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Lime and Nitrogen Fertiliser Interaction in Influencing Root System Architecture in Sandy - Textured Soils in Zimbabwe

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Abstract: The plant rhizosphere should be treated as an indispensable plant organ in influencing an avalanche of crop plant physiological processes. The overall appearance of the rooting system of a plant is referred to as root system architecture (RSA). Soil scientists and plant breeders have made significant efforts in manipulating, inter alia; the structure, depth and functions of plant roots in order to boost the productivity of crops by withstanding both biotic and abiotic stresses. Morphological root characterisation together with other growth and yield parameters under irrigated conditions in a field trial was done using sandy loam soil occupied by a yellow/orange dent maize genotype SC402. Dolomitic lime (calcium magnesium carbonate) was used in the 9 treatments to determine the chemotropic response of maize plant roots to different levels of lime and nitrogen fertilisers. Maize has a moderate terminal root depth of $\pm$30cm with a root divergence angle of > 180^{o}. SC402 is an early maturing maize genotype of the 400 series suitable for low rainfall areas of Zimbabwe. It is one of the best yielding variety in terms of above ground biomass as well as kernel yield under both rainfall and soil nutrient – marginal conditions. Its organoleptic orange /yellow colouration due to presence of carotenoids has created a demand for culinary and livestock uses. A linear relationship was observed in the measured agronomic parameters of soil type, texture, depth, type and amount of lime applied in abiotic acidic soil stress conditions induced largely by nitrogen fertilisers. The findings of the study have revealed that morphological markers are more applicable in phenotypic root characterisation under field trials. A linear association was noted to exist between root density and maize growth and yield parameters under the influence of different lime and nitrogen regimes.

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Keywords: maize, root, root system architecture, abiotic stress, dolomitic lime, root characterisation.

1.0 Introduction

Plant roots are very indispensable in several plant processes. These include absorption of water and mineral salts, buttressing the plant, disease prevention through allelopathy as well as acting as sinks for photo assimilates in root crops like carrots, beetroot, radish and parsnip. Germination is technically considered the initial process of radicle emergence from the seed germplasm following imbibition. The major role of plant roots in plant growth and development has generated a lot of interest in the undertaking of processes that influence root system architecture (Meister et al, 2014, Furbank and Tester, 2011, Rascher et al, 2011). This study aims to explore the relationship between soil pH following liming and root development and architecture using coarse grained soil under field conditions. Roots exhibit an elasticity property in response to changes in soil chemical properties. This scientific phenomenon is called chemotropism, defined as the growth of organisms navigated by chemical stimulus from outside the organism (Reger et al, 1992). Thus roots can be positively or negatively chemotropic. Roots also grow down wards in the direction of the gravity vector and this is termed geotropism or gravitropism. Roots are by nature, positively geotropic in order to fulfil their role of support, nutrient and water scavenging as well as allelopathic functions.

The dynamism of root system architecture is influenced by environmental factors such as soil pH, climate and the ambient biota community to which roots detect and respond to (Bao et al., 2014, Robbins and Dinney, 2015). Root density, divergence angle and type of rooting system vary from one plant species to another although scientific principles can be implemented to manipulate root appearance and function. A lot of studies have paid more attention to the aerial plant parts at the neglect of below ground (root) parts yet plant abiotic stress tolerance is, to a larger extent, root dependant. Several scientific studies have revealed a linear relationship among yield parameters and stress factors with root characteristics (Kell, 2011; Hufnagel et al, 2014; Sugimoto et al., 2013, Nyarayanan et al., 2014). The element phosphorous is important in influencing root growth and development, but if the soil

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environment is not conducive relative to pH, ambient temperature, texture, depth and moisture; root development and architecture is compromised or deterred.

Maize (Zea mays L.) classical manual root characterisation despite being cumbersome remains useful in phenotypic root studies especially in developing countries with less advanced technologies (Beebe et al., 2013). Feyer et al (2014) contends that roots of plants are the prime organs to react to adverse drought conditions. However, it is sad to note that characterisation of roots is rarely conducted under actual field setting. Root density especially for those going deeper in search of water and leached nutrients like nitrate ions is very significant in the physiology of crop plants given the negative effects of climate change. Analysis of root depth, root branching as well as divergence angle are still considered and recommended as sound characterisation methods. This can be achieved through careful root excavation techniques to evaluate the aforesaid parameters. The study evaluated the response of maize genotype SC402 to different levels of dolomitic lime application rates in nitrate fertiliser acid induced field conditions using loam soils in Masvingo, Zimbabwe.

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2.0 MATERIALS AND METHODS

2.1 Plant Material and Experimental Reagents

A field study was conducted during the 2018/2019 and 2019/2020 agricultural summer season in Masvingo by the School of Agriculture and Natural Sciences under Great Zimbabwe University, Zimbabwe (latitude -21.446815, longitude 31.838409 and altitude 1.075m above sea level). The texture of the soil at the two experimental sites was classified as sandy. Maize (Zea mays L.) of a commercial yellow/orange dent cultivar SC402 known for its provitamin A properties was used. Prior to the onset of the experiment, a soil analysis for pH status, texture, depth and organic matter content was done in the Chemistry Laboratory of Great Zimbabwe University, Zimbabwe. The seed rate was 20 kgs per hectare.

