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Development of maize single cross hybrids for tolerance to low phosphorus

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Low available phosphorus (P) is one of the major hindrances to maize (*Zea mays* L.) productivity in acid soils. The objectives of this study were to: (1) develop P-efficient maize inbred lines, (2) develop single cross hybrids from the P-efficient inbred lines, and (3) determine their response to P application in the P-deficient acid soils of western Kenya. Ninety-eight inbred lines and 49 single crosses were developed and screened at P-deficient (2.0 to 2.2 mg P/kg soil) soils of Sega and Bumala. Mean grain yield (GY) for the hybrids was 75.3% higher with P-fertilizer than without P for the same hybrids. Thirty-three percent (33%) of these hybrids were inefficient but responsive to P application, 27% were efficient and none responsive, only 13% were efficient and responsive, while the rest were inefficient and non-responsive. GY was positively correlated ($r = 0.57^{}$) with plant height (PH) and ear height (EH) ($r = 0.60^{**}$) and PH was correlated with EH ($r = 0.86^{***}$). This study has developed and identified P-efficient maize germplasm that can be utilized directly or in developing other hybrids for use in acid soils of western Kenya and in other acid soils where P is limiting.**

Key words: Phosphorus, interaction, efficiency, responsiveness, acid soils.

INTRODUCTION

Maize (*Zea mays* L) is a major staple food crop for the majority of people in developing countries (Lopes and Lakirns, 1991). However, its grain yield (GY) is low on infertile acid soils (pH < 5.5) characterized by low available Phosphorus (P) (Kochian, 1995). In acid soils, P is made unavailable through fixation by Aluminium (Al) and Iron (Fe) oxides (Kochian, 1995). Most soils in sub-Saharan Africa (SSA) are generally deficient in available P (Bekunda et al., 1997). Moreover, P is being depleted at the rate of 2.5 kg P/ha/year from the soils (Sanchez et al., 1997) through crop harvests. Insufficient P-fertilization and high P-fixation by Al and Fe oxides in the soil have been identified as the key causes of P-deficiency (Kochian, 1995).

The available P in western Kenyan acid soils ranges between 2 to 5 mg P/kg soil which is far below the optimal range (10 to 15 mg P/kg soil) required for high crop productivity (Kisinyo et al., 2009). In such P-deficient soils, maize tends to have delayed maturity, which under low moisture stress causes further decrease in grain yields. Although, Jama et al. (1997) showed that a single large recaptalization rate of P could even double or triple yields in the P-deficient and high P-fixing acid soils of western Kenya, the smallholder farmers still do not apply (sufficient) fertilizers to replenish the soil nutrients. Furthermore, due to the high P-fixing capacity of acid soils, about 80% of the inorganic P added becomes unavailable for crop use. In situations of low P, the ability of maize to use added P with high efficiency is extremely an important attribute.

Many plant species including maize have the ability to take up sparingly soluble P from the rhizosphere

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Table 1. Description of maize inbred lines used as parents of the hybrids.

Original source of the germplasm	No. of inbred lines developed from various sources
Brazilian	31
KARI-Kitale	7
Kenyan landrace (203B)	14
KARI-Muguga	18
KARI-Kakamega	14
KARI-Kitale	14

(Marschner, 1995). Parentoni et al. (2010) have documented the existence of P-efficient maize cultivars that have significant yield improvement over P-inefficient ones grown under similar conditions. Such technologies are sustainable and suitable for low input agriculture practiced by small-scale farmers in the maize ecosystems of Kenya. However, there are no P-efficient maize cultivars for farmers to use. Evidently, it would be appropriate to employ an integrated approach of combining the use of tolerant genotypes together with optimized soil nutrient cycling to achieve optimal maize GY increase on acid soils. In Kenya, most maize growing takes place in acid soils which occupy about 13.5% of arable land (Kanyanjua et al., 2002; Muhammad and Underwood, 2004). In western Kenya, P-deficiency leads to a reduction in maize GY of between 28 to 50% especially on the smallholder farms where agriculturally-based P-mining has been occurring for years without replenishment (Kisinyo et al., 2009). P-based fertilizers are routinely used in agricultural systems to overcome P-deficiency or to replenish used up P. However, the recommended level of P-fertilizer required to attain reasonable maize yield in acid soils is beyond the reach of resource-poor smallholder farmers in western Kenya. Empirical data indicates that farmers in this region often apply P-fertilizer below the recommended rates (Ayaga, 2003) and this is partly responsible for the unsustainable low (< 2.0 t/ha) and declining maize GY in Kenya.

According to Parentoni et al. (2010), the selection criteria adequate to select for P-efficiency in tropical maize include GY under low P environments to determine P acquisition efficiency under low P soils, and grain P concentration under high P environments to determine P internal utilization efficiency. Moreover, the use of GY under low P conditions as appropriate selection criteria for nutrient efficiency have also been proposed in maize and in other crops (Ozturk et al., 2005; Parentoni et al., 2010). Accordingly, this study adapted this approach in assessing various maize germplasm for tolerance to P-deficiency.

