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DETERMINATION OF THE EXTERNAL PHOSPHATE REQUIREMENTS OF TWO SOUTH AFRICAN SOILS IN A GLASSHOUSE POT EXPERIMENT

[DETERMINACIÓN DE LA NECESIDAD DE FOSFATO DE DOS SUELOS SUDAFRICANOS EN UN EXPERIMENTO CON MACETA EN INVERNADERO]

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SUMMARY

A glasshouse experiment was conducted to evaluate the external P requirement of two soils (Flagstaff and Qunu) from the Transkei region of South Africa with varying sorption properties using oat (*Avena sativa L.*) as a test crop. Eight levels of P application estimated from the Langmuir equations that gave a range of P concentrations in the soil solution were evaluated. The rates were 0, 45, 90, 135, 180, 225, 270, and 315 mg P kg^{-1} for Flagstaff soil and 0, 10, 20, 30 40, 50, 60, and 70 mg P kg^{-1} for Qunu soil and these resulted in equilibrium soil solution concentrations of between 0 to 0.35 mg P l^{-1} for both soils. Harvesting was done 10 weeks after planting. Biomass yield and tissue P concentration was increased significantly ($P< 0.05$) by addition of fertilizer P when compared with the control and the responses were curvilinear for both soils. Biomass yield ranged from 25.3 to 53.6 g for Flagstaff soil and 5.1 to 52.9 for Qunu soil. Maximum biomass yield was achieved at an equilibrium P concentrations of 0.24 and 0.26 mg P l^{-1} for Flagstaff and Qunu soils, but, the yield obtained from these concentrations were not significantly different from those obtained at a soil solution P concentration of 0.2 mg P l^{-1} reported in the literature to be a threshold for many crops, over which no response to P is observed. Phosphorus accumulation in the plant tissue followed a pattern similar to that of biomass accumulation and was also curvilinear for both soils. The P accumulation was highly correlated with levels of P applied ($r = 0.904$) for Flagstaff and ($r = 0.955$) for Qunu soil. The good relationships between P in solution and biomass yield indicate the usefulness of P sorption approach for making fertilizer recommendations. The results thus confirmed that a soil solution concentration 0.2 mg P l^{-1} is critical for optimum yields and that this index is independent of soil type.

Key words: External P requirement, Langmuir equation, biomass yield, plant P-uptake

RESUMEN

Se realizó un experimento de invernadero para evaluar las necesidades de P externo de dos suelos (Flagstaff and Qunu) de la región Transkei de Sudáfrica empleando avena (*Avena sativa L.*) como cultivo control. Se evaluaron ocho niveles de aplicación de P estimados a partir de la ecuación de Langmuir. Las tasas de aplicación fueron 0, 45, 90, 135, 180, 225, 270 y 315 mg P kg^{-1} para el suelo Flagstaff soil y 0, 10, 20, 30 40, 50, 60 y 70 mg P kg^{-1} para el suelo Qunu. Estas tasa resultaron en una concentración de solución de equilibrio en el suelo de 0 a 0.35 mg P l^{-1} para ambos suelos. La cosecha se realizó a las 10 semanas de siembra. La producción de biomasa y concentración tisular de P se incrementó ($P<0.05$) con la adición de fertilizante (P) comparado con el tratamiento control y la respuesta fue curvilínea para ambos suelos. La producción de biomasa varió de 25.3 a 53.6g para Flagstaff y de 5.1 a 52.9g para Qunu. La máxima producción de biomasa se obtuvo a la concentración de equilibrio de P de 0.24 y 0.26 mg P l^{-1} para Flagstaff and Qunu, pero la producción obtenida a estos niveles no fue significativamente de la obtenida con una concentración en la solución del suelo de 0.2 mg P l^{-1} reportado en la literatura como el umbral, para varios cultivos, sobre el cual ya no existe respuesta a P adicional. La acumulación de P en el tejido vegetal siguió un patrón similar a la acumulación de biomasa y fue también curvilínea para ambos suelos. La acumulación de P estuvo correlacionada con los niveles de P aplicados ($r=0.904$) para Flagstaff y ($r=0.955$) para Qunu. La asociación entre la solución de P y la producción de biomasa sugiere la utilidad de emplear la absorción de P para hacer recomendaciones de fertilización. Los resultados confirmaron que la concentración en la solución del suelo de 0.2 mg P l^{-1} es crítica para obtener una producción óptima y que este indicador es independiente del tipo de suelo.

