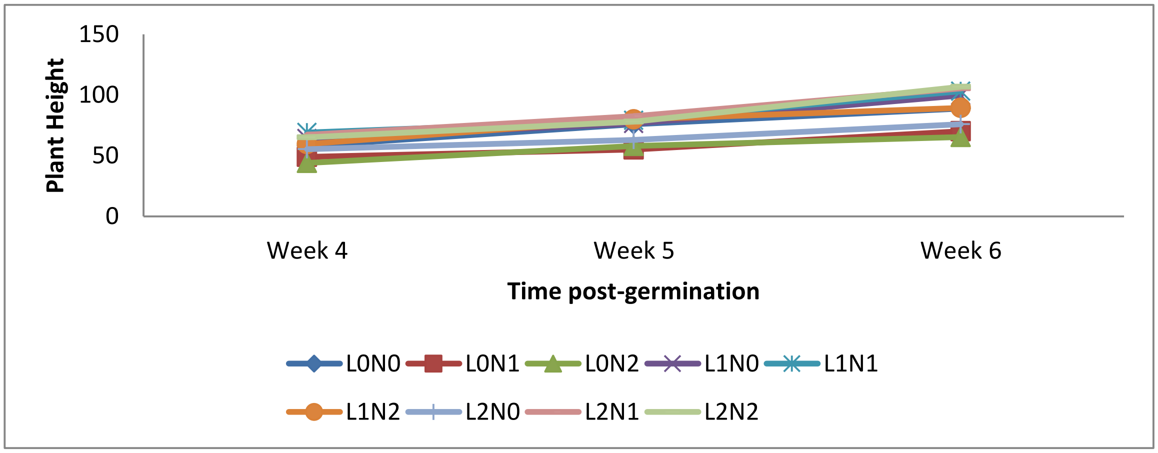


Figure 13 Plant height from 4 to 6 weeks after top dressing

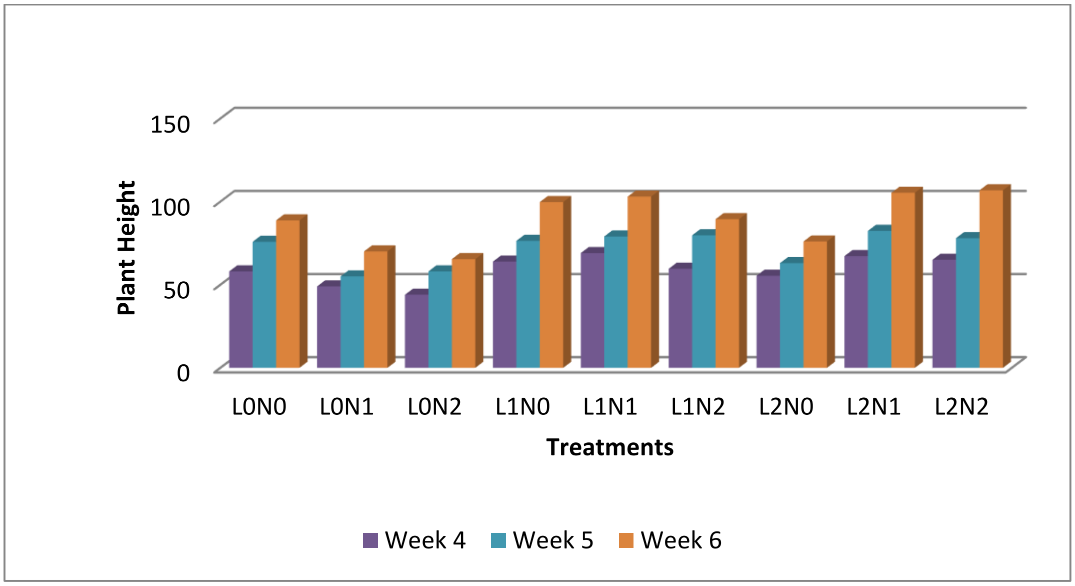


Figure 14: **Lime and Nitrogen Interactive after top Dressing**

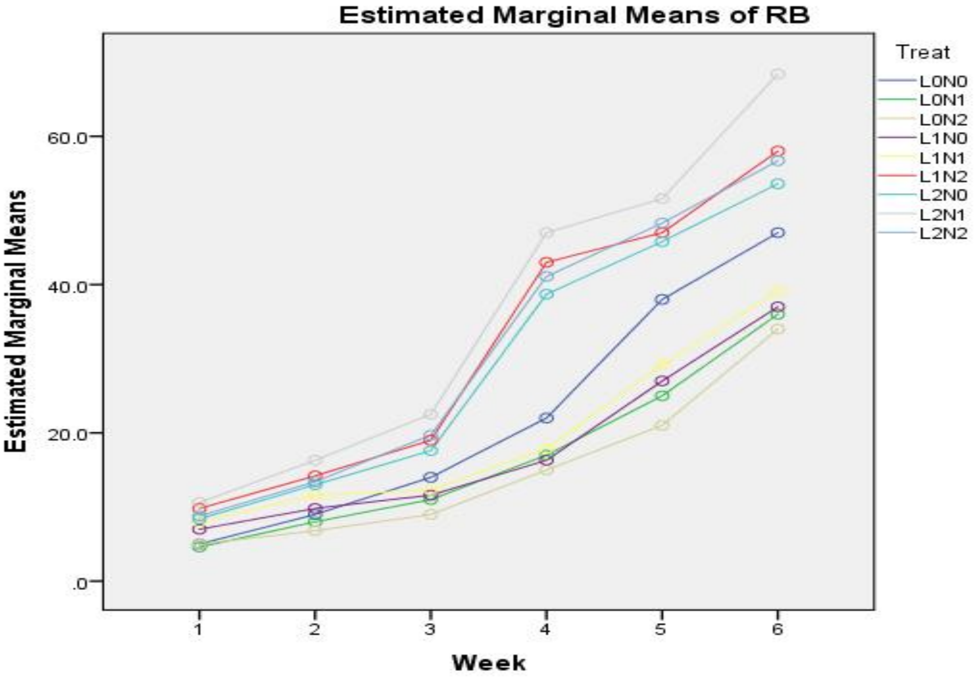


Figure 15: **Estimated Marginal Means for Root Biomass**

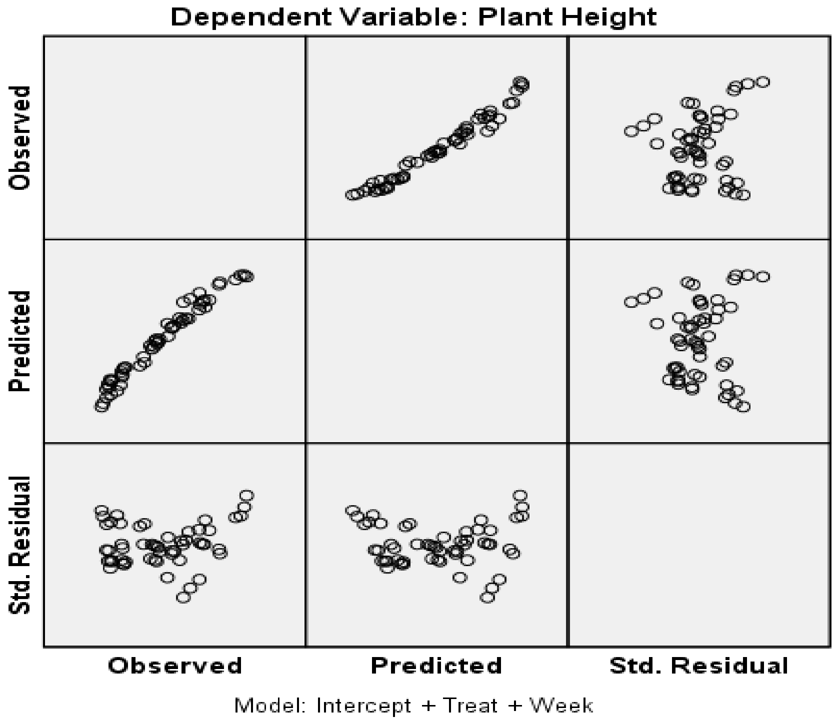


Figure 16: Plant Height Using Scatter Diagrams

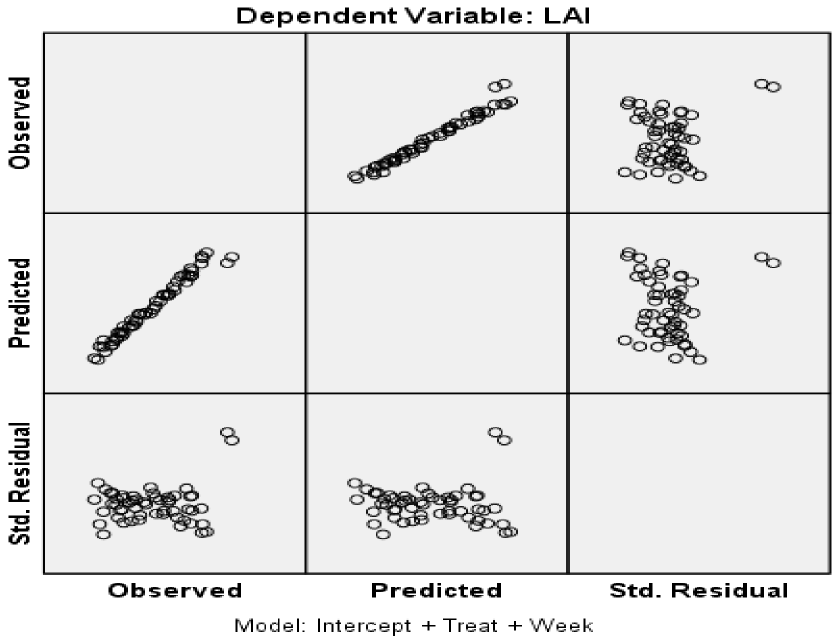


Figure16: Dependant Variable Leaf Area Index (LAI)

