Prediction of wheat response to an application of phosphorus under field conditions using diffusive gradients in thin-films (DGT) and extraction methods

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Abstract
The ability of the Diffusive Gradients in Thin Films (DGT) technique and two other established testing methods (Colwell, resin) to predict wheat responsiveness to applied P from 34 field trials across southern Australia was investigated. Regression analysis of relative early dry matter production and grain yield responses demonstrated that the DGT method predicted plant responsiveness to applied P more accurately than Colwell P and resin P at sites where maximum yields were reached with P rates used (20 out of 34). DGT explained 77 % (C_E) or 81 % (C_{DGT}) of the variation in response for early dry matter and 80 % (C_E) or 84 % (C_{DGT}) for grain compared to 14 % for early dry matter and 46 % for grain using the resin P method. No significant relationships could be obtained for Colwell P although modifying the Colwell test data using PBI resulted in a correct response prediction for 11 of the 20 field sites compared to 18 for DGT and 15 for resin P. These observations suggest that the DGT technique can assess available P in soils with significantly greater accuracy than traditional soil P testing methods. The critical P threshold as assessed by DGT was 4021 µg/L C_E, 202 µg/L C_{DGT} for early dry matter and 1299 µg/L C_E, 59 µg/L C_{DGT} for grain. Initial work using the DGT method has also shown potential in establishing critical thresholds for different crop types (barley, peas and canola).

Key Words
Nutrient availability, phosphorus deficiency, soil testing, diffusive gradients in thin-films.

Introduction
Phosphorus is one of the most expensive nutrient inputs used in broadacre cropping, in Australia (McBeath *et al.* 2005) and globally (van Raij *et al.* 2002). Therefore, there is potential major economic benefit in developing a soil test capable of accurately predicting the P status of a soil, which in turn will facilitate efficient fertilisation strategies and reduce the risks of environmental pollution due to over fertilisation. The imperative for optimising fertiliser use has recently been emphasised in grain producing regions of southern Australia where there has been three consecutive seasons of drought coupled with fluctuating fertiliser and grain prices, resulting in small economic returns. Documented failure of established soil testing methods, such as Colwell and Olsen to reliably predict plant P requirements over a range of different soil types (e.g. Holford *et al.* 1985, Reuter *et al.* 1995, Saggar *et al.* 1999, McBeath *et al.* 2005) has generated interest in new test procedures. The proposed correction to the Colwell P method using the phosphorus buffering index (PBI), as suggested by Moody (2007), has not yet been tested as a predictive tool under field conditions. Substantial variations in soil types and soil pH provide challenges for any soil P test. Diffusive Gradients in Thin Films (DGT) is a new technique for measuring P that has recently been used for predicting tomato response to soil applications of P (Menzies *et al.* 2005) and for predicting wheat response to liquid and granular sources of P on acidic to neutral soils (McBeath *et al.* 2007). The resin method is already used widely in Brazil (van Raij *et al.* 1986). As with the resin method, the DGT method attempts to mimic the physico-chemical uptake of solutes by plant roots by providing a sink for the free phosphate ion. Possible advantages the DGT method may have over the resin method are firstly, the ferrihydrite binding layer used in DGT is highly specific for P and may thus be less subject to anionic interferences compared to the resin method (Mason *et al.* 2008). Secondly, the presence of a diffusive layer in DGT limits the maximum flux of P onto the binding layer, facilitating precise flux calculations, and prevents contamination of the binding layer with particulate material. Lastly, the DGT device is placed directly on to the soil and so does not require separation of soil and solution. The amount of P accumulated onto the binding layer depends on the concentration of P in the soil pore water as well as the rate at which P is supplied from the soil solid phase into the pore water, i.e. the rate of re-supply. In contrast, the resin method involves placing a resin strip into a soil solution and, as shown previously (Mason *et al.* 2008), the measurement of P that is obtained is influenced by a complex interaction between soil P buffer capacity and the ratio of soil to water employed.

The aim of this work was to compare the relationships between 'available P' as measured by three soil-testing methods and predicted versus actual dry matter or grain yield response to P fertiliser under field conditions. The three methods used were DGT, resin, and the traditional bicarbonate extraction method of Colwell (Colwell 1963) with and without correction for soil sorption using PBI.

