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White Lupin (*Lupinus albus L. cv.* Amiga) Increases Solubility of Minjingu Phosphate Rock, Phosphorus Balances and Maize Yields in Njoro Kenya

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Abstract

Exudation of high amounts of citrate in white lupin (*Lupinus albus L. cv. Amiga*) has the advantage of being effective in mobilization of a wide range of sparingly soluble P sources. To improve cultivation system of maize, a field experiment was conducted to assess effectiveness of white lupin (*Lupinus albus* L. cv. Amiga) in increasing solubility of minjingu phosphate rock (MPR), phosphorus balances and maize yields in Njoro sub-County, Kenya. The randomized complete block design experiment was conducted for four seasons; short (October – February) and long rain seasons (March-September) of 2010 and 2011. The treatments were; (i) fallow (F) – maize (M) rotation with triple superphosphate (TSP) applied (M_{TSP}- F), (ii) fallow - maize rotation with MPR applied (M_{MPR} –F), (iii) lupin (L) – maize rotation with MPR applied (M_{MPR}- L) and (iv) maize/lupin intercrop with MPR applied (M/L_{MPR} – F). Soil and plant P and maize grain yield were higher in M/L_{MPR} – F (with additional lupin grain yield) and M_{TSP}– F treatments. All treatments resulted in positive P balances at the end of two years with highest values in M_{TSP}– F treatment and lowest in M/L_{MPR} – F. Intercropping lupin with maize amid application of MPR is recommended for enhanced maize performance in the farming systems of resource poor farmers. Measurement of available soil nitrogen and comparison of lupin with other legumes in solubilizing MPR is recommended.

Keywords: carboxylates, intercrop, rotation, P balances, phosphorus mobilization, white lupin

1. Introduction

Phosphorus (P) is an essential macronutrient for plant growth and its availability is often the limiting factor for crop cultivation (Marschner, 1995). Maize, the primary staple crop of Kenya (Schroeder et al., 2013) has a high phosphorus requirement (Kogbe & Adediran, 2003). Small holder farmers in Njoro sub-County however, utilize sub optimal quantities of inorganic P fertilizers in the production of maize due to financial constraints (CBS, 1996; Henao & Baanante, 2001). The consequence has been soil fertility decline, low maize yields and unsustainable crop production (Lelei et al., 2009; Kwabiah et al., 2003).

To address soil fertility problems associated with depletion of phosphorus, minjingu phosphate rock (MPR) is an affordable alternative (Onwonga et al., 2013). It is the predominant type of phosphate rock (PR) deposit in Eastern Africa with sufficient quantity and reactivity cum potential for direct application (Okalebo et al., 2007). Interest in the use of PRs as alternative P sources has been increasing due to their relative lower costs, coupled with their potential for utilization, with or without amendments (Akande et al., 2010). The PRs are natural minerals requiring minimum processing, mainly involving grinding, are environmentally friendly and could be more efficient than the soluble fertilizers in terms of recovery of phosphate by plants (Schultz, 1992; Yeates & Clarke, 1993; Rajan et al., 1994).

The major impediment to wide use of PR is its insolubility (Thuita et al., 2005). This can however be enhanced in low pH and P limiting soils, with the application of organics and in the rhizosphere of vigorously growing legumes (Okalebo et al., 2007; Vanlauwe et al., 2000; Hassan & Karanja, 1997). During N_2 fixation, legumes take up excess cations over anions and release protons from roots (Lui et al., 1989). The resulting acidification of the rhizosphere enables legumes to take up significant amounts of sparingly soluble nutrients (Hinsinger & Gilkes, 1995).

Effect of white lupin (*Lupinus albus* L.) in mobilization of sparingly soluble minjingu phosphate rock has not been previously tested in the area. Previous experiments in the area with use of MPR have focused on acidic soils and the use of manure to enhance its solubility (Onwonga et al., 2013). Lupin has extreme tolerance for low P availability and one of the few agronomically important species that develop proteoid roots during adaptation to phosphorus deficiency (Yan et al., 2001; Avio et al., 1990).

White lupin (*Lupinus albus*) has evolved elegant adaptations for growth under P-deficient soil conditions (Dinkelaker et al., 1995; Keerthisinghe et al., 1998; Watt & Evans, 1999; Neumann & Martinoia, 2002). It has a highly synchronous, co-ordinated expression of genes which results in proliferation of cluster roots, root exudation of organic acids and acid phosphatase, as well as the induction of numerous transporters (Gilbert et al., 1999; Neumann & Martinoia, 2002; Vance et al., 2003; Uhde-Stone et al., 2003). Acid phosphatases that may aid in the release of organic phosphatases (Tadao & Sakai, 1991) are released coincident with the exudation of organic acids from proteoid roots (Miller et al., 2001). Exudation of organic acids and acid phosphatase has the advantage of being effective in the mobilization of a wider range of sparingly soluble P sources such as acid soluble Ca-P in calcareous soils (Dinkelaker et al., 1989), Fe and Al-P in acid soils and P complexed by soil organic matter (Gerke, 1995; Marschner, 1995). This causes an increase in the availability of P in cluster root zones (Lamont, 2003). Moreover, the formation of proteoid roots results in a striking increase in root surface area, thereby providing enhanced zones for P uptake (Dinkelaker et al., 1989, 1995; Gerke, 1995); Neumann et al., 1999; Lamont, 2003).

