Phosphorus as a nutrient for wheat in southern Australia

Introduction

This is a guide to information that enables land managers to make better decisions about P nutrition for wheat grown in south-eastern Australia.

Role of P in agriculture (description / contributing factors)

The basic components of phosphorus nutrition covered in this module are :
how plants access P fertiliser and soil P
the types of P plants absorb
the role of fertiliser P as a source of P nutrition
the role of 'fixed' soil P and residual P in crop nutrition

Phosphorus is an essential nutrient and impacts on root development which in turn effects shoot growth, access to water and other essential nutrients. In south-eastern Australia, many soils are naturally deficient in P. However, many wheat crops are no longer responsive to P fertiliser due to paddocks having a long history of P fertiliser use. It is important to note however that a lack of a response to applied P fertiliser may not mean that the crop is not P deficient. Other factors can limit a crop's response to P even when the crop is experiencing severe deficiencies.

Diagnosing P deficiency (management / how to measure)

Soil testing is the most effective means of detecting a deficiency in P before it impacts on grain yields. Several methods for testing soil P have been developed in Australia and overseas. These are designed to estimate the likelihood that a crop will respond to applied P fertiliser by attempting to estimate the quantity of plant available P in the soil. Soil tests recognised for cropping systems are Colwell P, PBI and DGT. Other soil tests including Olsen and Bray are more commonly associated with pasture-based systems. Good soil sampling technique is vital for ensuring accurate soil P values.

Phosphorus deficiency in a wheat crop can be detected by watching for foliar symptoms or through tissue testing.

Historical records of P applications, soil tests, and the grain yields and conditions in prior seasons can assist to estimate a paddock's P balance and indicate if P needs to be applied to the next wheat crop.

Correcting P deficiency (recommendations)

Applying the principles of good nutrition will ensure adequate P supply to wheat crops. The principles are right place, right time, right type and right amount. Special consideration needs to be given in the types of P fertiliser: granular or liquid are more effective on some soil types. Arbuscular mycorrhiza has an important role in P nutrition for many crops including sorghum but is not thought to be important in P nutrition of wheat in se Australia.

Wheat varieties vary widely in their P use efficiency and many widely used high yielding cultivars are also highly efficient at using P. However, correcting P deficiency will not necessarily lead to better growth of the current crop. The immediate benefit of P fertiliser is limited if other nutrients or other factors constrain plant growth. A proportion of the P in fertiliser remaining from previous applications has a residual effect on the next crop depending on several factors including soil type (especially P buffering capacity) and seasonal conditions in prior and current seasons.

Phosphorus as a nutrient for wheat in southern Australia

Scope

This review of the literature focuses on the function, importance and management of phosphorus (P) for wheat production in dryland cropping systems of south-eastern Australia. The review draws on a selection of cornerstone journal articles that provide foundation information about the role of and importance of P for wheat production. Information is sourced from the international literature and, where available, literature that provides specific Southern Regional content. The selected research and extension literature focuses at the regional level but is underpinned by the basic universal principles of P nutrition provided by cornerstone journal articles and texts. Region-specific literature may be in the form of conference papers, fact sheets, technical reports or decision support systems (DSS).

These information sources are selected to assist advisers and growers to improve their understanding of P and to provide the basis for improved decision making for managing P nutrition.

Outcome

This literature review is a guide that aims to enable advisers and growers to make better decisions about P management including whether P supply will be adequate or additional quantities of P need to be applied and if so, where, when, in what form and at what rate. The review summaries the function, importance and use of P by wheat plants in dryland cropping systems and provides a bibliography of reliable information sources. This literature review will be combined with reviews of other agronomic topics to provide growers and advisers with a carefully targeted source of information that will assist them to make more informed decisions about agronomic management.

Function of P in broad-acre grain crops

Nature of P in plants

Phosphorus is an essential nutrient required for the growth of wheat (Grundon 1987) with a key role in the structure of cell membranes, DNA and RNA, photosynthesis and respiration (Grant *et al.* 2001). Early plant growth is particularly dependent on adequate P due to its role in cell division. Subsequently, the symptoms of P deficiency are particularly evident during early growth stages (Grundon 1987). Mild P deficiency causes stunting while severe deficiency darkens leaves, causes older leaves to brown and die off and reduces tillering, head and grain numbers (Grundon 1987, Wurst *et al.* 2010).

Nature of P in soil

Soil P is in several forms which are not all equality available to wheat. Most P (70-90%) is fixed in soil, immobile and not readily available to plants (Hemwall 1957). However, as P is taken up by plants, P becomes available from less labile forms (Figure 1). The relationships between the various forms of P and how their interaction is related to other chemical factors is summarily described by Holford (1997) and detailed by Larsen (1967).

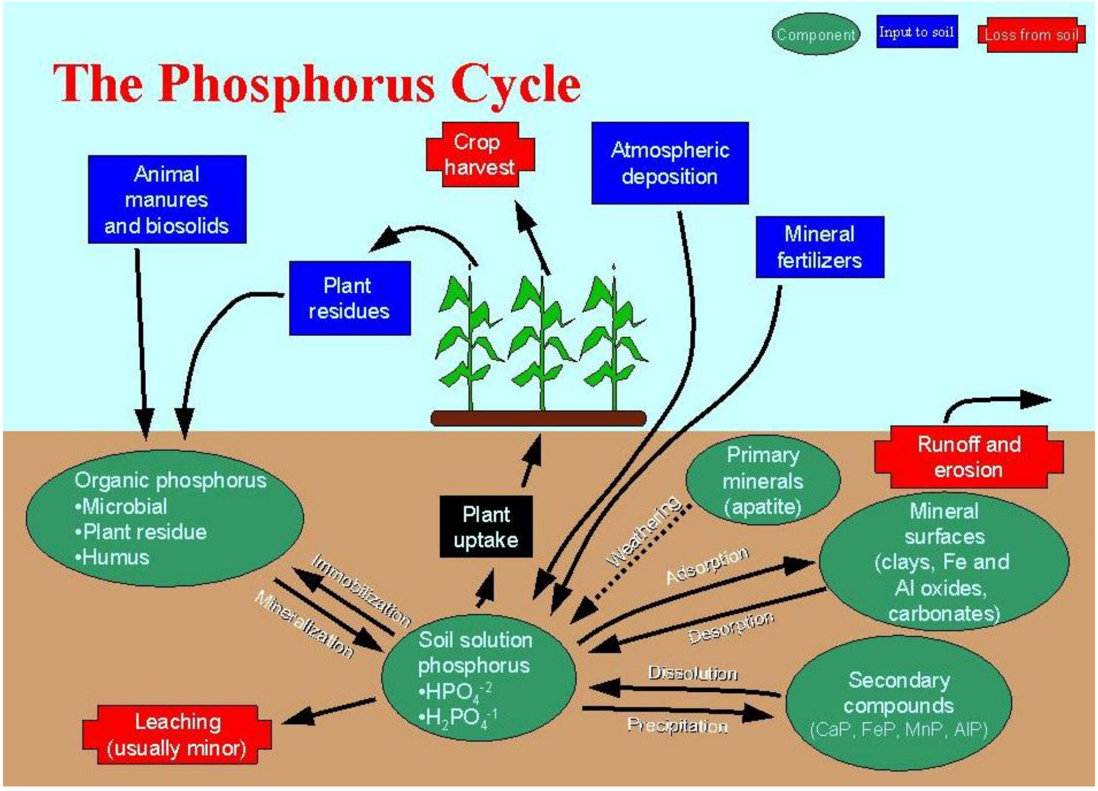


Figure 1. Phosphorus cycle in soil and plants. Sourced from Department of Geology, University of Illinois at Urbana-Champaign accessed in March 2014.

