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The effect of phosphorus fertilizer application rates on root biomass characteristics of irrigated sugarcane (*Saccharum officinarum.* L)

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Abstract

A field experimental study was carried out at Mwenezana Estate in the southeast lowveld of Zimbabwe (25º10’S, 31º15’E, >400 m elev.). The objective of the study was to determine the effect of varying P fertilizer application rates on sugarcane root biomass characteristics. Study results show that upgrading P application rates to 100-200 kg ha^{-1} and 250 – 300 bands improved cane root numbers in the soil by 78.6% and 250% respectively in comparison with the 0-77 kg P fertilizer ha^{-1} band root counts. Increasing P fertilizer application rates from zero to 300 kg ha^{-1} steadily diminished both lateral spread and vertical extension of cane roots. The no P fertilizer variants inflated their root volumes by 84.6% in excess of that recorded in the P_{300} treatments. Application of P_{200} systematically increased root intensities by 726.5% in excess of those in the control treatments. However, increasing application rates to 250 – 300 kg P ha^{-1} reduced the root intensities over those in the control plots to 256%. These results clearly demonstrate that extensive lateral spread and depth penetration of sugarcane root system do not necessarily indicate elevated root biomass accumulations. The highest root efficiency was recorded in the P_{200} to P_{250} replicated plots and the least was in the control variants. Results clearly show that the 200 – 300 P fertilizer application rate band, which recorded the highest root count and root intensity while at the same time scoring the lowest root volumes and root extensions, had the most efficient root systems.

Key words: *Phosphorus fertilizer rates, sugarcane biomass characteristics*

Introduction

Sugarcane (*Saccharum officinarum* L) is one of the world’s most important sugar crops. The sugarcane crop is normally grown as a perennial crop and is harvested several times before replanting. The first cycle is referred to as plant crop and subsequent crops as ratoons (Keating *et al.*, 1999). The planting material is taken from elongated stalks of cane plants, which are buried in the bottom of the furrow and covered with soil. Sprouting roots on the intercalary region are followed by germination of the axillary bud (Cock, 2003).

The newly sprouted plants enter into a

rapid tillering phase with new shoots being formed from the axillary buds at the base of those that are already established. Leaf appearance rate per shoot is rapid at this growth stage. Tillerig phase terminates when mutual shading occurs and stems begin to elongate (Cock, 2003). Many of the smaller tillers die and total shoot number is reduced by as much as 50% (Golden and Ricaud, 1963). It appears that as the tillers become autonomous, those that are short and shaded and cannot provide sufficient photosynthate for their development die. The leaf appearance rate per stalk declines during this period, whilst the leaf size of new leaves increase and reach the maximum as late as nine months after planting (Keating *et al.*, 1999) after which, it stays close to the maximum or decrease slightly. The dry matter content of the stalks increased from about 15% when elongation commences to about 30% (Cock, 2003). Sucrose as a percentage of the total dry matter increases and reaches levels of up to 55% of the dry matter (Martin and Plassard, 2001). The cane plant is indeterminate and does not cease to grow.

Roots anchor the plant and supply water and nutrients to the plant. Initial crop development of the ratoon crop depends on the stool roots, which die one to two months after harvesting (Mtunzi, 2005). Van Antwerpen (2000) noticed that by the time stool roots die, thick white flesh shoot roots would have developed which will take over the supply of the nutrients and water to the plant. The switch over from stool roots depends on the development of the shoot roots. Nyati (1997, un published) observed that it takes an average of about three months for the stool roots to die. Van Antwerpen (2000) also observed that in winter it could be delayed to more than three months, as there is no root development when temperatures go below 10^{o}C. The crop's thrust on physiological growth before rapid stalk elongation is on the root development (Mtunzi, 2005). With ideal growing conditions in the soil, a single shoot for sugarcane is capable of elongating at the rate of 28 mm/day in sandy soils. The rooting front develops at the rate of 11 mm day^{-1} (Van Antwerpen, 2000).

In the sugarcane plants, the root primordia (root initials) are located on the root ring, which is the basal region of internodes. When seed cane setts are planted two kinds of roots develop, namely sett roots and shoot roots. The sett roots originate from the root ring of the cane setts and the potential number is determined by the root primordia present in the seed sett. The shoot roots develop from the lower root rings of emerging tillers and they are thick and fleshy, white and less branched. Aerial roots that can be seen above ground may develop in response to lodging of cane or water logged conditions (Nyati, 1997, unpublished). In sugarcane, three types of roots can also be observed depending on their growth pattern. *Superficial* root systems are those, which are observed in the top 30 cm of soil. They are branched and interlocked like a net (Plate 1). A lot of rootlets can be observed on the superficial root system. *Buttress* roots are less branched and can extend up to one meter deep. These are for anchorage because they are thick. *Rope* root systems extend up to five meters deep and they are mostly branched at the tap ends. Their function is to scavenge for water and leached nutrients from deep soil horizons.

