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Maize Productivity, Economic Returns and Phosphorus Use Efficiency as Influenced by Lime, Minjingu Rock Phosphate and NPK Inorganic Fertilizer

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ABSTRACT

This study was conducted to examine the effects of Lime, Minjingu Rock Phosphate (MRP) and inorganic NPK fertilizer on maize productivity, profitability and phosphorus use efficiency (PUE) based on grain yield (PUE_Y) and economic returns (PUE_E). The study was carried out for two rain seasons in Kenya and the treatments were Lime, MRP, NPK, Lime + MRP, Lime + NPK, and a control. The highest height (185 cm) was recorded in MRP treated plots whereas the lowest values were observed in control (162 cm) and Lime (166 cm). The lowermost yield of 2.2 t ha^{-1} was attained from the non-amended plots. The value increased by 4.0, 2.9, 1.8, 1.7 and 0.8 t ha^{-1} in MRP, NPK, Lime + MRP, Lime + NPK and Lime treatments. The use of MRP proved to be the most lucrative with a disposable income of US$ 2122ha^{-1}. PUE_Y was such that Lime + NPK (95 kg of maize grain yield for every kg of p supplied) < Lime + MRP (116) < NPK (125) < control (139) < MRP (170) < Lime (188) whereas PUE_E was lowest in plots treated with Lime + NPK (38 $ kg^{-1}) and Lime + MRP (46 $ kg^{-1}), and highest in Lime (75 $ kg^{-1}) and MRP (68 $ kg^{-1}) plots. The results from the study indicate that MRP amendment is essential in optimizing not only maize productivity and economic returns but also phosphorus efficacy.

Keywords: Maize, Phosphorus, Minjingu rock phosphate, Soil acidity, Soil fertility

Soils in most parts of Kenya are generally infertile (FAO, 2001) and are characterized by nutrient imbalances such as potassium (K), phosphorus (P) and nitrogen (N) majorly caused by excessive uptake by crops with minimal replenishment (Gitari *et al.* 2019; Mugo *et al.* 2021; Ochieng' *et al.* 2021). Maize (*Zea mays* L.), which is a basic food item in Kenya is grown in soils characterized by low pH (Nyoro *et al.* 2004; Nduwimana *et al.* 2020) with low plant-available phosphorus (P), particularly in Western Kenya (Okalebo, 2009; Kisinyo *et al.* 2009). Therefore, acid soilsare normally infertile with poor plant growth caused by one or more interacting factors such as the buildup of manganese (Mn) or aluminium (Al) toxicities. Such factors have

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adverse effects on soil microbial activities and many nutrient deficiencies for instance phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca) and molybdenum (Mo) (Kamprath, 2015; Gudu *et al.* 2005; Hassan *et al.* 2020; Ngugi *et al.* 2021). Due to low and declining fertility, maize (grain) yield has stagnated at an average of 2 t ha^{-1}, a value that is below the attainable 6 t ha^{-1} (Kang'ethe, 2004; Ochieng' *et al.* 2021).

Maize responds to P application significantly even at low rates of about 10 kg P ha^{-1} (Jama *et al*. 1997; Waigwa *et al*. 2002; Kisinyo *et al*. 2009) suggesting the need of adding the nutrient seasonally to soils in this area to prevent not only its deficiency but also to reinstate and improve soil productivity. Major staple foods in Kenya such as maize, legumes and most of the horticultural crops perform very poorly on acidic soils (Nduwimana *et al*. 2020). Poor growth results in poor quality produce, low quantity of yields and low economic returns, a circumstance that results in food shortages, recurrent hunger, malnutrition crisis and eventually loss of lives (Nekesa *et al*. 2011; Nyawade *et al*. 2020). There have been suggestions of using improved and certified seeds but unfortunately, maize germplasm that most farmers use are quite sensitive to high aluminium saturation (less than 20%), which is prevalent in many parts of Kenya (Ligeyo *et al*. 2008, 2013; Guignard *et al*. 2017).

The soil acidity mainly results from continuous use of fertilizers like Diammonium phosphate (DAP) during sowing given that they have an acidifying effect and nutrients being carried away through runoff water (Nyawade *et al*. 2019; Gitari *et al*. 2019). Many soil fertility management innovations and technologies have been tried to mitigate this problem such as the application of inorganic fertilizers and multiple cropping (Sanginga and Woomer, 2009; Maitra *et al*. 2020; Otieno *et al*. 2021). Such strategies have several disadvantages, hence inhibiting their adoption in Kenya by smallholder farmers. Therefore, the application of lime and Minjingu Rock Phosphate (MRP) to acidic soils is highly recommended to restore fertility and improve crop productivity (Jafer and Hailu, 2017; Gitari *et al*. 2015; Goulding, 2016). These amendments encompass Mg and or Ca composites that dislocate Fe^{3+}, Al^{3+} and H^+ ions from exchangeable sites in soil colloids thus reducing P sorption sites in acidic soils, hence, increasing accessible P for plant uptake (Sanchez *et al*. 1997; Tisdale *et al*. 1990; Lino *et al*. 2018).

Additionally, use of NPK fertilizers is recommended because it has a less acidifying effect than DAP. With regard to NPK, N is available to plants in form of nitrate (NO_3^-), which releases OH^- into the soil solution thereby raising the soil pH. On the contrary, N in DAP is accessible to plants in ammonium (NH_4^+) form, which releases H^+ into the solution that decreases soil pH. Minjingu rock phosphate (MRP) is another soil amendment, which is a superlative phosphatic fertilizer ideal for highly acidic soils (Sanchez *et al*. 1997; Nekesa *et al*. 2011; Jama *et al*. 1997). Therefore, there is a need to amend soils in Kakamega County by using various soil amendments such as MRP, NPK and lime to improve phosphorus availability in soils, which will eventually improve maize productivity and economic benefits per unit area. It is against this background that this study was set with three objectives: (i) to evaluate the influence of Lime, MRP and NPK fertilizer on maize growth parameters (ii) to assess the effect of these treatments on crop produce (grain yield) and economic benefits and (iii) to examine the influence of same treatments on phosphorus uptake and use efficiency.