Palabras claves: Requerimiento de P externo, ecuación de Langmuir, producción de biomasa, absorción de P por plantas.

INTRODUCTION

Although a dynamic equilibrium exists between the solid and solution phases, P retention in the solid phase is favored by several-folds, resulting in insufficient soil solution P to meet plant needs (Gartley and Sims, 1994). Availability of P to plants has been shown to be related to its concentration in the soil solution (intensity) and the soils' ability to replenish or buffer it as the nutrient is removed by plants (Magdoff et al., 1999).

Evaluation of soil P status and calibration of soil test values with yield response data form an essential part of predicting the optimum rates of P fertilization (Thibaud and Farina, 1994). Many soil P tests have been developed and calibrated for making fertility recommendations and most of them involve chemical extraction procedures, which extract various forms and amounts of P in soil depending on the extraction solution used (Sharpley, 2000 cited by Schmidt et al., 2004).

A survey, conducted by the Fertilizer Society of South Africa, found that eight different extractants were being used among country's soil testing laboratories (Henry and Smith, 2006). A single measurement of soil phosphate removed by an extractant in the laboratory can give a misleading picture of the amount of P actually available for uptake by a crop. This is partly due to the adsorption/desorption reactions that are continually moving phosphate in and out of solution (Warren, 1992).

Phosphorus sorption relationships have been used successfully to compare the sorption of P by different soils and to determine the P requirements for crops in some highly weathered tropical soils (Warren, 1994, Iyamuremye et al., 1996; Nziguheba et al., 1998; Duffera and Robarge, 1999). The P requirements estimated from sorption isotherms aim at building up the status of soil phosphorus by a single application to a level which, thereafter, only requires maintenance application to replenish losses owing to plant uptake, removal by erosion or continuing slow reactions between phosphate and soil (Henry and Smith, 2003). It is also assumed that all the phosphorus recommended from sorption isotherms is broadcasted and incorporated (Henry and Smith, 2003). The external fertilizer phosphorus requirement (EPR) concept represents an effort of improving the empirical processes of calibrating soil P tests for fertilizer P recommendations based on the soil P status.

The EPR factor of crops has been defined as the concentration of P in solution known to be non-limiting to plant growth (Henry and Smith, 2004). The hypothesis of this approach to P requirements is that fewer costly field experiments are required if EPR values can be successfully predicted from the sorption data. Hernandez et al. (1987) postulated that for a given climate, and provided that the soil contains sufficient clay (5% or more) to ensure adequate reserves of labile P, the external phosphorus requirement is a crop constant independent of soil texture and clay mineralogy. Henry and Smith (2003) showed that the external P requirement decreased with increasing additional P. This demonstrated that P isotherms are useful for making fertilizer recommendations, as they are sensitive to P status in soils, and respond to build-up of the soil P content by fertilization. Holford (1979) postulated that successful analysis of soil P for plant growth response requires incorporation of both an intensity and quantity component.

The amount of P in equilibrium with 0.2 mg P l^{-1} ($P_{0.2}$) has been shown to be a threshold for many crops, over which no response to P is observed (Iyamuremye et al., 1996; Nziguheba et al., 1998). Even though the P concentration required by plants varies, $P_{0.2}$ (mg P kg^{-1}) has been used as a standard for comparing P requirement of different soils (Duffera and Robarge, 1999). In some instances, however, it is necessary to determine fertilizer P requirement at other P concentrations besides 0.2 mg P l^{-1} as the critical value is dependent on plant species and agronomic and nutritional factors (Fox, 1981, cited by Raven and Hossner, 1994). In South Africa, for example, an external P requirement factor of 0.11 mg P l^{-1} has been shown to be suitable for the low to moderately P fixing soils of the tobacco growing areas of Kwa-Zulu-Natal (Henry and Smith, 2006). Mokwunye (1977) cited by Warren (1992) showed that for maize grown in Samaru, Nigeria, maximum yields were obtained when the P concentration in the soil solution was 0.3 mg P l^{-1}. In contrast, Kang et al. (1980) as cited Warren (1992) found out that only 0.04 mg P l^{-1} was needed for 95% maximum cassava yield in an Alfisol which he attributed to the very effective mycorrhizal symbiosis formed by cassava and also to the long growing period (15 months).