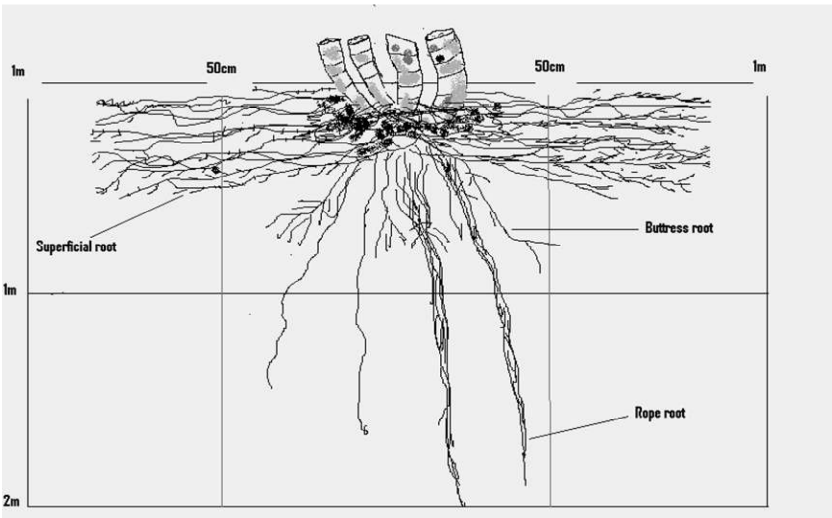

Plate 1. Generalized schematic presentation of three types of 14 months old sugarcane roots. (Modified from Evans, 1935).

Phosphorus, the second most important element of the macronutrients, is a component of adenosine diphosphate (ADP) and adenosine triphosphate (ATP), which are vital compounds in energy transformations in plants. ATP, which is synthesized from ADP in both respiration and photosynthesis processes, carries a high-energy phosphate bond that drives most biochemical reactions including the energy consuming active uptake of other nutrients from the soil solution by plant roots (Gubanov and Ivanov, 1988 and Kumakov, 1988). In a study on the behavior of P in soils, Olsen *et al.* (1977) reported significant influence of soluble P-containing calcium compounds in alkaline soil conditions on availability of P. Amongst a host of P-containing compounds, the most significant is tricalcium phosphate [$Ca_3(PO_4)_2$], which is of limited solubility (Velarde *et al.*, 2005). According to Olsen and Khasawneh (1980) the concentration of labile P in the soil solution is a measure of the intensity factor of P nutrition and if this factor is maintained at about 0.2mg kg^{-1} soil or above, maximum yield of most crops will occur.

Sugarcane growth is generally characterized by a period of rapid biomass accumulation (grand growth period, GGP), which corresponds to the near-linear portion of a sigmoidal growth curve (Golden and Ricaud, 1963). The quantity of nutrient elements removed per hectare by sugarcane harvest has been investigated to help determine the necessary fertilizer additions for subsequent crop. Golden and Ricaud (1963) concluded that 0.72 kg N, 0.18 kg P, and 1.22 kg K t^{-1} millable sugarcane were removed from the mineral soil in Louisiana. A graphic description of nutrient uptake and dry matter accumulation suggested a general sigmoidal pattern of dry matter and nutrient accumulation throughout the growing season (Golden and Ricaud, 1963). In a study on nutrient accumulation and removal by sugarcane, Coale *et al.* (1993) reported 0.15 t ha-1 d-1 dry matter accumulations during GGP. During this period of rapid growth, 64% of total crop dry matter was produced. P uptake in the GGP contributed 67% of total P accumulation by sugarcane (Gascho and Kidder, 1979).