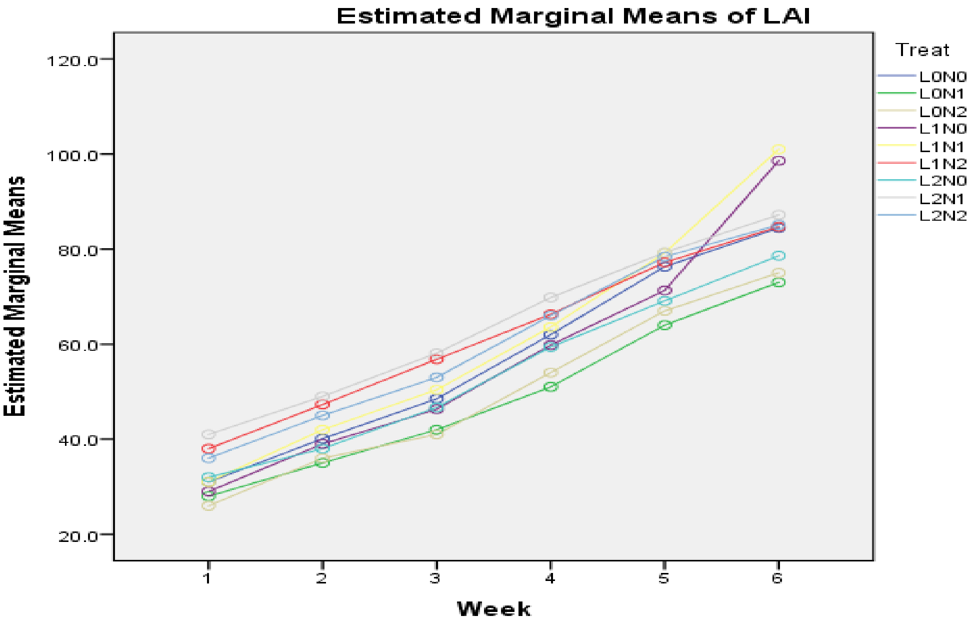


Figure 17: Estimated Marginal Means for Leaf Area Index (LAI)

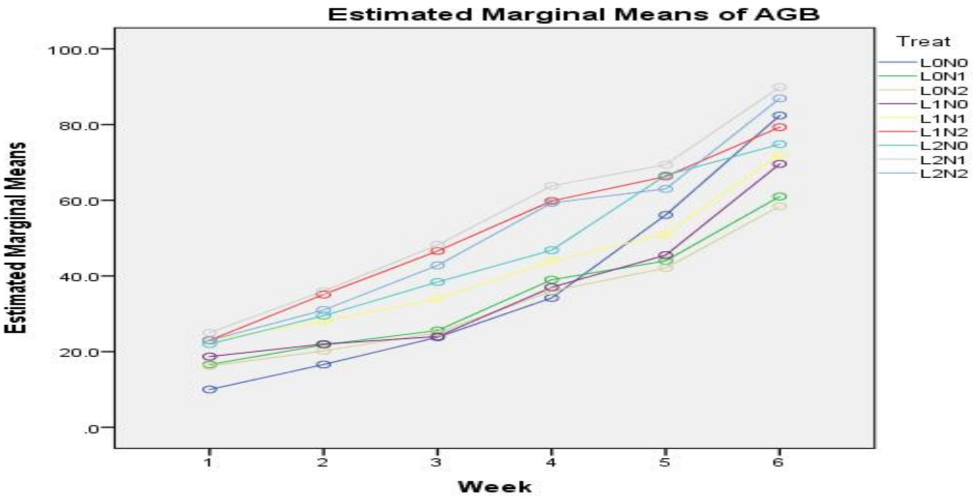


Figure 18: Estimated Marginal Means of Aboveground Root Biomass

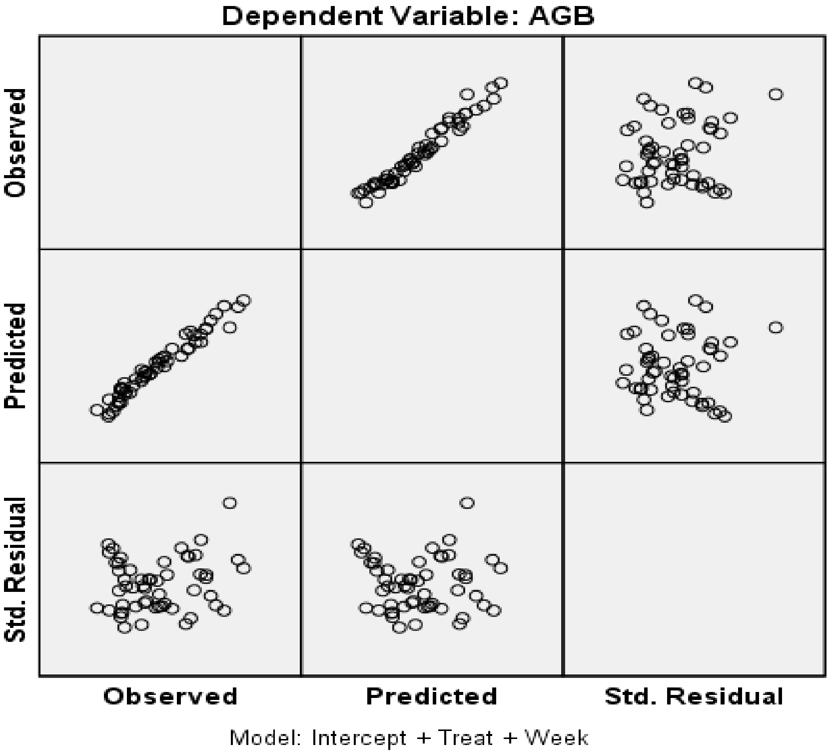


Figure 19: Graph for Scatter Diagrams for Aboveground Root Biomass (AGB)

APPENDIX 2: LIST OF TABLES

Table 14: Table of Plant Height Descriptive Statistics

Treat	Week	Mean	Std. Deviation	N
L0N0	1	15.000	.	1
	2	25.000	.	1
	3	45.000	.	1
	4	58.000	.	1
	5	75.800	.	1
	6	88.700	.	1
	Total	51.250	28.6110	6
L0N1	1	13.000	.	1
	2	22.000	.	1
	3	40.000	.	1
	4	49.000	.	1
	5	55.000	.	1
	6	70.000	.	1
	Total	41.500	21.1920	6
L0N2	1	12.000	.	1
	2	18.000	.	1
	3	37.000	.	1
	4	44.000	.	1
	5	58.000	.	1
	6	65.400	.	1
	Total	39.067	21.2459	6
L1N0	1	16.100	.	1
	2	25.000	.	1
	3	48.200	.	1
	4	63.900	.	1
	5	76.400	.	1
	6	99.700	.	1
	Total	54.883	31.6058	6
L1N1	1	19.000	.	1
	2	27.000	.	1
	3	50.000	.	1
	4	69.000	.	1
	5	79.000	.	1
	6	103.000	.	1
	Total	57.833	32.0401	6
L1N2	1	16.600	.	1
	2	25.800	.	1
	3	46.400	.	1
	4	59.600	.	1
	5	79.700	.	1
	6	89.400	.	1
	Total	52.917	28.9473	6
L2N0	1	15.200	.	1
	2	24.100	.	1
	3	39.300	.	1
	4	55.400	.	1
	5	63.000	.	1
	6	76.000	.	1
	Total	45.500	23.4478	6
L2N1	1	17.600	.	1
	2	27.700	.	1