Methods

Soil preparation

Soil samples (0-10 cm) were collected from the control plots (0P) from 34 phosphorus response trials in southern Australia conducted between 2006 and 2008 (Figure 1). Soil sampling was performed at the time of sowing of each trial and, where possible, each control plot was treated as a separate sample, otherwise a bulk sample of the control plots was obtained. Locations were representative of land used for grain production and the distribution of trials was as follows, Western Australia (3), South Australia (8), Victoria (9), New South Wales (12) and Queensland (2). Soils were dried at 40^{o}C for at least 2 days until constant weight was obtained and then sieved (< 2 mm) prior to analysis.

Soil tests with crop response

Three soil P tests (DGT (Mason *et al.* 2008), Colwell (Colwell 1963) and resin (Saggar *et al.* 1999, in Cl form) were evaluated for their ability to predict early dry matter and grain response of wheat to an application of P by assessing the available P pool from the control plots. Crop response was assessed by comparing the yield of the control (0P) with the maximum yield obtained with P application and was expressed as relative yield (%)

Relative yield (%) = Yield (control)/ Yield (Maximum) x 100

Each soil test was related to crop response (relative yield) by using a Mitscherlich equation in the form

$y = y_o + a(1\text{-}e^{-bx})$

where y_o = yield of control (0P) and $y_o + a$ = maximum yield achieved with P application (x).

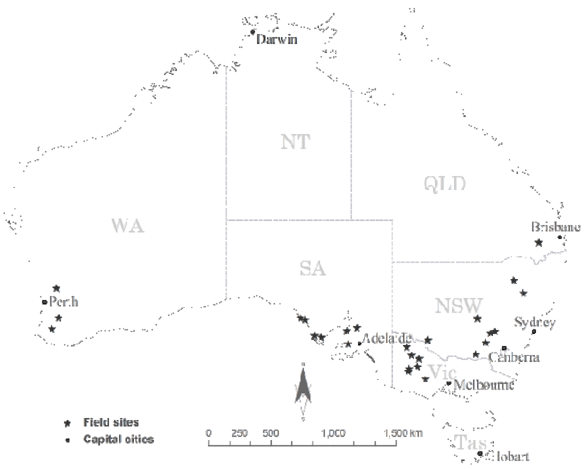

Figure 1. Field site locations across Australia.

Results and discussion

There was no significant relationship ($p \leq 0.05$) obtained for Colwell P values and wheat response to applied P using either early growth or maturity as the endpoints (Figure 2a). These results highlight the ineffectiveness of using the Colwell P method alone to assess plant-available P concentrations in soil across vastly different soil types, or to use this method to predict plant growth responses to additions of P. The inability of the Colwell P method to predict crop response meant that no deficiency thresholds could be obtained and therefore the predictive power of the test was negligible. Using the PBI values at each site meant that the theoretical critical Colwell P value could be determined by using the relationship established by Moody (2007). If the Colwell P value obtained from the control plots was higher than the critical Colwell P predicted using the corresponding PBI, then the site should not have been responsive (relative yield of control plots > 90 %) to P. Conversely if the Colwell P value was lower than the critical Colwell P (from PBI), then the site should have been responsive (relative yield of control plots < 90 %) to P applications. From the 20 field sites where maximum dry matter yields were reached (at GS30), the Colwell + PBI method correctly predicted the response of 11 sites (55 %).

Calculating the correlation of determination for the regression fit using a Mitscherlich curve between resin P measurements and wheat response from the 20 field sites produced a low (non significant) value for early dry matter ($R^2 = 0.14$) and a moderate value for grain endpoints ($R^2 = 0.46$) (Figure 2b). The deficiency threshold of P for grain production in terms of resin P values was ~20 mg/kg obtained by calculating the intercept of the Mitscherlich curve and 90 % relative yield. By using this value we could calculate the overall predictive power of the resin P test as determined for Colwell P. Resin P correctly predicted the response for 15 out of the 20 sites (75 %) an improvement on the Colwell P + PBI method (Table 4). Assessing the performance of DGT with wheat response produced high coefficients of determination for the regression fit for both early dry matter and grain production (Figure 2c). Relationships using C_{DGT} were $R^2 = 0.81$ early DM and $R^2 = 0.84$ grain. Phosphorus deficiency thresholds for early dry matter production obtained using the DGT technique were 202 µg/L (C_{DGT}), compared to thresholds for grain production of 59 µg/L (C_{DGT}). Using these thresholds to determine the predictive power of DGT for grain response to P as performed with the other methods revealed DGT correctly predicted the response for 18 of the 20 field sites (90%).