Each sugarcane harvest results in soil nutrient losses. Nutrients should be replaced to maintain soil fertility. Losses occur largely because whole stems are taken to the mill and residues are burned on the field (Salgado-Garcia *et al.*, 2000). Because of the growing need to use fertilizers efficiently, in terms of rising costs and environmental conservation, traditional ways to generate fertilization recommendations have been reviewed by soil fertility and economist specialists in the last decade (Wilcox, 1991; Cabrera, 1994; Salgado *et al.*, 1995; Weir *et al.*, 1996; Palma *et al.*, 1998). For instance, continuous fertilization of sugarcane over the past 20 years coupled with low mean productivity (50 t ha^{-1}) has raised both inorganic and organic P levels in the topsoil in northeastern Brazil. P fertilizer is normally applied at the time of planting for plant-cane crops and after initiation of ratoon regrowth for ratoon crops (Sanchez, 1990). The most efficient method of applying P fertilizer to sugarcane is generally subsurface banding (Jones, 1982). B. In spite of this practice, the efficiency of fertilizer-P use has been estimated at only 20% (Manhaes, 1977). In addition to that, very little is known about the residual effect of fertilizer-P accumulated over the years (Ball-Coelho *et al.*, 1992).

The soil is not a limitless reserve of plant nutrients especially under intensive cropping systems where essential soil plant nutrients are extensively 'mined' by root uptake and éxported' to distant locations in crop produce (Cooke, 1954, Tisdale *et al.*, 1985 and Harper *et al.*, 1987). Consequently, the need for replacement of nutrients extracted from the soil in order to achieve a positive soil nutrient balance is unquestionable. Such replenishments often come in the form of fertilizers impregnated with essential plant nutrients, the management of which is of fundamental importance not only from an economic standpoint, but also from an environmental position (Ritter and Chirnside, 1987). The management P fertilizer in sugarcane plantations of the Lowveld areas on vertic and high clay content (argillic) soils is made more complex by the fact that such soils have a high P-sorption capacity, where as much as 10-15% of fertilizer P is fixed by soil in the first year of application (Brady, 1990). In this respect, fertilizer-supplied P is quickly rendered unavailable to the sugarcane crop soon after application. Amongst a host of P management practices aimed at increasing availability of fertilizer-P to sugarcane, P fertilizer application rates that encourage a rapid build-up of phosphate reserve for neutralization of P sorption sites on clay complexes and enhance root biomass that rapidly absorb traces of labile P from the soil is a promising practical solution. In view of the above, a one and half year P fertility study was carried out at Mwenezana Estate of southeast lowveld of Zimbabwe (25º10′S, 31º15′E, >400 m elev.). The objective of our study was to determine the effect of varying P fertilizer application rates on sugarcane root biomass characteristics. In this study, we hypothesized that varying P fertilizer application rates introduced a mosaic of fertilizer P sorption events in the soil that controlled labile soil P quantities (P intensity factor), which influenced sugarcane biomass characteristics.

Methods and Materials

Trial site

The study was conducted at Mwenezana Estate of southeast lowveld of Zimbabwe (25º10′S, 31º15′E, >400 m elev.) about 198 km southeast of the city of Masvingo. The soils at the trial site are yellowish red sandy loams derived from granite and classified as Udic Kandiustalf under the USDA system of soil classification (Nyamapfene, 1991). The area lies in Natural Region V receiving rainfall ranging from 250 to 1000 mm annum $^{-1}$ (average 500 mm per annum) with a coefficient of variation of 19% and mean growing season of 70 days. The mean annual temperature is 26.5°C with insignificant frost occurrence in the months of June and July. The rainfall occurs during a single rainy season extending from November to April (Vincent and Thomas, 1960).

Experimental design and treatments

The field experiment was carried out in the Section 1 Field B6 of Mwenezana Estate during the 2004/2005 winter and summer seasons. A week before setting up the experiment, soil samples were taken for analyses using established standard laboratory procedures for determination of nutrient, mechanical composition, soil reaction and organic matter content. Results of the analyses are presented in Table 1 below:

Table 1: Composition of experimental soil

Mechanical composition, %			Org.matter, %	pH (Ca Cl_2)	K^+ (m.e %)	Ca^{2+} (m.e %)	Mg^{2+} (m.e %)	Na^+ (m.e %)
sand	silt	clay						
77	6	17	0.92	6.03	15	0.95	4.92	2.53

A Randomised Complete Block Design was used in field experiment in which the factor was P fertilizer application rates. Five blocks were run down the general slope. Each block comprised of ten plots, which were subjected to seven phosphate fertilizer treatments: 0 kg P fertilizer ha^{-1} (P_0), 50 kg P ha^{-1} (P_{50}), 77 kg P ha^{-1} (P_{77}), 100 kg P ha^{-1} (P_{100}), 200 kg P ha^{-1} (P_{200}), 250 kg P ha^{-1} (P_{250}) and 300 kg P ha^{-1} (P_{300}) replicated five times. Sugarcane variety N14 was planted in each plot on 10 February 2004 and harvested from 30 May to 2 June 2005. Each plot had 20 rows of cane plants spaced 1.5 m apart with a row length of 30 m. The plots were irrigated using furrows and weeded using herbicides.