In maize, the genetic control of P-efficiency is dependent on the selection criteria used, growing stage of the plants and the environmental conditions where the experiment is conducted whether under field, greenhouse

or nutrient solution (Parentoni et al., 2010). Tolerance to low P is a quantitatively inherited trait controlled largely by additive gene effects, although dominance and epistatic effects have also been shown to be important (Chaubey et al., 1994). Furthermore, P acquisition efficiency has been shown to have higher broad sense heritability (Coltman et al., 1985).

Genotypic differences for tolerance to P-deficiency exist in maize and this has allowed selection and development of P-efficient genotypes tolerant to P-deficiency in acid soils (Reiter et al., 1991; Da Silva and Gabelman, 1992). Although, Brazilian scientists have bred maize varieties with high P-efficiency from P-efficient inbreds and have improved yields in acid soils of Brazil (Parentoni et al., 2010), such varieties have not yet been developed in Africa. The yield advantage arising from the use of P-efficient inbred lines and hybrids has been attributed to genetic causes and for hybrids it is largely believed to arise from heterosis caused by heterozygosity in some genetic loci (Springer and Stupor, 2007). The objectives of this research were to: (1) develop P-efficient maize inbred lines and use them, (2) develop single cross hybrids from low P tolerant maize inbreds, and (3) evaluate single cross hybrids for responsiveness to P application. Such hybrids would be useful directly to farmers who could afford them or to maize breeders who could use them to develop 3-way or 4-way commercial hybrids for the P-deficient acid soils of western Kenya.

MATERIALS AND METHODS

Genetic material

Maize germplasm were obtained from various sources in 2002: Kenya Agricultural Research Institute (KARI)-Kitale, KARI-Kakamega and KARI-Muguga maize breeding programs. These materials are tolerant to maize streak virus (MSV) and gray leaf spot (GLS) diseases and were kindly provided by Dr D. Ligeyo of KARI-Kitale and Dr Jane Ininda, formerly of KARI-Muguga. Others were Brazilian introductions to Kenya (single crosses) containing L3 (Brazilian P-efficient inbred), while the rest were local collections including 203B landrace. All the sources were given as single crosses except the 203B landrace which was collected from low P soils of Muranga district in central Kenya. These were used to develop ninety-eight maize inbred lines between 2003 and 2007 (Table 1). The inbred lines were either developed from single cross hybrids from the various sources or through topcross of these single cross hybrids with the Kenyan testers for medium and high altitude. All the sources were individually selfed to F6 to obtain the respective inbred lines which were screened for tolerance to P-deficiency under field conditions. Fourteen inbred lines were selected for tolerance to low P-based on GY at low P and anthesis silk interval (ASI) under varying P regimes (data not shown). The single cross hybrids were then generated in 2009 by crossing the selected P-efficient inbred lines using factorial mating design as described by Comstock and Robinson (1948). A total of 49 single crosses were developed however, one of the single crosses did not yield enough seeds hence, was not included in the trial. A total of 48 single cross hybrids and one local check for mid altitude hybrids (H505) were evaluated for tolerance to low P at Bumala and Segal sites.

Experimental sites description

Sega is located at 0° 15'N and 34° 20'E. It has an elevation of between 1140 and 1400 m above sea level (a.s.l) with a bimodal annual average rainfall pattern between 800 and 1200 mm. The mean minimum temperature range lies between 15 to 17°C, while the mean maximum range is 27 to 30°C. The soils are orthic acrisols characterized by low pH (4.5) and a mean AI saturation of 43.1% and 2.2 mgP/kg of soil (Kisinyo et al., 2009). Bumala site is located at 0° 19'N and 34° 12'E and has an elevation of between 1135 to 1500 m a.s.l. The site has a bimodal rainfall distribution pattern with an average annual rainfall of between 900 to 1700 mm. The mean annual temperature range is 20.5 to 22.7°C. The site has orthic ferralsol soil type (Jaetzold, 1983) with a pH of 4.6, AI saturation of 26.52% and Olsen P levels of 2.74 mgP/kg (Kisinyo et al., 2009). These sites were selected because maize is a major food crop in the areas and the soils in the two sites are characterized by low pH and available phosphorus.