Calculations of soil nutrient balance in agricultural production systems provide some basic information for assessing their long term sustainability (Hanáčková et al., 2008). For soil phosphorus balances, it can provide basic information to evaluate the effect of incorporation of lupin with the application of MPR in maize based cropping systems on production. The difference between amount of nutrient exported with grains and applied as fertilizers indicates the level of increase or decrease in soil nutrient content. When the outputs of a particular nutrient are larger than the inputs in the farming system, the condition is one of unsustainability (Oenema et al., 2003). A negative balance, results in decreased soil fertility, which affects the yield and profitability of system resources and leads to soil degradation (Singh et al., 2002). It is therefore important for the adequate management of phosphate fertilization to estimate the balance of the nutrients in the soil.

The current study investigated effect of white lupin (*Lupinus albus L. cv.* amiga) on solubilization of MPR, P uptake and balances and maize yields.

2. Materials and Methods

2.1 Site

The experiment was conducted on a farmer's field in Njoro sub-County, Kenya (longitude 35º23' and 35 º 35' East and Latitude 0 º13' and 1 º10' south; 2200 m asl) for four seasons; long (LRS) and short (SRS) rain seasons of 2010 and 2011. The mean annual rainfall received in the area ranges between 840 to 1000 mm. The distribution is bimodal in nature with the LRS occurring from March to August and SRS from September/October with peaks in April and November, respectively. The mean air temperature is 15.9 ºC (Jaetzold et al., 2007). The total rainfall received in 2010 and 2011 was 918 mm and 982 mm while mean air temperature was 17.6 and 19.1 ºC, respectively. The soils are well drained, dark reddish in colour and are classified as mollic Phaozems (FAO/UNESCO, 1990).

Chemical and physical characteristics (Table 1) of the top (0 to 0.2 m) soil layer were, according to Landon (1991) classification ; neutral in pH (pH water 6.4), moderate in organic C (15 g kg^{-1}), high in total N (3.5 g kg^{-1}), low in Olsen extractable P (14.2 mg kg^{-1}) and exchangeable bases (cmol kg^{-1}); Ca (6.5), Mg (0.72) and K (1.42), and clay loam in texture with (%); sand (36), silt (29.6), and clay (34).

2.2 Treatments and Experimental Design

The experiment was laid out in a randomized complete block design with four replications. Plot sizes measured 3.75 m × 4.8 m. Space for foot path (0.5 m) between plots and blocks (1m), was provided. The treatments were; fallow (F) – maize (M) rotation with triple superphosphate (TSP) applied (M_{TSP}- F), (ii) fallow - maize rotation with MPR applied (M_{MPR} –F), (iii) lupin (L) – maize rotation with MPR applied (M_{MPR}- L) and (iv) maize/lupin intercrop with MPR applied (M/L_{MPR} – F).

2.3 Land Preparation and Application of Inputs

Land was prepared manually using hand hoes. MPR was incorporated to a depth of 0 - 0.15 m along the planting furrows two weeks before planting to allow for sufficient reaction with soil. TSP was applied at planting by banding. Both P sources were applied at the rate of 60 kg P ha^{-1}. MPR was applied only once during the entire experimental period while TSP was applied twice; at planting of maize in the LRS of 2010 and 2011. Nitrogen was applied at the rate of 75 kg N ha^{-1} as calcium ammonium nitrate (CAN) fertilizer to all plots, split into two applications; 45 and 30 kg N ha^{-1} at planting and at topdressing (a month after planting), respectively.

Table 1. Initial soil chemical and physical properties

Property	Unit	Soil Depth (cm)		
		0-15	15-30	30-60
pH (H_2O)	-	6.4	6.3	6
organic C	g kg^{-1}	15	13	12
available P	mg kg^{-1}	14.2	11.3	8.2
Total N	g kg^{-1}	3.5	2.4	2.7
Ca	cmol kg^{-1}	6.5	2.7	3.1
Mg	cmol kg^{-1}	0.72	0.83	0.42
K	cmol kg^{-1}	1.42	0.89	0.56
sand	%	36	34	32
clay	%	34	40	40
silt	%	29.6	25.6	27.6
Textural class	-	Clay loam	Clay loam	Clay loam

2.4 Planting Operations

Maize (*Zea mays* L., Hybrid, 513) was sown, at spacing of 75 cm × 30 cm, during the LRS of 2010 and 2011 in all treatments. Two maize seeds were sown into each planting hole and thinned to one plant 30 days after sowing (DAS). In M/L_{MPR} – F treatment, two lupin (*Lupinus albus L. cv.* Amiga*)* seeds were sown between the rows of maize i.e. one row of lupin between two rows of maize in the LRS of 2010 and 2011. Thinning to one plant (maize and lupin) was done a month after sowing. In the SRS of both 2010 and 2011 Lupin was sown at the rate of two seeds per hole at a spacing of 75 × 30 cm in the M_{MPR}- L treatment. Thinning to one plant per hole was done a month after sowing.