An initial basal dressing fertiliser using compound D fertiliser with an NPK of 7.14.7 with trace element boron was applied using the hill placement method. The application rate was 5g per planting station (Manufacturer: Zimbabwe Fertiliser Company, ZFC). Dolomitic lime (Calcium Magnesium Carbonate/ $CaMg(CO_3)_2$ with an SNV of 109.0 (Bolan, 2003) was applied through broadcasting and incorporated in the soil to a 15cm depth using a handfork. The three rates of lime application were 0 tonnes per hectare, 1.5 tonnes per hectare and 3 tonnes per hectare. Lime application was done five weeks well before planting to allow the lime to react with the acid soil.

2.2 Experimental Design and Planting

The study was structured in a Split-split plot experimental design with three replicates per treatment. The Split-plot experiments are used in all industrial experiments (Box et al,2005 p336) . Ledolter (2010) contends that Split-plot designs are a form of blocked experiments in which blocks resemble experimental units for each subset factor, hence its suitability in this study. Each experimental unit or block was considered as a split plot/subplot as recommended by Cuthbert in Box et al,(ibid). There were 9 treatments randomised in a factorial arrangement thus the study assumed a 3x3 factorial arrangement. The interacting factors were lime, nitrogen and irrigated conditions. The maize genotype was established in 18 rows with each of the 3 replicates occupying 6 crop rows. Interrow and inrow spacing was 900mm x 250mm respectively. The length of each row was 18m. Total area for the main/whole plot was $612m^2$, $204m^2$ for the sub - plot and $10m^2$ for the net/ sub – sub plot. Each of the three replicates was separated by 1m. In order to observe the boarder effect, data was collected from the three central rows of the sub – sub plot/ net plot of each replicate. At each planting station, one seed was dropped into a 5cm depth planting hole. Overhead irrigation was done at all critical growth stages that encompass germination, vegetative phase, top dressing and reproductive as well as grain - filling stages.

3.0 RESULTS

Hydrotropism affected root length or depth negatively as it confined roots within the wet zone. This induced lodging in all treatments at physiological maturity or the hard dough stage. We therefore, conclude that root length variability across all treatments was insignificant under irrigated conditions as opposed to root density and root biomass. Therefore, we accept H_0 since $p>0.05$.

In both season 1 (2018/2019) and Season 2 (2019/2020), treatment 2 (T_2) had no effect on root length implying higher and successive treatments that would result in significant root length.

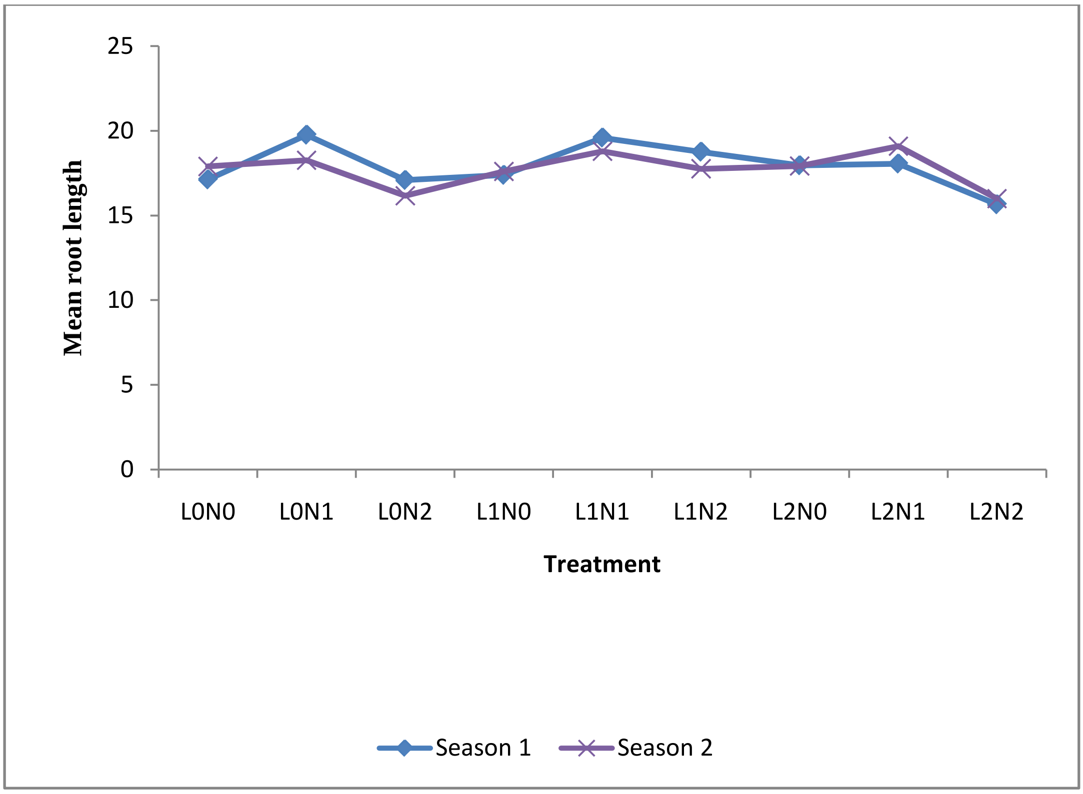
Total Standard Deviation (SD) for season 1 is 1.904 while for season 2 SD is 1.3643.