Access to P by plants

Wheat roots take up P from soil solution as water soluble orthophosphate ($H_2PO_4^-$ and HPO_4^{2-}) sourced from soil or fertiliser. The uptake of P from the soil and into the plant (Bolland *et al.* 2006) depends on:

- the chemical availability of the nutrient
- movement of the nutrient – mainly via diffusion from the soil to the root
- growth of roots through the soil (root interception)
- uptake of the nutrient at the root surface itself
- translocation of the nutrient from the root to other parts of the plant.

P in south-eastern Australian wheat cropping systems

Australian soils under wheat production tend to be inherently low in P (Wild 1958) and low compared to other countries (Moody and Bolland 1999). This is attributed to Australian soils arising from highly weathered parent material that has inherently

low phosphate content by international standards (Beadle 1962). The impact of P deficiency in both pastures and crops in southern Australia is long recognised and most agriculture soils have now had a long history of P application (McLaughlin *et al.* 2011). Adequate P in soil for wheat grain production is demonstrated by a nutrient analysis of grain harvested from the GRDC National Variety Trials program in 2008 and 2009 (Norton 2012). The regional analysis showed that grain P concentrations averaged 3329 mg P/kg which is higher than the critical value for P concentration (2700 mg/kg) given by Reuter *et al.* (1997) for Australian wheat grown in the field.

Local tools to help P fertiliser decision making

Research about P nutrition in wheat under south-eastern Australian conditions is summarised for local application in publications targeting growers and agronomists. The information acknowledges that there has been a long-term accumulation of P in many soils of south-eastern Australia due to extensive and consistent P applications over several decades (GRDC 2012). Subsequently, the rule of thumb is to apply enough P to replace P removed in the grain plus addition P to help counteract P fixation (BCG 2009, GRDC 2009). GRDC (2008) has a planning guide for the low rainfall environments after drought that is applied to cereal and canola crops. The key messages about P nutrition are:

- Apply P with or near seed at sowing for maximum efficiency
- Applying excess P can be detrimental to grain nutritive value and wastes money
- Use soil testing to guide decisions on P fertiliser application rates
- Soil testing is not required every year; good paddock records are an adequate substitute
- Farmers should expect some P applied in a dry year to be available the following year (Holloway 2007)?????
- An early break increases P mineralisation and therefore reduces the requirement for P fertiliser (Batten *et al.* 1999).

Specific advice for the year following the drought year of 2007 was:

- Apply half the normal rate of P if the crop yielded less than 0.5 t/ha
- For crops over 0.5 t/ha, use normal rates on calcareous soils and 66% on non-calcareous soils
- Use normal P rates on fallowed paddocks
- Fertiliser only for the immediate crop (this advice seemed to be based on financial risk rather than agronomy)
- Mining the soil for one year will not appreciably reduce wheat yields unless soil P is very low.

Wheat yields in south-eastern Australia in 2010 were considered by the industry to be good and there was unusually high rainfall in the summer of 2010/2011. These conditions contrast with the 2007 season and in response GRDC has a second guide that included P nutrition (GRDC 2011). The key messages apply to the whole region, not just the low rainfall environments. They messages are:

- Base P fertiliser rates on tests of the topsoil and potential yields (P removal from the paddock is estimated at 3 kg P per tonne wheat grain/ha at 12% protein (GRDC 2009)
- Large stubble loads may have immobilised more P than normally experienced.

Principals of better crop nutrition

The principles for effective fertiliser use are to select the right source of nutrients, applied as the right rate and in the right place and at the right time. These 4 rights (4Rs) of nutrient stewardship are all interlocking and if one is altered, the whole approach should be reconsidered (Bruulsema *et al.* 2012, Norton and Roberts 2012).

Right place

The definition of 'deep placement' varies between studies in Australia. Deep placement is defined as 8 mm by Officer *et al.* (2009a), 10 mm by Dunbabin *et al.* (2009), 12-15 mm by Alston (1980) and >30 mm by Ma *et al.* (2009). Logistically, placement can be shallow or at depth. However, unlike other nutrients such as nitrogen (N), P has low mobility (Dunbabin *et al.* 2009) as it mainly moves through the soil via diffusion rather than mass flow and the maximum length of the diffusion path is measured in millimetres rather than centimetres. As such, it is critical that P is placed to minimise the distance between the P source (from fertiliser or soil) and the root.

In Victorian soils, (Sodosol, Vertosol, Chromosol) banding mono-ammonium phosphate (MAP) fertiliser close to the seed (<40 mm) increases P uptake in the early vegetative stages of wheat growth (Officer *et al.* 2009a). This specific finding under glasshouse conditions agrees with overall findings that banding P near wheat seed is the best placement position (McLaughlin *et al.* 2011). The finding of Officer *et al.* (2009a) are supported by field studies that show no advantage of deep placement in soils that stay wet through the growing season (Alston 1980). These findings are applied by Seednet (2011) in their fact sheet for the winter-wheat cultivar Wedgetail which states that P fertiliser should be applied at sowing and banded with the seed.

A review of the low rainfall environments of South Australia focusing on deep placement of P fertiliser concludes that there are wheat yield benefits when this practice is applied to sandy soils. The benefit is attributed to P still being available at depth when the top soil is dry (Ma *et al.* 2009). Therefore optimal placement of P fertiliser depends on the soil type and whether the topsoil is likely to be wet or dry, especially in the early stages of crop growth.