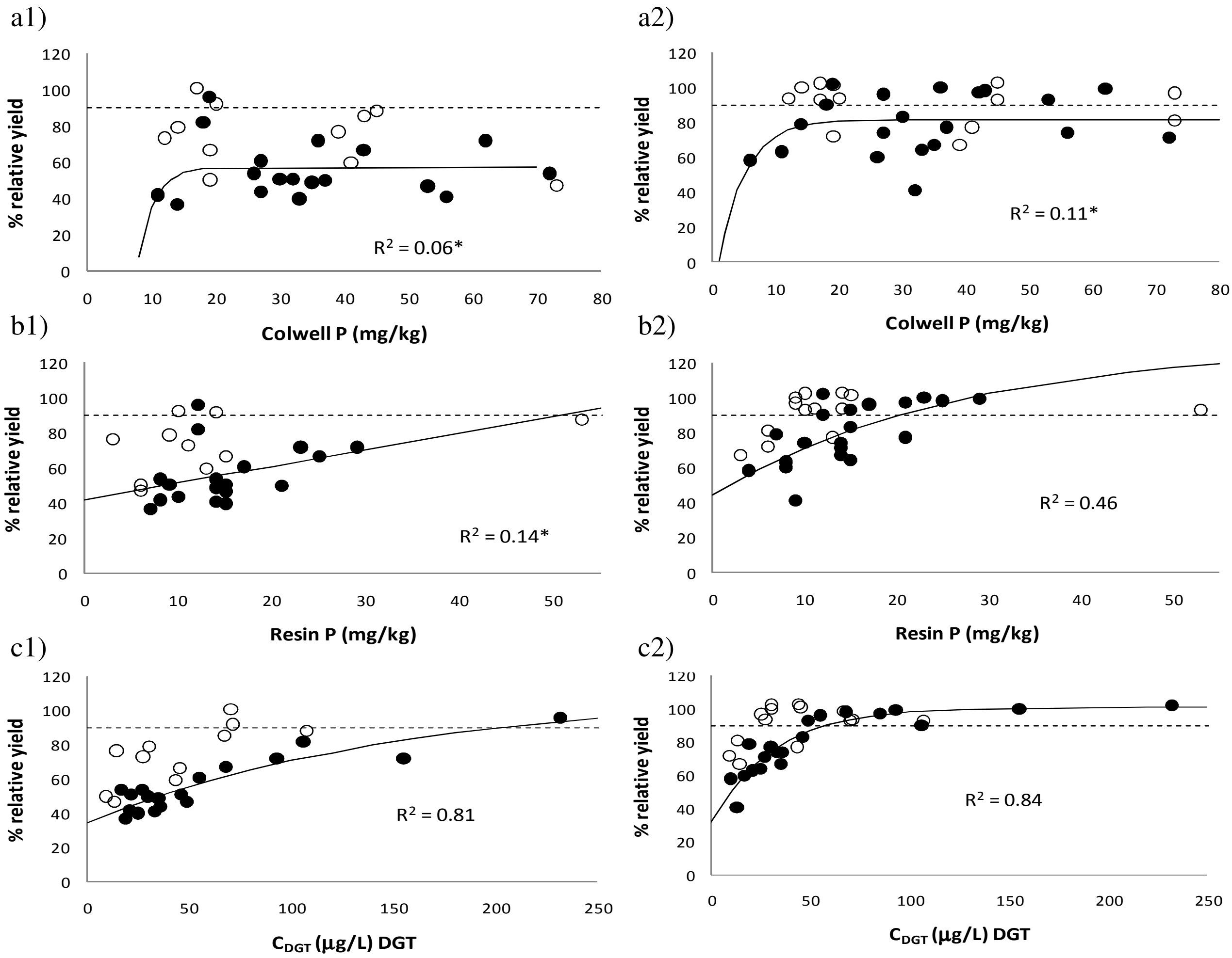

Figure 2. Relationship of soil test measurements using a) Colwell P, b) resin P and c) C_{DGT} (DGT) with wheat response (% relative yield) to P applications at two growth stages: 1) Early dry matter production (GS30); and 2) grain production. ● Field sites where maximum yields were reached with P application, ○ field sites where maximum yields could not be calculated at GS30 or maturity.

Conclusions

It is becoming generally accepted that extraction methods are inaccurate for determining plant available P across a wide range of soils. The extraction methods in some soils appear to extract sources of P that are unavailable to plants. This was notably evident in this study for the Colwell P method, which was unable to predict wheat responses to P at either early growth or maturity. Modifying the measured concentrations of Colwell P using the PBI correction, the method correctly predicted P responses for just over half of the field trials. The resin P method was more effective then the Colwell P (PBI) method in predicting grain responses to applied P. However, the DGT method was effective in predicting both early dry matter production and grain yield response to applied P across these soils over multiple growing seasons and management variables including time of sowing and wheat varieties which appear not to have substantially affected relationships between soil test values and crop response. The use of DGT for soil P testing has the potential to markedly improve identification of P deficient soils and hence improve the efficiency of P fertiliser use in dryland farming systems.

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References

Colwell JD (1963) The estimation of phosphorus fertilizer requirements of wheat in southern New South Wales by soil analysis. *Australian Journal of Experimental Agriculture and Animal Husbandry* **3**, 190-198.

Holford ICR, Morgan JM, Bradley J, Cullis BR (1985) Yield responsiveness and response curvature as essential criteria for the evaluation and calibration of soil phosphate tests for wheat. *Australian Journal of Soil Research* **23**, 167-180.