Grand Mean for season 1 for root length is 17.941 and 17.726 for season 2 . Therefore, the coefficients of variation (C.V.) for root length for season 1 and 2 were computed thus:

C.V = $\frac{SD}{\mu} \times 100 \left(\frac{1.5904}{17.941} X\ 100\right)$ C.V = $\frac{SD}{\mu} \times 100 \left(\frac{1.3643}{17.726} X\ 100\right)$

= 8.86 Season **1 (2018/2019)** = 7.70 Season **2 (2019/2020)**

The smaller the C.V. which is ≤ 15 is the expected C.V. of field crops like maize which is the crop under consideration in this study , the better or more precise the computed results.
The results of root length were both ≤ 15 thus making the outcomes valid and reliable also as confirmed by the Turkey's HSD Test and the Bonferroni Test.



3.1 Figure 1 Mean Root Length for season 1 and 2

Figure 1 above showed that the sample $\mu$for T_0 which is the control, was not significantly different, as well as that for the rest of the treatments T_1 to T_8. The mean root length ranges from 15.6 cm to 19.6 cm for minimum and maximum length in both season 1 and season 2. Cumulatively, they fall within the 16 – 20 cm range. Results in Figure 1 also show that, despite the lime level, nitrogen level 1 (0.2t/ha^{-1} N) has the highest mean root length.

3.2 Table 1 Root Length

Dependent Variable	Parameter	B	Std. Error	T	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Root Length Season 1	Intercept	15.667	.680	23.053	.000	14.239	17.094
	L0N0	1.467	.961	1.526	.144	-.553	3.486
	L0N1	4.100	.961	4.266	.000	2.081	6.119
	L0N2	1.433	.961	1.491	.153	-.586	3.453
	L1N0	1.733	.961	1.803	.088	-.286	3.753
	L1N1	3.933	.961	4.093	.001	1.914	5.953
	L1N2	3.100	.961	3.225	.005	1.081	5.119
	L2N0	2.300	.961	2.393	.028	.281	4.319
	L2N1	2.400	.961	2.497	.022	.381	4.419
	L2N2	0[a]	.	.	.	.	.
Root Length Season 2	Intercept	16.000	.637	25.132	.000	14.662	17.338
	L0N0	1.900	.900	2.110	.049	.008	3.792
	L0N1	2.267	.900	2.518	.022	.375	4.158
	L0N2	.167	.900	.185	.855	-1.725	2.058
	L1N0	1.600	.900	1.777	.092	-.292	3.492
	L1N1	2.800	.900	3.110	.006	.908	4.692
	L1N2	1.767	.900	1.962	.065	-.125	3.658
	L2N0	1.933	.900	2.147	.046	.042	3.825
	L2N1	3.100	.900	3.443	.003	1.208	4.992
	L2N2	0[a]	.	.	.	.	

Table 1 above shows that level 1 of nitrogen has significant effects ($p\text{-value}<0.05$) to root length in both season 1 and 2. This confirms the results displayed in Figure 1. The exclusion of 0 in the confidence intervals for treatment combinations with level 1 nitrogen also confirms the findings. However, in season 1 the treatment combination L0N1 had the highest significant increase in root length. In season 2, the combination L2N1 had the highest significant increase in root length implying that a treatment combination of $3t/ha^{-1}$L and $0.2t/ha^{-1}$N is the only significant treatment combination.

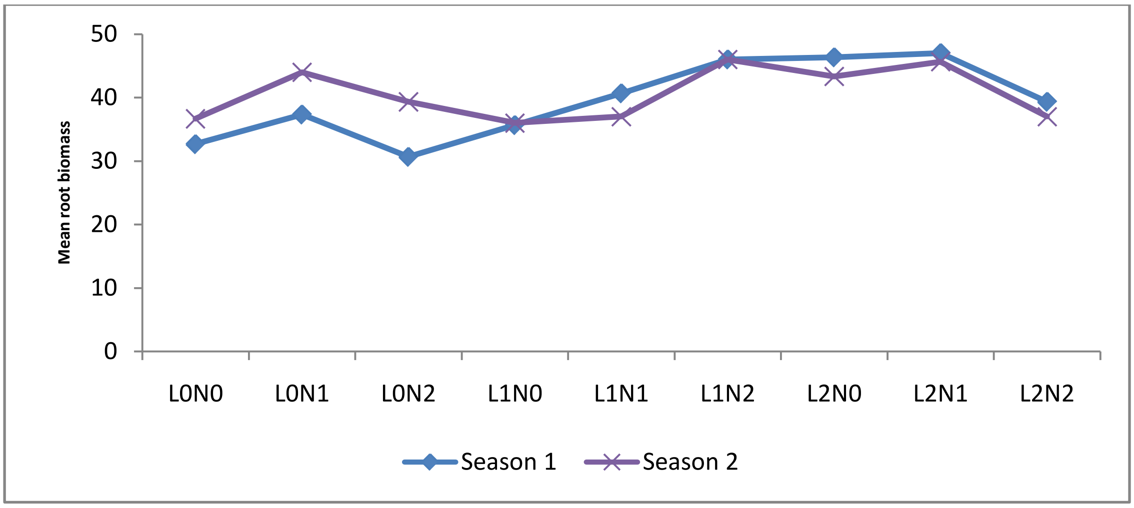
The study revealed a significant (>) root depth in treatments where lime rates were high coupled with increase in nitrate fertiliser rates. This was possibly linked to the type of lime used.