Root excavations

Root direct excavations for biometric characterisation were done when the cane was 14 months starting on 5 May 2005 and were completed on 27 May 2005. The block used for root studies was selected at random. Root excavations were done on all treatments in the block.

Determination of root number in soil cores

A spade 20 cm wide and marked at 20 cm depth was used to take 20 x 20 x 20 cm soil cores. One core was taken in the furrow about 30 cm away from the target stool and the other two were taken on the ridges 30 cm on either side of the target stool. Root pieces from the cores were washed using running water and a tally counter was used in counting the number of roots.

Measurement of root length

Trenches running along and across sugarcane rows were dug for randomly selected rows in each treatment. Trenches along rows ran on either side of the sugarcane row with the target stool sample. The trenches were 60 cm wide, 150 cm long and 150 cm deep. Trenches across cane rows of the target stool sample ran 200 cm apart in the inside dimension and 320 cm in the outside. Roots were washed starting from either side of the row with the target stool insitu. Water was sprayed at high pressure (not measured) using a tractor-mounted fire fighting equipment to remove soil from the roots. Three stools were washed and removed with the target stool in the middle. Water accumulating in the trenches was pumped out using a *lister* diesel water pump (Salister Diesels (Pvt) Ltd, model LT 1329). Water was pumped either into a nearby trench or to nearby waterway. Pumping water into the trench the day before root washing helped loosen the soil. Soil accumulating in the trenches was removed using shovels and was heaped on the sides of the trenches. After removing the stools, the soil was shoveled back to close the trenches. It took 3 days for six employees to dig and wash soil from a sugarcane stool sample. The excavated stools were suspended on a tripod-pulley system, in order to facilitate the separation of the middle target stool from the stools on either side of it. The lengths of ten longest lateral roots (superficial and buttress roots) were measured from the base of the stool using a tape measure. Superficial roots and buttress roots were indistinguishable and were thus were classified only as lateral roots. The lengths of ten vertical roots (rope roots) were also measured. The average lengths of lateral and rope roots on each plot were calculated and recorded. The stalks were then separated from roots using a knife. The cane was 14 months old when it was sampled.

Determination of plant biomass

The stalks, leaves and roots were weighed fresh soon after the stalks were separated from the roots. Stalks were shredded (Maintenance Engineering Services – South Africa) at ZSAES laboratory to facilitate easy of drying. The leaves, stalks and roots were placed in different trays labelled according to the phosphorus fertilizer treatments and the trays were placed in an oven (Larbo Tech - South Africa) and dried to constant weight at 100°C. Constant weights were obtained after 24 hours for roots and leaves and after 48 hours for stalks.

Root Volume

Root volume is an estimated volume of soil in which the roots spread both horizontally and vertically in search of moisture and nutrients. Evans (1935) referred to this root volume as the feeding zone (FZ). From measurements of vertical and horizontal spread, Evans (1935) derived a cone shaped feeding zone, which he estimated using the formula:

$$FZ = {}^{1}/_{3}\, \pi\, r^{2}v \ (m^{3})$$

Where:

r = one-way spread from stalk base to the tip of longest horizontal root, v = vertical spread and $\pi = 3.14$.

Root Intensity

Root intensity (RI) is the quantity of roots in grams dry mass (RDM) within the root volume. Root intensity was calculated as follows:

$$RI = \frac{RDM}{FZ} \ (kgm^{-3})$$

Root efficiency

Root mass provides a useful measure of plant investment in the root system. Root efficiency (RE) is the capability of roots to support its above ground dry mass (AGDM) calculated as the proportion of dry root weight to dry shoot weight. The most efficient root system in sugarcane would have a low root mass supporting heavy stalks. Root efficiency was calculated using the formula:

$$RE = \frac{AGDM}{RDM} \times 100$$

Dry weights of leaves and millable stalks constituted above ground plant dry weight. The above formulas were used in calculating root feeding zone, root intensity and root efficiency of the sugarcane crop.

Results and discussion

Results shown in Tables 1 - 4 and Fig 1 - 3 indicate, generally, that there were comparatively significant P fertilizer treatment signatures on the sugarcane biomass characteristics ($p < 0.05$). A brief reference to graphical data presented in Fig 1 show a relatively firm trend in the cane root biomass response to P fertilizer rates.

