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# Predicting the response of wheat (*Triticum aestivum* L.) to liquid and granular phosphorus fertilisers in Australian soils

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**Abstract.** Liquid forms of phosphorus (P) have been shown to be more effective than granular P for promoting cereal growth in alkaline soils with high levels of free calcium carbonate on Eyre Peninsula, South Australia. However, the advantage of liquid over granular P forms of fertiliser has not been fully investigated across the wide range of soils used for grain production in Australia.

We report results of a large glasshouse pot experiment undertaken with 28 diverse soils ranging from acidic through to alkaline non-calcareous collected from all over Australia to test if liquid P was more effective for growing spring wheat (*Triticum aestivum* L.) than granular P. Liquid P produced greater shoot dry matter responses, as measured after 4 weeks growth (mid to late tillering, Feeks growth stage 2-3) than granular P in 3 of the acidic to neutral soils and in 3 alkaline soils. Shoot dry matter responses of spring wheat to applied liquid or granular P were related to soil properties to determine if any of the properties predicted superior yield responses to liquid P. Only the calcium carbonate content of soil predicted when liquid P was more effective than granular P.

Five soil P test procedures (Bray, Colwell, resin, isotopically exchangeable P and diffusive gradients in thin films (DGT)) were used to measure soil test P on subsamples of soil collected before the experiment started. These soil test values were then related to the dry matter shoot yields to assess their ability to predict wheat yield responses to P applied as liquid or granular P. All five soil test procedures had similar ability to predict yield responses to applied P as either liquid or granular P, with the resin P test having a slightly greater predictive capacity on the range of soils tested.

**Additional keywords:** fluid fertilizers

## Introduction

Comparing the effectiveness for plant production of liquid and granular phosphorus (P) fertilisers first occurred in the USA in the early 1970's and showed that both fertiliser types were equally effective for plant production in acidic to neutral soils (Adriano and Murphy 1970; Dobson *et al.* 1970; Khasawneh *et al.* 1979; Khasawneh *et al.* 1974; Parent *et al.* 1985; Spratt 1973; Sutton and Larsen 1964; Tisdale *et al.* 1985). The Australian grains industry uses a wide diversity of soils ranging from acid through to highly alkaline and alkaline calcareous soils. Recent experiments demonstrated that liquid P fertilisers were more efficient in promoting the growth and P uptake of wheat than granular products in the highly calcareous soil types that dominate parts of southern Australia such as the Eyre Peninsula of South Australia (Holloway *et al.* 2001).

In calcareous soils, P fixation reactions predominantly occur with Ca, while in acidic to neutral soil types the fixation of P is closely related to soil Fe and Al (McLaughlin *et al.* 1981). Differential yield responses to liquid and granular P fertilisers have been related to differences in the moisture gradient, mobility and reaction products in the region of fertiliser application for soils where the fixation reactions are dominated by Ca or Al (Hettiarachchi *et al.* 2006; Lombi *et al.* 2004; Lombi *et al.* 2006).

There has been limited testing of liquid P forms on Australian soils other than the highly calcareous soils of South Australia. Several low pH soils collected from Victoria were found to be more responsive to liquid P fertiliser than traditional granulated water-soluble P fertiliser in a glasshouse study (McBeath *et al.* 2005) but the responses in non-calcareous soils has been variable. Consequently, we conducted a larger study using 28 divergent acidic to neutral soils collected from the major grain cropping regions of Australia. An alkaline soil with high levels of free calcium carbonate collected from Eyre Peninsula was also included as a positive control because liquid P is known to produce better wheat yield responses on this soil than granular P. It was decided that only one rate of P would be used due to the practical constraints of adding a range of P rates and testing such a wide range of soils and four fertiliser types. The study was conducted in the glasshouse rather than the field for practical reasons and to avoid the confounding interactions between climate and soil types inherent in field experiments. In the study reported here we measured several soil properties likely to influence plant yield responses to applied P. By testing the soils for response to fertiliser type from across the grain cropping regions of Australia and combining this data with comprehensive soil characterisation, we aimed to develop criteria that would assist to identify soils where liquid P fertilisers were more likely to outperform granular forms.

Soil P testing is widely used in P fertiliser decision support systems to estimate likely plant yields produced in the next growing season from P already present in the soil (from indigenous soil P and fertiliser P applied in previous years) (McLaughlin *et al.* 1999). It is then possible to determine likely profitable crop yield responses to P freshly-applied to the next crop. To achieve these predictions the relationship between the soil test and the yield responses of plants to applied P has to be calibrated for different soil types. These calibrations have been developed for granular P fertilisers, but it is not known if the calibrations also apply to liquid P fertilisers. This study provided the opportunity to evaluate whether commonly available soil P tests procedures differ in their ability to predict wheat yield responses to liquid and granular P fertilisers.

Therefore, the aims of this study were to (*i*) compare the effectiveness of liquid and granular P fertiliser for producing 4 week old dried shoots of spring wheat in a wide range of acidic to neutral soils used for cropping in Australia; (*ii*) identify soil properties that might help to predict which fertiliser type is most suitable for a given soil type; *(iii)* evaluate the ability of soil P tests to predict yields of dried wheat shoots to application of P as liquid or granular P; and *(iv)*identify soils in which liquid P is more effective than granular P for producing dried wheat shoots so these soils can be used for more detailed glasshouse and field studies in which several rates of P as both liquid and granular P are applied to adequately define complete wheat grain yield response curves to applied P for each P source.

## Materials and Methods

### *Soils*

The top 10 cm of soil was collected from 28 sites representing a wide range of soil types used for dry land grain production in Australia including:

1. Six soils from Western Australia (WA) (Alexander Bridge, Pemberton, Mt Barker, Gibson, Collie and Newdegate);
2. Four soils from Queensland (Qld) (Bauer-Kingaroy, A10-Kingaroy, Blackdown-Condamine, and Nebri-Drillham);
3. Four soils from New South Wales (NSW) (Balranald, Culcairn, Temora, Tudgey and Kelley);
4. Three soils from Victoria (Vic) (Birchip, Hamilton and Kalkee);
5. One soil from Tasmania (Tas) (Ulverstone);
6. One soil from the Australian Capital Territory (ACT) (Otterbourne); and
7. Seven soils from South Australia (SA) (Lenswood, Keith, Monarto, Bordertown, Jacka, Ilanson and Warramboo). The Warramboo soil collected from Eyre Peninsula contains high levels of free calcium carbonate, on which wheat yield responses to applied P have been consistently greater for liquid than granular P.

The geographic distribution of these sampling sites is illustrated in Figure 1.

*Insert Figure 1*

### *Soil properties*

Soil properties were measured on subsamples of soil collected from each of the 28 soil samples before the experiment started. All these soil analyses were conducted on soil after drying at 40°C for 3 days, sieving (<2 mm) and storage at room temperature. Air-dry moisture content was determined using the method of Rayment and Higginson (1992) and field capacity was measured using a pressure plate at – 10 kPa matric potential (Klute 1986).

Soil pH and EC were measured in a 1:5 soil:water extract (Rayment and Higginson 1992). Soil samples were digested in *aqua regia* (Zarcinas *et al.* 1996) and total P, Zn, Ca, Mn, Mg, and Cu were determined by inductively coupled plasma-atomic emission spectroscopy (ICP-AES, Spectroflame Modula, Spectro). Total organic carbon (TOC) was measured according to the method of Matejovic (1997). Particle size analysis was used to determine the proportion of clay, silt, coarse sand and fine sand in each soil type and was conducted according to the method of the USDA (1996). Calcium carbonate ($CaCO_3$) content was determined using the procedure of Sherrod *et al.* (2002), and cation exchange capacity (CEC) was measured using method 15D2 (Ammonium Acetate at pH 7.0, pretreatment for soluble salts) using procedure 15I3 of Rayment and Higginson (1992).