3.3 Table 2 Descriptive Statistics for Root Biomass

Descriptive Statistics

	Treatment	Mean	Std. Deviation	N
Root Biomass1	0	32.667	3.5119	3
	1	37.333	1.5275	3
	2	30.667	1.5275	3
	3	35.667	2.5166	3
	4	40.667	1.5275	3
	5	46.000	1.0000	3
	6	46.333	1.5275	3
	7	47.000	1.0000	3
	8	39.333	1.5275	3
	Total	39.519	6.0024	27
Root Biomass 2	0	36.667	1.5275	3
	1	44.000	3.0000	3
	2	39.333	6.5064	3
	3	36.000	1.0000	3
	4	37.000	1.0000	3
	5	46.000	3.0000	3
	6	43.333	3.7859	3
	7	45.667	3.2146	3
	8	37.000	1.0000	3
	Total	40.556	4.7824	27

Table 2 above shows that treatment 1 L0N1 (0t/ha^{-1}L and 0.2t/ha^{-1}N), treatment 3 (0t/ha^{-1}L and 0.4t/ha^{-1}N), treatment 4 (1.5t/ha^{-1}L and 0.2t/ha^{-1}N) and treatment 5 (1.5t/ha^{-1}L and 0.4t/ha^{-1}N) showed significant (p – value < 0.05) to root biomass in both season 1 and 2. However, in season 2 the treatment combinations of L0N1 and L1N2 (1.5t/ha^{-1}L and 0.2t/ha^{-1}N) had the highest significant increase in root biomass.

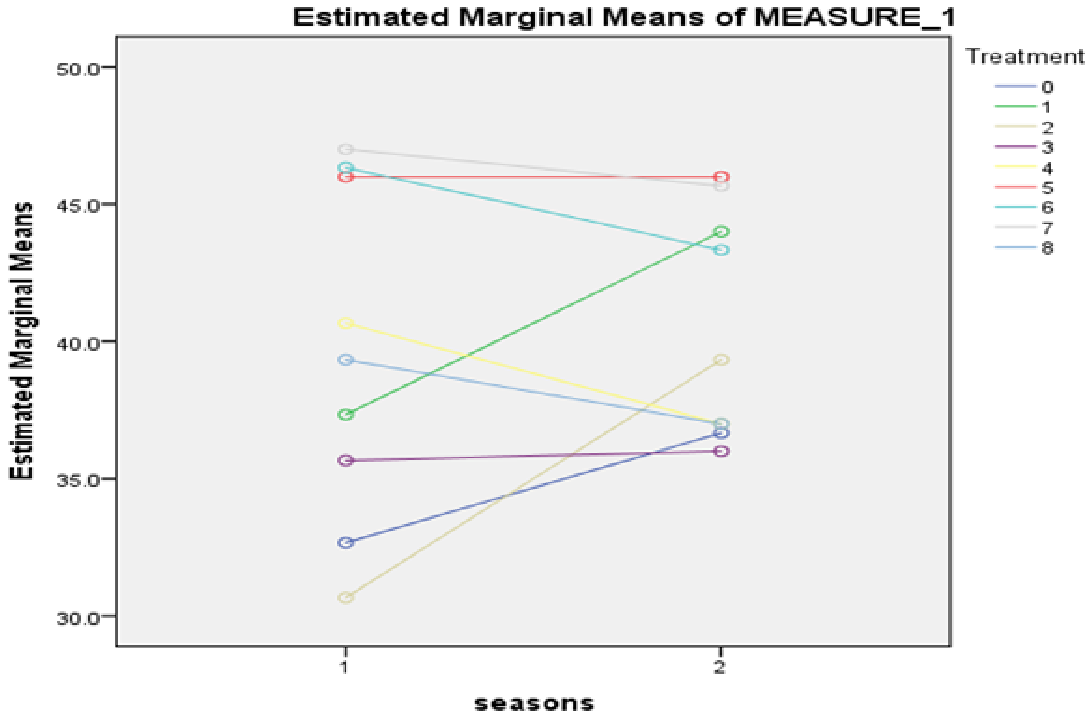


3.4 Figure 2: Comparisons of Root Biomass by Seasons

The mean (μ) for root biomass ranged from 37.3g for T_1 to 39.8 for T_8 with a coefficient of variation (CV) of 15.1. Hence the CV of maize and other cereals should not be more than 15, therefore, the 15.188 (CV) falls within the expected range. Season 2 showed an increase in mean (μ) root biomass as there was a paradigm shift from 37.3g for season 1 to 39.3g holding the control plot constant. There was a decline for T_8 to 37g signifying a point of inflexion/sufficiency following increased nitrogen and lime treatment combinations. Figure 2 graph, reflects the positive residual effect of lime and nitrogen treatment combinations for season 2 L0N1 and L0N2.