2.5 Management of Residues

Lupin residues and weed biomass in the natural fallow plots produced in the SRS were chopped into small pieces (5-20 cm), spread across the plots and incorporated in soil to a depth of 15 cm during land preparation for maize planting, using hand hoes. The residues of lupin grown in intercropping with maize in the LRS were similarly handled.

2.6 Soil and Plant Sampling

Composite soil samples were collected from three profile pits (0-60 cm depths) before application of treatments for analysis of initial physical and chemical properties (Table 1). Thereafter soil samples were collected from the top soil (0-20 cm) at; seedling, tasseling and maturity stages of maize (LRS) and lupin (SRS) growth to monitor changes in soil available P. The samples were obtained randomly from four locations in each plot between the plants within a row and bulked to get one composite sample.

Maize and lupin plant samples were collected during the same periods as of soil sampling. For maize at the seedling stage, four whole maize plants were sampled randomly while at flowering, the leaf opposite the ear was sampled from ten randomly selected plants. At physiological maturity the above ground portion of maize was harvested from two internal rows. Maize samples at maturity were divided into stover (stalk and leaves), cob and grains. For lupin at seedling and 50% flowering growth stages, plant samples, were obtained from four randomly selected plants per plot by cutting the shoot two (2) cm above ground. At harvest, samples were collected from two internal rows and divided into stover, pods and grains. Fallow plots (weeds) in the SRS were sampled at the same intervals as for lupin plots.

Plant samples collected at seedling, tasseling and harvest (stover or residues) were chopped into small pieces and sub-samples oven dried at 65 ºC for 72 hours. The weights of the oven dry sub-samples were recorded and used to calculate the total above-ground dry matter yields. Oven dried biomass samples were ground to pass through a 0.5 mm sieve for analysis of total P.

2.7 Soil and Plant Analysis

Air - dried soils sieved through 2 mm mesh were analyzed for pH (Soil: H_2O: 1:2.5), texture, total N, organic carbon and available P according to standard procedures (McLean, 1982). Exchangeable bases (K, Ca and Mg) were extracted with 1.0 M-ammonium acetate at pH 7 and measured by atomic adsorption spectrophotometry. Ground plant samples were analyzed for P according to McLean (1982) to determine nutrient uptake.

2.8 Calculation Procedures

Total phosphorus uptake (TNU): was calculated from nutrient concentrations and the final dry matter measured (Peterburgski, 1986);

$$TNU\ (kg\ ha^{-1}) = DM\ (kg\ ha^{-1}) \times P/100; \text{ the value obtained was converted to mg } g^{-1} \text{ dry matter} \tag{1}$$

Maize and lupin grain yield: The maize and legume samples for grain yield determination were obtained from two internal rows of each plot. Grain yield (adjusted to 13 % moisture content) was recorded and converted to kg ha^{-1} using the following formula;

$$Grain\ yield\ (kg\ ha^{-1}) = kg\ grain\ yield\ m^{-2} \times 10{,}000\ m^2 \tag{2}$$

Determination of P balances: Soil P balance (kg ha^{-1} yr^{-1}) was calculated after the second year of the experiment as the sum of the total amount of P nutrient applied as fertilizer (kg ha^{-1}), the change in the amount of P in a layer of soil to 0.20 m depth (kg ha^{-1}) and the total amount exported in harvested grain (kg ha^{-1}), all divided by the duration of the assessment period (years), according to the following equation (Steiner et al., 2012; Raij et al., 1997);

$$Soil\ P\ balance = [P_{Fertilizer} + (P_{InitialSoil} - P_{FinalSoil}) - P_{Exported}]\ /\ assessment\ period \tag{3}$$

The amount of P exported in the form of maize (grain and DM) and lupin (grain) was estimated based on the concentration of each nutrient in the grains and stover.

2.9 Statistical Analysis

To detect statistical variation in treatment effects, the measured soil parameters were subjected to analysis of variance (ANOVA) using the SPSS software (SPSS, 1999) appropriate for a randomized complete block design (RCBD). The Tukey's Honestly Significant Difference ($P < 0.05$) was used for mean separation. The results in the tables are presented as mean values ± SD (standard deviations).

3. Results and Discussion

3.1 Changes in Soil Available Phosphorus During Plant Growth

Soil available P declined from plant seedling towards maturity in the treatments M_{TSP} – F and M_{MRP}- F in both years (Table 2). An increase in soil available P was observed at 50% flowering in M/L_{MPR} – F in the LRS and M_{MPR}- L treatments in the SRS of both years. The level of available P in soil was higher in M_{MPR}– L than M_{MPR}– F in the SRS of 2010 and 2011. Soil available P was significantly ($P < 0.05$) higher in the M_{TSP}– F treatment at seedling stage of maize during the LRS of 2010 and 2011 (Table 2). At 50% flowering of maize in the same period, the M/L_{MPR} – F treatment had significantly higher soil available P values. In the SRS of 2010 soil available P was significantly ($P < 0.05$) higher in M_{MPR}- L and M/L_{MPR} – F treatments at the seedling stage while at 50% flowering and maturity, levels of available P in the soil were significantly higher in the M_{MPR}– L treatment. During the SRS of 2011 at seedling and maturity stage of lupin, the M/L_{MPR} – F contained significantly higher levels of soil available P. At 50% flowering however significantly higher amounts of soil available P were found in the M_{MPR}- L treatment.