Soil test P was measured by 5 procedures: bicarbonate-extractable P measured as described by Colwell (1963) (0.5 M $NaHCO_3$ at pH 8.5), ammonium fluoride-extractable (Bray) P measured as described by Bray and Kurtz (1945), resin-exchangeable P determined using anion-exchange resin strips (McLaughlin *et al.* 1994), and the isotopically exchangeable P pool (E-value) determined using the isotopic dilution method of Hamon and McLaughlin (2002). In the determination of resin exchangeable P, soil solutions were shaken with the resin strip for 16 h after which the strips were removed and P was extracted from the strip using a 0.1 M NaCl: 0.1 M HCl eluant with 2 h of shaking. The P concentration in the eluant was measured colorimetrically (Murphy and Riley 1962). The E-value was determined by mixing 10 g of soil was mixed for 24 h with 100 mL of deionised water to which 2 drops of toluene were added to inhibit microbial activity. The samples were shaken on an end-over-end shaker for 24 h. Carrier-free $^{32}$P (75 $\mu$L of 500 kBq/mL) was added to each sample and the samples were placed on the end-over end shaker for a further 16 h. The soil suspensions were centrifuged (1000 *g*) and 70 mL of the supernatant was filtered through 0.45-$\mu$m membrane filters (Sartorius). Two 5-cm$^2$ anion exchange resin strips (BDH) were pretreated as described by Hamon and McLaughlin (2002), placed in the filtered supernatant and placed on the end-over-end shaker for 16 h. The resin strips were then removed and P was eluted from the resin as described above. Phosphorus concentration in the eluant was measured using the method of Murphy and Riley (1962), and $^{32}$P activity was measured by Cerenkov counting (RackBeta II, Wallac). The total activity introduced in each sample, R, was determined by treating spiked solutions without soil in parallel to the soil suspensions. E-values (mg P/kg) were calculated by applying the isotopic dilution principle:

$$E_t = C_p/r_t \times R \times df \quad (1)$$

where $E_t$ was the total quantity of P that was isotopically exchangeable at time t (min), $C_p$ was the solution concentration of $^{31}$P (mg/L), $r_t$ was the amount of $^{32}$P (Bq) in solution at time t (min), R was the total amount of $^{32}$P added to the soil (Bq), and df was the dilution factor (volume of solution/mass of soil) (L/kg).

The phosphorus buffering index (PBI + ColP) is a single-point P sorption index and was measured by adding P (1000 mg P/kg, as $KH_2PO_4$) to a soil suspension (1:10, soil: 0.01 M $CaCl_2$, w/v) (Burkitt *et al.* 2002). The PBI + ColP was calculated using the following equation:

$$\text{PBI + ColP} = (P_s + \text{Colwell P})/c^{0.41} \quad (2)$$

where $P_s$ was the amount of P sorbed (mg P/kg) from a single addition of 1000 mg P/kg, and c was the concentration of P (mg P/L) measured in the final extract solution.

The theory of Diffusive Gradients in Thin Films (DGT) has been discussed in detail previously (Zhang et al. 1995). Recently with the development of a Mixed Binding Layer (MBL) the DGT technique now allows for simultaneous assessment of selected cations and anions. The MBL was used in this current study for the assessment of P and detailed information on the production and testing of the MBL is available in Mason *et al.* (2005). Two DGT devices containing a MBL, 0.8 mm diffusive layer and a protective filter membrane were deployed on each control soil (100g) at 80 % WHC for 24 h. On removal the DGT devices were rinsed with ultra pure $H_2O$ (Milli-Q) and the MBL retrieved and placed in 1 ml of 1 M HCL for at least 24 h. The resulting eluant solution was analysed using an inductive coupled plasma-mass spectrometer (ICP-MS) and the concentrations were converted to effective concentration ($C_E$) (Zhang *et al.* 2001). The effective concentration ($C_E$) incorporates both the soil solution concentration and its enhancement from the solid phase (Zhang *et al.* 2001).

*Glasshouse experiment*

The experiment comprised 28 soils, 3 P fertilisers, 2 rates of P (0 and 16.7 mg P/pot, equivalent to ~12 kg P/ha), replicated 4 times. The 3 P fertilisers were: granular monoammonium phosphate (MAP, 18:22:0 w/w %) (approximately 3mm granule diameter), liquid technical grade monoammonium phosphate (TGMAP; 12:26:0 w/w %) and liquid ammonium polyphosphate (APP; 16:23:0 w/v %). The pots were arranged in a split-plot design where each soil treatment was a whole plot and each fertiliser treatment was a subplot. Each replicate formed a block. The positions of whole plots within blocks, and subplots within whole plots, were randomised and these positions were re-randomised after two weeks of growth. Due to the large number of pots the trial was run as two batches with two replicates in each batch to give a total of 224 pots per batch.

A total of 1000 $cm^3$ of air-dry sieved (< 2 mm) soil was used in each pot (soil weight for each soil was dependent on the soil bulk density). An equivalent soil volume approach was used due to the wide range in bulk density and water retention characteristics in the 28 soils used. Plastic pots, 11.2 cm in diameter and 12 cm high, were used. The pots were lined with polyethelene bags and were not free draining.

Basal nutrient solutions were applied to each pot to ensure that P was the only nutrient to limit wheat growth. Nitrogen was applied as urea ammonium nitrate (UAN) at a rate of 0.18–0.22 mL/pot, adjusted according to the N content of the P fertiliser to achieve a total N application of 69.5 mg/pot. Other basal nutrients, mixed through out the pot, comprised (per pot): 2.5 mg manganese as manganese sulphate ($MnSO_4.H_2O$, 31% Mn), 6.3 mg zinc as zinc sulphate ($ZnSO_4.7H_2O$, 22.7% Zn), 3.1 mg copper as copper sulphate ($CuSO_4.5H_2O$, 25.5% Cu), 6.3 mg iron as iron sulphate ($Fe\ SO_4.7H_2O$, 20% Fe), 0.06 mg boron as boric acid ($H_3BO_{3,}$ 17.5% B), 0.05 mg molybdenum as molybdenum oxide ($MoO_3$, 66.7% Mo), 0.01 mg cobalt as cobalt sulphate heptahydrate ($CoSO_4.7H_2O$, 21% Co) and 50 mg potassium as potassium sulphate ($K_2SO_4$, 22% K). After the soils had dried following application of the solutions, the soils were shaken in the polyethelene bags to mix the basal nutrients through the soil.

Gypsum was applied at a rate of 6250 mg/pot to alkaline soil types to overcome sodicity problems known to occur with some of the soils used. For the acid soils (pH <5.5), no Mn, Cu, or gypsum was applied.

In each pot, 16.7 mg P (equivalent to 12 kg P/ha on a surface area basis) was applied 2 cm below the seed for each of the different P fertilisers. The P fertiliser was applied at 5 equidistant points around a template of 52 mm diameter. Liquid fertilisers were diluted to 5 mL with reverse osmosis (RO) water, and 1 mL of fertiliser solution placed at each point of application. Monoammonium phosphate (MAP) was applied as pre-weighed granules with one granule per point of application.