From available literature no documented study has been conducted to test and calibrate the external P requirements against actual fertilizer responses by crops in soils from the Transkei region of South Africa. Therefore, the objective of this study was to test a range of soil solution P concentrations calculated from the Langmuir equations (Gichangi et al., 2007) to evaluate the external P requirement for two soils from the Transkei region of South Africa in the glasshouse using oat (Avena sativa L.) as a test crop.

MATERIAL AND METHODS

Soil characterization

Two soils from Flagstaff and Qunu locations in the Transkei region of South Africa with different sorption properties were used in this study. They were among 7 soils earlier characterized for their sorption characteristics in a P sorption study (Gichangi et al., 2007). Flagstaff soil an Oxisol (Soil Survey Staff, 1990) had the highest P retention (909.1 mg P kg^{-1}) whereas the Qunu soil an Alfisol (Soil Survey Staff, 1990) was among the lowest P sorbers among the seven soils characterized.

Bulk surface soil samples (0-15 cm), collected from cultivated farmers' fields, were air dried and sub-samples sieved (< 2 mm) prior to physical and chemical analysis. Total C and N were determined by dry combustion using a LECO TRUSPEC C/N auto-analyzer (LECO Corporation, 2003). Total P was estimated following wet digestion with H_2O_2/H_2SO_4 (Okalebo et al., 2002). Soil pH was measured both in water and in 1 M KCl solution at a soil: solution ratio of 1:2.5 using a pH meter with a glass and reference calomel electrode (Model pH 330 SET-1, 82362, Weilheim, Germany) after the soil suspensions were shaken for 30 minutes and equilibrated for 1 hour. The exchangeable cations Ca^{2+}, Mg^{2+}, K^+, and Na^+, were determined using 1 M ammonium acetate at pH 7 as described by Okalebo et al., (2002). Potassium, Na^+, Ca^{2+} and Mg^{2+} in the extracts were determined by Atomic Absorption Spectroscopy. The exchangeable acidity (Al^{3+} + H^+) was displaced by 1 M KCl and titrated with 0.05 M NaOH to the first permanent pink endpoint using phenolphthalein indicator as described by Okalebo et al., (2002). Effective cation exchange capacity was determined by the summation of exchangeable cations and exchangeable acidity. All the analyses were done in triplicate. Soil extractable P was extracted using Ambic-2 solution (0.25M NH_4HCO_3 + 0.01 M Na_2EDTA + NH_4F + Superfloc) (Non-Affiliated Soil Working Committee, 1990). The P concentration in the extract was determined by the molybdenum-blue method (Olsen and Sommers, 1982).

Experimental details

An experiment was initiated in a glasshouse at the University of Fort Hare, South Africa using oat (Avena sativa) as a test crop planted in pots each containing 7 kg of soil. Treatments consisted of a control and 8 phosphate application rates selected to provide a range of P concentrations in the soil solution calculated from the Langmuir equations reported earlier in Gichangi et al. (2007). The equations were as follows:

Flagstaff soil $\quad y = 0.0011x + 0.0014$

Qunu soil $\quad y = 0.0052x + 0.0426$

Where:
y = Desired or critical P concentration in the soil solution (mg P l^{-1}) and,
x = External P requirement (mg P kg^{-1})

Triple super phosphate containing 20% P was used at rates of 0, 10, 20, 30, 40, 50, 60, and 70 mg P kg^{-1} for Qunu soil and 0, 45, 90, 135, 180, 225, 270, and 315 mg P kg^{-1} for Flagstaff soil corresponding to soil solution P concentration (EPR factor) of between 0 to 0.35 mg P l^{-1} for both soils. The treatments were applied by uniformly mixing the added P with the soil in each pot. Nitrogen and potassium were applied as lime ammonium nitrate (28 % N) and KCl (60-62% K_2O), respectively to all experimental pots at rates equivalent to 200 kg N ha^{-1} and 100 kg K ha^{-1} for each soil type. In addition, each pot received 5.7 kg Zn ha^{-1}, 2.5 kg Cu ha^{-1}, 4.0 kg Mn ha^{-1}, 0.1 kg Mo ha^{-1}, 1.1 kg B ha^{-1} and 56.1 kg S ha^{-1} after the plants had established. Nutrient carriers were; $ZnSO_4.7H_2O$, $CuSO_4.5H_2O$, $MnCl_2.4H_2O$, $Na_2MoO_4.2H_2O$, $Na_2B_4.O_7.10H_2O$ and elemental sulphur, respectively. Treatments were applied assuming the plough layer of 1 hectare represented 2 * 10^6 kg of soil.