The mean available P value taken across sampling periods was significantly higher in the M/L_{MPR} – F treatment during the LRS of both years (Table 2). In the SRS of 2010, the treatments M_{MPR}- L and M/L_{MPR} – F had significantly higher mean values across sampling periods. The value was significantly higher in the latter treatment during the SRS of 2011.

Table 2. Means of soil available P (mg kg^{-1}) in the long and short rain seasons (Mean ± SD)

	2010							
Treatment	Long Rain Season				Short Rain Season			
	seed	flw	mat	aver	seed	flw	mat	aver
M$_{TSP}$- F	21.8±0.80^{a}	7.5± 0.31^{b}	5.4±-0.22^{c}	10.2±1.20^{b}	8.2± 0.09^{b}	7.2± 0.12^{d}	7.6± 0.93^{c}	7.7± 1.16^{d}
M$_{MPR}$ –F	12.8±0.91^{b}	8.6± 0.12^{b}	7.1± 0.76^{b}	8.2± 1.18^{c}	9.1± 0.22^{b}	8.5± 0.36^{c}	8.1± 0.51^{c}	8.6± 0.89^{c}
M$_{MPR}$- L	13.8±0.72^{b}	8.8± 0.94^{b}	7.2± 0.35^{b}	8.6± 0.79^{c}	11.9±0.35^{a}	12.3±1.54^{a}	9.7± 0.09^{a}	10.8±1.20^{a}
M/L$_{MPR}$ – F	12.6±0.41^{b}	18.3±0.76^{a}	9.2± 0.93^{a}	13.4±0.35^{a}	11.6±0.42^{a}	10.8±0.37^{b}	9.1± 0.33^{b}	11.0±0.57^{a}
	2011							
Treatment	Long Rain Season				Short Rain Season			
	seed	flw	mat	aver	seed	flw	mat	aver
M$_{TSP}$- F	21.7±0.33^{a}	9.2± 0.07^{d}	5.5±0.32^{b}	12.1±0.41^{a}	7.4± 0.22^{c}	6.7± 0.09^{b}	5.2± 0.78^{c}	6.4± 0.21^{d}
M$_{MPR}$ –F	11.1±0.46^{b}	10.1±0.12^{c}	7.8±0.45^{a}	9.7± 0.39^{b}	7.9± 0.51^{c}	8.9± 0.41^{c}	6.9± 0.34^{b}	7.9± 0.72^{c}
M$_{MPR}$- L	14.2±0.32^{b}	15.6±0.86^{b}	7.6±0.31^{a}	12.5±0.74^{a}	8.2± 0.39^{b}	12.7±0.27^{a}	7.1± 0.45^{b}	9.3± 0.09^{b}
M/L$_{MPR}$ – F	13.5±0.93^{b}	17.4±0.46^{a}	8.1±0.96^{a}	13.0±0.92^{a}	10.2±0.61^{a}	10.6±0.11^{b}	11.1±0.22^{a}	10.6±0.18^{a}

Key: seed = seedling; flw = 50% flowering; mat = maturity; aver = average of sampling periods values. Means in a column followed by the same letter are not significantly different at $P < 0.05$, using the Tukey mean separation procedure.

Declining available P levels in soil with progression of maize growth is attributable to uptake of P for normal plant growth and development. Most crops take up majority of the nutrients during the periods of vegetative growth (Mengel, 1995). The significantly higher values in the M$_{TSP}$- F treatment (Table 2) at first sampling in the LRS of 2010 and 2011 may be due to the high solubility of TSP fertilizer. This treatment however had lower values at subsequent sampling times after seedling demonstrating low residual effects. Thuita et al. (2005) studied the solubility and availability of P from phosphate rocks and observed higher values of available P in the control TSP treatment at 20 days after planting. They attributed it to high solubility of TSP fertilizer.

The higher levels of available P in soil at 50% flowering of maize (M/L$_{MPR}$ – F treatment) and lupin (M$_{MPR}$- L treatment) in the LRS and SRS, respectively is attributable to solubilization of MPR by lupin as a result of acidification of the rhizosphere by release of acids. White lupin (*Lupinus albus*) has developed mechanisms for chemical mobilization of sparingly available P sources in the rhizosphere, involving formation of cluster roots. When exposed to P starvation, white lupin excretes large amounts of citric and malic acids from proteoid roots (Neumann et al., 2000). The acids desorb P from sparingly soluble Ca, Al and Fe-P (Neumann et al., 2000). Acidification during the process of nitrogen fixation may have also played a role. At the 50 % flowering stage of the lupin, biological nitrogen fixation process was close to maximum values. Voisin et al. (2003) reported that symbiotic nitrogen fixation was maximum at flowering and declined to low values at seed filling of *Pisum sativum*. Symbiotic nitrogen fixation initiates a chain of reactions leading to increased availability of rock phosphate-P (Ahiabor & Hirata, 2003). During N_2 fixation legumes take up excess cations over anions and release protons from roots (Lui et al., 1989). The resulting acidification of the rhizosphere enables legumes take up significant amounts of sparingly soluble nutrients (Hinsinger & Gilkes, 1995).