Experimental design

The experiment for screening the 98 inbred lines for tolerance to P-deficiency was set up in a randomized complete block design (RCBD) with 2 P treatments (0, 26 kgP/ha) in the form of triple super phosphate (TSP) and 3 replications. For testing the response of single cross hybrids to P application a 2*2*49 split plot arrangement in RCBD replicated 3 times was used. The treatments comprised of maize single cross hybrids and two levels of P similar to what was used for testing inbred lines. Planting was done at Sega and Bumala in March, 2010 at a spacing of 0.75 × 0.3 m in a 3 m long plot. Each plot consisted of 2 rows. Weeding was done manually thrice and the crop protected from stalk borer (*Buseola fusca* L.) damage using 2 to 3 granules of Beta-cyhalothrin (Bulldock GR 0.05) at a rate of 6 kg ha⁻¹ applied in the whorl of each plant after thinning. The crop was also protected from Grey leaf spot disease (GLS) by spraying with Folicur fungicide. Data was recorded on GY (t/ha) plant height (PH, cm), ear height (EH, cm), days to 50% tasseling (DFT) and days to 50% silking (DFS). The statistical models used to estimate variance, interaction and effects of environment are as shown from Kearsey and Pooni (1998) and Falconer (1989) as follows:

$$X_{ijk} = \mu + \alpha_i + \beta_j + \Sigma_{ij} + \lambda_k + Y_{ik} + \Sigma_{ijk}$$

Where X_{ijk} , Plot observation; μ , overall mean; α_i , treatment effect; β_j , block effect; Σ_{ij} , experimental error due to main plot; λ_k , sub-plot effect; Y_{ik} , interaction (main and sub-plot); Σ_{ijk} , experimental error due to main plot and sub-plot interaction

$$V_p = V_g + V_E + V_{(g \times E)}$$

Where:

V_p , Total phenotypic variation; V_g , variation due to heredity/genotype; V_E , variation due to environmental effects; $V_{(g \times E)}$, variation due to genotype by environment interaction.

Statistical analysis

Means of data on grain yield, plant height, EH and days to 50% flowering were computed through 2-way analysis of variance (ANOVA) to determine the performance of the inbreds and the single cross hybrids in the different sites. All ANOVA was done using the General Linear Models procedure of Genstat and means separated by Tukey's range test since the treatments were unstructured. A combined ANOVA for the single crosses was

computed for the 2 environments (Table 4). Variance homogeneity was verified before doing combined ANOVA. Pearson correlation coefficients were calculated between traits, using regression and correlations by Genstat (Payne et al., 2009).

RESULTS

Genotypic differences to low available P among inbred lines and hybrids

The maize inbred lines differed significantly ($p < 0.05$) with regard to GY, PH, EH, DFT and DFS. Majority of the inbred lines (34%) expressed GYs of 0.5 to 0.9 t/ha, 26.5% (0 to 0.4 t/ha), 22.4% (1.0 to 1.4 t/ha), 12.4% (1.5 to 1.9t/ha), while the rest gave 2.0 to 2.4 t/ha. Some of the lines (HS 20 × 22 - 9 and HS 945 × 954 - 11) did not produce any GY under the control treatment (Table 2 and Figure 1).

The single cross hybrids performed better than their inbred parental lines under P-deficient conditions. Approximately 59.3% of the single cross hybrids expressed GY above 3.1 t/ha. On the other hand, all the inbred lines gave GY below 2.5 t/ha under similar conditions. The rest of the single cross hybrids gave GY of between 1.1 and 3.0 t/ha (Figure 2).

GY of the single cross hybrids under control treatment was 1.16 to 6.6 t/ha, whereas with the application of P it was 3.41 to 8.7 t/ha. Mean GY for the hybrids was 75.3% higher with P-fertilizer than without P. The hybrid MUL125 × EMIL-1336 exhibited the highest GY (8.47 t/ha) with P, while MUL116 × MUL104 expressed the lowest GY (3.41 t/ha) with P application. On the other hand, CML181 × MUL817 exhibited the highest GY (6.6 t/ha) without P, whereas MUL116 × MUL104 expressed the lowest GY (1.16 t/ha) under the same conditions (Figure 3a and b). P application caused significant ($p \leq 0.05$) increase in both PH and EH, while it reduced days to tasseling and silking days by between 7.7 to 8.8% (Table 3).

ANOVA for the single cross hybrids across the 2 sites showed significant variation ($p < 0.05$) for GY, PH, EH, DFT and DFS. Treatments (P and no P) were significantly different at $p < 0.01$ for all the traits measured similarly; the environments (E) were significantly different for all the traits measured except for GY. Significant interaction was observed between environment (E) and treatment (Trt) for GY and PH. Genotype × environment (G × E) interactions were significant ($p < 0.05$) for all traits measured except DFT and DFS. Additionally, significant interaction ($p < 0.05$) was observed between G × Trt and G × E × Trt for GY (Table 4).

The selected single cross hybrids were further classified in terms of P-efficiency and responsiveness to add P-based on their GY under low P and high P conditions. 33% of these crosses were inefficient but responsive to P application, 27% were efficient and none

Table 2. Response to P application of selected maize inbred lines at Sega.