3.5 Analysis of Variance for root biomass

Results of the analysis of variance using the F-test also depict a significant interaction among the three factors namely Lime, Nitrogen and irrigation conditions when type 111 sum of squares has been factored in. This satisfies that the treatments to which belowground maize organs were exposed to vary significantly with seasons with an increase with successive seasons of lime applications. In both season 1 (2018/2019 and season 2 2019/2020) , Treatment L1N2 (1.5t/ha^{-1}L and 0.2t/ha^{-1}N) had the most significant effect on root biomass implying that a moderate lime application and optimal nitrogen rate are effective in promoting root biomass.



3.6 Figure 3 Marginal Means for Root biomass

The Estimated Marginal Means for T_1 and T_2 were higher in season 2 reflecting the same residual pattern of lime and nitrogen interactive effect. This is possibly the most favourable treatment combinations for promotion of a good root system architecture.

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3.8 Root diameter

3.9 Table 3 Statistical Description on Root Diameter

Descriptive Statistics

	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

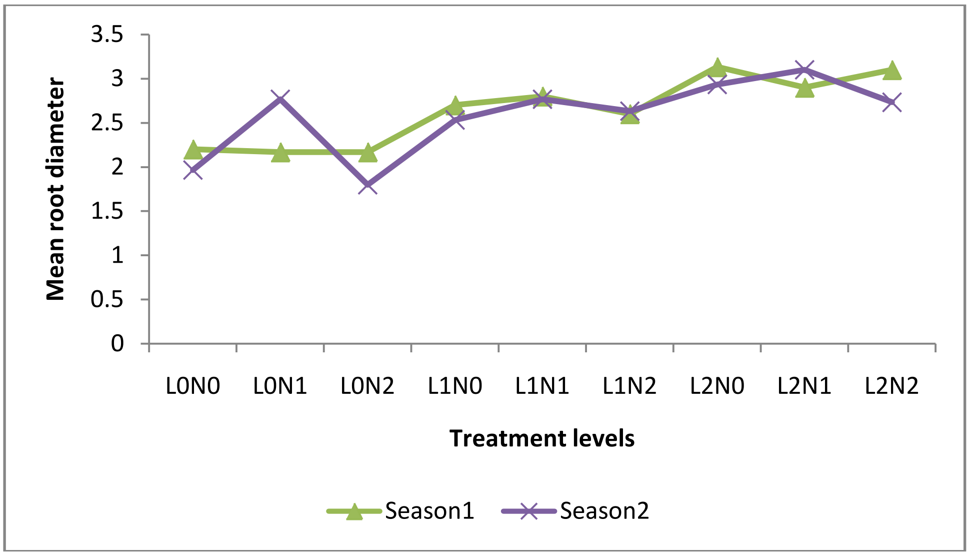
4	2.767	.3055	3
5	2.633	.5686	3
6	2.933	.3055	3
7	3.100	.1000	3
8	2.733	.1528	3
Total	2.581	.4699	27

Table 3 above shows that treatment L1N1 has a significant effect to root diameter in both season 1 and 2. This is a confirmation of the results displayed in figure 4 below. However, in season 1 all treatment in the combinations were insignificant in influencing root diameter hence it is apparent from the results of this study that lime and nitrogen combinations have no significant effect in promoting root diameter . The results are shown below

3.10 Table 4 Analysis of variance for Root Diameter

Source		Type III Sum of Squares	Df	Mean Square	F	Sig.
Seasons	Sphericity Assumed	.047	1	.047	.427	.522
	Greenhouse-Geisser	.047	1.000	.047	.427	.522
	Huynh-Feldt	.047	1.000	.047	.427	.522
	Lower-bound	.047	1.000	.047	.427	.522
seasons * Treatment	Sphericity Assumed	1.143	8	.143	1.285	.311
	Greenhouse-Geisser	1.143	8.000	.143	1.285	.311
	Huynh-Feldt	1.143	8.000	.143	1.285	.311
	Lower-bound	1.143	8.000	.143	1.285	.311
Error(seasons)	Sphericity Assumed	2.000	18	.111		
	Greenhouse-Geisser	2.000	18.000	.111		
	Huynh-Feldt	2.000	18.000	.111		
	Lower-bound	2.000	18.000	.111		

Results of the analysis of variance Table 4 using the F-test also reflect an insignificant interaction among the three factors namely lime, nitrogen and irrigation conditions when type 111 sum of squares was administered. This shows that the below ground maize parts, in particular root diameter, did not vary with seasons. In both season 1 (2018/2019 and season 2 2019/2020), only one Treatment L2N1out of the 8 treatment combinations had a significant lime – nitrogen interaction in influencing root diameter. This therefore, implies such treatment combinations have no significant positive effect in maize but could be more applicable in root crops like carrots, beetroot, parsnip and radish where root diameter matters most since the root structure is the edible part of economic importance.