Lack of significant differences in soil available P content in M$_{MPR}$- F and M$_{MPR}$- L treatments in the first season of planting (LRS of 2010) with maize crop was because both had received MPR and therefore experienced similar treatment effects. In subsequent seasons, however, lower levels observed in M$_{MPR}$- F treatment was due to low solubility of the MPR. White lupin, however enhanced its solubilization as attested by the higher available P in soil in M$_{MPR}$- L than M$_{MPR}$- F treatments in the SRS of 2010 and 2011 and M/L$_{MPR}$ – F treatment in the LRS of both years. In a rhizosphere experiment using isotope exchange kinetics on the same soil, lupin rhizosphere was able to solubilize the less soluble P fractions for P uptake (Kay & Hill, 1998). Higher amounts in M$_{MPR}$- L than M$_{MPR}$- F treatments in the LRS of 2011 can also be attributed to the presence of lupin residues incorporated during land preparation for planting of maize. The residues enhanced solubilization of MPR and/or released P upon its mineralization. McLenaghen et al. (2004) in an experiment on effect of lupin green manure on phosphate rock availability, observed reduction in resin-P values in fallow plots after maize, compared with the lupin green manure (GM). The lupin GM treatment retained resin-P levels close to original values even though P was being taken up and lost via crop removal. This indicated that the lupin GM extracted otherwise non-available native P sources and released this P to the following maize crop.

The availability of P in subsequent seasons in MPR applied plots was due to continual solubilization of MPR by lupin and residual effects. Nekesa et al. (2005) studying the potential of Minjingu phosphate rock from Tanzania as a liming material in acid soils of Western Kenya reported decrease in available P in the order of MPR > diammonium phosphate (DAP) > DAP + lime (L) > L alone > control. Their results demonstrated the residual effect of MPR. MPR has also been quoted to persist in the soil for as long as 10 consecutive seasons (Noordin, 2002).

The higher mean values of available P across sampling periods for the M/L_{MPR} – F treatment during the LRS of 2010 and 2011 was as a result of mobilization of MPR by lupin and incorporation of its residues after harvest. In a four year experiment in an agricultural site in which P was the major limiting soil nutrient, a P nutrition improvement in faba bean/maize intercropping treatment was reported (Li et al., 2007). Interspecific rhizosphere effect plays an important role in the interspecific facilitation between intercropped species (Li et al., 2007).

3.2 Phosphorus Uptake

Increased P uptake was noted from seedling growth stage to 50% flowering in both maize and lupin followed by a decline thereafter towards crop physiological maturity across all treatments and years (Table 3 and 4). At maize seedling, during the LRS of 2010 and 2011, amount of P taken up was significantly higher in M_{TSP}- F treatment. At 50% flowering of maize, treatments M_{TSP}- F and M/L_{MPR} – F had significantly higher P uptake in the LRS of both years.

Table 3. Means of P uptake (mg g-1) in the long rain season (Mean ± SD)

				2010	
Treatment	plant	seedling	50% flw	maturity	average
M_{TSP}- F	Maize	2.5±0.30^{a}	3.3±0.21^{a}	1.1±0.06^{a}	2.3±0.12^{a}
M_{MPR} –F	Maize	1.4±0.08^{b}	2.4±0.43^{c}	1.2±0.03^{a}	1.7±0.06^{b}
M_{MPR}- L	Maize	1.6±0.03^{b}	2.6±0.07^{c}	1.2±0.05^{a}	1.8±0.02^{b}
M/L_{MPR} – F	Maize	1.8±0.03^{b}	3.5±0.12^{a}	1.2±0.01^{a}	2.2±0.02^{a}
	Lupin	1.2±0.01	2.1±0.05	0.9±0.04	1.4±0.01
				2011	
Treatment	plant	seedling	50% flw	maturity	average
M_{TSP}- F	Maize	2.9±0.06^{a}	3.5±0.09^{a}	1.1±0.02^{b}	2.5±0.15^{a}
M_{MPR} –F	Maize	0.8±0.01d	1.6±-.04^{c}	0.8±0.04^{c}	1.1±0.04^{c}
M_{MPR}- L	Maize	1.4±0.02^{c}	2.8±0.10^{b}	1.4±0.01^{b}	1.9±0.03^{b}
M/L_{MPR} – F	Maize	2.1±0.05^{b}	3.7±0.12^{a}	1.9±0.03^{a}	2.6±0.21^{a}
	Lupin	1.3±0.04	1.9±0.03	0.7±0.08	1.3±0.04

Key: flw = flowering. Means in a column followed by the same letter (for maize) are not significantly different at P<0.05, using the Tukey mean separation procedure.

