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Corrigendum

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Soil phosphorus-crop response calibration relationships and criteria for winter cereal crops grown in Australia

R. Bell, D. J. Reuter, B. J. Scott, L. Sparrow, W. Strong, and the late Wen Chen (2013)

Replace para 2, p. 491 with:

"The *BFDC Interrogator* can be used to re-examine published estimates of the critical P concentrations. For example, Holford and Cullis (1985*a*) concluded that the critical value (90% Ymax) was 25 ± 4 mg/kg for the Colwell soil P test on a 0–10 cm soil sample. The treatment series within the *BFDC Interrogator* for the NSW wheatbelt covering a similar area (approximately bounded by the Murray River in the south, and Cootamundra in the north) gave a critical value for Colwell-P of 27 (20–36) mg/kg over 126 experiments with a soil pH_{CaCl_2} <5.6. This was consistent with the value reported by Holford and Cullis (1985*a*).

In the northern NSW Slopes and Plains, the previously reported critical Colwell value ranged from 30 mg/kg (Holford and Doyle 1992) to 57 mg/kg (Holford and Cullis 1985*b*). The latter and higher estimate was derived from 49 sites reported by Colwell and Esdaile (1968) and Colwell (1970). Based on all 49 sites, which have been entered in the BFDC National Database, the critical value for Colwell-P estimated by *BFDC Interrogator* was 25 (18–34) mg/kg, suggesting that the value of 57 mg/kg was misleading."

Corrigendum: References, p. 495

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Soil phosphorus–crop response calibration relationships and criteria for winter cereal crops grown in Australia

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Abstract. Soil testing is the most widely used tool to predict the need for fertiliser phosphorus (P) application to crops. This study examined factors affecting critical soil P concentrations and confidence intervals for wheat and barley grown in Australian soils by interrogating validated data from 1777 wheat and 150 barley field treatment series now held in the BFDC National Database. To narrow confidence intervals associated with estimated critical P concentrations, filters for yield, crop stress, or low pH were applied. Once treatment series with low yield (<1 t/ha), severe crop stress, or pH_{CaCl2} <4.3 were screened out, critical concentrations were relatively insensitive to wheat yield (>1 t/ha). There was a clear increase in critical P concentration from early trials when full tillage was common compared with those conducted in 1995–2011, which corresponds to a period of rapid shift towards adoption of minimum tillage. For wheat, critical Colwell-P concentrations associated with 90 or 95% of maximum yield varied among Australian Soil Classification (ASC) Orders and Sub-orders: Calcarosol, Chromosol, Kandosol, Sodosol, Tenosol and Vertosol. Soil type, based on ASC Orders and Sub-orders, produced critical Colwell-P concentrations at 90% of maximum relative yield from 15 mg/kg (Grey Vertosol) to 47 mg/kg (Supracalcic Calcarosols), with other soils having values in the range 19–27 mg/kg. Distinctive differences in critical P concentrations were evident among Sub-orders of Calcarosols, Chromosols, Sodosols, Tenosols, and Vertosols, possibly due to differences in soil properties related to P sorption. However, insufficient data were available to develop a relationship between P buffering index (PBI) and critical P concentration. In general, there was no evidence that critical concentrations for barley would be different from those for wheat on the same soils. Significant knowledge gaps to fill to improve the relevance and reliability of soil P testing for winter cereals were: lack of data for oats; the paucity of treatment series reflecting current cropping practices, especially minimum tillage; and inadequate metadata on soil texture, pH, growing season rainfall, gravel content, and PBI. The critical concentrations determined illustrate the importance of recent experimental data and of soil type, but also provide examples of interrogation pathways into the BFDC National Database to extract locally relevant critical P concentrations for guiding P fertiliser decision-making in wheat and barley.

Additional keywords: Better Fertiliser Decisions for Crops (BFDC), critical concentration, confidence interval, Australian Soil Classification, soil acidity.

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Introduction

Phosphorus (P) deficiency limits wheat grain yield principally by depressing early growth, leaf emergence rate, and maximum rate of tiller emergence (Rodríguez *et al*. 1999). In severely P-deficient wheat, partitioning of carbon and P between shoots and roots favours P retention in roots (Hawkesford *et al*. 2012), delaying the onset of depressed root growth (Elliott *et al*. 1997). Phosphorus deficiency also delays phenological development in cereals (Rodríguez *et al*. 1999).