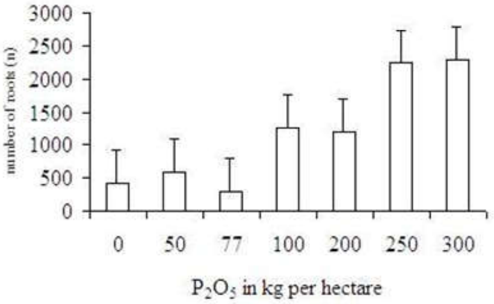

Fig 1: *Mean root count response to P fertilizer rates*

However, at low rates of fertilizer application, increasing P fertilizer rates from 0 through 50 to 77 kg ha^{-1} did not confer substantial root count build-up in P_{50} and P_{77} variants. In these variants, amplifying P fertilizer rate from 0 to 50 kg ha^{-1} increased root count in the 20 x 20 x 20 cm furrow slice by a paltry 2.0% while an application increase to 77 kg ha^{-1} diminished root count by 1% when compared with the no P fertilizer plots. Boosting P application rates to 100-200 kg ha^{-1} and 250 – 300 kg ha^{-1} bands improved cane root numbers in the soil by 770 counts or 78.6% and 2000 counts or 250% in comparison with the 0-77 kg P fertilizer ha^{-1} band root counts respectively. It should be noted, however, that root biomass count responses in the P_{100} and P_{200} variants were comparatively similar, clearly indicating an indifferent sugarcane root build-up within the same P fertilizer application band. This indifference in the cane root count response to P fertilizer rate increase within the same band was also perpetuated in the 0-77 and 250-300 kg ha^{-1} bands. In this study, improving P fertilizer application rates from 0-77 through 100-200 to 250- 300 kg ha^{-1} bands amplified sugarcane root counts in the topsoil by strikingly similar and visually equal gradations of 1000 root count from one band to another (Fig 1). In this respect, upgrading P fertilizer rates from the 0-77 kg ha^{-1} to 100-200 kg ha^{-1} band had the effect of increasing root biomass by approximately 1000 counts. Likewise, elevating P fertilizer application rates from the 100-200 kg ha^{-1} band to the 250-300 kg ha^{-1} band triggered a biomass increase of about 1000 counts. Nevertheless, the highest sugarcane root counts were recorded in variants with the highest P fertilizer application rates (2750-3000).

In the background to these firm root biomass responses to P fertilization is the vital role that plant roots play not only in providing an upright anchor for the plant but also in the active uptake of important nutrients for the optimal development and growth of the plant. A higher number of root count implies a correspondingly larger specific surface area for the uptake of nutrients. Numerous research results elsewhere have demonstrated the rapid P nutrient fixing capacity of soils with high clay content (Olsen *et al.*, 1977; Velarde *et al.*, 2005). In this study, we attributed very low root counts in P_0, P_{50} and P_{77} variants to the rapid fixation of the limited quantities of applied fertilizer P containing radicals on P fixing exposed edges of clay colloidal particles (Brady, 1990). At low rates of P fertilizer application, the P fixing sites on clay complexes are far from being exhausted and may continue to deplete the intensity factor P otherwise meant for uptake by root systems (Olsen and Khasawneh, 1980). The active uptake of vital nutrients such as N and K for biomass synthesis from the soil is an energy expending metabolic process, which requires ample amounts of labile P for the energy releasing cyclic generation of ATP and ATP (Gubanov and Ivanov, 1988 and Kumakov, 1988). In addition to that, the energy consuming initial reduction of NO_3 form of N to amine forms is a necessary step in the assimilation of N into plant biomass. Limitations, therefore, of P reserve in the soil environment diminish active nutrient uptake and assimilation of N into plant biomass, which have the cumulative effect of dwarfing plant biomass accumulation and that includes a reduction of the root counts observed in this study. In a study on the impact of the first three post harvest irrigations on root and crop development of sugarcane, Mtunzi (2005) reported that the crop's thrust on physiological growth before rapid stalk elongation is on the root development. As complimentary contribution to his findings, we report in this paper on root biomass diminishing effect of low P fertilizer application rates.