Five pre-germinated seeds of wheat (*Triticum aestivum* cv. Yitpi) were sown in each pot at 1–1.5 cm depth using the same template as that used for application of the P fertilisers to ensure that the seed was placed over the fertiliser. The seedlings were thinned to three per pot at the 2-leaf growth stage by leaving the most uniform seedlings in each pot.

Immediately after sowing, the soil surface in each pot was covered with 50 g of alkathene granules to minimise evaporation. Pots were watered to weight with RO water every 2–3 days in order to maintain 85% field capacity. The experiment was conducted in a glasshouse at 18°C for 4 weeks.

After 4 weeks of growth, when plants were at mid to late tillering (Feekes growth stage 2–3, Large (1954)), the shoots were cut at ground level. Shoots were oven-dried at 70°C for 48 h, the dry weight recorded, and the plant samples were ground and acid-digested before measuring concentration of P in dried shots by ICP-AES.

*Statistical analysis*

Least significant difference (*l.s.d.*), from analysis of variance, was used to compare mean dry matter as a result of P treatments, to test for significant difference between treatments.

For the same soil type, the yield (g/pot) of dried wheat shoots to the 1 rate of TGMP and APP was averaged, to give average yields produced for application of the 1 rate of liquid P. The average yield produced for the 1 rate of liquid P was then used to calculate percentage yield increase or decrease relative to granular P using the following equation:

$$\text{dliquid/granular(\%)}= \frac{liquiddrymatter - granulardrymatter}{granulardrymatter} \times 100 \quad (3)$$

Responses of liquid fertiliser over the control ‘dliquid/ control’ and granular fertiliser over the control ‘dgranular/control’ were also calculated where:

$$\text{dliquid/control(\%)}= \frac{liquiddrymatter - controldrymatter}{controldrymatter} \times 100 \quad (4)$$

$$\text{dgranular/control (\%)}= \frac{granulardrymatter - controldrymatter}{controldrymatter} \times 100 \quad (5)$$

Stepwise linear regression was used to develop the most statistically sound model by testing the ability of ten of the measured soil properties to explain the effect of soil properties on fluid dry matter responses over granular, fluid dry matter responses over the control, and granular dry matter responses over the control, in this experiment and for the pooled results of this experiment and a previous glasshouse experiment (McBeath *et al.* 2005).

The GENSTAT 8 package was used to conduct all statistical analyses including regression curve fitting. Curves were plotted using Sigma Plot 9.0.

## Results and discussion

### *Soil properties*

The soils selected exhibited a wide range of soil chemical and physical properties for the 28 representative soils used in Australia to grow wheat (Table 1). Soil pH ($H_2O$) ranged from 5.2 to 8.9 while $CaCO_3$ content varied from below detection to 61% w/w, and the total carbon content ranged between 0.5% and 6.5%. The Resin P values varied from 0.5-46.8 mg P/kg, while the E-value (isotopically exchangeable P) or potentially available P varied from below detection (0.02 mg P/L solution P) to 68 mg P/kg and the DGT effective concentration $C_E$ varied from 66 to 3686 µg/L.

*Insert Table 1*

### *Dry matter yield*

Wheat responded to P application in 93% of soils of the soils tested. In 21% of soils wheat yields responses were significantly ($P \leq 0.05$) larger for P applied as 1 or both liquid P sources compared to the granular P source (Table 2), with the liquid source producing 15-50% greater biomass than with granular P fertiliser. There were no distinct characteristics or groupings of soil types however in which wheat significantly and systematically showed larger yield responses to liquid than to granular fertiliser. Soils in which wheat showed larger responses to liquid than granular P included a diverse range of soils collected from different locations with a range in soil pH values. As also found in the previous glasshouse study (McBeath *et al.* 2005) liquid P was more effective than granular P in alkaline soils with increasing amounts of free calcium carbonate.

Several soils in the current experiment were also common to the previous experiment and therefore have the same site name (Hamilton, Keith, Bordertown and Lenswood). However these soils are not from exactly the same location and possessed quite different characteristics, as can be observed by comparing Table 1 from the current study with those reported in McBeath et al. (2005). Therefore, comparison of responses wheat to applications of liquid or granular P fertilizer for these site names, between the two studies is not possible. The exception was the Warramboo soil, which was identical in both studies and could therefore act as a control.

Although liquid P did not perform as well as granular P in several soils, the differences in wheat response between liquid and granular P were small and were only statistically significantly for one soil type: Hamilton from Victoria (Table 2). Shoot yields varied markedly among the different soil types for the nil-P and the 3 sources of P applied, and were particularly low for 3 soils (Sandilands, Keith and Warramboo, Table 2). Though basal fertilisers were applied, it is possible that, in addition to P, some nutrient element deficiencies or soil chemo-physical properties (salinity) may also have influenced growth of the wheat plants.

The magnitude of the plant response to liquid fertiliser over granular is not as high in this glasshouse experiment as in the previous experiment (McBeath *et al.* 2005). This may in part be due to the use MAP as the granular P source in this study instead of used triple superphosphate used in the study of McBeath *et* al. (2005) in the previous study. The Warramboo control soil shows a fluid response of 66% greater than granular MAP, compared to a fluid response of 157% greater than granular triple superphosphate in the previous experiment. There is strong anecdotal evidence from grain growers that superphosphate often performs poorly compared to either MAP or DAP (di-ammonium phosphate). Glasshouse studies (Thomas and Rengel 2002) suggested that the better growth performance of canola plants supplied with either MAP or DAP compared to triple superphosphate (TSP) was due to the better N nutrition of plants supplied with the former P sources, even when urea was added to produce equivalent amounts of N between the different P sources. Furthermore only 1 soil with high levels of calcium carbonate was tested in this experiment, with highly calcareous soils showing the greatest yield advantage for liquid P fertilisers as compared to granular in soils tested so far (Lombi *et al.* 2004).

*Insert Table 2*

The limitation of only testing one P rate is that only a single yield point is attained for each treatment; therefore, response versus non-response is only descriptive for the 12 kg P/ha application rate. We therefore could not determine well-defined yield response curves for the different sources of P.

This large screening study was undertaken to identify soils in which liquid P outperformed granular P for growing wheat enabling suitable soils to be used for glasshouse and field studies in which well defined yield response curves of wheat grain to applied P can be obtained by applying multiple rates of P as liquid or granular P. It is then possible to determine the rate of P as liquid or granular fertiliser required to produce the same yield, so that substitution values of P from liquid fertiliser can be determined relative to P from granular fertiliser.

### *Tissue P concentration and dry matter yield of wheat*

Shoot tissue P concentration was positively correlated with shoot dry matter (Fig. 2). In several control (nil-P treatment) soils the plant tissue P concentration was below the 2000 mg P/kg critical tissue test value (the concentration of P in wheat shoots that was related to 90% of the maximum yield) for wheat at 4 weeks growth , below which deficiency is likely to reduce plant growth (Reuter and Robinson 1997). When P was applied, the only P treatment that produced plants with a P concentration in shoots below the critical value was for granular MAP in the Warramboo soil with much calcium carbonate. In all other cases when P was applied all 3 P fertiliser sources (MAP, TGMAP and APP) resulted in a tissue P concentration above the critical tissue test value.

*Insert Figure 2*

### Phosphorus uptake and biomass

There was a positive relationship ($R^2 = 0.66$) between the advantage in plant P uptake with liquid P fertilisers compared to granular for increases in dry matter for liquid P forms over and above granular MAP. This suggests that in soils where improved plant growth was recorded for liquid P fertilisers, it was associated with increased plant P uptake.