The pots were then placed on saucers on benches in the glasshouse and arranged in a randomized complete block design with four replications. The soils were then wetted to field capacity and left to incubate overnight to remove the effects of sample handling (sieving, drying and mixing). Twenty four seeds of oat were then sown in each pot at a depth of 2.5 cm. The plants were thinned after establishment to 16 plants per pot. Tap water was added to the pots to maintain adequate soil moisture for the growing plants as required throughout the growing period and watering was differentiated according to field capacity of each soil.

Biomass and Plant tissue P determination

The shoots were harvested 10 weeks after planting by cutting the shoots 0.5 cm above the soil surface, oven dried at 65^{o}C to a constant weight and dry matter was determined. The plant samples were then ground to less than 1 mm and analyzed for total tissue P following the method described by Okalebo et al. (2002). Plant tissue P was determined after digesting 0.3 g of the plant samples with a mixture of H_2SO_4 and H_2O_2, selenium and salicylic acid. The P concentration in the digests was then determined by the molybdenum-blue method (Olsen and Sommers, 1982).

Statistical analysis

Statistical analysis was done using Genstat statistical software (GenStat Release 4.24DE, 2005). Analysis of variance was conducted by running a full model (8 treatments, 7 df) for each soil type. Differences at p = 0.05 were considered significant. The effect of P rate, soil effect and interaction between these variables on plant biomass and tissue P concentration were evaluated. Nonlinear regression analysis was used to find the models best describing the curvilinear relationships, while linear regression was used where data appeared linearly related.

RESULTS

The two soils had a wide range of chemical properties and characteristics expected to affect P retention (Table 1). For example, they had differing levels of Ambic-2 extractable P (Flagstaff, 53.3 and Qunu 3.0 mg kg^{-1}). The amounts of Oxalate Al, exchangeable Al and exchangeable acidity differed in these soils with higher amounts observed in the soil from Flagstaff. Similarly Flagstaff soil was more acidic than Qunu indicating higher leaching of the bases in the Flagstaff soil.

Table 1. Selected soil chemical and physical properties of two South African soils.

Soil Parameter	Soil	
	Flagstaff	Qunu
$pH_{water\ (1:2.5)}$	4.7	5.5
$pH_{KCl\ (1:2.5)}$	4.0	4.9
Bulk density (g cm^{-3})	1.43	1.49
Moisture at Field capacity (%)	18.7	13.8
Total P (g kg^{-1})	0.42	0.14
Total N(g kg^{-1})	1.30	0.70
Total carbon (g kg^{-1})	21.9	10.4
Ambic-2 P (mg P kg^{-1})	53.3	3.0
Exchangeable Al (mg P kg^{-1})	76.3	0.8
Oxalate Al (g P kg^{-1})	3.5	0.1
Exchangeable acidity (cmol (+) kg^{-1})	1.7	0.1
∑Bases (cmol (+) kg^{-1})	14.5	7.3
ECEC (cmol (+) kg^{-1})	16.2	7.4

Effect of P rate on biomass yield

Biomass yield and tissue P concentration were increased significantly ($p \leq 0.05$) by addition of fertilizer P when compared with the control and the responses were curvilinear for both soils (Figure 1). Biomass yield ranged from 1.35 to 3.35 g $plant^{-1}$ for Flagstaff soil and from 0.32 to 3.33 g $plant^{-1}$ for Qunu soil (Table 2). Yield in the control pots where no external fertilizer P was applied were approximately 47.3% and 9.6% of the maximum yields of the Flagstaff and Qunu soils, respectively.

Maximum biomass yield was achieved at an equilibrium P concentrations of 0.20 and 0.25 mg P l^{-1} for Flagstaff and Qunu soils (Figure 1) but, the yield obtained from this concentration in the Qunu soil was not significantly different from those obtained at a soil solution P concentration of 0.2 mg P l^{-1} (Table 2). There was a negative response to applied P above 180 mg P kg^{-1} for Flagstaff and 40 mg kg^{-1} for Qunu soil (Table 2).

Table 2. Effect of soil solution equilibrium P concentrations on biomass yield and plant tissue P.