Phosphorus fertilisers are applied to agricultural soils for winter cereal production in many parts of the world, and they represent a significant proportion of crop production costs. In many parts of the world, P fertilisers are added to overcome deficiency in winter cereals because of low plant-available P levels in soils. Elsewhere, P fertiliser is principally used to maintain adequate soil P levels for cropping. Other areas now have high plant-available soil P levels, and regular application of P fertilisers is no longer required to achieve profitable yields (Sims and Vadas 2005). However, in all cases, soil testing can provide key information for improved decision-making about P management.

Phosphorus is highly reactive in soils, and this behaviour controls the key processes affecting P cycling in agricultural soils. McLaughlin *et al*. (1988) demonstrated that P fertiliser principally accumulated as inorganic forms of P in the soil. By contrast, incorporated legume pasture residues primarily cycled to the soil organic P and microbial biomass pools. Only 12% of the applied P fertiliser and 5% of the P from incorporated legume residue accumulated in the wheat plants over a 95-day period (McLaughlin *et al*. 1988). Given the relatively low recovery of P fertiliser by the current crop, determining the fate of the P remaining in the soil and its subsequent availability for crops is a key role for soil testing. Recently, Weaver and Wong (2011) calculated that although 11.3 kg P/ha was applied on average for each grain crop in southern Australia, only 5.6 kg P/ha was removed in harvested grain. The net gain of P (median value 6.1 kg P/ha) per crop has led to a progressive accumulation of soil P on most grain cropping soils. Of 109 000 soil samples collected in the south-west of Australia recently (2008–10; 0–10 cm depth), 87% were above apparent critical soil P levels as defined by Moody (2007). Soil testing can play a key role in managing P inputs to reduce costs of P fertiliser where levels are well above critical values or to guide increased P fertiliser rates where soil P levels are too low for crop growth. With further increases in P fertiliser prices globally, the imperative has strengthened for improved soil testing prediction of P fertiliser requirements.

The proportion of applied P fertiliser available to crops on acid soils depends largely on sorption by iron (Fe) and aluminium (Al) oxyhydroxides (Moody and Bolland 1999; Bertrand *et al*. 2003). By contrast, on calcareous soils, high soil solution calcium (Ca) concentrations may lead to P precipitation within or proximal to the fertiliser granule, causing inefficient P use by crops (Bertrand *et al*. 2003; Hettiarachchi *et al*. 2006). Hence, the P reactivity of a soil and the principal forms of P in soils are likely to affect the extractability of P by soil tests. Although soil tests are designed to predict the plant availability of the soil P, including a proportion of the sorbed P, the relationship between extractable soil P and crop response to P fertiliser is likely to vary with soil type and the extractant used (Moody and Bolland 1999).

Several soil P tests have been developed (see Rayment and Lyons 2011), with the Olsen test (Olsen *et al*. 1954) now most widespread internationally. A variation of the Olsen test, the Colwell $NaHCO_3$ soil P test (Colwell 1965), was developed for Australia, using the same extracting solution but a wider soil : solution ratio and longer extraction time than the Olsen P test. The Colwell test has become the most widely used test in Australia for estimating soil P status, mainly determined in the surface 0–10 cm horizon. Some studies have used 0–7.5 or 0–15 cm sampling depths, and deeper horizons (to 30 cm) are often sampled on sands in Western Australia (WA). Standardised laboratory soil P testing methods recommended for use in Australasia have been revised recently (Rayment and Lyons 2011).

Several soil-testing procedures for characterising P sorption properties in Australian soils have been developed (e.g. Ozanne and Shaw 1967; Moody and Bolland 1999). All have now been superseded in Australia by the single-point P buffer index, or PBI (Burkitt *et al*. 2002, 2008). The PBI is now considered a vital property for interpreting soil P tests; soils with high PBI values are likely to have lower residual P values after P fertiliser addition than soils with lower PBI status (Moody and Bolland 1999; Moody 2007). On the other hand, leaching of P on soils with very low PBI may prevent such soils from accumulating high soil test P levels, even after many years of repeated P application (Weaver and Wong 2011).