RESEARCH METHODOLOGY

Experimental site

This field study was carried out for two rain seasons (short rains of 2019 and long rains of 2020) at Bukura Agricultural Training Centre in Western Kenya, located 0° 14′ 15′′ North, 34° 37′ 44′′ East and 1463 m above sea level. It is located in the Lower Midland agro-ecological zone (LM1), mainly dubbed the sugar cane zone, and with Orthic Ferralsols as the dominant soil type (FAO-UNESCO, 1990). The area receives approximately 1900 mm of rainfall per annum, which is well distributed over the two main cropping seasons; the short rains that run between August and December and the long rains that occur from March to July. The annual mean temperature is roughly 22 °C with a range of 10 °C and 26 °C. Specifically, during the short rains, total rainfall of 1044 mm was received whereas in 2020 long rains the rainfall amounted to 1092 mm (Fig. 1). The highest rainfall intensity was received in October (344 mm) and March (346 mm). Throughout

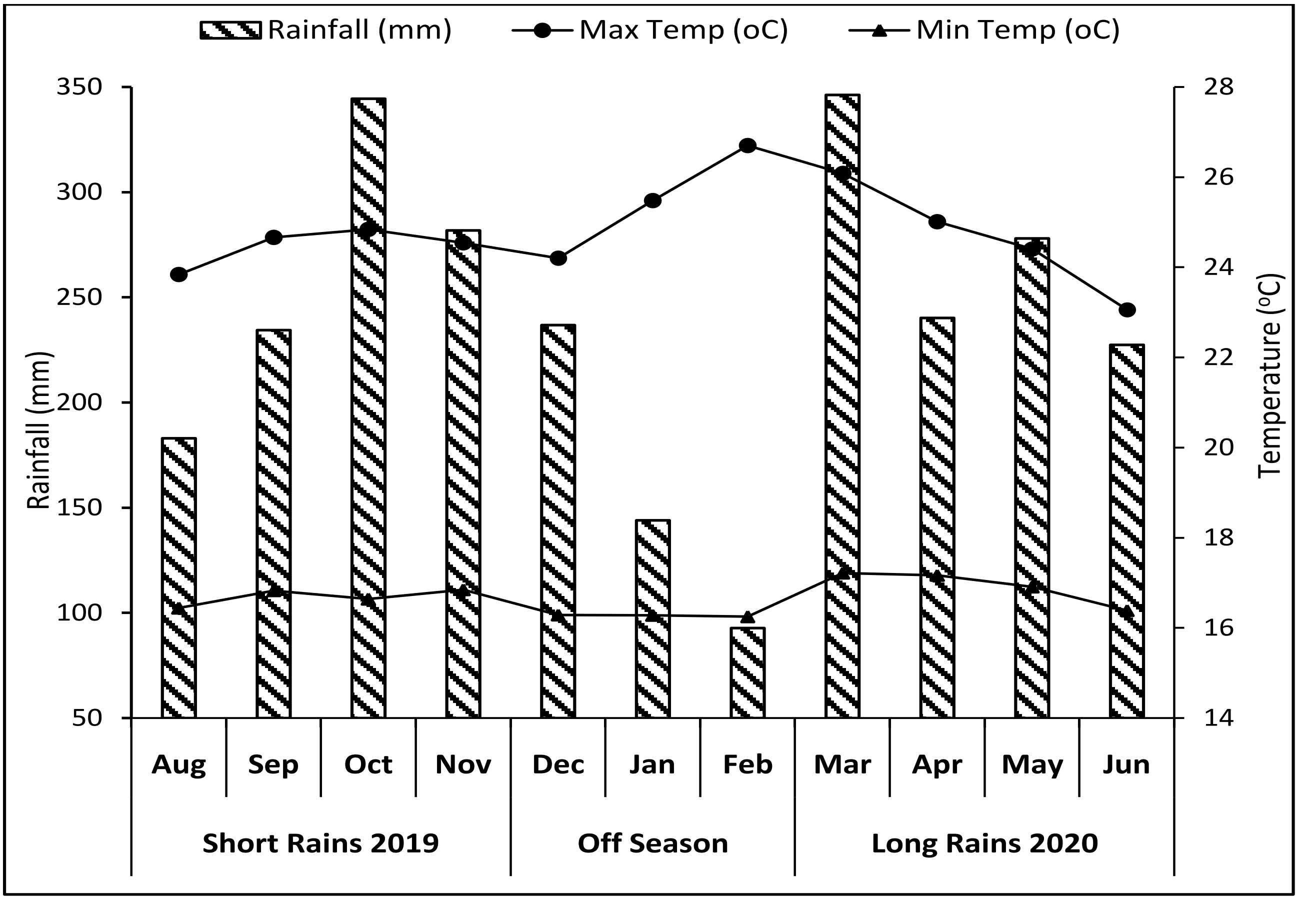

Fig. 1: Monthly total rainfall and mean temperature (minimum and maximum) as recorded at Bukura Agricultural College Meteorological Station from August 2019 to June 2020

the off-season (December 2019 to February 2020), about 470 mm of rainfall was received. The mean air temperature raised gradually to the highest value (27 °C) in February then decreased gradually to the lowest value of 16 °C in June.

Experimental design and layout

The experiment adopted a Randomized Complete Block Design (RCBD) with three replications where each experimental unit measured 5 m long by 4.5 m wide making a net area of 22.5 m^2 $plot^{-1}$. The gross plot had four harvestable rows and two border rows. The blocks and plots were separated by paths of 0.8 m and 0.5 m, respectively. There were six treatments for this experiment (Lime, MRP, NPK, Lime + MRP, Lime + NPK, and a control), which were replicated three times.

Soil sampling and preparation for analysis

Soil sampling was carried out using a soil auger approximately three weeks (21 days) before the onset of 2019 short rains. The samples were obtained from 22 points that were uniformly distributed along zigzag transects on the site at a depth of 0–0.3 m as described by Pennock and Yates (2008). The samples were mixed scrupulously then a composite sample was drawn for physical (texture) and chemical analyses. This disturbed sample was air-dried for three days and sieved through a 2 mm sieve. In addition, undisturbed soil samples were taken in core rings measuring 2.5 cm in radius and 5 cm in length.