	3	47.800	.	1
	4	67.200	.	1
	5	82.400	.	1
	6	105.300	.	1
	Total	58.000	33.3814	6
L2N2	1	18.000	.	1
	2	26.000	.	1
	3	47.000	.	1
	4	65.000	.	1
	5	78.000	.	1
	6	106.800	.	1
	Total	56.800	33.3670	6
Total	1	15.833	2.3000	9
	2	24.511	2.9493	9
	3	44.522	4.5891	9
	4	59.011	8.4155	9
	5	71.922	10.3211	9
	6	89.367	15.7282	9
	Total	50.861	27.2186	54

Table 15 Plant Height for Treatment 1

Treat	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
L0N0	51.250	2.248	46.707	55.793
L0N1	41.500	2.248	36.957	46.043
L0N2	39.067	2.248	34.523	43.610
L1N0	54.883	2.248	50.340	59.427
L1N1	57.833	2.248	53.290	62.377
L1N2	52.917	2.248	48.373	57.460
L2N0	45.500	2.248	40.957	50.043
L2N1	58.000	2.248	53.457	62.543
L2N2	56.800	2.248	52.257	61.343

Table 16 Plant Height for Week 2

Week	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	15.833	1.836	12.124	19.543
2	24.511	1.836	20.801	28.221
3	44.522	1.836	40.813	48.232
4	59.011	1.836	55.301	62.721
5	71.922	1.836	68.213	75.632
6	89.367	1.836	85.657	93.076

Table 17 Plant Heights Multiple Comparisons

	(I) Week	(J) Week	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	1	2	-8.678*	2.5958	.021	-16.445	-.911
		3	-28.689*	2.5958	.000	-36.456	-20.922
		4	-43.178*	2.5958	.000	-50.945	-35.411
		5	-56.089*	2.5958	.000	-63.856	-48.322
		6	-73.533*	2.5958	.000	-81.301	-65.766
	2	1	8.678*	2.5958	.021	.911	16.445
		3	-20.011*	2.5958	.000	-27.778	-12.244
		4	-34.500*	2.5958	.000	-42.267	-26.733
		5	-47.411*	2.5958	.000	-55.178	-39.644
		6	-64.856*	2.5958	.000	-72.623	-57.088
	3	1	28.689*	2.5958	.000	20.922	36.456
		2	20.011*	2.5958	.000	12.244	27.778
		4	-14.489*	2.5958	.000	-22.256	-6.722
		5	-27.400*	2.5958	.000	-35.167	-19.633
		6	-44.844*	2.5958	.000	-52.612	-37.077
	4	1	43.178*	2.5958	.000	35.411	50.945
		2	34.500*	2.5958	.000	26.733	42.267
		3	14.489*	2.5958	.000	6.722	22.256
		5	-12.911*	2.5958	.000	-20.678	-5.144
		6	-30.356*	2.5958	.000	-38.123	-22.588
	5	1	56.089*	2.5958	.000	48.322	63.856
		2	47.411*	2.5958	.000	39.644	55.178
		3	27.400*	2.5958	.000	19.633	35.167
		4	12.911*	2.5958	.000	5.144	20.678
		6	-17.444*	2.5958	.000	-25.212	-9.677
	6	1	73.533*	2.5958	.000	65.766	81.301
		2	64.856*	2.5958	.000	57.088	72.623
		3	44.844*	2.5958	.000	37.077	52.612
		4	30.356*	2.5958	.000	22.588	38.123
		5	17.444*	2.5958	.000	9.677	25.212
LSD	1	2	-8.678*	2.5958	.002	-13.924	-3.431
		3	-28.689*	2.5958	.000	-33.935	-23.443
		4	-43.178*	2.5958	.000	-48.424	-37.931
		5	-56.089*	2.5958	.000	-61.335	-50.843
		6	-73.533*	2.5958	.000	-78.780	-68.287
	2	1	8.678*	2.5958	.002	3.431	13.924
		3	-20.011*	2.5958	.000	-25.257	-14.765
		4	-34.500*	2.5958	.000	-39.746	-29.254
		5	-47.411*	2.5958	.000	-52.657	-42.165
		6	-64.856*	2.5958	.000	-70.102	-59.609
	3	1	28.689*	2.5958	.000	23.443	33.935
		2	20.011*	2.5958	.000	14.765	25.257
		4	-14.489*	2.5958	.000	-19.735	-9.243
		5	-27.400*	2.5958	.000	-32.646	-22.154
		6	-44.844*	2.5958	.000	-50.091	-39.598
	4	1	43.178*	2.5958	.000	37.931	48.424
		2	34.500*	2.5958	.000	29.254	39.746
		3	14.489*	2.5958	.000	9.243	19.735
		5	-12.911*	2.5958	.000	-18.157	-7.665
		6	-30.356*	2.5958	.000	-35.602	-25.109

	5	1	56.089*	2.5958	.000	50.843	61.335
		2	47.411*	2.5958	.000	42.165	52.657
		3	27.400*	2.5958	.000	22.154	32.646
		4	12.911*	2.5958	.000	7.665	18.157
		6	-17.444*	2.5958	.000	-22.691	-12.198
	6	1	73.533*	2.5958	.000	68.287	78.780
		2	64.856*	2.5958	.000	59.609	70.102
		3	44.844*	2.5958	.000	39.598	50.091
		4	30.356*	2.5958	.000	25.109	35.602
		5	17.444*	2.5958	.000	12.198	22.691
Bonferroni	1	2	-8.678*	2.5958	.027	-16.781	-.574
		3	-28.689*	2.5958	.000	-36.792	-20.585
		4	-43.178*	2.5958	.000	-51.281	-35.074
		5	-56.089*	2.5958	.000	-64.192	-47.985
		6	-73.533*	2.5958	.000	-81.637	-65.430
	2	1	8.678*	2.5958	.027	.574	16.781
		3	-20.011*	2.5958	.000	-28.115	-11.908
		4	-34.500*	2.5958	.000	-42.604	-26.396
		5	-47.411*	2.5958	.000	-55.515	-39.308
		6	-64.856*	2.5958	.000	-72.959	-56.752
	3	1	28.689*	2.5958	.000	20.585	36.792
		2	20.011*	2.5958	.000	11.908	28.115
		4	-14.489*	2.5958	.000	-22.592	-6.385
		5	-27.400*	2.5958	.000	-35.504	-19.296
		6	-44.844*	2.5958	.000	-52.948	-36.741
	4	1	43.178*	2.5958	.000	35.074	51.281
		2	34.500*	2.5958	.000	26.396	42.604
		3	14.489*	2.5958	.000	6.385	22.592
		5	-12.911*	2.5958	.000	-21.015	-4.808
		6	-30.356*	2.5958	.000	-38.459	-22.252
	5	1	56.089*	2.5958	.000	47.985	64.192
		2	47.411*	2.5958	.000	39.308	55.515
		3	27.400*	2.5958	.000	19.296	35.504
		4	12.911*	2.5958	.000	4.808	21.015
		6	-17.444*	2.5958	.000	-25.548	-9.341
	6	1	73.533*	2.5958	.000	65.430	81.637
		2	64.856*	2.5958	.000	56.752	72.959
		3	44.844*	2.5958	.000	36.741	52.948
		4	30.356*	2.5958	.000	22.252	38.459
		5	17.444*	2.5958	.000	9.341	25.548

Table 18 Plant Height Showing Post Hoc Tests

	Treat	N	Subset			
			1	2	3	4
Tukey HSD[a,b]	L0N2	6	39.067			
	L0N1	6	41.500	41.500		
	L2N0	6	45.500	45.500	45.500	
	L0N0	6		51.250	51.250	51.250
	L1N2	6			52.917	52.917
	L1N0	6			54.883	54.883
	L2N2	6				56.800
	L1N1	6				57.833
	L2N1	6				58.000
	Sig.		.537	.082	.107	.473

Table 19 Descriptive Statistics for Leaf Area Index (LAI)

Treat	Week	Mean	Std. Deviation	N
L0N0	1	31.000	.	1
	2	40.100	.	1
	3	48.500	.	1
	4	62.000	.	1
	5	76.300	.	1
	6	84.450	.	1
	Total	57.058	20.9037	6
L0N1	1	28.000	.	1
	2	35.000	.	1
	3	42.000	.	1
	4	51.000	.	1
	5	64.000	.	1
	6	73.000	.	1
	Total	48.833	17.2675	6
L0N2	1	26.000	.	1
	2	36.000	.	1
	3	41.000	.	1
	4	54.000	.	1
	5	67.000	.	1
	6	75.000	.	1
	Total	49.833	18.8830	6
L1N0	1	29.000	.	1
	2	39.000	.	1
	3	46.300	.	1
	4	59.800	.	1
	5	71.300	.	1
	6	98.600	.	1
	Total	57.333	25.1584	6
L1N1	1	31.000	.	1
	2	42.000	.	1
	3	50.400	.	1
	4	63.600	.	1