*EPR factor (mg P l^{-1})	Dry matter (g $plant^{-1}$)	P-uptake (g $plant^{-1}$)
Flagstaff soil		
0.00	1.58 ± 0.15	0.09 ± 0.01
0.05	2.34 ± 0,14	0.41 ± 0.05
0.10	2.76 ± 0.12	0.59 ± 0.06
0.15	2.91 ± 0.20	0.75 ± 0.05
0.20	3.35 ± 0.10	0.87 ± 0.01
0.25	3.16 ± 0.07	0.89 ± 0.05
0.30	3.04 ± 0.06	0.73 ± 0.05
0.35	2.98 ± 0.14	0.79 ± 0.07
Qunu soil		
0	0.32 ± 0.03	0.01 ± 0.01
0.05	1.66 ± 0.22	0.17 ± 0.02
0.10	2.54 ± 0.18	0.37 ± 0.03
0.15	2.90 ± 0.11	0.55 ± 0.03
0.20	3.15 ± 0.21	0.61 ± 0.05
0.25	3.33 ± 0.22	0.75 ± 0.05
0.30	3.23 ± 0.13	0.76 ± 0.02
0.35	3.21 ± 0.17	0.82 ± 0.04
Lsd (p = 0.05)	0.22	0.06
s.e.	0.16	0.04
Cv (%)	5.9	7.3

*EPR_{factor} = External phosphate requirement, s.e. = standard error of treatment means, Cv = Coefficient of variation, Lsd = least significant difference ± = standard deviations

The nature of response to added P depended on the soil and the change in biomass yield with P addition was described by the relationship

$$y = a + bx + cx^2$$

Where:
Y= aboveground biomass yield (g),
X= rate of P application (mg kg^{-1} soil);
A= (intercept),
B= (linear coefficient), and
c= (quadratic coefficient).

The constants were obtained by fitting the model to the data (Figure 1). The relationship between applied P and biomass yield (y) was described by the following regression equations:

Flagstaff:

$$y = 215.96 * EPR_{factor} – 453.51 * (EPR_{factor})^2 + 26.20 \quad R^2 = 92.33\%$$

Qunu:

$$y = 351.68 * EPR_{factor} – 671.94 * (EPR_{factor})^2 – 8.26 \quad R^2 = 95.25\%$$

Calculation of the derivatives (dy/dx = 0) of the quadratic equations for both soils showed the maximum biomass yield would be achieved at an equilibrium P concentrations of 0.24 and 0.26 mg P l^{-1} for Flagstaff and Qunu soils, respectively. The plateau yields were considered to be maximum yields. The equation for the relationship between the EPR factors with biomass yield (Figure 1) for Flagstaff soils (r^2 = 92.3) gave a better yield prediction than that derived for Qunu soil (r^2 = 88.7) (Figure 2).

Effect of P rate on plant tissue P concentration

Trends of plant tissue P concentration were similar to those of biomass yield (Figure 2) and were curvilinear for both soils with plant P concentration increasing with increased levels of P addition. The P concentration in the plant tissue was significantly increased by application of P fertilizer (Table 2).

Regression analysis showed that P accumulation in the plant tissue was also significantly ($p < 0.05$) and positively correlated with biomass yield (Figure 2). The data showed that the accumulation was highly correlated with levels of P applied, r = 0.90 and r = 0.96 for Flagstaff and Qunu soils, respectively (Table 3). Plant P accumulation in the control was used as a measure of native P supply by the soils, assuming that other nutrients or water were not limiting P uptake; that is, differences in tissue P in the control treatment in the two soils were purely as a result of the difference in soil P supply. The plant tissue P in the control pots were 0.06 and 0.04% for Flagstaff and Qunu soils, respectively. The rate of increase in P concentration for each additional increase in P was much higher for Qunu than for Flagstaff soil as indicated by the linear coefficients of the fitted equations (Figure 2).

Table 3. Correlation coefficients between external P requirement factor and biomass yield, and tissue P.