Soil texture was determined by employing hydrometer procedures (Gee and Bauder, 1979) while bulk density was analyzed as described by Doran and Mielke (1984). Measurement of soil pH was done in 1:2.5 v/v (soil: water solution) with the help of a pH meter as explained by Ryan *et al*. (2001). Exchange acidity was determined according to Mehlich (1976) by leaching the soil with 0.6 N $BaCl_2$. Cations (Na^+, K^+, Mg^{2+} and Ca^{2+}) were determined using Atomic Absorption Spectrophotometer (AAS)

(Jackson, 1967). Bray 1 method (Aura, 1978), was employed in the determination of phosphorus using the double acid extraction method and the concentration read on UV–vis spectrophotometer (Murphy and Riley, 1962). For the determination of total nitrogen (N), the Kjeldahl digestion method was used (Bremner and Keeney, 1965). Soil organic carbon (OC) determination was done following Walkley-Black (wet oxidation) method (Yeomans and Bremner, 1988).

Site preparation, planting and crop management

Prior to instituting this experiment, the site had lied uncultivated for four seasons. Hence, the bush was cleared three weeks before the onset of short (July 2019) rains followed by deep ploughing and harrowing to achieve the recommended tilth. Agricultural lime ($CaCO_3$) was evenly broadcasted on the soil surface and thoroughly integrated into the top 2.5 cm layer using a rake to lime treated plots before actual planting. The fertilizers were applied at planting time in the holes where they were mixed with soil to avert seed scorching. Maize (variety- SC DUMA 43) obtained from local agro-vet dealers was used as the test crop at the rate of 55 kg ha^{-1}.

Sowing was done on August 28, 2019, and March 25, 2020, for short and long rains, respectively. Seeds were sown manually at a depth of 0.075 m (two seeds per hole) at an inter-row spacing of 0.75 m with the intra row space being 0.25 m. Thinning (removal of extra plants) was done around 14 days after sowing to be left with one plant per hole when the young plants were at the 3-4 leaf stage. Where there was germination failure, gapping was done immediately to achieve a plant population of 5.3 plants m^{-2}. Cultural practices such as weed, pest and disease control were carried out uniformly in all plots. Weeding was done manually and fall armyworm control was done using Escort pesticide containing Emamectin benzoate 19 g L^{-1} as the active ingredient. All treatments were supplied with 75 kg N ha^{-1} calcium ammonium nitrate (26-0-0) as top-dress.

Data collection procedures and analyses

Data on plant leaf area (LA), leaf area index (LAI), height, and phosphorus uptake were collected at two maize phenological stages based on Biologische Bundesarstalt Bundessoztenamt and Chemical industry (BBCH) scales (Hack, 1992). The first stage was BBCH-19, characterized by at least eight unfolded leaves whereas the second was BBCH-59 marked by a fully emerged and separated tassel. The yield data were collected at BBCH-89 when maize was fully ripe with hard and shiny kernels. A section with a net area of 2 m^2 was identified and marked at the centre of each plot. From this area, four plants were selected then tagged randomly for data collection.

The plant height was measured from the surface of the soil up to the collar of the upper leaf (with developed leaf sheath)using a steel tape measure. LAfor each plant was determined as a product of the leaf width (taken from the widest middle portion of the leaf) and the length and then multiplying it by 0.75, a correction factor (cf) for maize (Rajeshwari *et al*. 2007). LAI on the other hand was estimated by multiplying the total LA of the plant with the corresponding number of leaves plant^{-1} and dividing it with the space occupied by a single maize stand (Sadik *et al*. (2001) (Equation 1).

$$LAI = \frac{\text{leaf area (cm}^2\text{/plant)* leaf number}}{\text{ground area (cm}^2\text{/plant)}} \quad \ldots(1)$$

Besides the plant height, LA and LAI, additional data on P uptake were taken. This involved sampling plant tissues at BBCH-19 and BBCH-59, where two maize plants plot^{-1} were selected randomly, cut and chopped with a machete. The samples were then mixed and a representative sample (weighing about one kilogram) taken and packaged in khaki paper bags, oven-dried to a persistent weight at 60 °C and ground. The dry ashing method as described by Motsara and Roy (2008) was used to measure the concentration level of P in the plant sample. One gram of the sample was ashed at 500-600°C, placed in a silica crucible, and then heated in a furnace for 4 hours. The ash residue was dissolved in diluted hydrochloric acid (HCl) then the solution was filtered gently into 250 ml volumetric flasksto remove dehydrated silica and filled up to the mark. This was followed by a transfer of a 25 ml aliquot of the plant solution into another volumetric flask (100 ml capacity) where distilled water was added to have a total volume of 70 ml. The reagent, consisting of 10ml 2.5% ammonium molybdate and

4 ml of 0.25% aminonaphthol sulfonic acid were added. The volumetric flask was gently shaken and left to stand for ten minutes after which it was filled to the mark. The solution was permitted to stand for about 2 hours for full color development and its concentrations read on a colorimeter spectrophotometer at 430 nanometers.

Grain yield and economic analysis

At the BBCH-89 phenological stage, cobs from 4 plants plot^{-1} were randomly selected and sun-dried separately for 7 days. Shelling was done manually and thereafter, the dry grains were weighed with a weighing balance to determine grain yield in kilograms and then converted to t ha^{-1}. The total cost of production was determined by summing up all the expenses used in the production (fertilizer, seeds, pesticides and labor) including the cost of leasing the land (20 US\$ ha^{-1}). Gross income was obtained by multiplying the grain yield with the prevailing market price of maize (0.4 US\$ kg^{-1}). Net income and cost: benefit ratios were determined as shown in Equations 2 and 3.

$$\textit{Net income} = \textit{Gross income} - \textit{Total cost of production} \quad \ldots(2)$$

$$\textit{Cost: Benefit ratio} = \frac{\text{Net income}}{\text{Total cost of production}} \quad \ldots(3)$$

Determination of phosphorus use efficiency

Phosphorus use efficiency (PUE) was computed using Equation 4 (Fageria, 2009; Gitari *et al*. 2018).

$$PUE = \frac{Y}{P\ applied} \quad \ldots(4)$$

Where Y = yield obtained per treatment based on either grain yield (PUE_Y) or economic (PUE_E) terms. In this case, the economic returns were taken as the net income.