Table 4. Means of plant P uptake (mg g-1) in the short rain season (Mean ± SD)

Treatment	plant	2010			
		seedling	50% flw	maturity	average
M_{TSP}- F	weeds	0.9±0.02^{c}	1.2±0.01^{c}	0.8±0.02^{d}	1.0±0.01^{c}
M_{MPR} –F	weeds	1.2±0.01^{bc}	1.1±0.04^{c}	1.1±0.03^{c}	1.1±0.04^{c}
M_{MPR}- L	lupin	1.9±0.04^{a}	3.9±0.35^{a}	2.9±0.82^{a}	2.9±0.02^{a}
M/L_{MPR} – F	weeds	1.4±0.01^{b}	1.9±0.05^{b}	1.6±0.05^{b}	1.6±0.03^{b}
Treatment	plant	2011			
		seedling	50% flw	maturity	average
M_{TSP}- F	weeds	0.7±0.03^{c}	0.8±0.02^{c}	0.6±0.03^{c}	0.7±0.02^{c}
M_{MPR} –F	weeds	0.9±0.07^{bc}	0.7±0.01^{c}	0.7±0.01^{c}	0.8±0.81^{c}
M_{MPR}- L	lupin	1.8±0.05^{a}	3.4±0.24^{a}	2.2±0.46^{a}	2.5±0.52^{a}
M/L_{MPR} – F	weeds	1.1±0.01^{b}	1.5±0.03^{b}	1.4±0.61^{b}	1.3±0.31^{b}

Key: flw = flowering. Means in a column followed by the same letter are not significantly different at $P<0.05$, using the Tukey mean separation procedure.

Uptake of P was significantly higher in M/L_{MPR} – F treatment at physiological maturity of maize in the LRS of 2011, while in 2010 no significant differences were observed in all treatments. The M_{MPR} –F treatment had lowest P uptake values in all seasons and years. The mean of P uptake value across the three maize growth stages was significantly higher in M/L_{MPR} – F and M_{TSP}- F treatments in LRS of both years (Table 3). During the LRS in 2010, the mean P uptake values for M_{MPR}- L and M_{MPR} –F treatments were not significantly different but in 2011 the former had significantly higher value. Uptake of P by lupin was higher in the SRS (Table 4) of both years compared to when intercropped with maize (Table 3). In the SRS of 2010 and 2011, uptake of P was significantly higher in lupin crop than fallow (Table 4). Comparing uptake of P by weeds in fallow plots in the SRS, significantly higher values were obtained in M/L_{MPR} – F treatments in both years. The mean uptake of P value across the three growth stages in the SRS showed significant P uptake in treatment M_{MPR}- L followed by M/L_{MPR} – F in both years.

The increasing P uptake value from seedling to 50% flowering of both maize and lupin can be attributed to continuous uptake throughout crop growth. The higher uptake in M_{TSP}- F at seedling stage in the LRS of both years was due to the high solubility of TSP fertilizer and consequently availability in soil (Table 2). P is immediately released into soil with addition of mineral fertilizers (Steiner et al., 2012). Wasonga et al. (2008) found significantly ($P < 0.05$) increases in P uptake by maize varieties following TSP application. The significantly higher P uptake in treatments M_{TSP}- F and M/L_{MPR} – F at 50% flowering of maize in both years and higher mean P uptake across the three maize growth stages in these treatments is attributable to higher availability of P compared to M_{MPR}- L and M_{MPR} –F treatments (Table 2). TSP is a highly soluble P source (Govere et al., 2003) whereas lupin intercrop in M/L_{MPR} – F treatments enhanced solubility of MPR and subsequently availability in soil (Table 2). Lowest uptake in M_{MPR} –F treatment was as a result of low amounts available in soil arising from insolubility of MPR (Table 2). The significantly higher uptake of P in M/L_{MPR} – F treatment at physiological maturity of maize in LRS of 2011 can be attributed to residual effects of MPR. The higher P uptake values for M_{MPR}- L than M_{MPR} –F treatment was due to higher available P in soil P as a result of mobilization by legume lupin (Table 2). Release of P during decomposition of lupin residues may have contributed to higher P uptake values in treatments with lupin. McLenaghen et al. (2004) who studied increasing phosphate rock availability using a lupin green manure (GM) crop reported significant increase in lupin P uptake and attributed it to increased P availability from PR dissolution, acidification of the rhizosphere or extraction of native non-available P by lupin GM.