	5	79.200	.	1
	6	101.000	.	1
	Total	61.200	25.7337	6
L1N2	1	38.000	.	1
	2	47.300	.	1
	3	56.800	.	1
	4	66.300	.	1
	5	77.200	.	1
	6	84.700	.	1
	Total	61.717	17.7959	6
L2N0	1	32.000	.	1
	2	38.000	.	1
	3	46.700	.	1
	4	59.400	.	1
	5	69.100	.	1
	6	78.600	.	1
	Total	53.967	18.1968	6
L2N1	1	41.000	.	1
	2	49.000	.	1
	3	58.100	.	1
	4	69.800	.	1
	5	79.300	.	1
	6	87.200	.	1
	Total	64.067	17.8592	6
L2N2	1	36.000	.	1
	2	45.000	.	1
	3	53.000	.	1
	4	66.000	.	1
	5	78.400	.	1
	6	85.100	.	1
	Total	60.583	19.2485	6
Total	1	32.444	4.9272	9
	2	41.267	4.9353	9
	3	49.200	5.9904	9
	4	61.322	6.0245	9
	5	73.533	5.7918	9
	6	85.294	9.5550	9
	Total	57.177	19.4253	54

Table 20 Leaf Area Index (LAI) for Six Weeks Duration

Week	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	32.444	1.277	29.864	35.025
2	41.267	1.277	38.686	43.847
3	49.200	1.277	46.620	51.780
4	61.322	1.277	58.742	63.902
5	73.533	1.277	70.953	76.114
6	85.294	1.277	82.714	87.875

Table 21 Leaf Area Index (LAI) for Individual Treatment Combinations

Dependent Variable: LAI

				95% Confidence Interval	
Treat	Week	Mean	Std. Error	Lower Bound	Upper Bound
L0N0	1	32.326	1.950	28.385	36.267
	2	41.148	1.950	37.207	45.089
	3	49.081	1.950	45.140	53.023
	4	61.204	1.950	57.262	65.145
	5	73.415	1.950	69.474	77.356
	6	85.176	1.950	81.235	89.117
L0N1	1	24.101	1.950	20.160	28.042
	2	32.923	1.950	28.982	36.864
	3	40.856	1.950	36.915	44.798
	4	52.979	1.950	49.037	56.920
	5	65.190	1.950	61.249	69.131
	6	76.951	1.950	73.010	80.892
L0N2	1	25.101	1.950	21.160	29.042
	2	33.923	1.950	29.982	37.864
	3	41.856	1.950	37.915	45.798
	4	53.979	1.950	50.037	57.920
	5	66.190	1.950	62.249	70.131
	6	77.951	1.950	74.010	81.892
L1N0	1	32.601	1.950	28.660	36.542
	2	41.423	1.950	37.482	45.364
	3	49.356	1.950	45.415	53.298
	4	61.479	1.950	57.537	65.420
	5	73.690	1.950	69.749	77.631
	6	85.451	1.950	81.510	89.392
L1N1	1	36.468	1.950	32.526	40.409
	2	45.290	1.950	41.349	49.231
	3	53.223	1.950	49.282	57.164
	4	65.345	1.950	61.404	69.287
	5	77.556	1.950	73.615	81.498
	6	89.318	1.950	85.376	93.259
L1N2	1	36.984	1.950	33.043	40.926
	2	45.806	1.950	41.865	49.748
	3	53.740	1.950	49.799	57.681
	4	65.862	1.950	61.921	69.803
	5	78.073	1.950	74.132	82.014
	6	89.834	1.950	85.893	93.776
L2N0	1	29.234	1.950	25.293	33.176
	2	38.056	1.950	34.115	41.998
	3	45.990	1.950	42.049	49.931
	4	58.112	1.950	54.171	62.053
	5	70.323	1.950	66.382	74.264
	6	82.084	1.950	78.143	86.026
L2N1	1	39.334	1.950	35.393	43.276
	2	48.156	1.950	44.215	52.098
	3	56.090	1.950	52.149	60.031
	4	68.212	1.950	64.271	72.153
	5	80.423	1.950	76.482	84.364
	6	92.184	1.950	88.243	96.126
L2N2	1	35.851	1.950	31.910	39.792
	2	44.673	1.950	40.732	48.614
	3	52.606	1.950	48.665	56.548

4	64.729	1.950	60.787	68.670
5	76.940	1.950	72.999	80.881
6	88.701	1.950	84.760	92.642

Table 22 Leaf Area Index (LAI) showing Post Hoc Tests

	(I) Treat	(J) Treat	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	L0N0	L0N1	8.225*	2.2112	.016	.979	15.471
		L0N2	7.225	2.2112	.051	-.021	14.471
		L1N0	-.275	2.2112	1.000	-7.521	6.971
		L1N1	-4.142	2.2112	.635	-11.388	3.105
		L1N2	-4.658	2.2112	.483	-11.905	2.588
		L2N0	3.092	2.2112	.892	-4.155	10.338
		L2N1	-7.008	2.2112	.065	-14.255	.238
		L2N2	-3.525	2.2112	.802	-10.771	3.721
	L0N1	L0N0	-8.225*	2.2112	.016	-15.471	-.979
		L0N2	-1.000	2.2112	1.000	-8.246	6.246
		L1N0	-8.500*	2.2112	.011	-15.746	-1.254
		L1N1	-12.367*	2.2112	.000	-19.613	-5.120
		L1N2	-12.883*	2.2112	.000	-20.130	-5.637
		L2N0	-5.133	2.2112	.354	-12.380	2.113
		L2N1	-15.233*	2.2112	.000	-22.480	-7.987
		L2N2	-11.750*	2.2112	.000	-18.996	-4.504
	L0N2	L0N0	-7.225	2.2112	.051	-14.471	.021
		L0N1	1.000	2.2112	1.000	-6.246	8.246
		L1N0	-7.500*	2.2112	.038	-14.746	-.254
		L1N1	-11.367*	2.2112	.000	-18.613	-4.120
		L1N2	-11.883*	2.2112	.000	-19.130	-4.637
		L2N0	-4.133	2.2112	.638	-11.380	3.113
		L2N1	-14.233*	2.2112	.000	-21.480	-6.987
		L2N2	-10.750*	2.2112	.001	-17.996	-3.504
	L1N0	L0N0	.275	2.2112	1.000	-6.971	7.521
		L0N1	8.500*	2.2112	.011	1.254	15.746
		L0N2	7.500*	2.2112	.038	.254	14.746
		L1N1	-3.867	2.2112	.714	-11.113	3.380
		L1N2	-4.383	2.2112	.564	-11.630	2.863
		L2N0	3.367	2.2112	.838	-3.880	10.613
		L2N1	-6.733	2.2112	.086	-13.980	.513
		L2N2	-3.250	2.2112	.863	-10.496	3.996
	L1N1	L0N0	4.142	2.2112	.635	-3.105	11.388
		L0N1	12.367*	2.2112	.000	5.120	19.613
		L0N2	11.367*	2.2112	.000	4.120	18.613
		L1N0	3.867	2.2112	.714	-3.380	11.113
		L1N2	-.517	2.2112	1.000	-7.763	6.730
		L2N0	7.233	2.2112	.051	-.013	14.480
		L2N1	-2.867	2.2112	.927	-10.113	4.380
		L2N2	.617	2.2112	1.000	-6.630	7.863
	L1N2	L0N0	4.658	2.2112	.483	-2.588	11.905