Statistical analysis

Each parameter was carefully studied and the average was calculated accordingly. The combined ANOVA for the two consecutive cropping seasons (2019 short rains and 2020 long rains) data was performed using GenStat (2010). Mean separation and interpretation were done according to the LSD test ($p \leq 0.05$). Moreover, regression analysis was used to indicate the relationship between LAI and maize grain yield.

RESULTS

Soil physical and chemical properties of the experimental site

At the beginning of the experiment, analyses of the soil at the study site indicated it had a mean bulk density of 1.03 g cm^{-3} and clay loam texture with clay, silt and sand of 300, 400 and 300 g kg^{-1}, respectively (Table 1). It was relatively acidic (pH of 5.05) and with exchangeable acidity of 8.2 cmol kg^{-1}. Organic carbon, available P and total N were 15.3 g kg^{-1}, 3.83 mg kg^{-1} and 2.6 g kg^{-1}, respectively. Its exchangeable cations: Na, K, Ca and Mg were averaged at 0.32, 0.08, 3.21 and 1.31 cmol kg^{-1}, respectively.

Effect of soil amendments on maize growth parameters

Plant height: Soil amendments had a substantial ($p \leq 0.05$) influence on plant height both at BBCH-19

Table 1: Soil chemical and physical properties of the study site at 0–0.3 m depth

Physical properties	Value	Chemical properties	Value
Sand (g kg^{-1})	300	pH (water) 1:2.5	5.05
Clay (g kg^{-1})	300	Exchangeable Na (cmol kg^{-1})	0.32
Silt (g kg^{-1})	400	Exchangeable K (cmol kg^{-1})	0.08
Textural class	Clay loam	Exchangeable Ca (cmol kg^{-1})	3.21
Bulk density (g cm^{-3})	1.03	Exchangeable Mg (cmol kg^{-1})	1.31
		Exchangeable acidity (cmol kg^{-1})	8.2
		Organic carbon (g kg^{-1})	15.3
		Total N (g kg^{-1})	2.6
		Available P (mg kg^{-1})	3.83

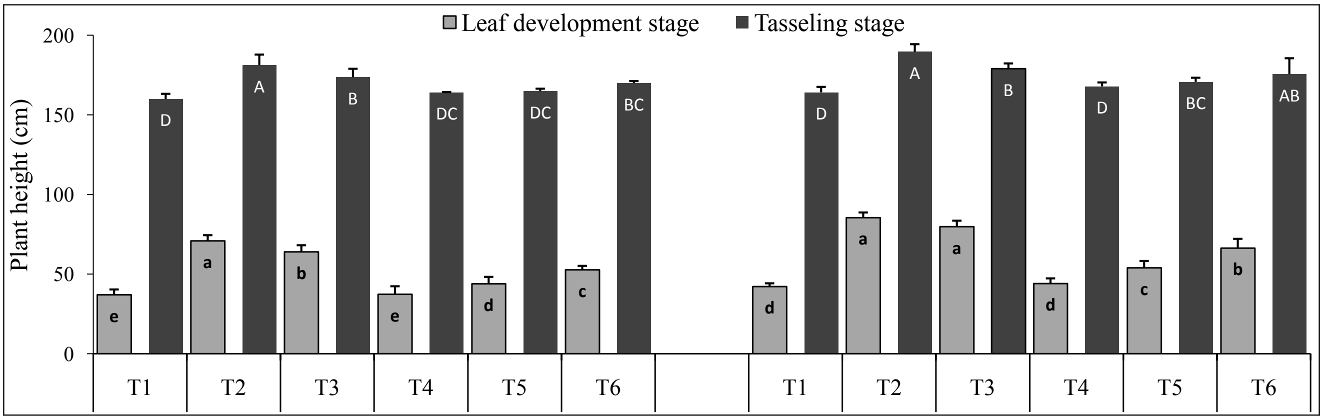

Fig. 2: Plant height at leaf development (gray bars) and tasseling stages (black bars) in 2019 short rains and 2020 long rains as affected by different amendments: Control (no amendment applied) (T1); Minjingu rock phosphate (MRP) (T2); NPK (T3); Lime (T4); Lime + NPK (T5) and Lime + MRP (T6). Bars with the similar alphabet letters (lower case for leaf development and upper case for tasseling) within the same growth stage and season represent means that are substantially the same at $p \leq 0.05$. Error bars show standard error of the means

and BBCH-59 scales and the effect differed with seasons (Fig. 2). Across the seasons, generally at BBCH-19 (leaf development) stage, plant heights according to treatments were: the control (38 cm) < Lime (41 cm) < Lime + NPK (49 cm) Lime + MRP < (60 cm) < NPK (72 cm) < MRP (78 cm). On the other hand, the highest height (185 cm) at the tasseling stage was recorded in MRP treated plots whereas the least values were recorded in the control (162 cm) and Lime (166 cm) treatments. The heights with Lime + NPK treatment differed slightly from those with NPK and Lime + MRP but not with lime treated plots.