The low uptake of P by lupin in intercropping system with maize (Table 3) rather than when grown singly in pure stand (Table 4) can be explained in terms of competition for nutrients by component crops in intercrop (Hauggaard-Nielsen & Jensen, 2001). Significantly higher uptake of P by lupin crop than weeds in the SRS of 2010 and 2011 was due to higher available P in soil (Table 2) and high P requirements by legume. Symbiotic nitrogen fixation has a high P demand because the process consumes large amounts of energy (Schulze et al., 1999), and energy- generating metabolism strongly depends upon availability of P (Israel, 1987; Plaxton, 2004). Comparing uptake of P by weeds in fallow plots in the SRS, significantly higher values were obtained in M/L_{MPR} – F treatments in both years and this was due to higher available P in soil (Table 2). The significantly higher mean uptake of P value for the three maize growth stages in treatment M_{MPR}- L followed by M/L_{MPR} – F in the SRS of both years was due to higher availability of soil available P (Table 2). Odiete et al. (2005) studied response of maize to single super phosphate and reported significant increased P uptake irrespective of P source.

3.3 P balances in Soil

P balances calculated over a period of two years were positive in all treatments and significantly higher in M_{TSP}- F treatment followed by M_{MPR} – F and M_{MPR}- L (Table 5). Lowest P balance was found in M/L_{MPR} – F treatment. The higher P balance in M_{TSP}- F treatment was partly due to higher import of P. TSP fertilizer was applied at beginning of each rain season at planting of maize unlike MPR which was applied only once. The positive balance in treatments containing MPR was due to residual effects in addition to release of P during mineralization of soil organic matter and the incorporated lupin residues.

Steiner (2012) working on phosphorus and potassium balance in soil under crop rotation and fertilization in Parana Brazil explained that the absence of any nutrient source impact on amount of soil P in crop succession system was likely due to residual effect. Hanáčková et al. (2008) found that the incorporation of cover crop residues into soil resulted in a positive balance of 4 kg P ha^{-1} $year^{-1}$ in both succession and rotation cropping systems.

Table 5. P balances in soil in different treatments (kg ha $^{-1}$ yr^{-1})

Treatment	P fertilizer	P initial soil	P final soil	P exported			
				Maize Grain	Maize DM	LupinGrain	P balance
M_{TSP}- F	120	18.4	10.4	20.2	11.4	-	75.43^{a}
M_{MPR} –F	60	18.4	13.8	15.08	7.8	-	16.38^{b}
M_{MPR}- L	60	18.4	14.2	19.33	12.8	0.73	11.35^{b}
M/L_{MPR} – F	60	18.4	22.2	20.1	16.4	0.63	1.2^{c}

Means in a column followed by the same letter are not significantly different at $P < 0.05$, using the Tukey mean separation procedure.

The positive values obtained in this study indicate that the treatments and cropping systems were sustainable. When the outputs of a particular nutrient are larger than the inputs in the farming system, the condition is one of unsustainability (Steiner et al., 2012).

3.4 Grain and DM Yields

In the LRS of 2010, maize grain and dry matter yields were significantly higher ($P < 0.05$) in M_{TSP}- F treatment followed by M/L_{MPR} – F treatments, M_{MPR}- L and M_{MPR}- F in that order (Table 6). There were no significant differences in grain and DM yield in the latter two treatments in 2010. In the LRS of 2011, maize grain and DM yields were significantly higher in M/L_{MPR} – F treatment. This was followed by M_{MPR}- L and M_{TSP}- F treatments and of which there were no significant differences in grain and DM yields. Least yields were obtained in M_{MPR} –F treatment in the LRS of 2011 (Table 6). The mean grain yield values across both years showed significantly higher maize grain and DM yields in M/L_{MPR} – F and M_{TSP}- F treatments, followed by M_{MPR}- L and lastly M_{MPR} –F. The treatment M/L_{MPR} – F had an additional lupin grain yield from lupin intercrop (Table 6). Lupin yields obtained from the intercropping system with maize were higher in the LRS of 2011 than LRS of 2010 (Table 6). Lupin grain and DM yield obtained in rotation system (M_{MPR}- L) in the SRS of both years (Table 7) was higher than in intercropping system (M/L_{MPR} – F) during the LRS of both years (Table 6).

The biomass of lupin and weeds in fallow plots during the SRS were significantly ($p = 0.005$) higher in 2011 than in 2010 (Table 7). Biomass of weeds was significantly higher than that of lupin (Table 7). Weed biomass obtained in fallow plots in M/L_{MPR} – F treatment was significantly higher than in M_{TSP}- F and M_{TSP}- L treatments (Table 7). The mean biomass value in the SRS for the two years was significantly higher in M/L_{MPR} – F treatment.

The higher grain yield in M_{TSP}- F treatment in the LRS of 2010 is attributable to higher availability of P from the highly soluble TSP fertilizer source. Wasonga et al. (2008) in a study on phosphorus requirements by maize varieties reported that TSP fertilizer application resulted in significant increases in maize grain yields. Maize has a high phosphorus requirement and it is a limiting nutrient in its production (Kogbe & Adediran, 2003).

The P from MPR was not available in M_{MPR}- L and M_{MPR}- F treatments causing lower maize yields in the LRS of 2010 (Table 2). This can be attributed to insolubility of MPR (Waigwa et al., 2003). Various factors could be responsible for P availability to crop plants. These include the form of native soil P, the type of P applied to soil, and soil reaction (Kogbe and Adediran, 2003). The higher grain yields in second year were partly as a result of elevated available P content in soil due to residual effect of MPR (Buresh et al., 1997) and subsequent uptake by maize.