		L0N1	12.883*	2.2112	.000	5.637	20.130
		L0N2	11.883*	2.2112	.000	4.637	19.130
		L1N0	4.383	2.2112	.564	-2.863	11.630
		L1N1	.517	2.2112	1.000	-6.730	7.763
		L2N0	7.750*	2.2112	.028	.504	14.996
		L2N1	-2.350	2.2112	.976	-9.596	4.896
		L2N2	1.133	2.2112	1.000	-6.113	8.380
	L2N0	L0N0	-3.092	2.2112	.892	-10.338	4.155
		L0N1	5.133	2.2112	.354	-2.113	12.380
		L0N2	4.133	2.2112	.638	-3.113	11.380
		L1N0	-3.367	2.2112	.838	-10.613	3.880
		L1N1	-7.233	2.2112	.051	-14.480	.013
		L1N2	-7.750*	2.2112	.028	-14.996	-.504
		L2N1	-10.100*	2.2112	.001	-17.346	-2.854
		L2N2	-6.617	2.2112	.097	-13.863	.630
	L2N1	L0N0	7.008	2.2112	.065	-.238	14.255
		L0N1	15.233*	2.2112	.000	7.987	22.480
		L0N2	14.233*	2.2112	.000	6.987	21.480
		L1N0	6.733	2.2112	.086	-.513	13.980
		L1N1	2.867	2.2112	.927	-4.380	10.113
		L1N2	2.350	2.2112	.976	-4.896	9.596
		L2N0	10.100*	2.2112	.001	2.854	17.346
		L2N2	3.483	2.2112	.812	-3.763	10.730
	L2N2	L0N0	3.525	2.2112	.802	-3.721	10.771
		L0N1	11.750*	2.2112	.000	4.504	18.996
		L0N2	10.750*	2.2112	.001	3.504	17.996
		L1N0	3.250	2.2112	.863	-3.996	10.496
		L1N1	-.617	2.2112	1.000	-7.863	6.630
		L1N2	-1.133	2.2112	1.000	-8.380	6.113
		L2N0	6.617	2.2112	.097	-.630	13.863
		L2N1	-3.483	2.2112	.812	-10.730	3.763
LSD	L0N0	L0N1	8.225*	2.2112	.001	3.756	12.694
		L0N2	7.225*	2.2112	.002	2.756	11.694
		L1N0	-.275	2.2112	.902	-4.744	4.194
		L1N1	-4.142	2.2112	.068	-8.611	.327
		L1N2	-4.658*	2.2112	.041	-9.127	-.189
		L2N0	3.092	2.2112	.170	-1.377	7.561
		L2N1	-7.008*	2.2112	.003	-11.477	-2.539
		L2N2	-3.525	2.2112	.119	-7.994	.944
	L0N1	L0N0	-8.225*	2.2112	.001	-12.694	-3.756
		L0N2	-1.000	2.2112	.654	-5.469	3.469
		L1N0	-8.500*	2.2112	.000	-12.969	-4.031
		L1N1	-12.367*	2.2112	.000	-16.836	-7.898
		L1N2	-12.883*	2.2112	.000	-17.352	-8.414
		L2N0	-5.133*	2.2112	.025	-9.602	-.664
		L2N1	-15.233*	2.2112	.000	-19.702	-10.764
		L2N2	-11.750*	2.2112	.000	-16.219	-7.281
	L0N2	L0N0	-7.225*	2.2112	.002	-11.694	-2.756
		L0N1	1.000	2.2112	.654	-3.469	5.469
		L1N0	-7.500*	2.2112	.002	-11.969	-3.031
		L1N1	-11.367*	2.2112	.000	-15.836	-6.898
		L1N2	-11.883*	2.2112	.000	-16.352	-7.414
		L2N0	-4.133	2.2112	.069	-8.602	.336

		L2N1	-14.233*	2.2112	.000	-18.702	-9.764
		L2N2	-10.750*	2.2112	.000	-15.219	-6.281
	L1N0	L0N0	.275	2.2112	.902	-4.194	4.744
		L0N1	8.500*	2.2112	.000	4.031	12.969
		L0N2	7.500*	2.2112	.002	3.031	11.969
		L1N1	-3.867	2.2112	.088	-8.336	.602
		L1N2	-4.383	2.2112	.054	-8.852	.086
		L2N0	3.367	2.2112	.136	-1.102	7.836
		L2N1	-6.733*	2.2112	.004	-11.202	-2.264
		L2N2	-3.250	2.2112	.149	-7.719	1.219
	L1N1	L0N0	4.142	2.2112	.068	-.327	8.611
		L0N1	12.367*	2.2112	.000	7.898	16.836
		L0N2	11.367*	2.2112	.000	6.898	15.836
		L1N0	3.867	2.2112	.088	-.602	8.336
		L1N2	-.517	2.2112	.816	-4.986	3.952
		L2N0	7.233*	2.2112	.002	2.764	11.702
		L2N1	-2.867	2.2112	.202	-7.336	1.602
		L2N2	.617	2.2112	.782	-3.852	5.086
	L1N2	L0N0	4.658*	2.2112	.041	.189	9.127
		L0N1	12.883*	2.2112	.000	8.414	17.352
		L0N2	11.883*	2.2112	.000	7.414	16.352
		L1N0	4.383	2.2112	.054	-.086	8.852
		L1N1	.517	2.2112	.816	-3.952	4.986
		L2N0	7.750*	2.2112	.001	3.281	12.219
		L2N1	-2.350	2.2112	.294	-6.819	2.119
		L2N2	1.133	2.2112	.611	-3.336	5.602
	L2N0	L0N0	-3.092	2.2112	.170	-7.561	1.377
		L0N1	5.133*	2.2112	.025	.664	9.602
		L0N2	4.133	2.2112	.069	-.336	8.602
		L1N0	-3.367	2.2112	.136	-7.836	1.102
		L1N1	-7.233*	2.2112	.002	-11.702	-2.764
		L1N2	-7.750*	2.2112	.001	-12.219	-3.281
		L2N1	-10.100*	2.2112	.000	-14.569	-5.631
		L2N2	-6.617*	2.2112	.005	-11.086	-2.148
	L2N1	L0N0	7.008*	2.2112	.003	2.539	11.477
		L0N1	15.233*	2.2112	.000	10.764	19.702
		L0N2	14.233*	2.2112	.000	9.764	18.702
		L1N0	6.733*	2.2112	.004	2.264	11.202
		L1N1	2.867	2.2112	.202	-1.602	7.336
		L1N2	2.350	2.2112	.294	-2.119	6.819
		L2N0	10.100*	2.2112	.000	5.631	14.569
		L2N2	3.483	2.2112	.123	-.986	7.952
	L2N2	L0N0	3.525	2.2112	.119	-.944	7.994
		L0N1	11.750*	2.2112	.000	7.281	16.219
		L0N2	10.750*	2.2112	.000	6.281	15.219
		L1N0	3.250	2.2112	.149	-1.219	7.719
		L1N1	-.617	2.2112	.782	-5.086	3.852
		L1N2	-1.133	2.2112	.611	-5.602	3.336
		L2N0	6.617*	2.2112	.005	2.148	11.086
		L2N1	-3.483	2.2112	.123	-7.952	.986
Bonferroni	L0N0	L0N1	8.225*	2.2112	.022	.627	15.823
		L0N2	7.225	2.2112	.080	-.373	14.823
		L1N0	-.275	2.2112	1.000	-7.873	7.323
		L1N1	-4.142	2.2112	1.000	-11.740	3.456
		L1N2	-4.658	2.2112	1.000	-12.256	2.940
		L2N0	3.092	2.2112	1.000	-4.506	10.690

		L2N1	-7.008	2.2112	.105	-14.606	.590
		L2N2	-3.525	2.2112	1.000	-11.123	4.073
	L0N1	L0N0	-8.225*	2.2112	.022	-15.823	-.627
		L0N2	-1.000	2.2112	1.000	-8.598	6.598
		L1N0	-8.500*	2.2112	.015	-16.098	-.902
		L1N1	-12.367*	2.2112	.000	-19.965	-4.769
		L1N2	-12.883*	2.2112	.000	-20.481	-5.285
		L2N0	-5.133	2.2112	.916	-12.731	2.465
		L2N1	-15.233*	2.2112	.000	-22.831	-7.635
		L2N2	-11.750*	2.2112	.000	-19.348	-4.152
	L0N2	L0N0	-7.225	2.2112	.080	-14.823	.373
		L0N1	1.000	2.2112	1.000	-6.598	8.598
		L1N0	-7.500	2.2112	.057	-15.098	.098
		L1N1	-11.367*	2.2112	.000	-18.965	-3.769
		L1N2	-11.883*	2.2112	.000	-19.481	-4.285
		L2N0	-4.133	2.2112	1.000	-11.731	3.465
		L2N1	-14.233*	2.2112	.000	-21.831	-6.635
		L2N2	-10.750*	2.2112	.001	-18.348	-3.152
	L1N0	L0N0	.275	2.2112	1.000	-7.323	7.873
		L0N1	8.500*	2.2112	.015	.902	16.098
		L0N2	7.500	2.2112	.057	-.098	15.098
		L1N1	-3.867	2.2112	1.000	-11.465	3.731
		L1N2	-4.383	2.2112	1.000	-11.981	3.215
		L2N0	3.367	2.2112	1.000	-4.231	10.965
		L2N1	-6.733	2.2112	.148	-14.331	.865
		L2N2	-3.250	2.2112	1.000	-10.848	4.348
	L1N1	L0N0	4.142	2.2112	1.000	-3.456	11.740
		L0N1	12.367*	2.2112	.000	4.769	19.965
		L0N2	11.367*	2.2112	.000	3.769	18.965
		L1N0	3.867	2.2112	1.000	-3.731	11.465
		L1N2	-.517	2.2112	1.000	-8.115	7.081
		L2N0	7.233	2.2112	.080	-.365	14.831
		L2N1	-2.867	2.2112	1.000	-10.465	4.731
		L2N2	.617	2.2112	1.000	-6.981	8.215
	L1N2	L0N0	4.658	2.2112	1.000	-2.940	12.256
		L0N1	12.883*	2.2112	.000	5.285	20.481
		L0N2	11.883*	2.2112	.000	4.285	19.481
		L1N0	4.383	2.2112	1.000	-3.215	11.981
		L1N1	.517	2.2112	1.000	-7.081	8.115
		L2N0	7.750*	2.2112	.041	.152	15.348
		L2N1	-2.350	2.2112	1.000	-9.948	5.248
		L2N2	1.133	2.2112	1.000	-6.465	8.731
	L2N0	L0N0	-3.092	2.2112	1.000	-10.690	4.506
		L0N1	5.133	2.2112	.916	-2.465	12.731
		L0N2	4.133	2.2112	1.000	-3.465	11.731
		L1N0	-3.367	2.2112	1.000	-10.965	4.231
		L1N1	-7.233	2.2112	.080	-14.831	.365
		L1N2	-7.750*	2.2112	.041	-15.348	-.152
		L2N1	-10.100*	2.2112	.002	-17.698	-2.502
		L2N2	-6.617	2.2112	.170	-14.215	.981
	L2N1	L0N0	7.008	2.2112	.105	-.590	14.606
		L0N1	15.233*	2.2112	.000	7.635	22.831