Inbred lines	Grain yield (t/ha)		Plant height (cm)		Days to 50% tasselling	
	P	Cntl	P	Cntrl	P	cntrl
HS 20 × 22 - 10	3.6 ^{ab}	2.4 ^a	113.8 ^{ab}	104.4 ^{a-c}	46.3 ^b	45 ^a
CML 312	3.8 ^{ab}	2.3 ^a	137.8 ^{ab}	114 ^{a-c}	58.8 ^b	38 ^a
REUNION	4.1 ^a	2.1 ^a	182.5 ^{ab}	160.4 ^{a-c}	71 ^a	59 ^{ab}
HAS R	4.4 ^a	2.1 ^a	198.5 ^{ab}	204.6 ^a	73 ^a	83.5 ^{a-c}
CON 5	4.6 ^a	1.5 ^{ab}	179.0 ^{ab}	152.5 ^{a-c}	80 ^a	84 ^{a-c}
A089	4.3 ^a	1.1 ^{a-c}	202.5 ^{ab}	127.5 ^{a-c}	73 ^a	83 ^{a-c}
CATAL 237/67 × L5-5	2.5 ^{a-d}	1.0 ^{a-c}	109.6 ^{ab}	91.1 ^{a-c}	84 ^a	84 ^{a-c}
HS 161 × 36-10	1.7 ^{b-e}	1.0 ^{a-c}	123.3 ^{ab}	81.5 ^{a-c}	80 ^a	82 ^{a-c}
203B	2.8 ^{a-d}	0.8 ^{a-d}	168.3 ^{ab}	95.2 ^{a-c}	90 ^a	87 ^{a-c}
HS942 954 -17	3.0 ^{a-c}	0.7 ^{a-d}	141.0 ^{ab}	92.5 ^{a-c}	76 ^a	90 ^{a-c}
HS L3 × 5046-8	3.6 ^{ab}	0.5 ^{b-e}	125.0 ^{ab}	104.0 ^{a-c}	83 ^a	85 ^{a-c}
CML 389	1.0 ^{ef}	0.3 ^{c-e}	187.4 ^{ab}	103.5 ^{a-c}	84 ^a	87 ^{a-c}
HS L3 × 5046-2	3.1 ^{a-c}	0.3 ^{c-e}	87.4 ^{ab}	106.6 ^{a-c}	84 ^a	88 ^{a-c}
MUL 229	1.5 ^{b-e}	0.3 ^{c-e}	77.8 ^b	114.5 ^{a-c}	82 ^a	84 ^{a-c}
HS 20 × 22 - 9	1.5 ^{b-e}	0.0 ^g	76.0 ^b	116.2 ^{a-c}	70 ^a	88 ^{a-c}
HS 945 × 954-11	1.2 ^{c-e}	0.0 ^g	125.2 ^{ab}	62.8 ^{bc}	90 ^a	88 ^{a-c}
Treatment mean	2.7	0.9	138.1	116.4	80.4	84.8
G. mean	2.2	2.2	132.2	132.2	81.7	81.7
CV %	30.0	30.0	23.9	23.9	5.6	5.6
SE	0.6	0.6	11.2	11.2	1.6	1.6
SED	0.8	0.8	15.8	15.8	2.3	2.3

Note: Means in the same column followed by the same letter are not significantly different at $p \leq 0.05$ according to Tukeys range test. Selection of the inbred list presented above was based on clustering of the means of 98 inbreds into 16 homogenous groups; the inbreds therefore represented each of the groups. Cntl, control (0 kgP/ha applied); P, phosphorous (26 kgP/ha) added; CV, coefficient of variation; G. mean, grand mean; SE, standard error; SED, standard error of difference between means.