Right time

Extension literature espouses applying granular or liquid P at the time of sowing (GRDC 2008, GRDC 2009, GRDC 2011). This advice is based on the principles of P nutrition for all annual crops and practical considerations. Firstly, P needs to be available to the crop early in their growth (i.e. first six weeks) since P is an essential nutrient for cell formation and deficiencies at this stage tends to adversely impact on plant growth of the rest of the season (Grant *et al.* 2001). Secondly, P has a limited

rate of movement through the soil and therefore needs to be close to the young plant's roots. In practical terms, this means fertiliser P in a granular or liquid form needs to be applied with the seed at sowing. In future, there may be scope to apply P in a foliar form as the crop demands, however the physiological and technical constraints are yet to be fully understood (Noack *et al.* 2010).

Right type

Granular

The main types of P fertiliser used for wheat production in south-eastern Australia are granular and liquid. Granulated types of P fertiliser easily dominate over liquid types due to the ease of manufacture, transport, application and cost per unit. Field-based evidence from NSW and Victoria shows that the type of granular P [single superphosphate (SS), triple superphosphate (TSP), mono-ammonium (MAP) or di-ammonium phosphate (DAP)] does not affect P response of wheat or canola (Harbison *et al.* 2003). However, it is worth noting that DAPP becomes available as water extractable P more rapidly than P in superphosphate when granules are shaken in water. Granular P fertilisers should not be broadcast or top-dressed as this greatly increases the risk of nutrient run-off (Nash *et al.* 2003).

Liquid type

There is some interest in using liquid P forms (Armstrong *et al.* 2006) due to the ability to make mixtures with other chemicals (nutrients and fungicides) and reduced susceptibility to fixation on some soils. Granular and liquid forms have been compared in south-eastern Australia with the conclusion that granular is sufficient in many soils but liquid fertiliser is better at providing P to plants on highly calcareous soils (> 10% $CaCo_3$) such as those that dominate part of the Eyre Peninsula due to less P fertiliser becoming fixed. Less fixation subsequently leads to higher P uptake and higher wheat grain yields (Bertrand *et al.* 2006, Holloway *et al.* 2001, McBeath *et al.* 2007). These conclusions are promoted to growers and agronomist by GRDC (GRDC 2009) with particular reference to the alkaline and calcareous soils on Eyre Peninsula, South Australia.

Rock phosphate and manures

Rock phosphates and organic manures do not contain phosphates that are readily available to plants and are unsuitable for wheat cropping systems. The use and effectiveness of rock phosphate in Australia is far less effective than other forms of P fertiliser (Bolland *et al.* 1997). This is principally due to Australian soils tending to have pH(H_2O) >5.5 and therefore not being acidic enough to effect rapid dissolution of P into the soil. An exception suggested by Bolland *et al.* (1997) is the higher rainfall regions of southern Australia with sandy acidic Podzols in permanent pasture systems where partially acidulated rock phosphates may have application. Manures are also unsuitable for P nutrition in no-tillage systems because they require incorporation (GRDC 2009).

Foliar P fertiliser

The potential for foliar fertilisation with P in Australia has been reviewed (Noack *et al.* 2010). Foliar application would have the advantage of allowing timing of P application to be strategic based on seasonal progress the same as practised for N application. The review shows that at this stage, foliar P has limited applicability for wheat crops. Firstly, there are physiological impediments to P uptake through the leaf. Secondly, a large leaf area is required which is contrary to any requirements for P to be applied early in the season. Foliar P fertilisation as a supplement to granular or liquid P later in the season is a form that may have use with further research and development.

Right amount

There are three general approaches to determining the right amount of nutrient to apply to a wheat crop: soil testing, historical records and plant testing.

Soil testing

Soil testing is commonly used in Australia as a pre-emptive indicator of the P fertiliser requirements of a planned crop. Soil testing allows changes in soil P to be monitored over time and provides information to prevent P deficiency in the upcoming crop. Numerous soil tests are available to measure soil P however few soil test results can be converted to another (e.g. Olsen to Colwell P) (Moody and Bolland 1999).

Soil sampling technique

Soil testing of the top 10 cm layer is promoted as being relevant for making decisions about P fertiliser rates and the potential for soils to be mined of P by wheat crops (GRDC 2009). Testing only in the 0-10 cm soil layer is appropriate for the major cropping soils in the south-east of Australia as that is where most soil P resides (Vu *et al.* 2009). However, recent research on Vertosols in Queensland highlights that P deeper in the soil layer (10 to 30 cm) has a role in crop nutrition when there is little water in the top 10 cm soil layer (Moody *et al.* 2010).

Soil samples for nutrient analysis must be taken at the same time each year to be comparable. This is due to the effects of soil moisture on nutrient form and roots as a potential source of soil elements. Placement of soil sampling points influences soil test results with higher P values occurring if all samples are taken on existing rows rather than between rows (Bolland and Brennan 2006). Brown 1999 discusses the issues of within paddock variability and the need for sampling to be conducted to capture this variability. In particular, no-till systems promote the accumulation of P in the surface soil above the roots of wheat plants. The degree to which this occurs will, in part, relate to variation in soil texture, waterlogging etc. and this is best sampled using a stratification technique (e.g. Figure 3.4 in Brown 1999).

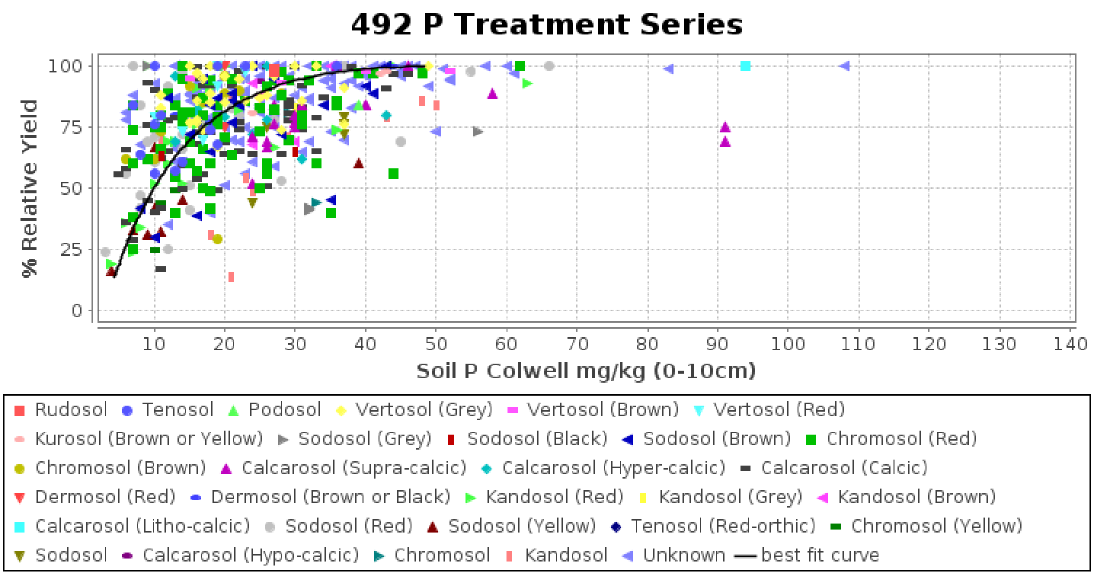
Colwell P

Available P is commonly measured in cropped soils (0-10cm layer) by extraction in 0.5M $NaHCO_3$ (Colwell 1963). This soil analysis technique is based on an empirical relationship between the values determined for 27 soils in New South Wales and the grain yield responses obtain from wheat by P experiments conducted from 1958 to 1960.