*Insert Figure 3*

*Relationship between yield response of dried wheat shoots to applied P and soil properties*

The potential use of soil properties to predict shoot responses to applied P as the 3 different fertilisers was assessed using stepwise linear regression. Ten soil properties were multiple tested for inclusion in a predictive model: $CaCO_3$ content, PBI + ColP, pH ($H_2O$), total Al, total Fe, total N, total P, water content at field capacity, clay content and TOC. Analyses were undertaken to test the ability of soil properties to predict dliquid/granular, dliquid/control and dgranular/control responses, but in only one of these cases (the dliquid/control) could a model be developed in which all parameters tested were statistically significant ($P \leq 0.05$) and 65% of the variance was accounted for. The significant best fit equation was:

$$\text{dliquid/control} = 550.9(86) - 49.4\ (12.0)\ \text{pH} + 5.6\ (1.4)\ CaCO_3 + 0.003(0.0007)\ \text{Fe} - 0.6\ (0.09)\ \text{P}\ (R^2=0.65) \quad (6)$$

where dliquid/ control is percentage increase in wheat biomass in the liquid fertiliser treatments (average of TGMAP and APP) over the control treatment (no P applied), $CaCO_3$ is percentage calcium carbonate, pH is the soil pH measured in water, Fe is total iron, P is total phosphorus and numbers in parentheses are standard error for each parameter.

The results from the current glasshouse experiment (Experiment 2) were pooled with those from the experiment reported in Mcbeath *et al*.(2005) (Experiment 1) and the same ten soil characteristics were used as a variable in stepwise linear regressions to predict the dliquid/ granular, dliquid/ control and dgranular/ control responses in the larger suite of soils. Again there was only one case in which there was a model in which all parameters were statistically significant ($P \leq 0.05$) and a majority of the variance was accounted for ($R^2$=0.73), although in this instance it was the prediction of liquid efficiency over granular (dliquid/granular). Calcium carbonate content was the only significant predictor in this model, accounting for 73% of the observed variance in dliquid/granular values. The best fit equation was:

$$\text{dliquid/ granular}=16.22\ (6.12)+1.73(0.21)\ \text{CaCO}_3\ (R^2=0.73)\ (7)$$

where dliquid is percentage increase in wheat biomass in the liquid fertiliser treatments (average of APP and TGMAP or of $H_3PO_4$ and TGMAP) over the granular P treatment (MAP or triple superphosphate P). $CaCO_3$ is percentage calcium carbonate and numbers in parenthesis are standard error estimates.

Figure 4 illustrates the relationship between percentage $CaCO_3$ and the efficiency of liquid fertiliser relative to granular P. It shows that while all soils used in the 2 experiments that had measurable quantities of $CaCO_3$ resulted in a greater response in wheat biomass to liquid P sources than to granular P, there were also significant responses in some soils with a very low $CaCO_3$ content. This combined analysis does have a weakness in that the P sources were not the same in the 2 experiments, with $H_3PO_4$ and TGMAP compared to triple superphosphate in the previous experiment of McBeath *et al*. (2005) and APP and TGMAP compared to MAP in the current experiment. Therefore it is probable that this outcome has been leveraged by the strong response of liquid over granular triple P in the first glasshouse experiment as shown by the dominance of calcareous soil data points from previous experiment in the top right hand corner of Figure 4.

*Insert Figure 4*

*Ability of soil P tests to predict wheat response to liquid and granular sources of P*

Five soil P tests (Bray P, P E-value, Colwell P, resin P and P DGT $C_E$) used to assess plant available soil P status were assessed for their ability to predict the response of wheat to liquid and granular fertilisers (Figure 5). All 5 soil tests gave reasonable predictions of both liquid and granular P fertilizers to produce seedling growth responses in wheat compared to the nil-P control. The resin extraction procedure generally explained most of the variance and was better than the other soil test procedures at predicting yield responses to P applied as either liquid or granular P compared to the nil-P treatment. In some cases, soil test procedures were better at predicting wheat yield responses to applied P as either liquid or granular P. For example, the Bray test was a significantly better predictor of wheat yield response to applications of P as liquid ($R^2$=0.70) than granular ($R^2$=0.53) P. However, the prediction of yield responsnes to liquid P was generally more consistent ($R^2$= 0.70-0.88) than the prediction of responses to granular P ($R^2$=0.53-0.82).

*Figure 5- Relationship between wheat yield responses to applied liquid or granular P P and soil test P*

The fit of the curve for Colwell P versus fluid response over the control was significantly better in this experiment with only 1 highly calcareous soil (Fig. 5e) than the previous experiment (McBeath *et al.* 2005). The 1 highly calcareous soil, is the obvious outlier on the graph, supporting previous findings that Colwell P is not an appropriate extraction technique for calcareous soils (Bertrand *et al.* 2003).

## ***Conclusions***

Liquid and granular P sources were equally effective in producing dry matter responses in wheat for most of the acidic to neutral soils tested, with liquid P being more effective for alkaline soils as the calcium carbonate content in the soils increased. Calcium carbonate content was the only soil characteristic tested that consistently predicted whether a soil would respond better to application of P fertiliser in liquid form compared to granular P, with higher $CaCO_3$ contents indicating a greater response to liquid P. All 5 soil P tests evaluated adequately predicted responses of dried wheat shoots to P applied as all 3 sources, but resin P was generally the best predictor of yield responses to applied P. The ultimate value of any fertilizer source however will depend on its ability to produce consistent wheat grain yield responses to applied liquid or granular P under commercial field conditions and this has yet to be determined under Australian conditions.

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**Table 1. Geographic origin of soils used in the glasshouse experiment and some properties of the soils.**

| Soil (Location) | State | Clay content % | Field Capacity % w/w | pH ($H_2O$) | $CaCO_3$ % | TOC % | E-value mg/kg | Resin P mg/kg |
|---|---|---|---|---|---|---|---|---|
| Otterbourne | ACT | 10.38 | 30.18 | 5.38 | bdl[A] | 3.0 | 8.9 | 6.6 |
| Balranald | NSW | 21.39 | 23.97 | 8.87 | 3.8 | 1.8 | 21.8 | 13.0 |
| Culcairn | NSW | 10.53 | 26.82 | 5.91 | bdl | 1.7 | 9.8 | 5.8 |
| Kelley | NSW | 52.84 | 65.49 | 8.10 | 1.1 | 1.4 | 19.9 | 8.5 |
| Temora | NSW | 15.41 | 26.22 | 6.74 | bdl | 2.1 | 16.7 | 7.9 |
| Tudgey | NSW | 48.86 | 58.74 | 8.13 | 1.0 | 1.6 | 14.3 | 6.5 |
| A10-Kingaroy | Qld | 35.68 | 26.18 | 8.71 | bdl | 2.8 | 0.3 | 4.6 |
| Bauer- Kingaroy | Qld | 76.37 | 34.87 | 6.67 | bdl | 0.9 | bdl | 0.8 |
| Blackdown-Condamine | Qld | 41.30 | 28.92 | 8.90 | 1.9 | 0.5 | 7.4 | 6.3 |
| Nebri-Drillham | Qld | 38.11 | 38.08 | 8.26 | 1.3 | 1.0 | 12.5 | 6.4 |
| Bordertown | SA | 18.21 | 22.41 | 6.77 | bdl | 2.4 | 35.5 | 20.6 |
| Ilanson | SA | 14.00 | 28.02 | 5.64 | bdl | 1.5 | 11.7 | 7.0 |
| Jacka | SA | 29.69 | 38.74 | 7.6 | bdl | 2.9 | 67.5 | 23.2 |
| Keith | SA | 0.71 | 4.44 | 5.73 | bdl | 0.7 | 1.4 | 1.0 |
| Lenswood | SA | 8.76 | 42.13 | 6.03 | bdl | 3.7 | 25.1 | 13.6 |
| Monarto | SA | 6.95 | 13.66 | 7.04 | bdl | 0.8 | 3.4 | 2.3 |
| Sandilands | SA | 30.09 | 30.36 | 8.20 | 8.6 | 2.6 | 52.5 | 46.8 |
| Warramboo | SA | 5.18 | 18.07 | 8.95 | 60.7 | bdl | 10.5 | 3.5 |
| Ulverstone | Tas | 23.82 | 43.11 | 5.62 | bdl | 6.5 | bdl | 8.5 |
| Birchip | Vic | 32.87 | 35.06 | 8.66 | 0.7 | 1.2 | 13.0 | 5.8 |
| Dooen | Vic | 34.37 | 42.56 | 8.53 | 1.4 | 1.1 | 11.4 | 6.0 |
| Hamilton | Vic | 24.65 | 46.16 | 5.24 | bdl | 5.0 | 42.9 | 16.6 |
| Alexander Bridge | WA | 21.77 | 26.34 | 6.51 | bdl | 1.7 | bdl | 0.5 |
| Collie | WA | 4.80 | 21.75 | 6.07 | bdl | 4.4 | 7.0 | 2.6 |
| Gibson | WA | 3.24 | 8.23 | 6.27 | bdl | 0.5 | bdl | 0.8 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Mt Barker | WA | 7.60 | 22.33 | 6.73 | bdl | 4.0 | 4.4 | 2.0 |
| Newdegate | WA | 27.12 | 17.71 | 5.38 | bdl | 1.6 | bdl | 2.0 |
| Pemberton | WA | 7.67 | 28.94 | 6.95 | bdl | 4.1 | bdl | 0.7 |