		L0N2	14.233*	2.2112	.000	6.635	21.831
		L1N0	6.733	2.2112	.148	-.865	14.331
		L1N1	2.867	2.2112	1.000	-4.731	10.465
		L1N2	2.350	2.2112	1.000	-5.248	9.948
		L2N0	10.100*	2.2112	.002	2.502	17.698
		L2N2	3.483	2.2112	1.000	-4.115	11.081
	L2N2	L0N0	3.525	2.2112	1.000	-4.073	11.123
		L0N1	11.750*	2.2112	.000	4.152	19.348
		L0N2	10.750*	2.2112	.001	3.152	18.348
		L1N0	3.250	2.2112	1.000	-4.348	10.848
		L1N1	-.617	2.2112	1.000	-8.215	6.981
		L1N2	-1.133	2.2112	1.000	-8.731	6.465
		L2N0	6.617	2.2112	.170	-.981	14.215
		L2N1	-3.483	2.2112	1.000	-11.081	4.115

Table 23 Above Ground Biomass Descriptive (AGB) Statistics

Treat	Week	Mean	Std. Deviation	N
L0N0	1	10.000	.	1
	2	16.600	.	1
	3	23.800	.	1
	4	34.200	.	1
	5	56.100	.	1
	6	82.400	.	1
	Total	37.183	27.3971	6
L0N1	1	16.600	.	1
	2	21.800	.	1
	3	25.600	.	1
	4	39.000	.	1
	5	44.000	.	1
	6	61.000	.	1
	Total	34.667	16.5740	6
L0N2	1	16.200	.	1
	2	20.200	.	1
	3	25.000	.	1
	4	36.000	.	1
	5	42.100	.	1
	6	58.400	.	1
	Total	32.983	15.7927	6
L1N0	1	18.700	.	1
	2	22.000	.	1
	3	24.000	.	1
	4	37.000	.	1
	5	45.500	.	1
	6	69.600	.	1
	Total	36.133	19.2842	6
L1N1	1	23.000	.	1
	2	28.000	.	1
	3	34.000	.	1
	4	44.000	.	1
	5	51.000	.	1
	6	72.000	.	1
	Total	42.000	17.9221	6

L1N2	1	23.000	.	1
	2	35.100	.	1
	3	46.600	.	1
	4	59.800	.	1
	5	66.300	.	1
	6	79.300	.	1
	Total	51.683	20.8124	6
L2N0	1	22.000	.	1
	2	29.500	.	1
	3	38.400	.	1
	4	46.800	.	1
	5	66.600	.	1
	6	74.800	.	1
	Total	46.350	20.7832	6
L2N1	1	25.000	.	1
	2	36.000	.	1
	3	48.200	.	1
	4	63.800	.	1
	5	69.400	.	1
	6	89.900	.	1
	Total	55.383	23.7030	6
L2N2	1	23.000	.	1
	2	31.000	.	1
	3	42.800	.	1
	4	59.300	.	1
	5	63.000	.	1
	6	86.900	.	1
	Total	51.000	23.4646	6
Total	1	19.722	4.7827	9
	2	26.689	6.8504	9
	3	34.267	10.0757	9
	4	46.656	11.4792	9
	5	56.000	10.7208	9
	6	74.922	10.8776	9
	Total	43.043	20.8593	54

Table 24 Estimated Marginal Means for Aboveground Biomass Treatment 1

			95% Confidence Interval	
Treat	Mean	Std. Error	Lower Bound	Upper Bound
L0N0	37.183	1.996	33.149	41.218
L0N1	34.667	1.996	30.632	38.701
L0N2	32.983	1.996	28.949	37.018
L1N0	36.133	1.996	32.099	40.168
L1N1	42.000	1.996	37.965	46.035
L1N2	51.683	1.996	47.649	55.718
L2N0	46.350	1.996	42.315	50.385
L2N1	55.383	1.996	51.349	59.418
L2N2	51.000	1.996	46.965	55.035

Table 25 Estimated Marginal Means for Aboveground Biomass Week 2

Week	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	19.722	1.630	16.428	23.017
2	26.689	1.630	23.394	29.983
3	34.267	1.630	30.972	37.561
4	46.656	1.630	43.361	49.950
5	56.000	1.630	52.706	59.294
6	74.922	1.630	71.628	78.217

Table 26 Estimated Marginal Means for Aboveground Biomass at 95% C.I

Treat	Week	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
L0N0	1	13.863	2.490	8.831	18.895
	2	20.830	2.490	15.797	25.862
	3	28.407	2.490	23.375	33.440
	4	40.796	2.490	35.764	45.829
	5	50.141	2.490	45.108	55.173
	6	69.063	2.490	64.031	74.095
L0N1	1	11.346	2.490	6.314	16.379
	2	18.313	2.490	13.281	23.345
	3	25.891	2.490	20.858	30.923
	4	38.280	2.490	33.247	43.312
	5	47.624	2.490	42.592	52.656
	6	66.546	2.490	61.514	71.579
L0N2	1	9.663	2.490	4.631	14.695
	2	16.630	2.490	11.597	21.662
	3	24.207	2.490	19.175	29.240
	4	36.596	2.490	31.564	41.629
	5	45.941	2.490	40.908	50.973
	6	64.863	2.490	59.831	69.895
L1N0	1	12.813	2.490	7.781	17.845
	2	19.780	2.490	14.747	24.812
	3	27.357	2.490	22.325	32.390
	4	39.746	2.490	34.714	44.779
	5	49.091	2.490	44.058	54.123
	6	68.013	2.490	62.981	73.045
L1N1	1	18.680	2.490	13.647	23.712
	2	25.646	2.490	20.614	30.679
	3	33.224	2.490	28.192	38.256
	4	45.613	2.490	40.581	50.645
	5	54.957	2.490	49.925	59.990
	6	73.880	2.490	68.847	78.912
L1N2	1	28.363	2.490	23.331	33.395
	2	35.330	2.490	30.297	40.362
	3	42.907	2.490	37.875	47.940
	4	55.296	2.490	50.264	60.329
	5	64.641	2.490	59.608	69.673

	6	83.563	2.490	78.531	88.595
L2N0	1	23.030	2.490	17.997	28.062
	2	29.996	2.490	24.964	35.029
	3	37.574	2.490	32.542	42.606
	4	49.963	2.490	44.931	54.995
	5	59.307	2.490	54.275	64.340
	6	78.230	2.490	73.197	83.262
L2N1	1	32.063	2.490	27.031	37.095
	2	39.030	2.490	33.997	44.062
	3	46.607	2.490	41.575	51.640
	4	58.996	2.490	53.964	64.029
	5	68.341	2.490	63.308	73.373
	6	87.263	2.490	82.231	92.295
L2N2	1	27.680	2.490	22.647	32.712
	2	34.646	2.490	29.614	39.679
	3	42.224	2.490	37.192	47.256
	4	54.613	2.490	49.581	59.645
	5	63.957	2.490	58.925	68.990
	6	82.880	2.490	77.847	87.912