Critical values for Colwell P have been developed for Australian soils based on soil P status and P sorption for wheat with critical values ranging from <15 mg P/kg for low P soils with low P sorption to >90 mg P/kg for soils with high P status and moderate to high P sorption (Moody and Bolland 1999). These critical Colwell P values are not crop specific.

The critical range of P values (27 – 33 mg P/kg) as determined by multi-site analysis of wheat experiments in NSW and Victoria is within the broad range developed by Moody and Bolland (1999) for the whole of Australia (Harbison *et al.* 2003). A key part of the multi-site analysis in south-eastern Australia is that all experiments had additional N applied to adjust for different N quantities supplied through differing rates of TSP, MAP and DAP and N is considered to be unrestrictive at all sites. Unfortunately some region-specific experiments cannot be used to assess the response of a crop to a single element such as P as they are designed to assess differing rates of fertiliser products rather than nutritional elements. In additional, basal N appears to be inadequate in some experiments to ensure that this element is not deficient and restricting plant growth.

Phosphorus response experiments conducted in south-eastern Australia show that Colwell P has limited application as a stand-alone test on alkaline soils that and calibrations for one soil type cannot be extrapolated to other soil types. An analysis of wheat data in the Better Fertiliser Decisions for Crops database (BFDC) for all of Australia (which included many Northern Region sites) shows that Colwell P is well correlated to wheat yield for some soil types (all Chromosols except red, red Sodosols and all Vertosols except grey) but not for others (most Calcarosols and grey Vertosols) (Bell *et al.* 2013). A similar data analysis restricted to south-eastern Australia shows poor correlation between Colwell P and wheat yield when applied to all soil types in the region (Figure 2) and there is no improvement when analysis is separated for soil orders common in the region (Table 1). Further restrictions of data in south-eastern Australia to sub-orders (e.g. grey Vertosols) creates datasets that are too small to analyse.



Soil test calibration:

80% Relative Yield: 19.0 (17.0 - 21.0)
90% Relative Yield: 26.0 (23.0 - 28.0)
95% Relative Yield: 31.0 (28.0 - 35.0)

Correlation R: 0.45
Slope RY(50-80): 3.3 (2.7 - 3.9)
Regression equation: $x = e^{(2.0482(\arcsin(\mathrm{sqrt}(y/100))) + 0.68629)}$
70% confidence limit at 90% Relative Yield: 26.0 (24.0 - 27.0)

Figure 2: Phosphorus response curve for wheat using data extracted from the Better Fertiliser Decisions for Crops database (BFDC) for all of south-eastern Australia under rainfed crop production (data with severe crop stress rating excluded). Data is P as measured by Colwell P in 0-10 cm layer. (http://www.bfdc.com.au/interrogator/frontpage.vm)

Table 1: Data for Colwell P (0-10 cm layer) with wheat from the Better Fertiliser Decisions for Crops database (BFDC) for all of south-eastern Australia under rainfed, winter wheat production (data with severe crop stress rating excluded). Critical concentrations and confidence intervals apply to 90% relative grain yield (GY). Data sourced from http://www.bfdc.com.au/interrogator/frontpage.vm in March 2014.

Soil order	Treatment series	Critical concentration (mg P/kg)	Confidence interval (mg P/kg)	R value
Calcarosol	102	30	26-35	0.41
Chromosol	80	27	23-32	0.39
Sodosol	78	30	25-37	0.44
Vertosol	41	20	17-23	0.35

P buffering capacity

P buffering is the ability of a soil to ‘moderate changes in P solution concentration when P is added to or removed from the soil’ (Ozanne 1980). Soils vary in their P buffering capacity (PBC) and an estimate of PBC is needed to better interpret test results from some soils (Moody and Bolland 1999).

The collation by Harbison *et al.* (2003) was completed before P buffering capacity (Burkitt *et al.* 2002), was commonly measured and is not adjusted using single-point P buffering index (PBI). P buffering capacity is a measure of a soil’s ability to fix P and is the amount of P in solution after shaking soil for several hours with a solution of added P (1000 mg P/kg soil as KH_2PO_4 in 0.01M $CaCl_2$). The recent addition of testing

soil for P buffering capacity (Burkitt *et al.* 2002) is enabling critical soil P values determined by the Colwell method to be adjusted for the soil's ability to fix P and thus improve the accuracy of critical P values required for crop nutrition. As P buffering capacity increases, the critical value for Colwell P increases (Moody 2007).

Colwell P adjusted for P buffering capacity is recognised as a more accurate means of measuring plant available P than using Colwell P alone (BCG 2009, Mason *et al.* 2011). Colwell P with PBI have been locally applied by BCG (2009) to develop a 'rule of thumb' for soils in the Wimmera and Mallee without reference to any particular crop type. The 'rule of thumb' is that crop response to P fertiliser is unlikely when: Colwell P >15mg/kg and PBI < 100 and there has been a history of applying P fertiliser and the soil type is heavy and alkaline. Under these conditions BCG (2009) recommends only applying enough P fertiliser required to replace the P removed through crop production.

Diffusive gradient thin-films (DGT)

An alternative method for measuring plant-available P using diffusive gradient thin-films (DGT), has been trialled in Australia's major cropping regions and is gaining acceptance (Mason *et al.* 2010). Unlike the other methods mentioned earlier, the DGT method relates available P directly to grain yield. The DGT method accounts for 75% of the variation in early above ground biomass and grain yield at the chosen sites and appears to be a much more reliable measure of plant available P for grain production than the Colwell method (Figure 3). The DGT method is currently undergoing commercialisation (Mason et al. 2011).