3.11 Figure 4 Comparison of root diameter by season

As confirmed by post hoc Levene's Test of Equality of Error Variances and the Huynh-Feldt Tests inter alia, only the control L0N0, and L0N1as well as L2N1 had significant effects in influencing root diameter.

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3.12 Root morphology/sets- prop/brace roots, crown roots and cluster or adventitious roots

Root angle and root morphology were examined from the 9 treatments over a period of six weeks. Root angle or divergence from the node was measured using a protractor, 45^o set square and 90^o set square. From the sampled plants, the minimum angle was $\geq$ 180^o. Root divergence angle increased with time for the period of evaluation. Liming increases the pH of the soil, providing a conducive environment for nutrient acquisition and plant organ development.

4. DISCUSSION

Hydrotropism affected root length or depth negatively as it confined roots within the wet zone. This induced lodging in all treatments at physiological maturity or the hard dough stage. We therefore, conclude that root length variability across all treatments was insignificant under irrigated conditions as opposed to root density and root biomass. Therefore, we accept H_0 since p>0.05.

The electro negativity and electro positivity of the water molecule confers a property of electrical conductivity which results in the attraction of water to the mineral ions in the soil. It is therefore apparent that both processes of hydrotropism and chemotropism are not independent. Soils that have low nitrogen content under maize with long and few adventitious roots showed a 30% higher yield compared to those with dense but short lateral roots (Hufnagel et al., 2014). Modification of the root structure aids in optimising water and nutrient utilisation (Marcelis et al., 2015). These findings corroborate with the outcome of this study which revealed a higher net plot yield in association with maize root depth $\leq$30cm ploughing depth.

In both season 1 (2018/2019) and Season 2 (2019/2020), treatment 2 (T_2) had no effect on root length implying higher and successive treatments that would result in significant root length.

Therefore, the coefficients of variation (C.V.) for root length for season 1 and 2 were computed thus:

C.V = $\frac{SD}{\mu} \times 100 \left(\frac{1.5904}{17.941}\ X\ 100\right)$ C.V = $\frac{SD}{\mu} \times 100 \left(\frac{1.3643}{17.726}\ X\ 100\right)$

= 8.86 Season **1 (2018/2019)** = 7.70 Season **2 (2019/2020)**

The smaller the C.V. which is $\leq$ 15 is the expected C.V. of field crops like maize which is the crop under consideration in this study , the better or more precise the computed results.

The results of root length were both $\leq$ 15 thus making the outcomes valid and reliable also as confirmed by the Turkey's HSD Test and the Bonferroni Test.

Table 1 above shows that level 1 of nitrogen has significant effects (p-value<0.05) to root length in both season 1 and 2. This confirms the results displayed in Figure 1. The exclusion of 0 in the confidence intervals for treatment combinations with level 1 nitrogen also confirms the findings. However, in season 1 the treatment combination L0N1 had the highest significant increase in root length. In season 2, the combination L2N1 had the highest significant increase in root length implying that a treatment combination of 3t/ha^{-1}L and 0.2t/ha^{-1}N is the only significant treatment combination.

Results of the Analysis of Variance using the F test also depict an insignificant interaction among the three factors namely Lime, Nitrogen and Irrigation conditions when the type 111 sum of squares is factored in. This shows that the treatments that the roots were exposed to vary significantly with seasons. In both Season 1 (2018/2019) and Season 2 (2019/2020), Treatment 2 had no effect on root length implying a higher treatment should be applied that could result in significant root depth/length.

Root depth has so often been treated as a trait of significant importance in plant growth and development. Crop plants with deep rooting systems display a better response to hydrotropic root sensitivity as well as both mobile and immobile plant nutrients such as phosphorous and nitrogen respectively. Nitrogen is a very soluble and mobile element that is liable to leaching to deeper horizons of the soil. This field study has unearthed more confounding factors that impact root depth, and this has secondary effects on the productivity of the crop relative to yield and abiotic stress. The pH of the soil, soil depth, texture, nutrient status, plant genotype and soil moisture regimes all affect root depth. The findings resonates well with the Garcia and Monteros (2015) research outcomes which found maize plant roots growing deeper in well aerated soil conditions. Deeper root exploration is associated with enlarged cortical tissues of the root aerenchyma since there is a reduction in metabolic root activities that come into being due to increase in root biomass.

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The study revealed a significant (>) root depth in treatments where lime rates were high coupled with increase in nitrate fertiliser rates. This was possibly linked to the type of lime used. Dolomitic lime has a higher SNV of 109.0 which could possibly trigger the *DRO1*gene which encodes the root plasma – membrane protein which seems to be controlled by the growth hormone auxin (Uga et al., 2013). Although the exact physiological and biochemical role of the DRO1 gene is still sketchy, we strongly attribute the genetic positive chemotropic deeper root soil exploration to lime treatment in sampled plants. The limited root development in the 0 lime control plots was linked to the gravitropic /geotropic root growth movement.