Table 27 Multiple Comparisons for Aboveground Biomass and Post Hoc Tests

						95% Confidence Interval	
	(I) Treat	(J) Treat	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
Tukey HSD	L0N0	L0N1	2.517	2.8233	.992	-6.735	11.769
		L0N2	4.200	2.8233	.855	-5.052	13.452
		L1N0	1.050	2.8233	1.000	-8.202	10.302
		L1N1	-4.817	2.8233	.739	-14.069	4.435
		L1N2	-14.500*	2.8233	.000	-23.752	-5.248
		L2N0	-9.167	2.8233	.054	-18.419	.085
		L2N1	-18.200*	2.8233	.000	-27.452	-8.948
		L2N2	-13.817*	2.8233	.001	-23.069	-4.565
	L0N1	L0N0	-2.517	2.8233	.992	-11.769	6.735
		L0N2	1.683	2.8233	1.000	-7.569	10.935
		L1N0	-1.467	2.8233	1.000	-10.719	7.785
		L1N1	-7.333	2.8233	.220	-16.585	1.919
		L1N2	-17.017*	2.8233	.000	-26.269	-7.765
		L2N0	-11.683*	2.8233	.005	-20.935	-2.431
		L2N1	-20.717*	2.8233	.000	-29.969	-11.465
		L2N2	-16.333*	2.8233	.000	-25.585	-7.081
	L0N2	L0N0	-4.200	2.8233	.855	-13.452	5.052
		L0N1	-1.683	2.8233	1.000	-10.935	7.569
		L1N0	-3.150	2.8233	.968	-12.402	6.102
		L1N1	-9.017	2.8233	.061	-18.269	.235
		L1N2	-18.700*	2.8233	.000	-27.952	-9.448
		L2N0	-13.367*	2.8233	.001	-22.619	-4.115
		L2N1	-22.400*	2.8233	.000	-31.652	-13.148
		L2N2	-18.017*	2.8233	.000	-27.269	-8.765
	L1N0	L0N0	-1.050	2.8233	1.000	-10.302	8.202

		L0N1	1.467	2.8233	1.000	-7.785	10.719
		L0N2	3.150	2.8233	.968	-6.102	12.402
		L1N1	-5.867	2.8233	.502	-15.119	3.385
		L1N2	-15.550*	2.8233	.000	-24.802	-6.298
		L2N0	-10.217*	2.8233	.021	-19.469	-.965
		L2N1	-19.250*	2.8233	.000	-28.502	-9.998
		L2N2	-14.867*	2.8233	.000	-24.119	-5.615
	L1N1	L0N0	4.817	2.8233	.739	-4.435	14.069
		L0N1	7.333	2.8233	.220	-1.919	16.585
		L0N2	9.017	2.8233	.061	-.235	18.269
		L1N0	5.867	2.8233	.502	-3.385	15.119
		L1N2	-9.683*	2.8233	.034	-18.935	-.431
		L2N0	-4.350	2.8233	.829	-13.602	4.902
		L2N1	-13.383*	2.8233	.001	-22.635	-4.131
		L2N2	-9.000	2.8233	.062	-18.252	.252
	L1N2	L0N0	14.500*	2.8233	.000	5.248	23.752
		L0N1	17.017*	2.8233	.000	7.765	26.269
		L0N2	18.700*	2.8233	.000	9.448	27.952
		L1N0	15.550*	2.8233	.000	6.298	24.802
		L1N1	9.683*	2.8233	.034	.431	18.935
		L2N0	5.333	2.8233	.625	-3.919	14.585
		L2N1	-3.700	2.8233	.922	-12.952	5.552
		L2N2	.683	2.8233	1.000	-8.569	9.935
	L2N0	L0N0	9.167	2.8233	.054	-.085	18.419
		L0N1	11.683*	2.8233	.005	2.431	20.935
		L0N2	13.367*	2.8233	.001	4.115	22.619
		L1N0	10.217*	2.8233	.021	.965	19.469
		L1N1	4.350	2.8233	.829	-4.902	13.602
		L1N2	-5.333	2.8233	.625	-14.585	3.919
		L2N1	-9.033	2.8233	.060	-18.285	.219
		L2N2	-4.650	2.8233	.773	-13.902	4.602
	L2N1	L0N0	18.200*	2.8233	.000	8.948	27.452
		L0N1	20.717*	2.8233	.000	11.465	29.969
		L0N2	22.400*	2.8233	.000	13.148	31.652
		L1N0	19.250*	2.8233	.000	9.998	28.502
		L1N1	13.383*	2.8233	.001	4.131	22.635
		L1N2	3.700	2.8233	.922	-5.552	12.952
		L2N0	9.033	2.8233	.060	-.219	18.285
		L2N2	4.383	2.8233	.824	-4.869	13.635
	L2N2	L0N0	13.817*	2.8233	.001	4.565	23.069
		L0N1	16.333*	2.8233	.000	7.081	25.585
		L0N2	18.017*	2.8233	.000	8.765	27.269
		L1N0	14.867*	2.8233	.000	5.615	24.119
		L1N1	9.000	2.8233	.062	-.252	18.252
		L1N2	-.683	2.8233	1.000	-9.935	8.569
		L2N0	4.650	2.8233	.773	-4.602	13.902
		L2N1	-4.383	2.8233	.824	-13.635	4.869
LSD	L0N0	L0N1	2.517	2.8233	.378	-3.189	8.223
		L0N2	4.200	2.8233	.145	-1.506	9.906
		L1N0	1.050	2.8233	.712	-4.656	6.756
		L1N1	-4.817	2.8233	.096	-10.523	.889
		L1N2	-14.500*	2.8233	.000	-20.206	-8.794

	L2N0	-9.167*	2.8233	.002	-14.873	-3.461
	L2N1	-18.200*	2.8233	.000	-23.906	-12.494
	L2N2	-13.817*	2.8233	.000	-19.523	-8.111
L0N1	L0N0	-2.517	2.8233	.378	-8.223	3.189
	L0N2	1.683	2.8233	.554	-4.023	7.389
	L1N0	-1.467	2.8233	.606	-7.173	4.239
	L1N1	-7.333*	2.8233	.013	-13.039	-1.627
	L1N2	-17.017*	2.8233	.000	-22.723	-11.311
	L2N0	-11.683*	2.8233	.000	-17.389	-5.977
	L2N1	-20.717*	2.8233	.000	-26.423	-15.011
	L2N2	-16.333*	2.8233	.000	-22.039	-10.627
L0N2	L0N0	-4.200	2.8233	.145	-9.906	1.506
	L0N1	-1.683	2.8233	.554	-7.389	4.023
	L1N0	-3.150	2.8233	.271	-8.856	2.556
	L1N1	-9.017*	2.8233	.003	-14.723	-3.311
	L1N2	-18.700*	2.8233	.000	-24.406	-12.994
	L2N0	-13.367*	2.8233	.000	-19.073	-7.661
	L2N1	-22.400*	2.8233	.000	-28.106	-16.694
	L2N2	-18.017*	2.8233	.000	-23.723	-12.311
L1N0	L0N0	-1.050	2.8233	.712	-6.756	4.656
	L0N1	1.467	2.8233	.606	-4.239	7.173
	L0N2	3.150	2.8233	.271	-2.556	8.856
	L1N1	-5.867*	2.8233	.044	-11.573	-.161
	L1N2	-15.550*	2.8233	.000	-21.256	-9.844
	L2N0	-10.217*	2.8233	.001	-15.923	-4.511
	L2N1	-19.250*	2.8233	.000	-24.956	-13.544
	L2N2	-14.867*	2.8233	.000	-20.573	-9.161
L1N1	L0N0	4.817	2.8233	.096	-.889	10.523
	L0N1	7.333*	2.8233	.013	1.627	13.039
	L0N2	9.017*	2.8233	.003	3.311	14.723
	L1N0	5.867*	2.8233	.044	.161	11.573
	L1N2	-9.683*	2.8233	.001	-15.389	-3.977
	L2N0	-4.350	2.8233	.131	-10.056	1.356
	L2N1	-13.383*	2.8233	.000	-19.089	-7.677
	L2N2	-9.000*	2.8233	.003	-14.706	-3.294
L1N2	L0N0	14.500*	2.8233	.000	8.794	20.206
	L0N1	17.017*	2.8233	.000	11.311	22.723
	L0N2	18.700*	2.8233	.000	12.994	24.406
	L1N0	15.550*	2.8233	.000	9.844	21.256
	L1N1	9.683*	2.8233	.001	3.977	15.389
	L2N0	5.333	2.8233	.066	-.373	11.039
	L2N1	-3.700	2.8233	.197	-9.406	2.006
	L2N2	.683	2.8233	.810	-5.023	6.389
L2N0	L0N0	9.167*	2.8233	.002	3.461	14.873
	L0N1	11.683*	2.8233	.000	5.977	17.389
	L0N2	13.367*	2.8233	.000	7.661	19.073
	L1N0	10.217*	2.8233	.001	4.511	15.923
	L1N1	4.350	2.8233	.131	-1.356	10.056
	L1N2	-5.333	2.8233	.066	-11.039	.373
	L2N1	-9.033*	2.8233	.003	-14.739	-3.327
	L2N2	-4.650	2.8233	.107	-10.356	1.056
L2N1	L0N0	18.200*	2.8233	.000	12.494	23.906
	L0N1	20.717*	2.8233	.000	15.011	26.423
	L0N2	22.400*	2.8233	.000	16.694	28.106
	L1N0	19.250*	2.8233	.000	13.544	24.956
	L1N1	13.383*	2.8233	.000	7.677	19.089