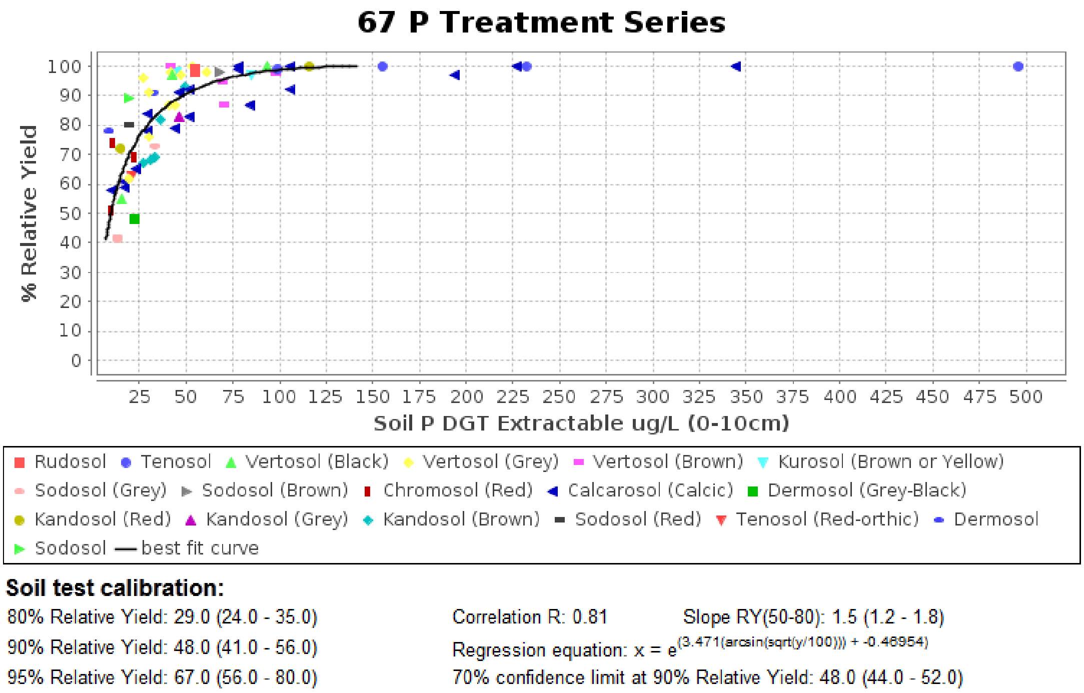


Figure 3: Phosphorus response curve for wheat using data extracted from the Better Fertiliser Decisions for Crops database (BFDC) for all of south-eastern Australia under rainfed, winter crop production. Data is P as measured by DGT in 0-10 cm layer. (http://www.bfdc.com.au/interrogator/frontpage.vm)

Historic records

Historical grain yield and fertiliser records are used to estimate the P balance in the paddock, that is how much P was removed by prior crops relative to the amount of P applied. A history of P deficiency in a crop indicates a need to apply P fertiliser but some loss to production has already occurred in these circumstances. Prior crop growth and seasonal conditions also effect residual P fertiliser as highlighted in decision support material (GRDC 2008, GRDC 2011).

Crop testing

Plant testing has little application for P nutrition in wheat as the element needs to be applied at sowing. Testing of the youngest emerged blade for P when plants are tested for other nutrients may show that P concentration is outside the range deemed adequate (0.22 to 0.47%) by Reuter *et al.* (1997).

Other factors affecting availability of P to crops

Residual value

P use efficiency is known to be low (<30%) in the year of application (Hemwall 1957, Bolland *et al.* 2006, McLaughlin *et al.* 2011, Officer *et al.* 2009a, McBeath *et al.* 2012). This does not mean P fertiliser is lost from the soil as P is relatively immobile compared to N, which is readily subject to leaching. A review of P management in Australian agricultural systems concludes that there has been an increase in soil P in systems with more P added than removed (McLaughlin *et al.* 2011). This includes cropped soils. Long-term application of P fertiliser is shown to increase available P and decrease P sorption in Victorian Calcarosols, Vertosols and Chromosols. Over an extended period of time, applied P fertiliser is found to be distributed in all P fractions (Vu *et al.* 2009) but predominantly in inorganic forms (McLaughlin *et al.* 2011).

A small amount of P can also be sourced by wheat from medic residues (McLaughlin *et al.* 1988a). However, the amount of P in wheat from this source is only about one quarter of the P sourced from fertiliser and comprises less than 15% of P in a wheat plant even when residues are added to soil as ground plant material (Figure 4) (McLaughlin and Alston 1986, Noack *et al.* 2013).

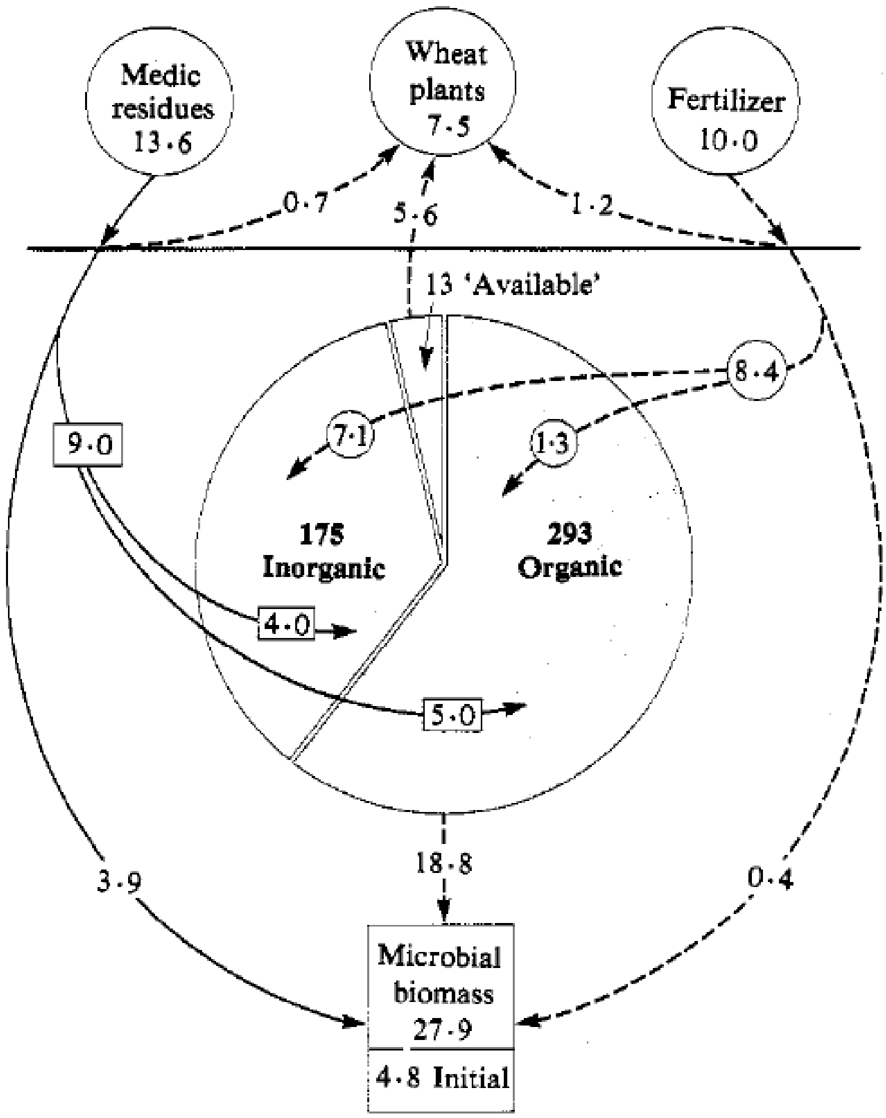


Figure 4. Amount of P (kg/ha) in medic residues, wheat plants, fertiliser and microbes, and the amount of P (kg/ha) transferred between those four items either directly or through the pools of inorganic P. organic P and available P in the soil at 95 days after sowing. Sourced from McLaughlin *et al.* 1988b.