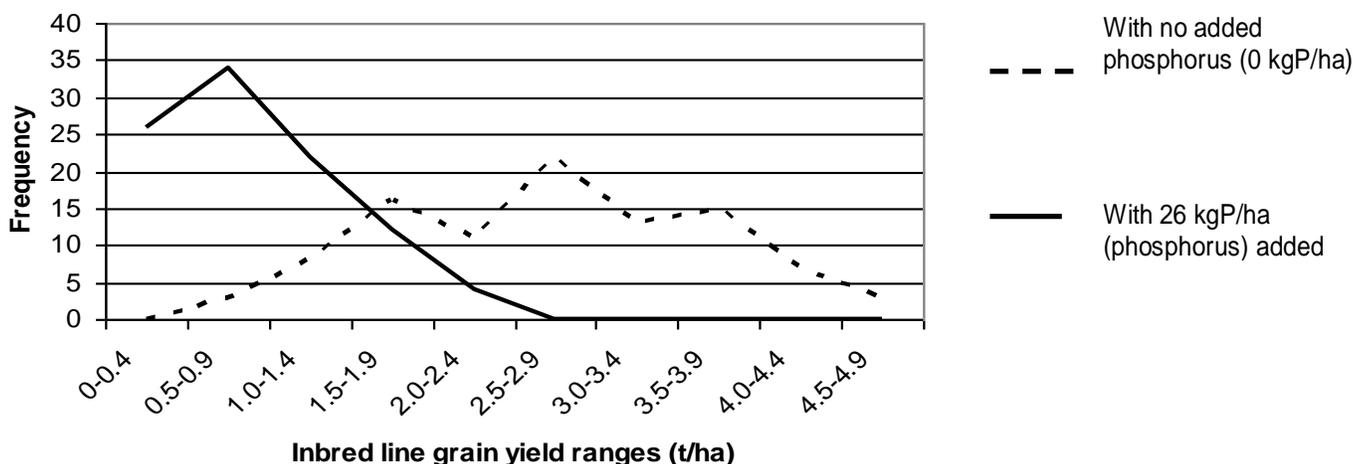


Figure 1. Trends in grain yield of maize inbred lines screened under two phosphorus regimes.

responsive, only 13% were efficient and responsive while the rest were inefficient and non-responsive (Table 5 and Figures 4 and 5).

Correlation analysis

GY for single cross hybrids was positively correlated ($r =$

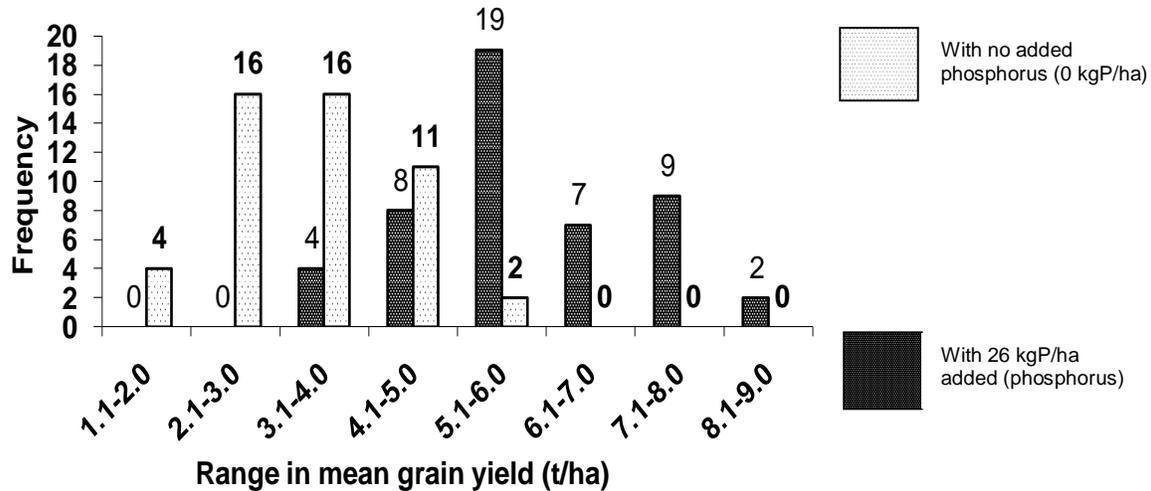


Figure 2. Trends in grain yield of maize single cross hybrids screened under two P regimes.

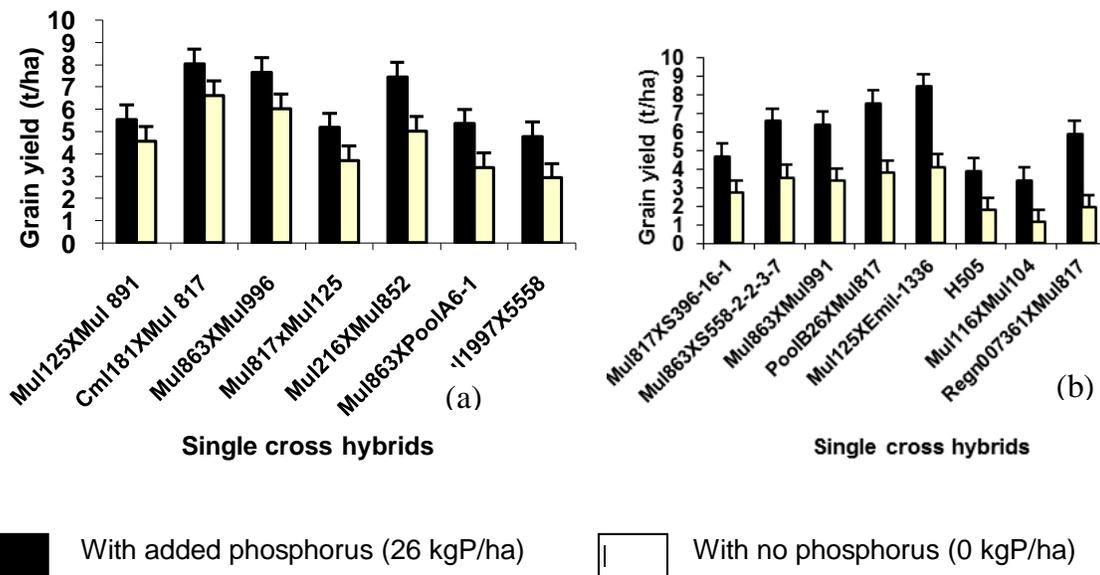


Figure 3. Means for grain yield of selected single cross hybrids tested for P-efficiency in Sega and Bumala. *The error bars are standard error bars (SE). Selection was based on clustering of the means into homogenous categories; the hybrids therefore represented each of the categories*.