Leaf area and leaf area index: Leaf area (LA) and leaf area index (LAI) were considerably ($p \leq 0.05$) affected by soil amendments both at leaf development and tasseling stages with lower values being recorded in 2019 short rains compared with 2020 long rains (Table 2). Across the seasons, LA at the leaf development stage was lowest in the control (0.16 cm^2) and in lime treated plots (0.17 cm^2) with an intermediate value of 0.20 cm^2 in Lime + NPK and highest record value of 0.42 cm^2 in plots that received MRP. Plots treated with NPK + Lime and MRP recorded 24 and 31% lower LA, respectively, when compared with those amended with MRP (0.42 cm^2). At tasseling stage, the variable differed between treatments whereby it increased in the order of control (0.48 cm^2) < Lime (0.59 cm^2) < Lime + NPK (0.64 cm^2) < Lime + MRP (0.71 cm^2) < NPK (0.83 cm^2) < MRP (0.97 cm^2). At the leaf development stage, LAI was lowest in control (0.73), followed by Lime (0.75) and Lime + NPK (0.89) treatments while the highest value was noted in the plot that received MRP (1.86). The LAI in NPK treatment did not differ from that in Lime + MRP treated plots. At the tasseling stage, the highest (4.3) LAI was observed in plots that received MRP while the lowest record was made in control (2.1) and lime-amended (2.6) plots. Lime + NPK, Lime + MRP and NPK recorded 34, 27 and 14% lower values for LAI, respectively, compared with MRP.

Effect of soil amendments on maize grain yield and economic returns

Maize grain yield and economic returns were substantially ($p \leq 0.05$) influenced by soil amendments with higher values being recorded in 2020 long rains compared with 2019 short rains (Table 3). Across the seasons, the least yield (2.2 t ha^{-1}) was noted in non-amended control plots. MRP treated plots recorded 4.0 t ha^{-1}higher than control whereas NPK, lime, Lime + NPK and Lime + MRP treatments recorded 2.9, 0.8, 1.7 and 1.8 t ha^{-1} higher values, respectively, compared with control. The cost of production ranged from US$ 246 in control to US$ 381 in Lime + NPK plots. Nevertheless, the use of MRP proved to be the most rewarding with a net income of US$ 2122 with NPK, Lime + MRP, Lime + NPK, Lime and control recording 22, 40, 45, 10 and 70% lower values, respectively, compared with MRP. This resulted in greater benefit: cost ratios in plots that received MRP and NPK (7.6 and 5.9, respectively) and lowest in Lime and non-amended treated plots (2.51 and 2.53, respectively).

Table 2: Leaf area and leaf area index (means ± standard error) at leaf development (BBCH-19) and tasseling (BBCH-59) stages as affected by soil amendments in 2019 short rains and 2020 long rains

Season	Treatment	Leaf area		Leaf area index	
		BBCH-19 (m²)	BBCH-59 (m²)	BBCH-19	BBCH-59
2019 Short rains	Control	0.15 ± 0.02[c]	0.47 ± 0.01[e]	0.67 ± 0.39[c]	2.06 ± 0.51[e]
	MRP	0.39 ± 0.03[a]	0.88 ± 0.03[a]	1.74 ± 0.42[a]	3.90 ± 0.53[a]
	NPK	0.30 ± 0.04[a]	0.77± 0.02[bc]	1.33 ± 0.08[b]	3.41 ± 0.06[ab]
	Lime	0.16 ± 0.01[b]	0.54 ± 0.02[ed]	0.70 ± 0.61[c]	2.39 ± 1.01[cd]
	Lime + NPK	0.19 ± 0.03[b]	0.59 ± 0.04[d]	0.86 ± 0.53[c]	2.62 ± 0.97[c]
	Lime + MRP	0.29 ± 0.03[a]	0.69 ± 0.04[c]	1.27 ± 0.12[b]	3.04 ± 0.18[b]
2020 Long rains	Control	0.18 ± 0.01[c]	0.50 ± 0.03[d]	0.78 ± 0.27[c]	2.22 ± 0.30[d]
	MRP	0.44 ± 0.01[a]	1.06 ± 0.05[a]	1.97 ± 0.28[a]	4.70 ± 0.40[a]
	NPK	0.33 ± 0.03[b]	0.89 ± 0.08[ab]	1.48 ± 0.16[b]	3.96 ± 0.10[ab]
	Lime	0.18 ± 0.02[c]	0.64 ± 0.01[c]	0.79 ± 0.42[c]	2.83 ± 0.63[c]
	Lime + NPK	0.21 ± 0.00[c]	0.69 ± 0.03[b]	0.91 ± 0.28[c]	3.07 ± 0.64[b]
	Lime + MRP	0.30 ± 0.02[b]	0.72 ± 0.03[b]	1.31± 0.12[b]	3.21 ± 0.15[b]
Summary of analyses of variance (p values)					
Treatment(T)		<.001	<.001	<.001	<.001
Season (S)		0.003	<.001	0.003	<.001
T × S		0.652	0.040	0.652	0.040

Means (± standard deviation) bearing dissimilar alphabet letters (down the column and per season) differ markedly at p ≤ 0.05 by LSD test.

Table 3: Maize yield and economic returns (means ± standard error) as influenced by soil amendments in 2019 short rains and 2020 long rains

Season	Treatment	Yield (t ha⁻¹)	Cultivation cost (US$ ha⁻¹)	Gross income (US$ ha⁻¹)	Net income (US$ ha⁻¹)	Benefit: cost ratio
2019 Short rains	Control	2.04 ± 0.20[e]	246.81	816 ± 81.18[e]	569.19 ± 81.18[d]	2.31 ± 0.36[d]
	MRP	5.86 ± 0.21[a]	281.18	2344 ± 83.72[a]	2062.82 ± 83.72[a]	7.34 ± 0.32[a]
	NPK	4.98 ± 0.21[b]	297.60	1992 ± 83.72[b]	1694.4 ± 83.72[b]	5.69 ± 0.30[b]
	Lime	2.78 ± 0.05[d]	334.61	1112 ± 20.46[d]	777.39 ± 20.46[d]	2.32 ± 0.07[d]
	Lime + NPK	3.68 ± 0.20[c]	380.40	1472 ± 81.18[c]	1091.6 ± 81.18[c]	2.87 ± 0.23[cd]
	Lime + MRP	4.02 ± 0.12[c]	363.98	1608 ± 48.78[c]	1244.02 ± 48.78[c]	3.42 ± 0.14[c]
2020 Long rains	Control	2.30 ± 0.16[e]	245.79	920 ± 63.87[e]	674.21 ± 63.87[e]	2.74 ± 0.28[de]
	MRP	6.16 ± 0.18[a]	281.30	2464 ± 70.86[a]	2182.7 ± 70.86[a]	7.76 ± 0.27[a]
	NPK	5.21 ± 0.07[b]	296.65	2084 ± 27.06[b]	1787.35 ± 27.06[b]	6.03 ± 0.10[b]
	Lime	3.10 ± 0.04[d]	335.50	1240 ± 17.72[d]	904.5 ± 17.7[d]	2.70 ± 0.06[e]
	Lime + NPK	4.07 ± 0.13[c]	381.47	1628 ± 53.15[c]	1246.56 ± 53.15[c]	3.28 ± 0.15[bc]
	Lime + MRP	4.16 ± 0.13[c]	362.56	1664 ± 53.15[c]	1301.44 ± 53.15[c]	3.60 ± 0.16[c]
Summary of analyses of variance (p values)						
Treatment (T)		<.001		<.001	<.001	<.001
Season (S)		<.001		<.001	<.001	<.001
T x S		0.703		0.703	0.683	0.397