Mason SD, Hamon RE, Zhang H, Anderson J (2008) Investigating chemical constraints to the measurement of phosphorus in soils using DGT (Diffusive Gradients in Thin-films) and resin methods. *Talanta* **74**, 779-787.

McBeath TM, Armstrong RD, Lombi E, McLaughlin MJ, Holloway RE (2005) Responsiveness of wheat to liquid and granular phosphorus fertilisers in southern Australia. *Australian Journal of Soil Research* **43**, 203-212.

McBeath TM, McLaughlin MJ, Armstrong RD, Bell M, Bolland MDA, Conyers MK, Holloway RE, Mason SD (2007) Predicting the response of wheat (Triticum aestivum L.) to liquid and granular phosphorus fertilisers in Australian soils. *Australian Journal of Soil Research* **45**, 448-458.

Menzies NW, Kusumo B, Moody PW (2005) Assessment of P availability in heavily fertilized soils using the diffusive gradient in thin films (DGT) technique. *Plant and Soil* **269**, 1-9.

Moody PW (2007) Interpretation of a single-point P buffering index for adjusting critical levels of the Colwell soil P test. *Australian Journal of Soil Research* **45,** 55-62.

Raij BV, Cantarella H, Quaggio JA (2002) Rationale of the economy of soil testing. *Communications in Soil Science and Plant Analysis* **33**, 2521-2536.

Raij BV, Quaggio JA, da Silva NM (1986) Extraction of phosphorus, potassium, calcium, and magnesium from soils by an ion-exchange resin procedure. *Communications in Soil Science and Plant Analysis* **17**, 547-566.

Reuter DJ, Dyson CB, Elliott DE, Lewis DC, Rudd CL (1995) An appraisal of soil phosphorus testing data for crops and pastures in South Australia. *Australian Journal of Experimental Agriculture* **35**, 979-995.

Saggar S, Hedley MJ, White RE, Perrot KW, Gregg PEH, Cornforth IS, Sinclair AG (1999) Development and evaluation of an improved soil test for phosphorus, 3: filed comparison of olsen, colwell and resin soil P tests for New Zealand pasture soils. *Nutrient Cycling and Agroecosystems* **55**, 35-50.