The practical implications of an accumulation of fertiliser P in soil and P in plant residue is that only a small proportion of P derived from previous fertiliser applications will be available to a wheat crop in the short to medium term (1 to 5 years) (McLaughlin *et al.* 2011). This is particularly relevant for soils with moderate or high sorption capacity (Moody and Bolland 1999). In the Wimmera, an experiment over 13 years of predominantly dry conditions concluded that applying 9 kg P/ha is sufficient to maintain soil P under wheat crops (Christie 2008).

Soil water

Soil water affects the availability of P to wheat plants because most movement of P in the soil is by diffusion (Larsen *et al.* 1967). Thus uptake of P by wheat plants is

reduced under drier conditions as the diffusion rate is decreased. Soil water also affects the availability of P to plants via its role in the dissolution of fertiliser granules (Nash *et al.* 2003). However, the presence of more soil water does not necessarily cause more P fertiliser to be available to the plants since P is fixed in soil with high P sorption capacity. This is the case on clay soils in Gippsland where less fertiliser P is available in a soil with high soil water (25%) and high P absorption capacity (78 kg P.kg) than a soil with low soil water (6%) and low P adsorption capacity (7 mg P/kg) (Nash *et al.* 2003).

Dry soil also restricts root growth and thus the ability of a wheat plant to seek out both soil and fertiliser P. Officer *et al.* (2009a) conclude from experiments on non-calcareous soils from the main cropping regions of Victoria that uptake of P from fertiliser is more efficient under wetter conditions and plants respond to P fertiliser on responsive soils provided plants are not water-stressed. This agrees with earlier studies in other environments as summarised by McLaughlin *et al.* (2011).

Under drier conditions roots cannot intercept or absorb P. This may be particularly detrimental in no-tillage systems where soil P is concentrated in the topsoil which is vulnerable to drying during the season (Vu *et al.* 2009).

Soil physicochemical constraints

Physiochemical constraints to crop growth are identified in several studies in south-eastern Australia and are found to differ between the major cropping soils (Dunbabin *et al.* 2009). In acid soils in higher rainfall environments, the principal physiochemical constraints are deemed to be high clay content and high soil density (MacEwan *et al.* 2010). In neutral to alkaline soils, physiochemical constraints are summarised as boron toxicity, carbonate, aluminate, salinity, sodicity and alkalinity (Adcock *et al.* 2007). In the neutral to alkaline soils of the Mallee, root growth of wheat is restricted in Calcarosol and Sodosol subsoils (Nuttall *et al.* 2003). Conversely, physiochemical constraints are rarely found in Vertosols in the Wimmera (Dunbabin *et al.* 2009, Dunsford *et al.* 2012).

The difference in root growth between Vertosols and the soils of the Mallee (Calcarosols and Sodosols) led to the recommendation that P fertiliser management should be region and soil-type specific (Dunbabin *et al.* 2009). In a limited way, this recommendation is transferred to publications aimed at growers and agronomists (BCG 2009, GRDC 2009) with reference to low P response on alkaline soils of the Wimmera and Mallee.

Effect of other nutrients on response to P

Wheat roots must actively grow into soil that contains P fertiliser to enable P uptake. This requirement means that the availability of more mobile nutrients like N affects P uptake as is demonstrated for wheat in the sandy soil of Western Australia with low P concentrations (< 10 mg P kg in the 0-10 cm layer) (Brennan and Bolland 2009). This interaction and the difference between P and N availability is summarised by Officer *et al.* (2009b) who show that N and P applied to wheat grown

in intact cores interact with the result that the concentration of P in the shoot is deficient when only N was applied.

The supply of sulphur (S) also effects the uptake of P and the redistribution of P from leaves to grain, with S deficiency causing P movement to be limited. This interaction extends into the grain with the highest concentration of P in grain occurring when there is adequate supply of S (Archer 1974).

Genetics for P efficiency

Wheat cultivars grown in southern Australia have been evaluated for their internal efficiency of using P sourced from fertiliser and soil (PE); that is the amount of grain produced for every kilogram of P in plant shoots. A review by Batten (1992) states that wheat breeders have inadvertently and broadly been selecting for higher PE. The unintended selection is due to breeders applying inadequate P fertiliser to field evaluation experiments. Jones *et al.* (1989) has the same conclusion when assessing differences in PE of 23 standard and semi-dwarf cultivars released in Australia between 1840 and 1983. However, Jones *et al.* (1989) and McDonald *et al.* (2010) both demonstrate a difference in the responsiveness of cultivars to low P fertiliser rates (0 and 2 kg P/ha) and high P fertiliser rates (30 and 40 kg P/ha). At low P fertiliser rates, there is no difference in grain yield between cultivars in either study. In summary, these studies indicate that there is no genetic variation for PE that could be selected for and would be more useful than selecting for high grain yield.

P through mycorrhizae and other living sources

Arbuscular mycorrhizae (AM) provides a source of P to some crops such as sorghum. Wheat can be colonised by (AM) however, the crop is unresponsive to AM in terms of P uptake and grain yield (Ryan and Angus 2003; Li *et al.* 2006).

Soil microorganisms are also a potential source of P both through their role in cycling P and through direct association with plants. They can also be a sink for P as it is immobilised in microorganisms (Richardson 2011). Some evidence for microorganisms as an indirect source of P is provided on sandy soil in the Mallee where microbial biomass P and soil P (DGT-P[1]) was higher under canola and cereal rye than under wheat (Gupta *et al.* 2011). Microorganisms have been trialled as a inoculant to promote P solubilisation. A review of this method of increasing plant-available P concludes that results were variable and application of this technique is limited (Richardson 2011).

References

Adcock D, McNeill AM, McDonald GK, Armstrong RD. (2007). Subsoil constraints to crop production on neutral and alkaline soils in south-eastern Australia: a review

[1] DGT-P is soil phosphorus as measured by diffusive gradient thin-film (Mason *et al.* 2010).

of current knowledge and management strategies. *Australian Journal of Experimental Agriculture*, **47**, 1245-1261.