**[A]bdl, below detection limit.**

**Table 1 continued. Summary of the general chemical properties and geographic origin of soils used in the glasshouse screening experiment.**

| Soil (Location) | Colwell P mg/kg | Bray P mg/kg | PBI +colP | $C_E$ (DGT) µg/L | PT mg/kg | AlT mg/kg | FeT mg/kg |
|---|---|---|---|---|---|---|---|
| Otterbourne | 17.0 | 8.9 | 64 | 235 | 299 | 6178 | 7272 |
| Balranald | 42.5 | 37.5 | 113 | 769 | 235 | 20938 | 14713 |
| Culcairn | 22.4 | 6.7 | 39 | 292 | 185 | 7212 | 8251 |
| Kelley | 22.9 | 15.1 | 187 | 329 | 353 | 49879 | 44443 |
| Temora | 24.5 | 17.1 | 50 | 493 | 267 | 13617 | 15146 |
| Tudgey | 18.5 | 17.8 | 117 | 213 | 203 | 42449 | 30553 |
| A10-Kingaroy | 11.1 | 2.0 | 88 | 124 | 314 | 27938 | 73457 |
| Bauer- Kingaroy | 6.3 | 1.4 | 298 | 66 | 274 | 45847 | 89423 |
| Blackdown-Condamine | 9.6 | 14.6 | 101 | 202 | 91 | 22239 | 15848 |
| Nebri-Drillham | 16.47 | 7.4 | 115 | 241 | 238 | 26187 | 57241 |
| Bordertown | 66.0 | 10.1 | 43 | 2819 | 216 | 10528 | 8773 |
| Ilanson | 22.6 | 14.3 | 43 | 340 | 252 | 13227 | 23269 |
| Jacka | 100.5 | 106.0 | 64 | 3686 | 555 | 23738 | 26806 |
| Keith | 5.7 | 1.8 | 7 | 156 | 13 | 614 | 398 |
| Lenswood | 37.4 | 19.2 | 98 | 367 | 462 | 8414 | 15908 |
| Monarto | 5.6 | 2.7 | 21 | 119 | 91 | 9983 | 12675 |
| Sandilands | 95.7 | 40.0 | 183 | 1909 | 432 | 29709 | 21525 |
| Warramboo | 32.9 | 1.1 | 117 | 217 | 381 | 4778 | 3920 |
| Ulverstone | 29.0 | 4.9 | 655 | 109 | 797 | 54211 | 88807 |
| Birchip | 19.2 | 17.1 | 123 | 269 | 200 | 33330 | 23989 |
| Dooen | 18.3 | 17.7 | 134 | 226 | 164 | 41845 | 27989 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Hamilton | 88.3 | 21.4 | 163 | 601 | 419 | 19364 | 23124 |
| Alexander Bridge | 5.6 | 0.8 | 304 | 76 | 59 | 72247 | 31968 |
| Collie | 7.1 | 4.2 | 159 | 95 | 92 | 18371 | 24128 |
| Gibson | 4.1 | 1.5 | 15 | 163 | 11 | 3802 | 6030 |
| Mt Barker | 7.7 | 11.0 | 170 | 97 | 91 | 20754 | 17680 |
| Newdegate | 9.5 | 9.9 | 57 | 112 | 79 | 21452 | 22059 |
| Pemberton | 5.6 | 0.7 | 434 | 75 | 102 | 26707 | 18322 |

**Table 2. Yield of dried shoots of wheat plants at mid tillering when no P was applied and when liquid (TGMAP and APP) or granular (MAP) P was applied**