		L1N2	3.700	2.8233	.197	-2.006	9.406
		L2N0	9.033*	2.8233	.003	3.327	14.739
		L2N2	4.383	2.8233	.128	-1.323	10.089
	L2N2	L0N0	13.817*	2.8233	.000	8.111	19.523
		L0N1	16.333*	2.8233	.000	10.627	22.039
		L0N2	18.017*	2.8233	.000	12.311	23.723
		L1N0	14.867*	2.8233	.000	9.161	20.573
		L1N1	9.000*	2.8233	.003	3.294	14.706
		L1N2	-.683	2.8233	.810	-6.389	5.023
		L2N0	4.650	2.8233	.107	-1.056	10.356
		L2N1	-4.383	2.8233	.128	-10.089	1.323
Bonferroni	L0N0	L0N1	2.517	2.8233	1.000	-7.185	12.218
		L0N2	4.200	2.8233	1.000	-5.501	13.901
		L1N0	1.050	2.8233	1.000	-8.651	10.751
		L1N1	-4.817	2.8233	1.000	-14.518	4.885
		L1N2	-14.500*	2.8233	.000	-24.201	-4.799
		L2N0	-9.167	2.8233	.085	-18.868	.535
		L2N1	-18.200*	2.8233	.000	-27.901	-8.499
		L2N2	-13.817*	2.8233	.001	-23.518	-4.115
	L0N1	L0N0	-2.517	2.8233	1.000	-12.218	7.185
		L0N2	1.683	2.8233	1.000	-8.018	11.385
		L1N0	-1.467	2.8233	1.000	-11.168	8.235
		L1N1	-7.333	2.8233	.471	-17.035	2.368
		L1N2	-17.017*	2.8233	.000	-26.718	-7.315
		L2N0	-11.683*	2.8233	.006	-21.385	-1.982
		L2N1	-20.717*	2.8233	.000	-30.418	-11.015
		L2N2	-16.333*	2.8233	.000	-26.035	-6.632
	L0N2	L0N0	-4.200	2.8233	1.000	-13.901	5.501
		L0N1	-1.683	2.8233	1.000	-11.385	8.018
		L1N0	-3.150	2.8233	1.000	-12.851	6.551
		L1N1	-9.017	2.8233	.099	-18.718	.685
		L1N2	-18.700*	2.8233	.000	-28.401	-8.999
		L2N0	-13.367*	2.8233	.001	-23.068	-3.665
		L2N1	-22.400*	2.8233	.000	-32.101	-12.699
		L2N2	-18.017*	2.8233	.000	-27.718	-8.315
	L1N0	L0N0	-1.050	2.8233	1.000	-10.751	8.651
		L0N1	1.467	2.8233	1.000	-8.235	11.168
		L0N2	3.150	2.8233	1.000	-6.551	12.851
		L1N1	-5.867	2.8233	1.000	-15.568	3.835
		L1N2	-15.550*	2.8233	.000	-25.251	-5.849
		L2N0	-10.217*	2.8233	.030	-19.918	-.515
		L2N1	-19.250*	2.8233	.000	-28.951	-9.549
		L2N2	-14.867*	2.8233	.000	-24.568	-5.165
	L1N1	L0N0	4.817	2.8233	1.000	-4.885	14.518
		L0N1	7.333	2.8233	.471	-2.368	17.035
		L0N2	9.017	2.8233	.099	-.685	18.718
		L1N0	5.867	2.8233	1.000	-3.835	15.568
		L1N2	-9.683	2.8233	.051	-19.385	.018
		L2N0	-4.350	2.8233	1.000	-14.051	5.351
		L2N1	-13.383*	2.8233	.001	-23.085	-3.682
		L2N2	-9.000	2.8233	.100	-18.701	.701
	L1N2	L0N0	14.500*	2.8233	.000	4.799	24.201
		L0N1	17.017*	2.8233	.000	7.315	26.718

	L0N2	18.700*	2.8233	.000	8.999	28.401
	L1N0	15.550*	2.8233	.000	5.849	25.251
	L1N1	9.683	2.8233	.051	-.018	19.385
	L2N0	5.333	2.8233	1.000	-4.368	15.035
	L2N1	-3.700	2.8233	1.000	-13.401	6.001
	L2N2	.683	2.8233	1.000	-9.018	10.385
L2N0	L0N0	9.167	2.8233	.085	-.535	18.868
	L0N1	11.683*	2.8233	.006	1.982	21.385
	L0N2	13.367*	2.8233	.001	3.665	23.068
	L1N0	10.217*	2.8233	.030	.515	19.918
	L1N1	4.350	2.8233	1.000	-5.351	14.051
	L1N2	-5.333	2.8233	1.000	-15.035	4.368
	L2N1	-9.033	2.8233	.097	-18.735	.668
	L2N2	-4.650	2.8233	1.000	-14.351	5.051
L2N1	L0N0	18.200*	2.8233	.000	8.499	27.901
	L0N1	20.717*	2.8233	.000	11.015	30.418
	L0N2	22.400*	2.8233	.000	12.699	32.101
	L1N0	19.250*	2.8233	.000	9.549	28.951
	L1N1	13.383*	2.8233	.001	3.682	23.085
	L1N2	3.700	2.8233	1.000	-6.001	13.401
	L2N0	9.033	2.8233	.097	-.668	18.735
	L2N2	4.383	2.8233	1.000	-5.318	14.085
L2N2	L0N0	13.817*	2.8233	.001	4.115	23.518
	L0N1	16.333*	2.8233	.000	6.632	26.035
	L0N2	18.017*	2.8233	.000	8.315	27.718
	L1N0	14.867*	2.8233	.000	5.165	24.568
	L1N1	9.000	2.8233	.100	-.701	18.701
	L1N2	-.683	2.8233	1.000	-10.385	9.018
	L2N0	4.650	2.8233	1.000	-5.051	14.351
	L2N1	-4.383	2.8233	1.000	-14.085	5.318

Table 28 Root Biomass with Type 111 Sum of Squares

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	14210.159[a]	13	1093.089	38.558	.000
Intercept	32595.054	1	32595.054	1149.760	.000
Treat	2833.925	8	354.241	12.496	.000
Week	11376.234	5	2275.247	80.257	.000
Error	1133.977	40	28.349		
Total	47939.190	54			
Corrected Total	15344.136	53			

Table 29 Root Biomass Estimated Marginal Means

Treat	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
L0N0	22.500	2.174	18.107	26.893
L0N1	16.933	2.174	12.540	21.327
L0N2	15.133	2.174	10.740	19.527
L1N0	18.117	2.174	13.723	22.510
L1N1	19.683	2.174	15.290	24.077
L1N2	31.833	2.174	27.440	36.227
L2N0	29.517	2.174	25.123	33.910
L2N1	36.067	2.174	31.673	40.460
L2N2	31.333	2.174	26.940	35.727

Table 30: Analysis of Variance for Root Length

Source	**Seasons**	**Type III Sum of Squares**	**Df**	**Mean Square**	**F**	**Sig.**
Seasons	Linear	.623	1	.623	.426	.522
seasons * Treatment	Linear	9.230	8	1.154	.789	.619
Error(seasons)	Linear	26.337	18	1.463		

Table 31 Analysis of Variance for Root Biomass

Source	seasons	Type III Sum of Squares	df	Mean Square	F	Sig.
Seasons	Linear	14.519	1	14.519	2.640	.122
seasons * Treatment	Linear	233.481	8	29.185	5.306	.002
Error(seasons)	Linear	99.000	18	5.500		

APPENDIX 3: LIST OF FIGURES

Figure 20: Crop stand during early growth stages

Figure 21: Root density and biomass due to lime treatment effect

Figure 22: Root system architecture due to lime and nitrogen treatment effect

Figure 23: Chemotropic root response to lime and irrigated conditions

Figure 24: Effect of lime and nitrogen treatment on drying down rate (Senescence)

Figure 25: Cob appearance at physiological maturity.

Figure 26: Cob with bare tips

Figure 27: Yield variability from different treatment plots

Figure 28: Measurement of Cob Length

Figure 29: 1000 kernel yield evaluation