Means with dissimilar alphabet letters (down the column) per season differ considerably at p ≤ 0.05 by LSD test.

Lime + MRP and Lime + NPK recorded ratios of 3.5 and 3.1, respectively.

Phosphorus uptake and P use efficiency

Phosphorus uptake and PUE were influenced considerably ($p \leq 0.05$) by soil amendments and the effect differed with seasons. P uptake and PUE was higher in 2020 long rains as compared to 2019 short rains. Across the seasons, phosphorus uptake was high at tasseling (BBCH-59) than at the leaf development (BBCH-19) stage (Table 4). At the leaf development stage, significant differences among

Table 4: Phosphorus (P) uptake at leaf development (BBCH-19) and tasseling (BBCH-59) stages and P use efficiency based on yield (PUE_Y) and economic returns (PUE_E) (means ± standard error) as affected by treatments in 2019 short rains and 2020 long rains

		Phosphorus uptake		Phosphorus use efficiency	
Season	**Treatment**	**BBCH-19 (kg ha^{-1})**	**BBCH-59 (kg ha^{-1})**	**PUE_Y(kg of grain yield kg of p applied^{-1})**	**PUE_E (\$kg^{-1})**
2019 Short rains	Control	1.9 ± 0.07^{c}	2.1 ± 0.02^{c}	130.1 ± 52.99^{b}	52.0 ± 21.20^{b}
	MRP	2.7 ± 0.04^{a}	6.9 ± 0.04^{a}	165.9 ± 8.91^{a}	66.4 ± 3.56^{a}
	NPK	2.2 ± 0.04^{b}	3.5 ± 0.02^{b}	122.1 ± 7.24^{b}	48.9 ± 2.90^{b}
	Lime	1.1 ± 0.03^{c}	$2.2. \pm 0.02^{c}$	177.2 ± 13.35^{a}	70.9 ± 5.34^{a}
	Lime + NPK	1.6 ± 0.03^{c}	2.9 ± 0.02^{c}	90.3 ± 7.02^{c}	36.1 ± 2.81^{c}
	Lime + MRP	1.8 ± 0.04^{c}	3.5 ± 0.04^{b}	113.9 ± 5.19^{c}	45.6 ± 2.08^{c}
2020 Long rains	Control	1.9 ± 0.04^{d}	2.3 ± 0.01^{c}	147.2 ± 41.69^{c}	58.8 ± 16.68^{b}
	MRP	3.6 ± 0.04^{a}	8.7 ± 0.03^{a}	174.2 ± 7.54^{b}	69.7 ± 3.02^{a}
	NPK	2.9 ± 0.03^{b}	3.9 ± 0.03^{b}	127.9 ± 2.34^{d}	51.9 ± 0.94^{b}
	Lime	1.6 ± 0.02^{d}	2.4 ± 0.02^{c}	198.0 ± 11.56^{a}	79.2 ± 4.63^{a}
	Lime + NPK	2.3 ± 0.01^{c}	2.6 ± 0.03^{c}	100.0 ± 4.60^{e}	40.0 ± 1.84^{c}
	Lime + MRP	2.2 ± 0.05^{c}	3.4 ± 0.04^{b}	117.8 ± 5.65^{d}	47.1 ± 2.26^{c}
Summary of analyses of variance (p values)					
Treatment (T)		<.001	<.001	<.001	<.001
Season (S)		<.001	<.001	<.001	<.001
T × S		0.337	0.337	0.103	0.004

Down the column (within a season), means with similar superscript alphabet letters are not substantially ($p \leq 0.05$) different by LSD test.

the soil amendments in plant P uptake were found, with average values for both seasons of 3.2, 2.6, 2.0, 1.9, 1.8 and 1.4 kg ha^{-1} in MRP, NPK, Lime + MRP, Lime + NPK, control and Lime treatments, respectively. Similarly, at the tasseling stage highest uptake was noted in MRP (7.8 kg ha^{-1}). Average plant P uptake in NPK, Lime + MRP, Lime + NPK, Lime and control-treated plots for the two seasons were significantly lower by 52, 55, 67, 71 and 72%, respectively, relative to MRP. P use efficiency based on grain yield (PUE_Y) was such that Lime + NPK (95 kg of maize grain yield per kg of p supplied) < Lime + MRP (116) < NPK (125) < control (139) < MRP (170) < Lime (188). P use efficiency based on economic returns (PUE_E) was lowest in plots treated with Lime + NPK (38 \$ kg^{-1}) and Lime + MRP (46 \$ kg^{-1}), and highest in Lime (75 \$ kg^{-1}) and MRP (68 \$ kg^{-1}) plots. NPK and control recorded 32 and 26% lower values, respectively, compared with that received lime.