Increasing P fertilizer application rates to 250-300 kg ha^{-1} in the P_{250} and P_{300} replicated plots significantly boosted root biomass counts for the reasons given above. We report in this study on the ***P fertilizer rate band barrier*** effect on the sugarcane root biomass response. The ***P fertilizer rate band barrier*** effect on root biomass response concept is based on the fact that within the same P fertilizer rate band there is a homogeneous root biomass response. A breach of either upper or lower limit of the P fertilizer rate barrier triggers a significant cane root biomass response. This spectacular root count response to bands of P fertilizer application rates was largely attributable to the gradual and comparatively wide bands of phosphate fixation events on the intensity/quantity (**I/Q**) factor interface soil colloidal complexes and soil solution (Olsen and Khasawneh, 1980). Within the same band of P fertilizer application rates, root biomass responses level out and will only assume significant alterations in the response if fertilizer rates leap out of the rate barrier.

Results displayed in Fig 2 clearly show that the lateral spread and vertical stretch of sugarcane roots at 14 months were significantly monitored by the rates of P fertilizers ($p < 0.05$). There was an inverse linear relationship of vertical stretch and lateral spread of roots with increase in application rates of P fertilizer. The upgrading of P fertilizer application rates from zero to 300 kg ha^{-1} steadily diminished both lateral spread and vertical extension of cane roots. The P_0-P_{100} plots, on average, supported 0.1 m or 14.1% and 0.45 m or 42.5% longer lateral and vertical cane roots than those in the P_{200}-P_{300} plots respectively. The widest spread of cane roots, however, was recorded in 0 kg ha^{-1} P fertilizer replicated treatments where roots lateral extensions clocked 1.34 m. The deepest cane roots were observed in the 50 kg P fertilizer ha^{-1} plots where the roots penetrated to a depth of 1.63 m. The shallowest (1.02 m) and narrowest spread (0.5 m) was recorded in the P_{250} and P_{77} variants respectively.

The spectacular inverse linear cane roots response to P fertilizer application rates was not particularly surprising. The P_0-P_{100} rates of P fertilizer applications introduced limited quantities of P within reach of the cane root system. The limited reserve of P in the plough layer escalated the need for sugarcane roots to expand the zone of nutrient mining by rapidly extending their lengths in search of the nutrient that was limiting growth and development following the Leibig's law of limiting factor. The concept of *root interception* implies that roots continually grow into new undepleted soil and may not cease to do so until when they encounter nutrient rich soil zones. In this study, the extended lateral and vertical spread of the cane roots in the P_0 – P_{100} variants was a direct response of the roots to the limited reserve of P in the soil. In a study on root dynamics in plant and ratoon crops of sugar cane Ball-Coelho *et al* (1992) reported appreciable residual effects of P fertilizers applied in the previous crop on root extensions. In this respect, we attributed the rapid root extensions under low P fertilizer application rates to the residual P reserve that remained in the soil the previous season. We noted for this study, the tendency of semi-arid region soils to fix about 85 – 90% of fertilizer P in the season of application (Brady, 1990).

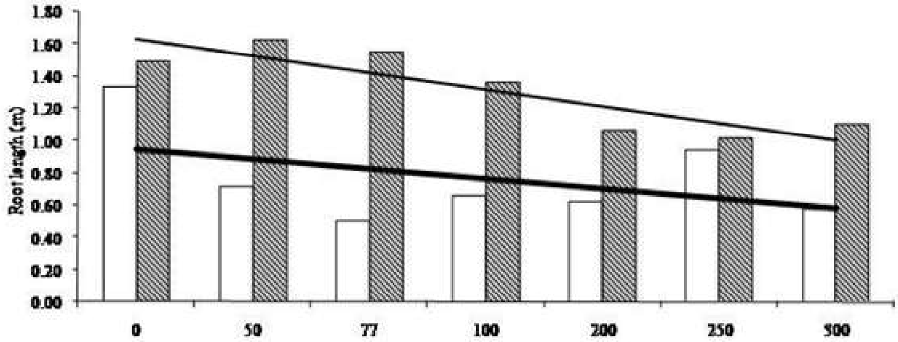

Fig 2: The lateral spread and vertical stretch of sugarcane root responses.

There was a significant sugar cane root volume response ($p < 0.05$) to phosphate fertilizer rate variations (Table 2). The P deficiency induced sugarcane root spread effect was perpetuated in root volume responses to P fertilizer rates. The largest root volume (2.836 m^3) was recorded in P_0 treatments. However, P_{250} replicated variants in the study scored comparatively high root volumes (1.954 m^3). In this respect, the no P fertilizer variants inflated their root volumes by 84.6% in excess of that recorded in the P_{300} treatments. The perpetuation of this trend in the root response to P fertilizer rates was largely attributed to wider spread and deeper root extensions observed in the lower P fertilizer application rates, which directly contributed to the larger root volumes (Evans, 1935). Nevertheless, a brief reference to Fig 1 clearly show that the P_{250} treatments conferred comparatively amplified cane root spread and depth penetration, which effectively contributed to high root volumes observed in this study.