| Soil (Location) | State | Control (g/Pot) | | MAP (g/Pot) | | TGMAP (g/Pot) | | APP (g/Pot) | | Grouped Liquid P dry matter response greater than Granular |
|---|---|---|---|---|---|---|---|---|---|---|
| Otterbourne | ACT | 0.225 | B | 0.680<br>(202%) | A | 0.539<br>(140%) | A | 0.638<br>(184%) | A | -13% |
| Balranald | NSW | 0.509 | B | 0.767<br>(51%) | A | 0.793<br>(56%) | A | 0.747<br>(47%) | A | 0% |
| Culcairn | NSW | 0.434 | C | 0.839<br>(67%) | B | 0.901<br>(108%) | AB | 1.045<br>(141%) | A | 34% |
| Kelley | NSW | 0.603 | B | 0.887<br>(47%) | A | 1.028<br>(70%) | A | 0.927<br>(54%) | A | 10% |
| Temora | NSW | 0.638 | B | 0.934<br>(46%) | A | 0.929<br>(46%) | A | 0.902<br>(41%) | A | -2% |
| Tudgey | NSW | 0.604 | C | 0.961<br>(59%) | B | 1.157<br>(92%) | A | 1.033<br>(71%) | AB | 14% |
| A10-Kingaroy | Qld | 0.396 | C | 1.000<br>(152%) | B | 1.138<br>(187%) | AB | 1.197<br>(202%) | A | 17% |
| Bauer- Kingaroy | Qld | 0.155 | B | 0.678<br>(337%) | A | 0.791<br>(410%) | A | 0.730<br>(371%) | A | 12% |
| Blackdown-Condamine | Qld | 0.500 | B | 1.028<br>(106%) | A | 0.981<br>(96%) | A | 0.998<br>(100%) | A | -4% |
| Nebri-Drillham | Qld | 0.448 | B | 0.927<br>(107%) | A | 1.052<br>(135%) | A | 0.984<br>(120%) | A | 21% |
| Bordertown | SA | 0.941 | A | 0.950<br>(1%) | A | 0.896<br>(-5%) | A | 1.004<br>(7%) | A | 0% |
| Ilanson | SA | 0.530 | C | 1.050<br>(98%) | AB | 1.172<br>(121%) | A | 0.974<br>(84%) | B | 2% |
| Jacka | SA | 0.958 | B | 0.914<br>(-5%) | AB | 0.993<br>(4%) | AB | 1.092<br>(14%) | A | 14% |
| Keith | SA | 0.137 | B | 0.531<br>(288%) | A | 0.478<br>(249%) | A | 0.554<br>(305%) | A | -3% |
| Lenswood | SA | 0.630 | C | 1.114<br>(77%) | A | 0.923<br>(47%) | B | 1.101<br>(75%) | A | -9% |
| Monarto | SA | 0.268 | B | 0.878<br>(228%) | A | 0.977<br>(265%) | A | 0.886<br>(231%) | A | 6% |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sandilands | SA | 0.476 | A | 0.477<br>(0%) | A | 0.528<br>(11%) | A | 0.610<br>(28%) | A | 19% |
| Warramboo | SA | 0.183 | C | 0.353<br>(93%) | B | 0.638<br>(249%) | A | 0.536<br>(193%) | A | 66% |
| Ulverstone | Tas | 0.262 | B | 0.514<br>(96%) | A | 0.563<br>(115%) | A | 0.603<br>(130) | A | 13% |
| Birchip | Vic | 0.574 | C | 0.844<br>(47%) | B | 1.001<br>(74%) | A | 0.959<br>(67%) | AB | 16% |
| Dooen | Vic | 0.590 | B | 1.184<br>(101%) | A | 1.12<br>(90%) | A | 1.077<br>(83%) | A | -7% |
| Hamilton | Vic | 0.633 | B | 0.894<br>(41%) | A | 0.687<br>(9%) | B | 0.675<br>(7%) | B | -24% |
| Alexander Bridge | WA | 0.222 | B | 0.718<br>(223%) | A | 0.774<br>(249%) | A | 0.804<br>(262%) | A | 10% |
| Collie | WA | 0.179 | B | 0.597<br>(234%) | A | 0.670<br>(274%) | A | 0.746<br>(314%) | A | 19% |
| Gibson | WA | 0.179 | B | 0.935<br>(422%) | A | 0.900<br>(403%) | A | 0.964<br>(439%) | A | 0% |
| Mt Barker | WA | 0.197 | B | 0.831<br>(322%) | A | 0.824<br>(318%) | A | 0.745<br>(278%) | A | -6% |
| Newdegate | WA | 0.175 | B | 0.515<br>(194%) | A | 0.645<br>(269%) | A | 0.597<br>(241%) | A | 21% |
| Pemberton | WA | 0.165 | B | 0.619<br>(275%) | A | 0.716<br>(334%) | A | 0.655<br>(297%) | A | 11% |

APP, ammonium polyphosphate; TGMAP, technical grade monoammonium phosphate; MAP, monoammonium phosphate; control, no P fertiliser; Y represents response to both APP And TGMAP; Numbers in brackets are yield response to fertiliser treatments greater than the control nil-P treatment (%); l.s.d. (*P* = 0.05) for individual soil data is 0.16. Within rows, values followed by the same letter are not significantly different (*P* < 0.05).

## Figure Captions

**Figure 1**. Soil sampling site locations

**Figure 2.** Relationship between plant tissue P and dry matter yield for each fertiliser treatment. The horizontal line at 2000 mg P/kg plant tissue P denotes deficiency threshold for wheat at tillering (Reuter and Robinson 1997).

**Figure 3.** Relationship between the dry matter response efficiency for liquid fertilisers compared with granular and the P uptake in liquid fertiliser treatments compared with granular.

**Figure 4.** Percentage dry matter response to liquid fertiliser above granular fertiliser response as a function of calcium carbonate content (%) of the soil.

**Figure 5.** Relationships between soil test P (Bray P [a and b], P E-value [c and d], Colwell P [e and f], Resin P [g and h], and P DGT $C_E$ (as measured by DGT) [i and j]) and liquid efficiency over control (a, c, e, g and i) or granular efficiency over control (b, d, f, h and j) fitting the function $y=a + b \times r^x$.

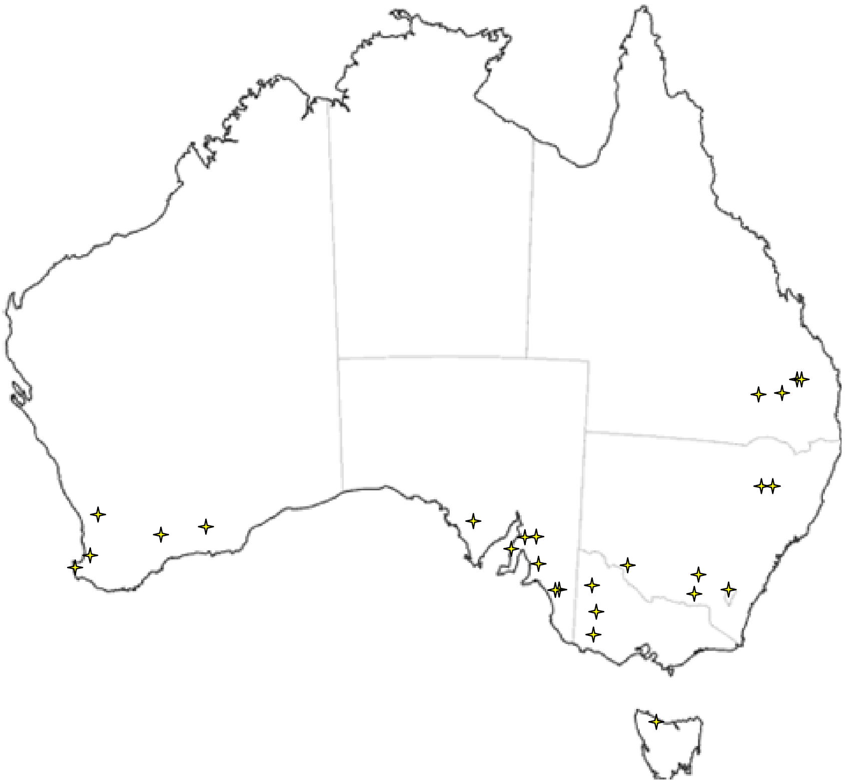

**Figure 1.**

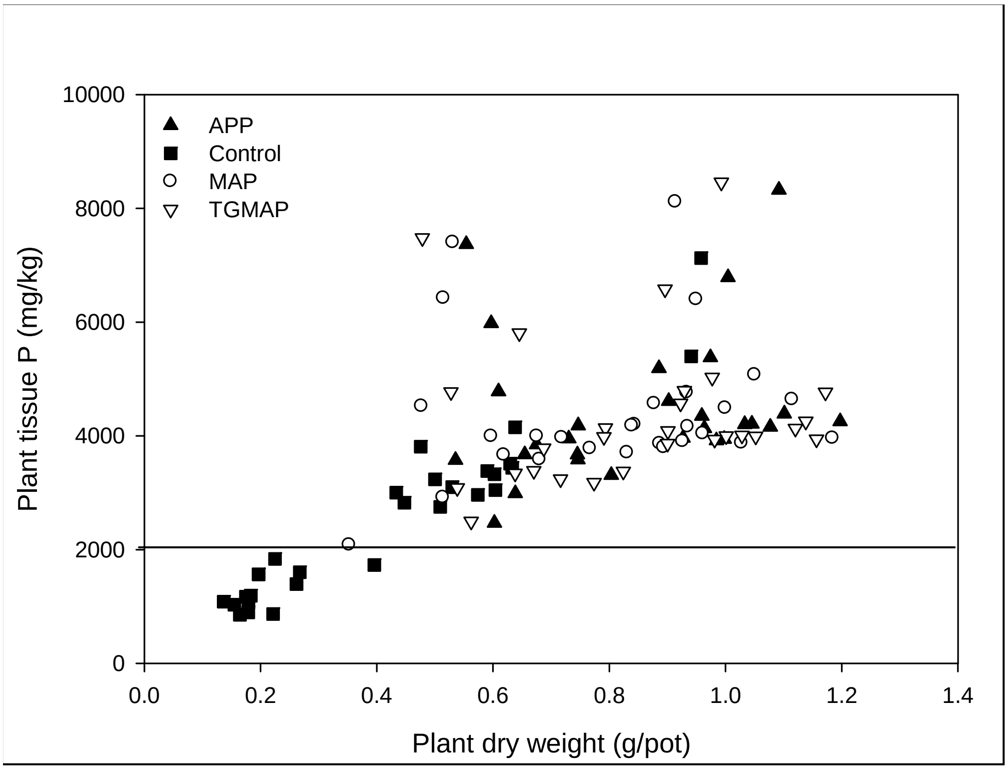
10000
8000
6000
4000
2000
0
Plant tissue P (mg/kg)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Plant dry weight (g/pot)
APP
Control
MAP
TGMAP