Calcium is discharged by massflow to the rhizosphere and absorbed by root tips where it performs the role of cell division of root meristematic tissues. Deeper roots in treatments where liming rates were raised could also be attributed to the chemical composition of CaMg

$(CO_3)_2$ which induces isomorphous substitution to the soil. The resultant is a replacement of H^+ ions on soil colloids with Ca cations. Both calcium and magnesium are believed to lower the leaching of bases (Sardi, 2000). This could be linked to increased root depth due to nutrient availability like calcium and phosphorous which are responsible for root development and cell division. However, whilst deeper roots are critical in overall mineral and water absorption as well as buttressing the plant, shallow roots are effective in foraging for immobile mineral elements like phosphorus. Plant roots are sensitive and respond promptly to biotic and abiotic soil and environmental stresses before conveying these signals through transduction pathways (Mooney et al., 2012). Though roots are by nature primarily positively gravitropic/geotropic, they are also significantly influenced by soil chemical properties through the process of chemotropism. Positive and negative chemotropism is revealed in plant roots where roots grow towards useful minerals showing a positive chemotropic response and away from toxic acids indicative of a negative chemotropic response (Henke et al, 2014). Terrestrial plant roots are not only hydrotropic but also chemotropic. We hypothesised that the gene responsible for hydrotropism in plant roots called pMIZ1::GUS fusion gene which is highly present in columella cells of the cambium root caps in higher plants like maize (Zea mays L.) also influences chemotropic root response. Liming was thought to provide a conducive environment for the gene to send signals through transduction to the root. It is not clear whether it is the chemical composition of dolomitic lime (CaMg $(CO_3)_2$ which influences root development or its neutralising effect. Hydrotropic root response was found to influence both yield parameters as well as above ground and below ground plant biomass in maize. The study found a strong linear relationship between hydrotropic and chemotropic root response. This is because soil water (H_2O) is a chemical in which dissolved mineral substances like magnesium, calcium, potassium, iron; amongst others are found.

One week after crop emergence, three maize seedlings were sampled using the systematic random sampling technique from each of the three replicates for both phenotypic and biomass characterisation. This was done after irrigating the soil to field capacity in order to enable easy excavation of the root system without damage. This form of sampling was destructive sampling since the sampling units were not replaced hence the need to have a great plant population in such studies. The plants were washed thoroughly to remove soil. Roots were cut from the last bottom node of the maize plants before oven drying for 24 hours. Quantitative root phenotyping was computed through physical measurement of root length. Each day, a biomass weight was recorded until a constant biomass was realised using a sensitive digital electronic scale. The readings were averaged and recorded. This form of destructive sampling was done for 6 weeks in order to determine root biomass increment. Root biomass was significant across all treatments when $p < 0.05$, this is possibly because under irrigated conditions, maize roots do not grow deeper as water, phosphorous and other mineral elements are readily available within the proximity of roots. This corroborates with the findings by Mooney et al., (2012) who postulated that shallow roots are effective in scavenging for nutrients. Time and resources spent by roots in growing deeper is compensated through root hair development which together with other root sets like prop roots, brace roots and adventitious roots increasing root density. Increase in root density results in root biomass due to increased water and nutrient uptake (Robbins and Dinney, 2015). Liming increases soil pH promoting nutrient availability through enhanced root growth as well as microbial activity such as those of the abuscular vesicular micorrhizae fungi which improve root density and nutrient absorption. These findings also concur with the Garcia et al, (2015) studies. Treatments 3 and 4 revealed higher standard deviations which assumed an asymptotic pattern and increased variability or spreadness of data set/observations.

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Lateral roots positively contribute to total underground (root) and aboveground biomass (Garcia et al., 2015). Root biomass recorded a significant difference in weight increment on a weekly basis for the six week evaluation period in all treated plots compared to the untreated plots .This was attributed to increase in root length, root density and root diameter. Roots naturally grow downwards due to the gravitropic environmental stimulus but this is exacerbated by the influence of specialised cells called statocytes as a result of sedimentation of intracellular statoliths (Galland et al, 2010). Geotropism/gravitropism is a vector since it possesses both magnitude and direction. Using the control treatment 1 with L0N0, any deviation from the mean of the control indicates the effects of liming due to root geotropic response. In all lime treatments, maize plants increased in root length, root biomass and divergence angle exponentially for the six week evaluation period. With no lime application, root biomass was insignificant and when lime and nitrogen were increased, results revealed a significant increase in root biomass. There was an insignificant increase when both nitrogen and lime rates reached point of inflexion. Considering the mean of all lime and nitrogen rates, optimum root biomass was recorded at nitrogen rates and lime rates $3t/ha^{-1}$L and

0.2t/ha^{-1}N. Beyond that, the results obeyed the law of diminishing yield increments as postulated by Bohm and Kirkham (1999) and Liebig and Mitscherlich, (1885).

Since root hairs increase root surface area for optimum water and mineral absorption, this manifestation depicts no surprise that it accounts for > 50% of root biomass. A combination of both long roots and dense adventitious/basal roots resulted in a 300% biomass in a study conducted using Field/Common beans (Phaselous vulgaris L.) (Monteros et al., 2015). This was attributed to optimum phosphorous acquisition since phosphorous improves root development. Young plants absorb phosphorous better and in maize this is optimum during the first 3 weeks after emergence.