Table 2: Root volume response to P fertilizer rates.

Phosphorus rates, kg ha^{-1}	Root volume, m^3
0	2.836^{a}
50	0.224^{e}
77	0.424^{c}
100	0.739^{b}
200	0.353^{d}
250	1.954^{a}
300	0.438^{c}
d.f	69
l.s.d	0.0904
c.v%	10.2

Means with the same letters are not significantly different (p<0.05)

Table 3: Comparison of means for root intensity responses to P fertilizer rates.

Phosphorus rates, kg ha^{-1}	Root intensity
0	0.083^{f}
50	0.540^{c}
77	0.652^{b}
100	0.554^{c}
200	0.686^{a}
250	0.134^{e}
300	0.457^{d}
d.f	69
l.s.d	0.02402
c.v%	6.1

Means with the same letters are not significantly different (p<0.05)

Data presented in Table 3 indicate that P fertilizer application rates to sugarcane strongly monitored ($p<0.05$) the distribution of root dry biomass in the root-feeding zone. In essence, cane root intensities are essentially root densities in the in the volume of soil that supplies the plant with nutrients and water. While down grading P fertilizer application rates to sugarcane amplified root extension and volume, its effect on root intensity was a direct opposite. In this study, upgrading P fertilizer rates to P_{200} systematically increased root intensities by a massive 726.5% in excess of those in the control treatments. However, increasing application rates to 250 – 300 kg P ha^{-1} whittled down the root intensities over those in the control plots to 256.0%. These results clearly demonstrate that an extensive lateral spread and depth penetration of sugarcane root system does not necessarily indicate elevated root biomass accumulations. In fact, the highest root biomass density was registered in variants with the shortest root extensions (P_{200}). The highest root intensities recorded in the P_{200} plots were largely attributable to the comparatively vigorous energy-expending uptake of vital nutrients from the P-satiated soil environment, which was strongly encouraged by the heightened energy-releasing cyclic ATP/ADP cell metabolic processes that require ample phosphatic materials present in these variants. In support of these results, Coale *et al*. (1993) reported 0.15 t ha^{-1} day^{-1} dry matter accumulations during GGP in a study on nutrient accumulation and removal by sugarcane. During this period of rapid growth, 64% of total crop dry matter was produced. P uptake in the GGP contributed 67% of total P accumulation by sugarcane (Gascho and Kidder, 1979). We, however, noted that P fertilizer application rates beyond P_{200} (P_{250} -P_{300}) whittled down root intensities to a modest 256.0% in excess of those recorded in the control plots. This downward trend in the root intensity response to P fertilizer rates variation beyond P_{200} was not particularly surprising as it conformed to research findings elsewhere. An oversupply P in the soil environment of the P_{250} – P_{300} variants triggered a bulge in the aboveground biomass build-up at the expense of the belowground plant parts. This had the effect of downgrading biomass weight of the cane roots in last two treatments of this study.

There was a very strong correlation between root intensity and the feeding zone. An inverse linear relationship between root volume and root intensity inferred that as the root volume decreased, the root intensity increased (Fig 4). The plants invested more in roots when the level of phosphorous was low (below 200 kg P_2O_5 ha^{-1}) but as the level of applied P increased beyond 200 kgha^{-1} the sugarcane plant invested more in above ground biomass. Nevertheless, it should be noted that the intensity of cane roots decreased with increasing distance from the plant station. At the same time the volume of nutrient and water supplying soil increased with increasing distance from the plant station. In fact, large volumes of soil effectively reduce the density of cane roots.