Table 6. Means of maize and lupin grain and dry matter yields (kg ha^{-1}) in the long rain season (Mean ± SD)

Treatment	Plant	Grain Yield			Dry Matter Yield		
		2010	2011	average	2010	2011	average
M_{TSP}- F	Maize	2247±3.2^a	2800±2.1^b	2523±3.3^a	4621±3.5^a	5699±5.2^b	5160.2±4.1^a
M_{MPR} –F	Maize	1984±1.8^c	1785±1.7^c	1884±1.1^c	3975±2.9^c	3735±3.5^c	3854.9±3.1^c
M_{MPR}- L	Maize	2009±5.4^c	2823±3.9^b	2416±4.2^b	4013±4.4^c	5678±3.7^c	4845.7±4.1^b
M/L_{MPR} – F	Maize	2095±3.8^b	2929±2.8^a	2512±3.6^a	4342±3.1^b	5893±5.1^c	5117.6±3.9^a
	Lupin	74.7±1.7	102±1.1	88.15±1.4	374±2.9	378±1.9	375.5±2.1

Key: Means in a column followed by the same letter (for maize) are not significantly different at P<0.05, using the Tukey mean separation procedure.

Table 7. Grain and biomass yield (kg ha^{-1}) in the short rain season (Mean ± SD)

Treatment	Plant	Grain Yield			DM yield		
		2010	2011	average	2010	2011	average
M_{TSP}- F	weeds	-	-	-	476.5±3.9^b	688.3±3.2^{ab}	582.4±3.1^b
M_{MPR} –F	weeds	-	-	-	466.5±4.1^b	645.1±5.5^b	555.8±4.7^b
M_{MPR}- L	lupin	82.6±2.1	119.8±3.8	101.25±3.2	365.7±6.7^c	561.7±2.8^c	463.7±5.5^c
M/L_{MPR} – F	weeds	-	-	-	501.7±2.1^a	726.4±4.2^a	614.1±3.5^a

Key: Means in a column followed by the same letter are not significantly different at P<0.05, using the Tukey mean separation procedure

Phosphorus from phosphate rock needs to be released into the solution before any residual phosphorus can manifest itself (Akande et al., 2005). The lupin, a legume, increased availability of phosphorus from MPR (Table 2).

Odiete et al. (2005) studied response of maize to single super phosphate and sokoto PR, reported increases in maize grain and DM yield irrespective of P source. This is also supported by other workers (Nekesa et al., 2005; Thuita et al., 2005). Higher maize yields in the M/L_{MPR} – F treatment in the LRS of 2011 was due partly to the higher available P (Table 2) due to mobilization by the legume intercrop. Li et al. (2007) found that, when intercropped with faba bean, maize grain over yielded by 43% (range: 17–74%) ($P < 0.0001$) compared with corresponding monocultured maize and faba bean, on average over 4 years experiment in an agricultural site in which P was the major limiting soil nutrient. The over yielding maize was attributed to below-ground interactions between faba bean and maize. On the P-deficient soils, a P nutrition improvement in faba bean/maize intercropping played an important role in the over yielding of maize through interspecific interactions between faba bean and maize (Li et al., 2007).

Lupin, by virtue of the fact that it is a legume, supplied additional N through biological nitrogen fixation and contributed to yield increases. The benefit of legumes in cropping systems is through biological nitrogen fixation which can be as much as 450 kg ha^{-1} (Wani et al., 2005).

Lower lupin grain and DM in the LRS than SRS of both years can be attributable to competition for resources with maize in intercropping system. The higher biomass of weeds than lupin may be due to rapid growth and establishment in comparison to legume species. Gathumbi et al. (2004) studying short term fallows reported highest biomass production in weedy fallow and observed that type of fallow species greatly influences biomass production.

Higher biomass production in the second year was due to improvement in soil productivity as a result of maintenance of soil organic matter levels through continuous input of organic materials and residual effects of the MPR. The higher biomass of weeds in M/L_{MPR} – F treatment was due to availability of nutrients due to mineralization of incorporated pre -fallow lupin and residual effects of MPR. Niang et al. (2002), in a study screening short term planted fallows however found that natural fallow contained low N contents despite large vegetative biomass.

4. Conclusions

Soil available P, plant P, maize grain and dry matter yields, were higher in maize lupin intercropping treatment with application of minjingu rock phosphate (M/L_{MPR} – F) in the second year and in M_{TSP}- F treatments in 2010. Higher yields in M/L_{MPR} – F treatment was due to increased mobilization of P by lupin which subsequently increased maize yields. Additionally, soil was enriched through BNF. The P balances were positive in all treatments. It was higher in the M_{TSP}- F treatment and lowest in M/L_{MPR} – F. The application of MPR in lupin maize intercropping systems is recommended for increased maize grain yields and can fit within the circumstances of the resource poor farmers. Additional lupin grain yield is obtained in this treatment with net benefit of a rich source of protein (33-47%) and oil (6-13%) and can be fed to dairy cows. Measurement of soil available N and comparison with other grain legumes is recommended.

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