Phosphorous availability in soils is low as it is most available at pH ~6.5, occurrence of phosphate rock is sketchy in Zimbabwe, combines with insoluble compounds in the soil in addition to its low diffusion rate of 0.015 – 1mm/hr (2cm day^{-1}) (Brady and Weil, 2008). This could have accounted for the low < root biomass in unlimed treatments in the study.

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Results of the analysis of variance using the F-test also depict a significant interaction among the three factors namely Lime, Nitrogen and irrigation conditions when type 111 sum of squares has been factored in. This satisfies that the treatments to which belowground maize organs were exposed to vary significantly with seasons with an increase with successive seasons of lime applications. In both season 1 (2018/2019 and season 2 2019/2020) , Treatment L1N2 (1.5t/ha^{-1}L and 0.2t/ha^{-1}N)had the most significant effect on root biomass implying that a moderate lime application and optimal nitrogen rate are effective in promoting root biomass.

4.1 Root diameter

L1N1 has a significant effect to root diameter in both season 1 and 2. This is a confirmation of the results displayed in figure 4. However, in season 1 all treatment in the combinations were insignificant in influencing root diameter hence it is apparent from the results of this study that lime and nitrogen combinations have no significant effect in promoting root diameter .

Results of the analysis of variance using the F-test also reflect an insignificant interaction among the three factors namely lime, nitrogen and irrigation conditions when type 111 sum of squares was administered. This shows that the below ground maize parts, in particular root diameter, did not vary with seasons. In both season 1 (2018/2019 and season 2 2019/2020), only one Treatment L2N1out of the 8 treatment combinations had a significant lime – nitrogen interaction in influencing root diameter. This therefore, implies such treatment combinations have no significant positive effect in maize but could be more applicable in root crops like carrots, beetroot, parsnip and radish where root diameter matters most since the root structure is the edible part of economic importance.

As confirmed by post hoc Levene's Test of Equality of Error Variances and the Huynh-Feldt Tests inter alia, only the control L0N0, and L0N1as well as L2N1 had significant effects in influencing root diameter.

3.5 Root morphology/sets- prop/brace roots, crown roots and cluster or adventitious roots

Root angle and root morphology were examined from the 9 treatments over a period of six weeks. Root angle or divergence from the node was measured using a protractor, 45^{o} set square and 90^{o} set square. The development of the lateral roots signify the general root system architecture since the cumulative root density determine total root biomass (Robbins and Dinney, 2015). From the sampled plants, the minimum angle was $\geq 180^{o}$. Root divergence angle increased with time for the period of evaluation. The Multiple Limitation Hypothesis (MLH) postulates that availability of one resource mineral element promotes the utilisation of other mineral elements. Availability of Ca, Mg, C supplied through $CaMg(CO_3)_2$/dolomitic lime as well as nitrogen used a treatment variable could have promoted the availability of other mineral elements. Liming increases the pH of the soil, providing a conducive environment for nutrient acquisition and plant organ development.

Studies using soy bean and wheat concluded that plants with more lateral roots are better adapted to phosphorus limited soils due to over expression of the β-expression gene which enhances RSA and phosphorous use efficiency due to increased lateral roots (Hufnagel et al., 2014). There was a correlation between root depth, root density and drying down rate or senescence and kernel yield.

5.0 CONCLUSIONS

Undesirable soil pH for plant growth and poor nutrient management affect crop productivity. The problem of soil acidity has affected agricultural productivity globally. Lime-nutrient interaction needs further research to determine specific lime and nutrient requirements. Different soils require lime and nutrient application rates. Sandy-textured soils are prone to nutrient loss through leaching particularly of mobile nutrients. Plant roots vary greatly in terms of depth, morphology, development and their chemotropic, geotropic and hydrotropic responses.

Maize plant roots are sensitive to soil pH thus impacting on above plant biomass. The availability of one plant nutrient in the soil continuum affects utilisation of other nutrients. Root architecture can be manipulated through agronomic and mineral nutrient practices. The elasticity of maize plant roots can best be understood under different stress field conditions. Root density and depth delays the drying down rate (DDR) or senescence of maize thus increasing their 1000 seed weight.

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Whilst lodging in maize can be partly genetic, climatic, it can also be a function of root system architecture influenced by both soil fertility management. Maize develop different types of roots such as prop/brace roots, crown roots and cluster or adventitious roots as a result of chemotropic and hydrotropic root response. Shallow roots are less beneficial in withstanding water-stress conditions and overall nutrient uptake but are efficient in foraging and utilisation of immobile elements like phosphorous.

Both coefficient of variations (C.Vs) for Root Length and Root Biomass were $\leq$ 15% thus revealing the suitability of the experimental design, sample size and sampling technique. Higher standard deviations (SD) such as those recorded in treatments 3 ad 4 for root biomass reveal kurtosis which is critical for comparison with other treatments. The coefficient of variations (C.Vs) of field crops like maize or corn should not exceed 15% as was the case in this study.

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