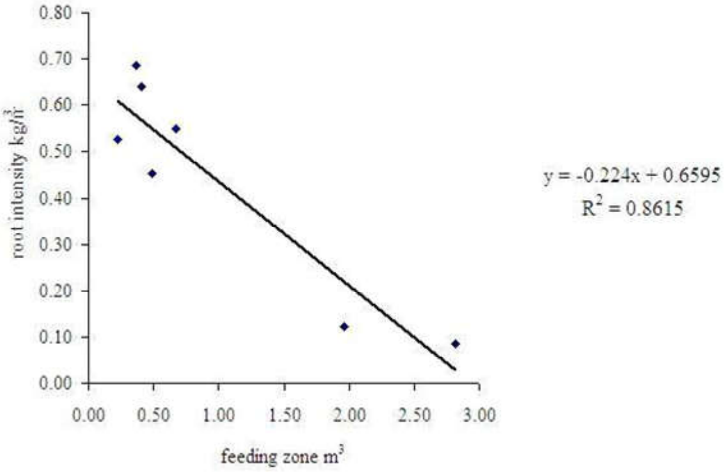

Fig 3: *Relationship between the root-feeding zone and root intensity.*

Table 4: Comparison of means for root efficiency responses.

Phosphorus rates, kg ha^{-1}	Mean root efficiency, %)
0	45.39^{g}
50	63.00^{c}
77	55.49^{e}
100	52.44^{f}
200	78.12^{b}
250	83.83^{a}
300	57.96^{d}
d.f	69
l.s.d	1.496
c.v%	2.7

Means with the same letters are not significantly different (p<0.05).

The sugar cane variety N14 responded significantly ($p<0.05$) to phosphate levels in root efficiency (Table 4). Root efficiency of sugar cane indicates the ratio between the dry mass of the vegetative stalk and the root. Sugar cane is grown essentially for its sugar laden succulent stem. The most root efficient cane plants are those that accumulated the highest stem mass with the least nutrient investment in the root biomass. The highest root efficiency was recorded in the P_{200} to P_{250} replicated plots and the least was in the control variants where no P fertilizer was applied. At the level of 50 kg P fertilizer ha^{-1}, the root efficiency was higher than those fertilized with 77 and 100 kg ha^{-1}. The P_{200} and P_{250} treatments scored about 32.7 percentage points or 72.1% and 38.4 percentage points or 84.7% higher root efficiencies than those recorded in the zero P fertilizer variants. Results clearly show that the 200 – 300 P fertilizer application rate band, which, incidentally, recorded the highest root count and root intensity while at the same time scoring the lowest root volumes or feeding zones and root extensions, had the most efficient root systems. We attributed this cane response to P fertilizer rate variations largely due to adequate P matter that was enough to appreciably satiate, though temporarily, the P fixation capacity of the soil (Brady, 1990) so as to leave a positive balance of dispensable labile P necessary for the cell energy metabolism in the active uptake of vital nutrients for cane stem biomass accumulation (Gascho and Kidder, 1979; Gubanov and Ivanov, 1988; Kumakov, 1988).

In conclusion, the study results have shown that upgrading P application rates to 100-200 kg ha^{-1} and 250 – 300 bands improved cane root numbers in the soil by 78.6% and 250% respectively in comparison with the 0-77 kg P fertilizer ha^{-1} band root counts. In this study, improving P fertilizer application rates from 0-77 through 100-200 to 250-300 kg ha^{-1} bands amplified sugarcane root counts in the topsoil by strikingly similar and visually equal gradations of about a 1000 root count from one band to another. We report in this study on the ***P fertilizer rate band barrier*** effect on the sugarcane root biomass response. The ***P fertilizer rate band barrier*** effect on root biomass response concept is based on the fact that within the same P fertilizer rate band there is a homogeneous root biomass response. A breach of either upper or lower limit of the P fertilizer rate barrier triggers a significant cane root biomass response. The upgrading of P fertilizer application rates from zero to 300 kg ha^{-1} steadily diminished both lateral spread and vertical extension of cane roots. The P deficiency induced sugarcane root spread effect was perpetuated in root volume responses to P fertilizer rates. The no P fertilizer variants inflated their root volumes by 84.6% in excess of that recorded in the P_{300} treatments. Application of P_{200} systematically increased root intensities by 726.5% in excess of those in the control treatments. However, increasing application rates to 250 – 300 kg P ha^{-1} whittled down the root intensities over those in the control plots to 256.0%. These results clearly demonstrate that extensive lateral spread and depth penetration of sugarcane root system do not necessarily indicate elevated root biomass accumulations. Sugar cane is grown essentially for its sugar laden succulent stem. The most root efficient cane plants are those that accumulated the highest stem mass with the least nutrient investment in the root biomass. The highest root efficiency was recorded in the P_{200} to P_{250} replicated plots and the least was in the control variants. Results clearly show that the 200 – 300 P fertilizer application rate band, which, incidentally, recorded the highest root count and root intensity while at the same time scoring the lowest root volumes and root extensions, had the most efficient root systems.

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