Alston AM. (1980). Response of wheat to deep placement of nitrogen and phosphorus fertilisers on a soil high in phosphorus in the surface layer. *Australian Journal of Agricultural Research*, **31**, 13-24.

Archer MJ. (1974). A sand culture experiment to compare the effects of sulphur on five wheat cultivars (*T. aestivum* L.). *Australian Journal of Agricultural Research*, **25**, 369-380.

Armstrong R, Nuttall J, Argall R, McLaughlin M, Lombi E, Holloway B. (2006). Fluid phosphorus fertilisers: How did they fare in Victoria in 2005? In "*BCG Crop and Pasture Manual 2005-2006*". Accessed from www.bcg.org.au in March 2014.

Batten GD. 1992. A review of phosphorus efficiency in wheat. *Plant and Soil*, **146**, 163-168.

Batten GD, Fettell NA, Mead JA, Khan MA. (1999). Effect of sowing date on the uptake and utilisation of phosphorus by wheat (cv. Osprey) grown in central New South Wales. *Australian Journal of Experimental Agriculture*, **39**, 161-170.

BCG (2009). Phosphorus in Victorian no-till systems. pp2. Accessed from www.bcg.org.au in March 2014.

Beadle NCW. (1962). An alternative hypothesis to account for the generally low phosphate content of Australian soils. *Australian Journal of Agricultural Research*, **13**, 434-442.

Bell R, Reuter D, Scott B, Sparrow L, Strong W, Chen W. (2013). Soil phosphorus – crop response calibration relationships and criteria for winter cereal crops grown in Australia. *Crop and Pasture*, **64**, 480-498.

Bertrand I, McLaughlin MJ, Holloway RE, Armstrong RD, McBeath T. (2006). Changes in P bioavailability induced by the application of liquid and powder sources of P, N and Zn fertilizers in alkaline soils. *Nutrent Cycling in Agroecosystems*, **74**, 27-40.

Bolland MDA, Allen DG, Barrow NJ. (2006). Sorption of phosphorus by soils: how it is measured in Western Australia. Bulletin 4591. Department of Agriculture, Western Australia. pp31. Accessed from www.agric.wa.gov.au/ in March 2014.

Bolland MDA, Brennan DF. (2006). Phosphorus, copper and zinc requirements of no-till wheat crops and methods of collecting soil samples for soil testing. *Australian Journal of Experimental Agriculture*, **46**, 1051–1059.

Bolland MDA, Lewis, DC, Gilkes RJ, Hamilton. (1997). Review of Australian phosphate rock research. *Australian Journal of Experimental Agriculture*, **37**, 845-859.

Brennan RF, Bolland MDA. (2009). Comparing the nitrogen and phosphorus requirements of canola and wheat for grain yields and quality. *Crop and Pasture Science*, **60**, 566-577.

Brown AJ. (1999). Soil sampling and sample handling for chemical analysis. In: "*Soil analysis: an interpretation manual*". (Eds KI Peverill, LA Sparrow, DJ Reuter). pp 35-53.

Bruulsema, TW, Garcia F, Satyanaryana T. (2012). The 4R nutrient stewardship concept. In: *4R plant nutrition a manual for improving the management of plant nutrition metric version*. International Plant Nutrition Institute, Norcross, USA. pp 2-1 – 2-7.

Burkitt LL, Moody PW, Gourley CJP, Hannah MC. (2002). A simple phosphorus buffering index for Australian soils. *Australian Journal of Soil Research*, **40**, 497-513.

Christie R. (2008). Effects from long-term application of nitrogen and phosphorus fertilisers. In "BCG 2008 Season Research Results". Accessed from www.bcg.org.au in April 2014.

Colwell JD. (1963). The estimation of the phosphorus fertiliser requirements of wheat in southern New South Wales by soil analysis. *Australian Journal of Experimental Agriculture and Animal Husbandry*, **3**, 190-197.

Dunbabin VM, Armstrong RD, Officer, SJ, Norton RM. (2009). Identifying fertiliser management strategies to maximise nitrogen and phosphorus acquisition by wheat in two contrasting soils from Victoria, Australia. *Australian Journal of Soil Research*, **47**, 74-90.

Dunsford K, Armstrong RD, Mason S. (2012). Sub-soil constraints affect responsiveness of wheat to applied Phosphorus. *Proceedings of the 16th Australian Agronomy Conference, Armidale, NSW*.

Grant CA, Flaten DN, Tomasiewicz DJ, Sheppard SC. (2001). The importance of early season phosphorus nutrition. *Canadian Journal of Plant Science*, **81**, 211-224.

GRDC (2008). Planning guide for low-risk farming – 2008. (Ed G. Jennings). pp31. Accessed from www.grdc.com.au in March 2014.

GRDC (2009). Targeted nutrition at sowing fact sheet. pp6. Accessed from www.grdc.com.au in March 2014.

GRDC (2011). Making the most of a wet summer in the Southern Region: A crop planning guide for 2011. (Ed. G. Jennings). pp20. Accessed from www.grdc.com.au/ in March 2014.

GRDC (2012). Southern region: Phosphorus management. Crop nutrition fact sheet November 2012. pp4. Accessed from www.grdc.com.au in March 2014.

Grundon NJ. (1987). Hungry crops: a guide to mineral deficiencies in field crops. Queensland Department of Primary Industries. pp 246.

Gupta VVSR, Vallejo Roosdorp L, Mason S, Kroker, S, Davoren W, McBeath T, Llewellyn E, Whitbread A. (2011). Break crops influence phosphorus availability in Mallee soils by changing soil microbial communities. In "*Mallee Sustainable Farming Results Compendium 2011*". Accessed from www.msfp.org.au in March 2014.

Harbison D, Speirs A, Flavel P, Motley K, Dyson C. (2003). Phosphorus – Yield responses in wheat, canola and field peas grown at different soil Colwell P and PBI levels. *Proceedings of the 11th Australian Agronomy Conference*, 2-6 February 2003, Geelong, Victoria. Accessed from www.regional.org.au in April 2014.

Hemwall J. (1957). The fixation of phosphorus by soils. *Advances in Agronomy,* **9**, 95-113.

Holford ICR. (1997) Soil phosphorus: its measurement, and its uptake by plants, *Australian Journal of Soil Research*, **35**, 227-239.

Holloway RE, Bertrand I, Frischke AJ, Brace DM, McLaughlin MJ, Sheppard W. (2001). Improving fertiliser efficiency on calcareous and alkaline soils with fluid sources of P, N and Zn. *Plant and Soil*, **236**, 209-219.

Jones GPD, Blair GJ, Jessop RS. (1989). Phosphorus efficiency in wheat – A useful selection criterion?. *Field Crops Research*, **21**, 257-264.

Larsen S. (1967). Soil phosphorus. *Advances in Agronomy*, **19**, 151-211.