Flagstaff soil	EPR factor	Biomass	Tissue P
EPR_{factor}	1.000	0.758 (0.448)	0.904 (0.003)
Biomass		1.000	0.904 (0.001)
Tissue P			1.000
Qunu soil			
EPR_{factor}	1.000	0.845 (0.672)	0.955 (0.002)
Biomass		1.000	0.946 (0.000)
Tissue P			1.000

EPR_{factor} = External phosphate requirement
( ) Standard Error P=0.000

DISCUSSION

The evaluation of soil P status and calibration of soil test values with yield response data form an essential part of the prediction of optimum rates of P fertilization (Thibaud et al., 1994; Schmidt et al., 2004). Yield response to applied P was much smaller for Flagstaff soil than for Qunu soil as indicated by the linear coefficients of the fitted curves, 216.0 for Flagstaff as compared to 351.7 for Qunu indicating a higher P requirement for Flagstaff soil than that of Qunu soil. The smaller coefficient could also indicate a lower relative availability of applied P in this soil due partly to its high amounts of exchangeable Al and high retention capacities (Gichangi et al., 2007). One factor that can cause lower availability coefficients is irreversible P sorption reactions (Yost et al., 1981).

Calculation of the derivatives (dy/dx = 0) of the quadratic equations for both soils showed the maximum biomass yield would be achieved at an equilibrium P concentrations of 0.24 and 0.26 mg P l^{-1} for Flagstaff and Qunu soils, respectively with the plateau yields considered to be maximum yields. Apparently, the yield obtained from these concentrations were not significantly different from those obtained at a soil solution P concentration of 0.2 mg P l^{-1} ($P_{0.2}$) reported in the literature to be a threshold for many crops, over which no response to P is observed (Iyamuremye et al., 1996; Nziguheba et al., 1998; Duffera and Robarge, 1999). However, as the critical value is dependent on plant species and agronomic factors, some studies elsewhere have shown that it may be necessary to determine fertilizer P requirement of some crops at other P concentrations besides 0.2 mg P l^{-1}. In South Africa, for example, an external P requirement factor of 0.11 mg P l^{-1} has been shown to be suitable for tobacco in the low to moderately P fixing soils of the tobacco growing areas of Kwa-Zulu-Natal (Henry and Smith, 2006). Mokwunye (1977) cited by Warren (1992) showed that for maize grown in Samaru, Nigeria maximum yields were obtained when the P concentration in the soil solution 0.3 mg P l^{-1}. Furthermore, the use of a single critical solution P concentration value for all soils also neglects any effect of the P buffering power (Raven and Hossner, 1994). The recovery rate of added P for Flagstaff soil was low relative to the higher amounts of P applied, suggesting that the soil has a strong P-sorbing ability. These observations are in agreement with earlier results reported in Gichangi et al. (2007) which indicated that the soil had relatively higher sorption retention characteristics with a sorption maximum of 908 mg P kg^{-1} of soil. These results thus showed that a soil solution P concentration of 0.2 mg P l^{-1} ($P_{0.2}$) could be optimal for oats and possibly other crops in these soils. It should, therefore, be given serious consideration as an index for P recommendations for the soils studied.

CONCLUSION

The results of this study confirmed that the critical concentration of phosphorus in soil solution which is non-limiting for plant growth is independent of soil type. The strong relationship between P in solution and biomass yield and P concentration in the plant indicate the usefulness of P sorption approach for making fertilizer P recommendations. This approach does provide a rational basis for both the need for P and the amount required for a given soil for a particular crop with an advantage over the conventional testing methods as it integrates P intensity, capacity and quantity aspects of the soil and that P fertilizer requirement can be determined directly from sorption curves. However, the relationships obtained in this pot study; need to be verified across a wider range of soils and under field conditions.