Table 3. Means for agronomic traits of 49 maize single cross hybrids tested for P-efficiency at Sega and Bumala.

Trait	With P	No P	Mean	SE
Grain yield (t/ha)	5.89 ^a	3.36 ^b	4.625	0.66
Plant height (cm)	205.78 ^a	175.15 ^b	190.465	7.9
Ear height (cm)	74.04 ^c	57.73 ^d	65.885	4.75
Days to 50% tasselling	69 ^b	76 ^c	72.5	0.92
Days to 50% silking	71 ^b	78 ^c	74.5	0.94

Note: Means in the same column followed by the same letter are not significantly different at $p \leq 0.05$ according to Tukeys range test.

0.57**) with PH and EH ($r = 0.60^{**}$) and PH correlated with EH ($r = 0.86^{***}$). However, GY had low and negative correlation with DFS ($r = -0.32$) and DFT ($r = -0.32$). Flowering dates were negatively associated with PH and EH though the association was low (Table 6).

DISCUSSION

Genetic variation for P-efficiency

Both the inbreds and the single cross hybrids showed

Table 4. Means squares for GY, PH, EH, DFT and DFS of maize single cross hybrids evaluated under 2 P regimes (0 kgP/ha, 26 kgP/ha) at Sega and Bumala.

Source of variation	d.f	Yield (t/ha)	Plant height (cm)	Ear height (cm)	Days to 50% tasseling	Days to 50% silking
Blocks	2	0.6987	3222.7	1138.6	84.04	139.96
Treatments (Trt)	1	998.345***	138935.6**	38130.3**	5479.63***	6042.90**
Error (a)	2	0.90	2919.7	620.6	49.49	33.81
Genotype (G)	48	13.0148***	3603.2***	1230.7***	47.48***	46.14***
Trt × G	48	2.7691**	246.3ns	154.9 ^{ns}	8.72 ^{ns}	10.65 ^{ns}
Error (b)	192	0.5441	771.8	283.4	13.769	14.43
Environment (E)	1	2.2798 ^{ns}	40565.8**	19206.4***	348.99***	9.06 ^{ns}
Treatment × E	1	9.8551**	4563.4*	233.4ns	186.33 ^{ns}	55.72 ^{ns}
G × E	48	6.6915***	1157.4**	375.2*	10.33 ^{ns}	8.85 ^{ns}
G × E × Trt	48	2.3295**	221.3 ^{ns}	201.4 ^{ns}	7.08 ^{ns}	5.13 ^{ns}
Error (c)	196	0.5835	764.1	280.8	7.49	7.19
CV		16.6	14.5	25	4.4	4.4
Grand mean		4.6	198.7	65.99	72.36	74.35

*, ** and *** indicates significance at $p \leq 0.05$, $P \leq 0.01$ and $p \leq 0.001$ levels, respectively; ns, non significant at $p > 0.05$.

Table 5. Selected maize single crosses varying in P-efficiency grouped into four classes based on grain yield at low P and in response to adequate P supply.

Single cross hybrid	Grain yield (t/ha)		Response to P class	
	Low P (A)	High P (B)	(B/A)	Categories
MUL125 × MUL891	4.55	5.53	1.21	EN
CML181 × MUL817	6.61	8.06	1.22	EN
MUL863 × MUL996	6.03	7.66	1.27	EN
MUL817 × MUL125	3.68	5.18	1.40	IN
MUL216 × MUL852	5.03	7.47	1.49	EN
MUL863 × POOLA6-1	3.38	5.35	1.58	IN
MUL1997 × 5558-2-2-3-7	2.91	4.78	1.64	IN
MUL817 × S396-16-1	2.75	4.70	1.71	IN
MUL863 × S558-2-2-3-7	3.56	6.61	1.86	IR
MUL863 × MUL991	3.36	6.46	1.92	IR
POOLB26 × MUL817	3.79	7.58	2.00	ER
MUL125 × EMIL-1336	4.13	8.47	2.05	ER
H505	1.81	3.93	2.17	IR
MUL116 × MUL104	1.16	3.41	2.93	IR
REGN007-361 × MUL817	1.96	5.92	3.02	IR
Trial mean	3.73	6.24	1.80	