**Figure 2.**

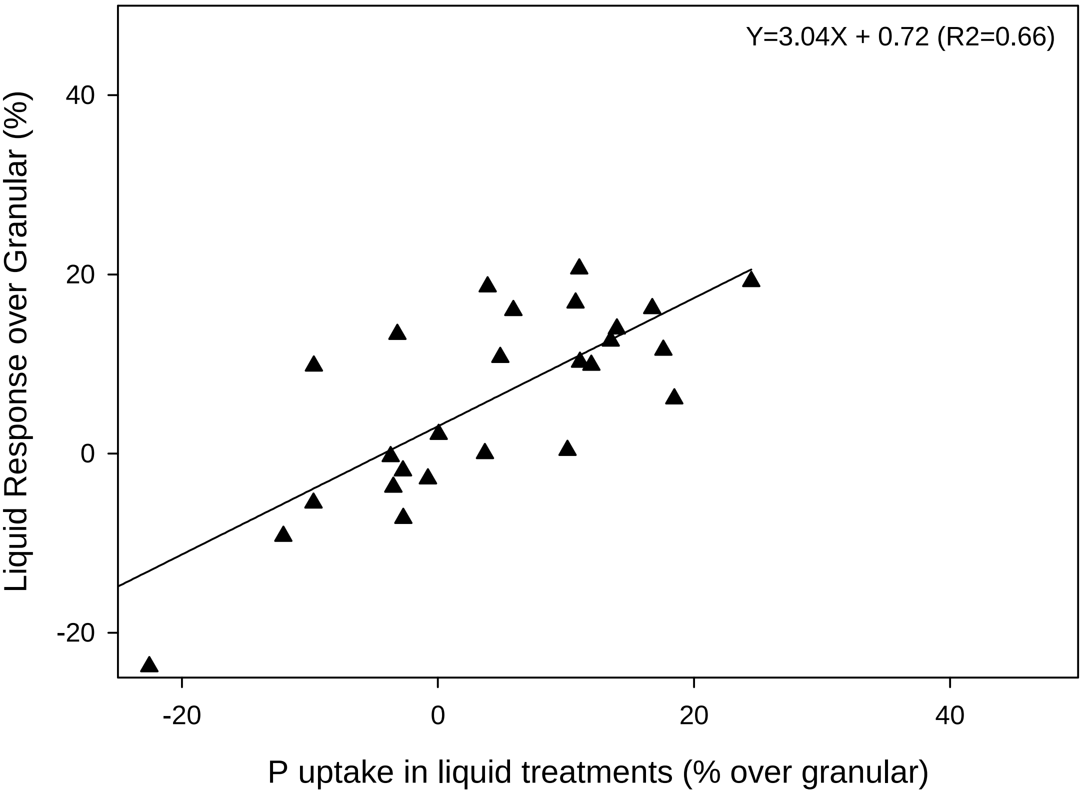
Y=3.04X + 0.72 (R2=0.66)
Liquid Response over Granular (%)
40
20
0
-20
-20
0
20
40
P uptake in liquid treatments (% over granular)

**Figure 3.**

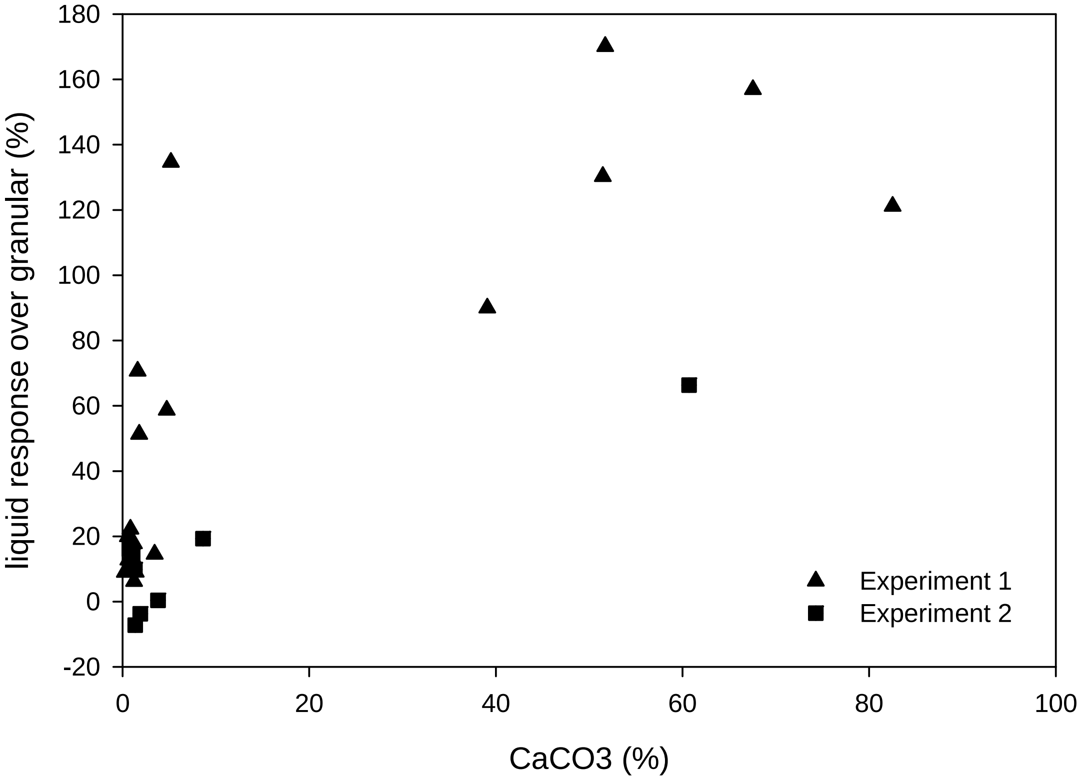
liquid response over granular (%)
180
160
140
120
100
80
60
40
20
0
-20
0
20
40
60
80
100
CaCO3 (%)
Experiment 1
Experiment 2