Relationship between yield and leaf area index

When yield was regressed against leaf area index (LA1), strong relationships were noted in Lime + NPK ($R^2 = 0.60$) and Lime ($R^2 = 0.86$) treatments, implying that with all factors held constant, increasing LAI by a unit would result in an increase in yield by 0.8 and 0.6 t ha^{-1}, respectively (Fig. 3). Similarly, a positive but moderate association ($R^2 = 0.41$) was observed between yield and MRP amended plots, an indication that increasing LAI by a unit would increase yield by 6%. Nonetheless, the relationship between yield and NPK gave a weak coefficient of regression ($R^2 = 0.32$) whereas, when yield in control and in plots that received Lime + MRP were regressed, no tangible relationship was established ($R^2 = 0.2$).

DISCUSSION

Effect of soil amendments on maize growth, yield and economic returns

From the research study, the soil amendments substantially influenced plant height, leaf area and leaf area index, yield, economic returns and P use efficiency with better maize performance being observed in 2020 long rains than 2019 short rains. During the 2019 short rain, maize supplied with lime recorded the shortest plant height. This could be as a result of the low neutralizing activity of lime which is associated with low rainfall (Fig. 1) hence low solubility of lime,which could have made it possible for aluminium ions to inhibit the uptake of available nutrients. In 2020 long rains, lime increased the maize growth compared with the un-amended control,and this could be accredited to the lime solubility into the soil due to sufficient rainfall received in the season, and also the activity of lime residues applied (Kimiti, 2018).

Better performance of MRP could be attributed to continuous slow discharge of Pinto the soil making it accessible by the plant. This could also be attributed to the extra plant nutrients (5% S, 0.5% Cu, 0.1% Band 0.5% Zn) that are available in MRP fertilizer,unlike other commercial fertilizers. Hence, the study indicates higher superiority of using MRP as compared with the other treatments, which is as per other findings (Nekesa *et al*. 2011) that MRP provides a liming effect on acidic soils especially orthicferralsols, which are widely distributed in some regions of Western Kenya. This is ascribed to the relatively high content of carbonates despite their low solubility in the soil. In NPK, Lime + NPK, Lime + MRP and Lime plots, the yield increased correspondingly by 2.9, 1.7, 1.9 and 0.8 t ha^{-1}, compared with non-amended plots. The control had the least yields, probably due to low available P where most of it was probably fixed by aluminium oxides in the acidic soils of the area. Hence, this rendered P unavailable or limited for the maize crop uptake (Gitari *et al*. 2015). Consequently, plants supplied with inadequate P exhibit purple-bluish leaves, poor crop growth and poor crop performance in terms of economic yields. This agrees with the observation made by Marschner (1995) that phosphorus is an important nutrient

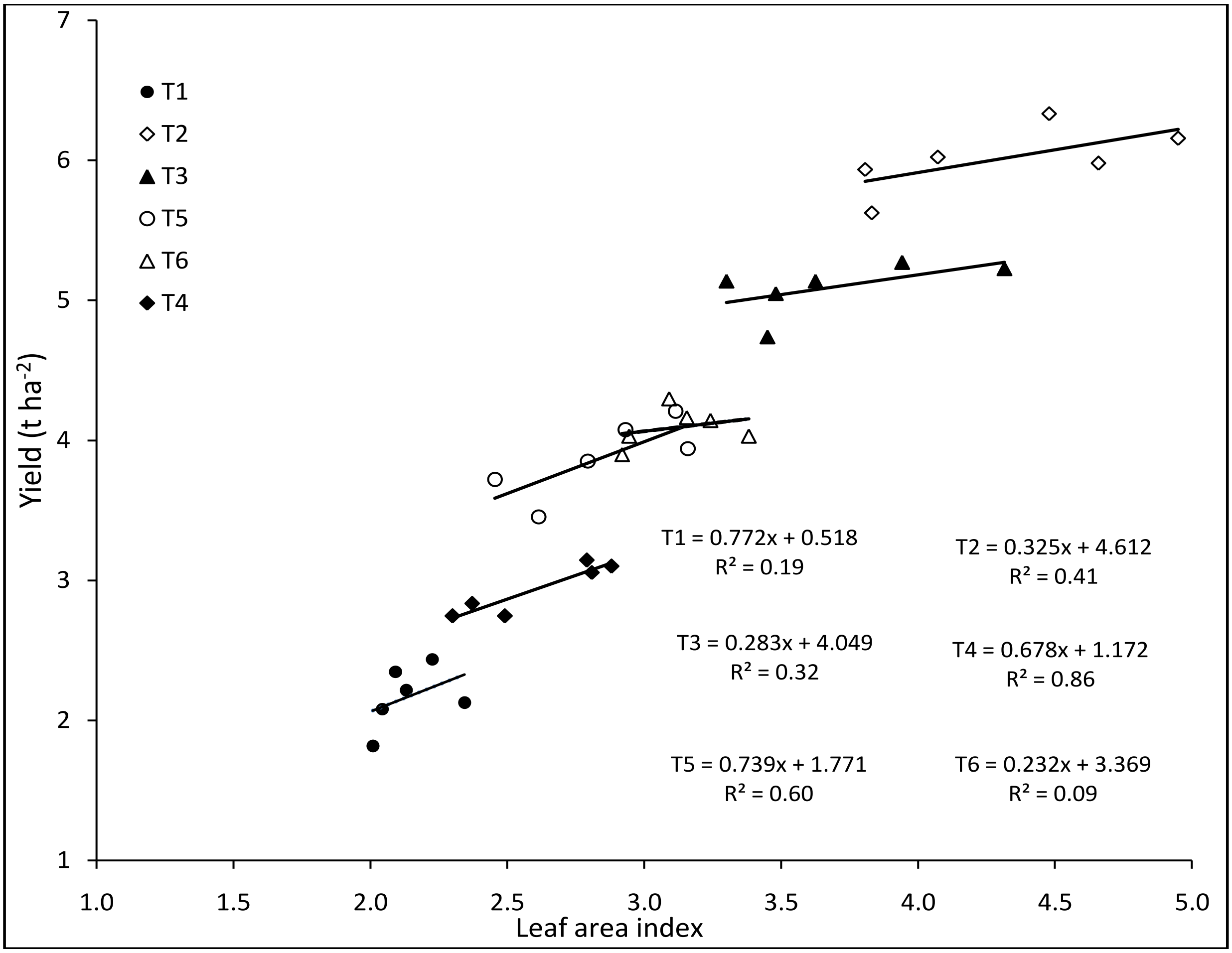

Fig. 3: Regression of yield against leaf area index for control (T1), MRP (T2), NPK (T3), Lime (T4), Lime + NPK (T5) and Lime + MRP (T6)

in crop production, and its application to soils is essential to achieve maximum crop production.