I, Inefficient; E, efficient; R, responsive; N, non-responsive; ER, efficient and responsive; IN, inefficient and non-responsive; IR, inefficient and responsive; EN, efficient and nonresponsive; A, low P; B, high P. Selection was based on clustering of the means into homogenous categories; the hybrids therefore represented each of the categories.

significant variation in GY, PH, EH and days to 50% flowering when no P was applied. Such variations for tolerance to low P among maize genotypes have been reported by other authors (Da Silva and Gableman, 1992; Parentoni et al., 2010). The observed differences can be attributed to genetic variation in P-efficiency that exists

among these inbreds and single cross hybrids. The differential P-efficiency was expected because the parental inbreds lines that were used to develop the single cross hybrids were of diverse sources. Besides, some of the inbreds were derived from KARI elite lines used for producing hybrids and synthetics. The

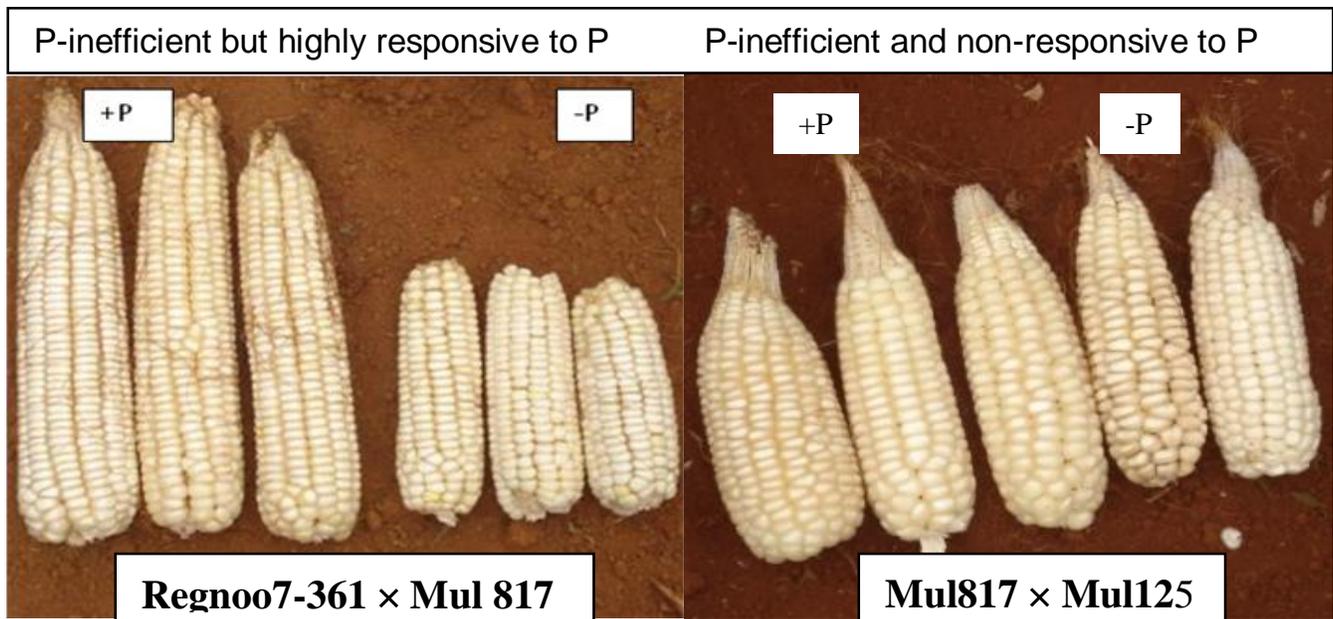


Figure 4. P-inefficient hybrids which are responsive and non-responsive to additional P, respectively.