*Figure 4.*

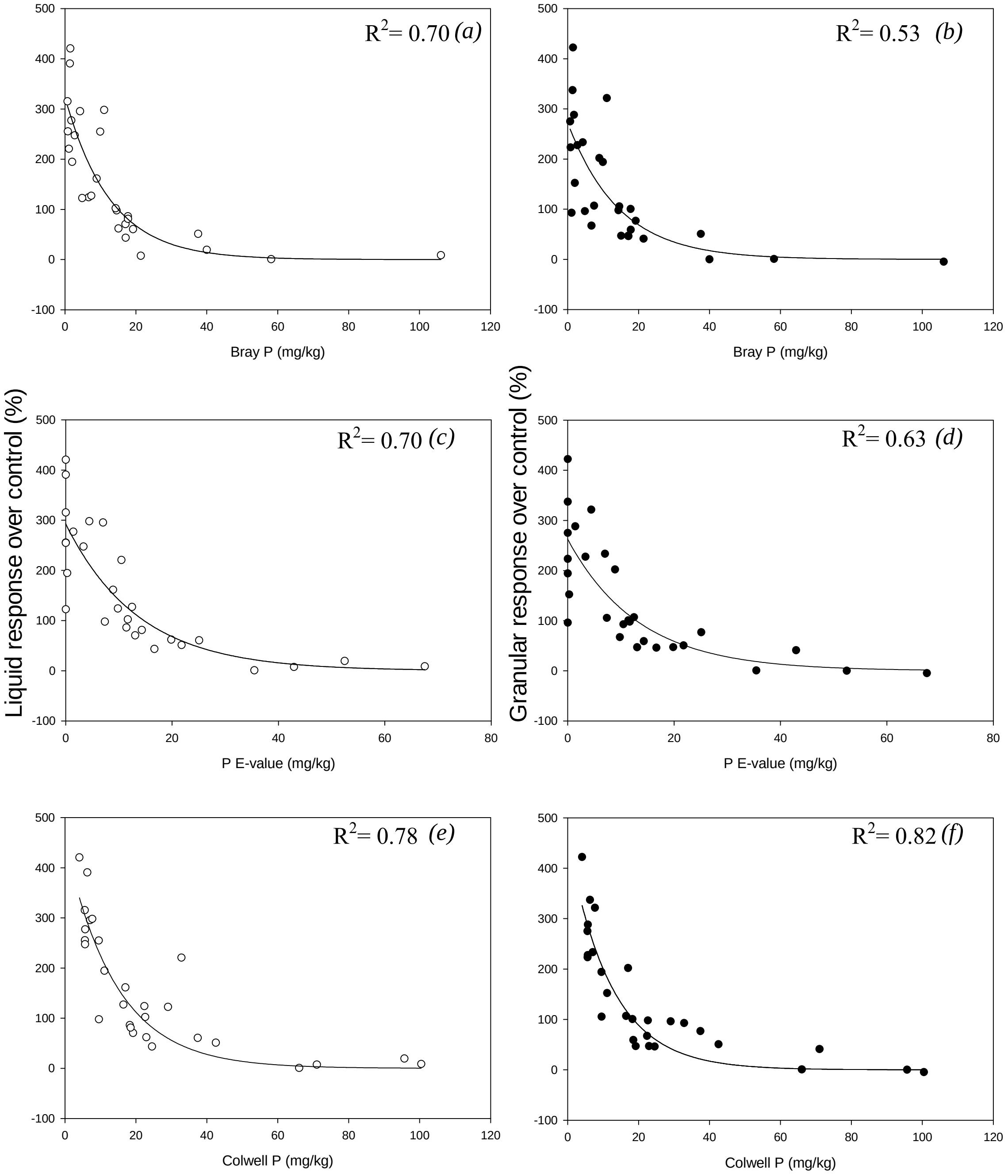
R$^2$= 0.70 (a)
R$^2$= 0.53 (b)
R$^2$= 0.70 (c)
R$^2$= 0.63 (d)
R$^2$= 0.78 (e)
R$^2$= 0.82 (f)
Liquid response over control (%)
Granular response over control (%)
Bray P (mg/kg)
P E-value (mg/kg)
Colwell P (mg/kg)
500
400
300
200
100
0
-100
0
20
40
60
80
100
120

**Figure 5.**

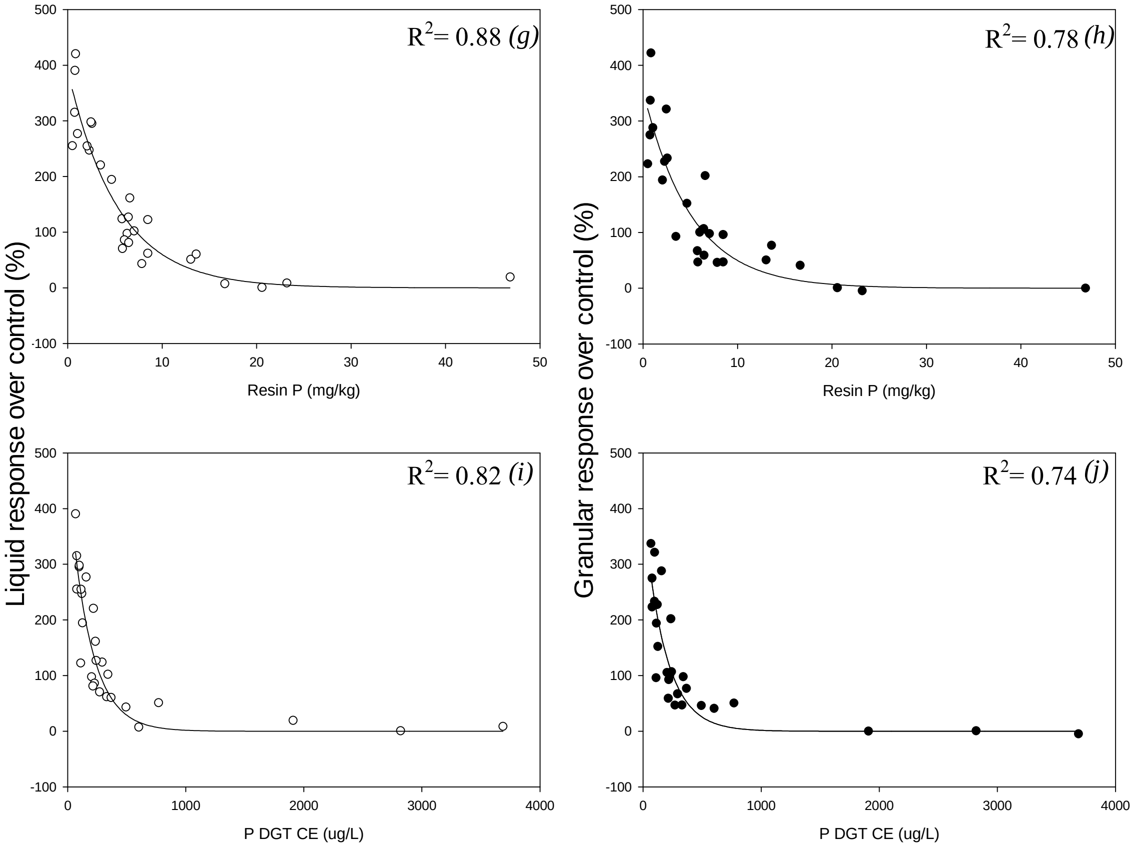
R$^2$= 0.88 (g)
R$^2$= 0.78 (h)
R$^2$= 0.82 (i)
R$^2$= 0.74 (j)
Liquid response over control (%)
Granular response over control (%)
Resin P (mg/kg)
Resin P (mg/kg)
P DGT CE (ug/L)
P DGT CE (ug/L)
500
400
300
200
100
0
-100
0
10
20
30
40
50
1000
2000
3000
4000

**Figure 5.**