Furthermore, higher yields achieved in MRP treatment could be as a result of large leaves denoted by LA and LAI, which could have enabled the plants to attain optimum photosynthetic capacity during the post tasseling period (Marschner, 1995; Uribelarrea *et al*. 2009; Nasar *et al*. 2021). Such argument is reinforced by previous observations made by Yan *et al*. (2011) and Raza *et al*. (2021) that plants with more leaves tend to have better growth and subsequent higher yield. This was further reinforced by the strong regression coefficients between yield and LAI, which agrees with the findings by Sandana (2016). Such associations may indicate that any factor that increases LAI would also increase grain yield (Seleiman *et al*. 2021). As noted by Zhou *et al*. (2019), optimal P supply corresponds well with a light interception, which enables the plant to utilize assimilates and meets their grain yield potential. Increased light interception not only results in increased photosynthetic capacity but also boosts carbon (c) translocation to the roots (Cheng *et al*. 2014; Wang *et al*. 2011; Zhou *et al*. 2021). In such cases, the partitioned C serves not only as a source of energy but also as a nutritional signal in driving heightened nutrient uptake, hence productivity.

The highest net income of 2123 US$ ha^{-1} was noted in the treatment that received MRP, which was 71% higher than control. Lime treatments recorded low net income possibly due to high input cost and labour employed in the application of the lime. The higher economic returns in MRP treatment could be associated with the low cost of production associated with it since the rock was locally and cheaply available hence making it the most economically viable soil amendment for maize production.

Effect of soil amendments on P uptake and P use efficiency

In the current study, maize that received MRP had higher P uptake, which might have resulted in more leaves with increased photosynthetic capacity in comparison with those in control plots (Fig. 2 and Table 2). Possibly, low P availability in control plots curbed the crop's P uptake. This could further be explained by the low values that were noted for LA and LAI in such plots (Fig. 2 and Table 2). The results infer that P deficiency has an unfavourable effect on leaf growth (Wang and Ning, 2019). Sustaining sufficient P concentration in leaves cereal crops such as maize is essential for photosynthesis, which is recycled later and translocated to the developing grains during the reproductive growth stage (Sklensky and Davies, 1993; Yaseen and Malhi, 2009; Meng *et al*. 2013). These results are in agreement with the findings reported by Marschner (1995) that P is taken up largely during the active growth stage,which thereafter gets re-translocated into storage organs such as seeds during reproductive stages. In addition, Marschner (1995) observed that the amount of P supplied during such reproductive stages controls the subdivision of photosynthates between the source leaves and the reproductive organs such as grains thus resulting in vigorous growth.

From the study, average plant P uptake in NPK, Lime + MRP, Lime + NPK, Lime and control-treated plots were significantly lower by 52, 55, 67, 71 and 72%, respectively, relative to MRP. It can be concluded from this study that among all the treatments, MRP proved to be a superior soil amendment in terms of P uptake by maize crop. The higher P uptake could be ascribed to an increase in the availability of P in the soil as influenced by the addition of MPR (Nekesa *et al*. 2011). According to Kochian (2005) and Swift *et al*. (1994), low P uptake in other treatments particularly control could be due to crop's sensitivity to high Al saturation (> 20%), which affects root development and growth of many crops thus making them inefficiently utilize the inherent P in the soil or added phosphate fertilizer (Schachtman *et al*. 1998; Faridvand *et al*. 2021; Soratto *et al*. 2021). Due to the low content of soil available phosphorus, maize production is not likely to increase without the addition of mineral or organic P (Vance *et al*. 2003; Veneklaas *et al*. 2012). As a result, availability of P has been associated with the application of P and increase in available P from organic amendments or mineral fertilizers thus resulting in higher P uptake (Kwabiah *et al*. 2003; Dobermann *et al*. 2002). Improved P uptake with MRP application especially during the long rains of 2020 could be attributed to increased soil moisture content, which probably enhanced dissolution of MRP resulting in more available P. This is affirmed by Dhillon *et al*. (2020) and Gitari *et al*. (2020) who reported improved P uptake under higher rainfall condition. The well-distributed rainfall during the long rains ensured that the soil remained moist throughout the growing season, therefore, promoting the dissolution of P, which met the plant P demands (Khasawneh and Doll 1978; Bolland *et al*. 1995).With higher P uptake, the higher yield was noted, especially in MPR treatment resulting in higher economic returns. Consequently, the higher yield and income translated to higher P efficacy. Thus, the current study demonstrates the feasibility of using MRP to increase not only maize productivity but also economic returns.

CONCLUSION

This study has demonstrated that the application of MRP improved maize growth. MRP treatment increased plant height by 14%, leaf area by 50% and leaf area index by 51% compared with non-amended plots. In addition, the application of MRP fertilizer showed improved maize grain yields and economic returns compared with NPK treatment. For instance, the highest yields were obtained in MRP treatments (6 t ha^{-1}). Average plant P uptake in NPK and control treatments were significantly lower by 52 and 72%, respectively, compared with MRP. P use efficiency based on maize grain yield (PUE_Y) was highest in Lime and MRP treatments and lowest in NPK treatment. P use efficiency based on economic returns (PUE_E) was lowest in treatments with Lime + NPK (38 $ kg^{-1}) and highest in Lime (75 $ kg^{-1}) and MRP (68 $ kg^{-1}) treatments. Generally, MRP treatment proved to be the best soil amendment for optimal maize growth, productivity and phosphorus uptake and use efficiency. Nonetheless, since this study was done for only two rainy seasons, it would be useful to consider a longer experiment to establish the effects of these soil amendments on the observed parameters as well as soil properties.

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