Li H, Smith SE, Holloway RE, Zhu Y, Smith FA. (2006). Arbuscular mycorrhizal fungi contribute to phosphorus uptake by wheat grown in a phosphorus-fixing soil even in the absence of positive growth responses. *New Phytologist*, **172**, 536-543.

Ma Q, Rengel Z, Rose T. (2009). The effectiveness of deep placement of fertilisers is determined by crop species and edaphic conditions in Mediterranean –type environments: a review. *Australian Journal of Soil Research*, **47**, 19-32.

MacEwan RJ, Crawford DM, Newton PJ, Clune TS. (2010). High clay contents, dense soils, and spatial variability are the principal subsoil constraints to cropping the higher rainfall land in south-eastern Australia. *Australian Journal of Soil Research*, **48**, 150-166.

Mason S, Craig S, McBeath T. (2011). Phosphorus management in 2011. In "*Mallee Sustainable Farming 2010 Results Compendium*". pp 93-95. Accessed from www.msfp.org.au in March 2014.

Mason S, McNeill A, McLaughlin MJ, Zhang Hao. (2010) Prediction of wheat response to an application of phosphorus under field conditions using diffusive gradients in thin-films (DGT) and extraction methods. *Plant and Soil*, **337**, 243–258.

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.

McBeath TM, McLaughlin MJ, Kirby JK, Armstrong RD. (2012). The effect of soil water status on fertiliser, topsoil and subsoil phosphorus utilisation by wheat. *Plant and Soil*, **358**, 337-348.

McDonald G, Wheeler, R, Porker K, Bovill B, McKay A, Smith A. (2010). Phosphorus use efficiency in wheat and barley. *Proceedings of 15th Agronomy Conference 2010*, 15-18 November 2010, Lincoln, New Zealand. Accessed from www.regional.org.au in March 2014.

McLaughlin MJ, Alston AM. (1986). The relative contribution of plant residues and fertiliser to the phosphorus nutrition of wheat in a pasture/cereal system. *Australian Journal of Soil Research*, **24**, 517-526.

McLaughlin MJ, Alston AM, Martin JK. (1988a). Phosphorus cycling in wheat-pasture rotations. I. The source of phosphorus taken up by wheat. *Australian Journal of Soil Research*, **26**, 323-331.

McLaughlin MJ, Alston AM, Martin JK. (1988b). Phosphorus cycling in wheat-pasture rotations. III. Organic phosphorus turnover and phosphorus cycling. *Australian Journal of Soil Research*, **26**, 343-353.

McLaughlin MJ, McBeath TM, Smernik R, Stacey SP, Ajiboye B, Guppy C. (2011). The chemical nature of P accumulation in agricultural soils – implications for fertiliser management and design: an Australian perspective. *Plant and Soil*, **349**, 69-87.

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.

Moody P, Bell M. Klepper K, Lawrence D, Pu G. (2010). Implications of minimum till dryland cropping systems for diagnostic P and K soil tests. In "*Proceedings of the 19th World Congress of Soil Science: Soil solutions for a changing world*", Brisbane, Australia, 1-6 August 2010. Accessed from www.iuss.org in March 2014.

Moody PW, Bolland MDA. (1999). Phosphorus. In: "*Soil analysis: an interpretation manual*". (Eds KI Peverill, LA Sparrow, DJ Reuter). pp 187-220.

Nash D, Hannah M, Clemow L, Halliwell D, Webb B, Chapman D. (2003). A laboratory study of phosphorus mobilisation from commercial fertilisers. *Australian Journal of Soil Research*, **41**, 1201-1212.

Noack SR, McBeath TM, McLaughlin MJ. (2010). Potential for foliar phosphorus fertilisation of dryland cereal crops: a review. *Crop and Pasture Science*, **61**, 659-669.

Noack SR, McBeath TM, McLaughlin MJ, Smernik RJ, Armstrong RD. (2013). Crop residue management affects the transfer of residue phosphorus to plant and soil pools: Results from a dual-labelling experiment. *Soil Biology & Biochemistry*, **71**, 31-39.

Norton RM. (2012). Wheat grain nutrient concentrations for south-eastern Australia. *Proceedings of 16th Australian Agronomy Conference 2012*, 14-18 October 2012, Armidale, NSW. Accessed from www.regional.org.au in March 2014.

Norton RM, Roberts T. (2012). Nutrient management to nutrient stewardship. *Proceedings of 16th Australian Agronomy Conference 2012*, 14-18 October 2012, Armidale, NSW. Accessed from www.regional.org.au in March 2014.

Nuttall JG, Armstrong RD, Connor DJ. (2003). Evaluating physicochemical constraints of Calcarosols on wheat yields in the Victorian southern Mallee. *Australian Journal of Agricultural Research*, **54**, 487-497.

Officer SJ, Armstrong RD, Norton RM. (2009a). Plant availability of phosphorus from fluid fertiliser is maintained under soil moisture deficit in non-calcareous soils of south-eastern Australia. *Australian Journal of Soil Research,* **47,** 103-113.

Officer SJ, Dunbabin VM, Armstrong RD, Norton RM, Kearney GA. (2009b). Wheat roots proliferate in response to nitrogen and phosphorus fertilisers in Sodosol and Vertosol soils in south-eastern Australia. *Australian Journal of Soil Research*, **47**, 91-102.

Ozanne PG. (1980). Phosphate nutrition of plants—A general treatise. In '*The role of phosphorus in agriculture*'. pp. 559–589. (American Society of Agronomy/Crop Science Society of America/Soil Science Society of America: Madison, WI).

Reuter DJ, Edwards, DG, Wilhelm NS. (1997). Temperate and tropical crops. In "*Plant analysis: an interpretation manual*" 2nd edition. (Eds. DJ Reuter, JB Robinson). pp 81-284.

Richardson AE, Barea, JM, McNeill AM, Prigent-Combart C. (2011). Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms. *Plant and Soil*, **321**, 305-339.

Ryan MH and Angus JF. (2003). Arbuscular mycorrhizae in wheat and field pea crops on a low P soil: increased Zn-uptake but no increase in P-uptake of yield. *Plant and Soil*, **250**, 225-239.

Seednet. (2011). EGA Wedgetail. pp2. Accessed from www.seednet.com.au in March 2014.

Vu DT, Tang C, Armstrong RD. (2009). Tillage system affects phosphorus form and depth distribution in three contrasting Victorian soils. *Australian Journal of Soil Research*, **47**, 33-45.

Wild A. (1958). The phosphate content of Australian soils. *Australian Journal of Agricultural Research*, **9**, 193-204.

Wurst M, Wilhelm N, Brennan R. (2010). Winter cereal nutrition: The ute guide. iOS or Android application.