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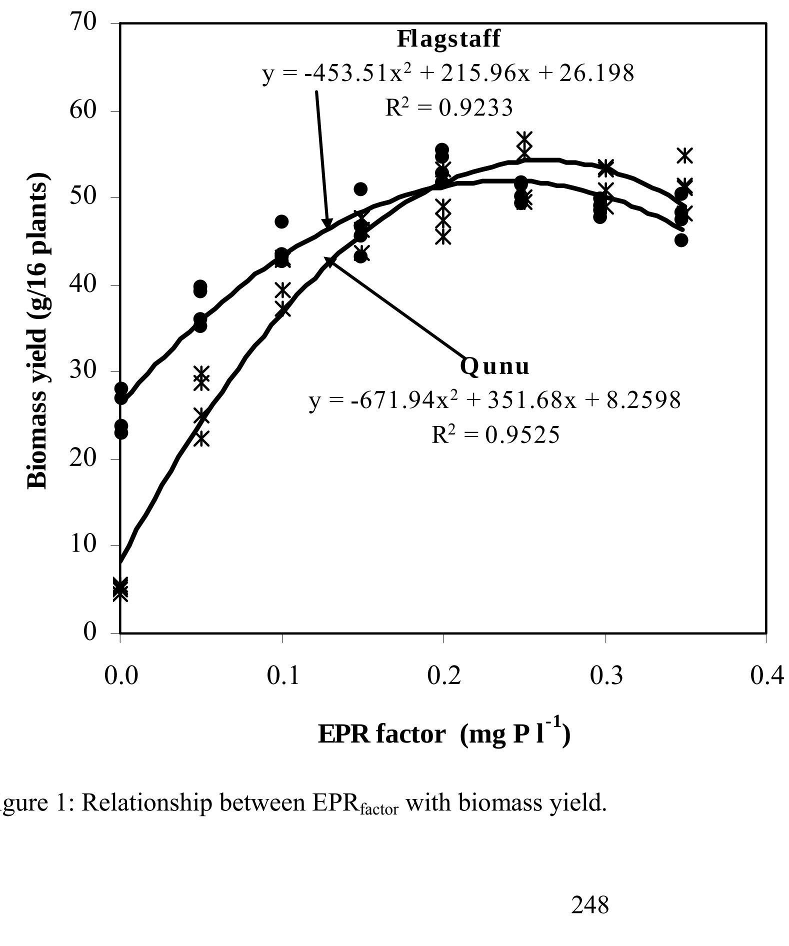

Figure 1: Relationship between EPR_{factor} with biomass yield.

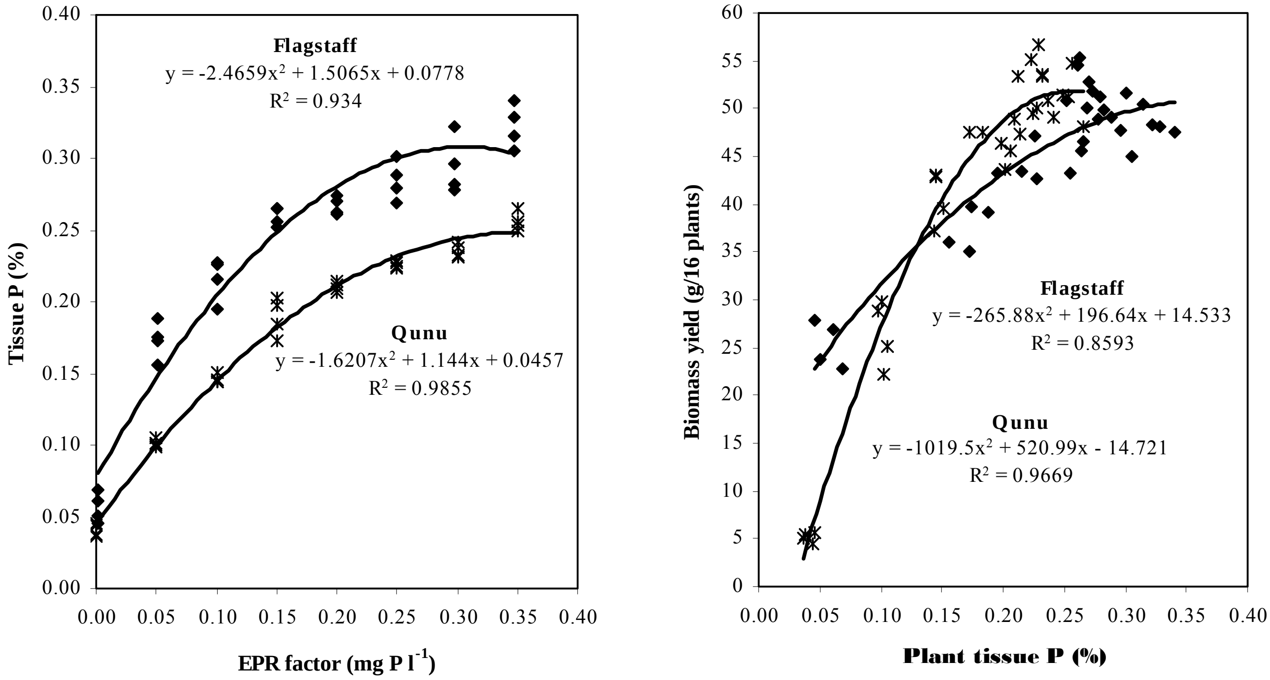

Figure 2: Relationship between plant tissue P concentration with EPR_{factor} and biomass yield.

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