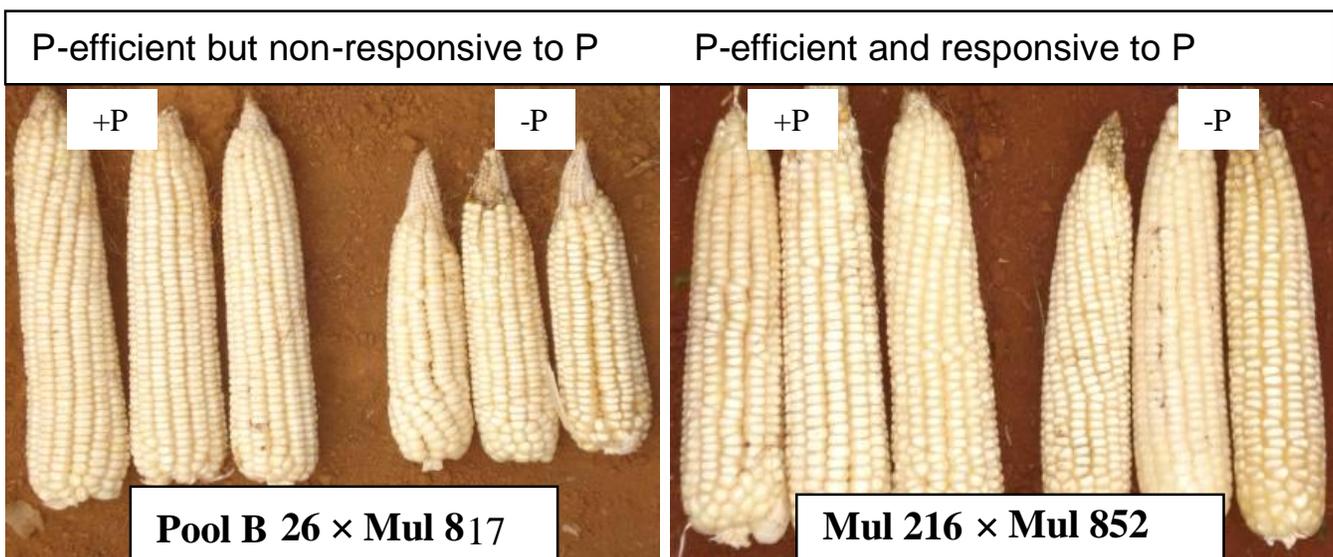


Figure 5. P-efficient hybrids which are responsive and non-responsive to additional P, respectively

Table 6. Correlation between GY, PH, EH and days to 50% flowering of single cross hybrids tested for P-efficiency in Sega and Bumala.

Variable	Grain yield	Plant height	Ear Height	Days to 50% tasseling	Days to 50% silking
Grain yield (t/ha)	1				
Plant height (cm)	0.57**	1			
Ear height (cm)	0.60**	0.86**	1		
Days to 50% tasseling	-0.32 ^{ns}	-0.12	0.01	1	
Days to 50% silking	-0.32 ^{ns}	-0.15	-0.03	0.98**	1

* and **, Significant at 5 and 1%, respectively.

differential P-efficiency among maize genotypes has also been attributed to: variation in mycorrhizal association (Marschner, 1995), root architecture (Lynch, 1998), capacity to release organic acid notably malate (Kochian, 1995).

The significant $G \times E$ interactions for GY, PH and EH imply that selection for adaptability and tolerance to low P-based on the 3 variables could best be done at individual site. The ANOVA further showed significant $Trt \times E$ interactions for GY and PH, implying that GY and PH were most affected by the different response of the sites to P application compared to other variables measured. This highlights the need for breeders to employ trait and site specific selection approach for tolerance to low P. Such observed interactions could have been due to the different available P levels. P treatments were significantly different, an indication that P had an effect on the general plant performance under field conditions. The significant $G \times E \times Trt$ interactions for GY was an indication that some of the single crosses could be suitable for the 2 environments irrespective of the two P levels tested. The expression of higher GY by the single cross hybrids than the inbreds under similar conditions is attributed to heterosis for GY. The genetic basis of heterosis includes dominance, over dominance or epistatic gene effects (Birchler et al., 1993). This study has shown the possibility to develop P-efficient maize single cross hybrids from low P tolerant inbred lines.

The significant phenotypic variations observed on the various traits measured at the different sites for the same genotype is an indication that these traits were significantly influenced by the environment. The total phenotypic variations (V_p) observed could therefore be attributed to the sum total of genotypic variations (V_g) among the single crosses, the environmental variations between the two sites (V_E) and the interaction between genotype and environment ($V_{g \times e}$) (Falconer, 1989).

Correlation analysis

GY had highly significant positive correlations with PH and EH as have been reported by Majid and Rogayyen (2010). The correlation between PH and EH was positive and significant. These are in agreement with the early findings of Obilana and Hallauer (1974) and those of Majid and Rogayyen (2010) who reported significant positive correlation between GY, PH and EH, in maize. The high positive correlation between PH, EH and GY is indication that these components may have a direct effect on maize GY and hence selection for one, may improve the other trait.

The association between GY and flowering dates was negative and significant. This finding did not agree with that of Yousuf and Saleem (2001) who reported positive and non-significant association between GY and days to silking. This is probably because modern bred varieties may produce high GY despite early flowering. Plant

height was found to be positively associated with flowering date. This association can be attributed to the fact that internode formation stops at floral initiation, which means that earlier flowering maize will usually be shorter (Troyer and Larkins, 1985).

Conclusions

There exists great genetic variability for both tolerance to low P and responsiveness to additional P among maize inbreds and single cross hybrids. Breeding for tolerance to low P in maize needs to focus on trait and site specific selection approaches. Besides, selection for adaptability to low P conditions could best be done at individual sites. This study has developed over 50 genetically variable maize inbred lines for tolerance to low P and fourteen single crosses that are P-efficient exceeding a threshold of 4 t/ha under no additional P. It is recommended that some of the identified P-efficient lines be used for further hybrid production.

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