The Colwell soil P test was calibrated for wheat and other crops in regional experiments conducted in different states, e.g. New South Wales (NSW) (Colwell and Esdaile 1968; Holford and Doyle 1992), Queensland (Moody 2007), South Australia (SA) (Reuter *et al*. 1995), Victoria (Burkitt *et al*. 2001), and WA (Bolland and Gilkes 1992), with a large body of data collected in four Australian states between 1968 and 1972 with wheat as the test plant (Colwell 1977). Several regional field and laboratory studies also compared the reliability of different soil P tests for predicting soil P status for growing wheat in NSW (e.g. Colwell 1963; Holford and Cullis 1985; Holford and Doyle 1992) and WA (Bolland *et al*. 1994). A comprehensive summary of regional or site-specific soil P test criteria for different agricultural crop species was compiled by Moody and Bolland (1999). However, the data on which these summaries are based are not readily accessible or available for further examination.

In Australian cropping regions, new farming systems have been progressively adopted. Changes include greater cropping intensity, especially increased sowing of pulse and oilseed crops in rotations with cereals (and lower prevalence of pastures); adoption of minimum tillage and crop residue retention systems (Llewellyn *et al*. 2012); greater use of newly marketed P fertilisers (double- and triple-superphosphate) and nitrogen(N)–P fertilisers [mono-ammonium and di-ammonium phosphate (MAP and DAP), including liquid P formulations]; earlier sowing; and the progressive adoption of higher yielding and disease-resistant cereal varieties. Given these changes in cereal cropping practices, plus the greater climate variability experienced in cropping regions in the last decade, there is a need to re-examine the appropriate soil P test calibrations and critical values and confidence intervals for cereal cropping.

When a large number of historical P fertiliser trial records can be assembled and analysed, improved insights into critical concentrations and factors affecting them can be gained compared with the traditional approach, which has been to develop calibrations for a single region or selection of soils. Kuchenbuch and Buczko (2011) assembled data from 9000 P trials conducted in Germany and Austria. Their data-mining approach was used to reveal the combined influence of clay, organic matter, and pH levels on the critical soil test P levels for P fertiliser recommendations. Recently in Australia, a national database of nutrient response trials for grain crops has been assembled (Watmuff *et al*. 2013). The treatment series entered were subject to rigorous checks to ensure they were valid for re-analysis in the database. The database represents a valuable resource with which to assess response of winter cereals to P across a wide range of cropping eras (modern *v.* earlier periods), soil types, seasonal conditions, sampling depths, soil test methods, and species. The present paper is the first comprehensive analysis of factors affecting critical soil test P values and ranges for predicting P fertiliser response in Australian winter cereal crops. Companion papers have examined critical concentrations for N in winter cereals (Bell *et al*. 2013*b*), N in oilseeds and summer cereals (Bell *et al*. 2013*b*, and the appendix therein), P in other crops (pulses, oilseeds, summer cereals; Bell *et al*. 2013*a*), and potassium (K) (Brennan and Bell 2013) and sulfur (S) (Anderson *et al*. 2013*b*) in all crops.

The objective of this study was to examine factors affecting critical soil P test concentrations and confidence intervals for wheat and barley grown in Australian soils, by interrogating validated data from 1777 wheat and 150 barley field treatment series held in the Better Fertiliser Decisions for Crops (BFDC) National Database at the time of analysis (October–December 2012). The present study examined the Colwell extractant only for soil P, since it was the most widely used test and the one for which the largest and most comprehensive dataset existed. The relative merits of alternative soil P extractants as predictors of crop P response are reported by Speirs *et al*. (2013).

Material and methods

Entries in the BFDC National Database cover trials conducted between 1958 and 2011 across the winter cereal growing regions of Australia. There were insufficient data to analyse critical concentrations for oats, triticale, or rye. Treatment series were classed as A or B as defined by Watmuff *et al*. (2013); briefly, class A treatment series were those whose maximum and minimum crop yield determinations could be taken with confidence, while those whose estimates were less confidently established were designated class B treatment series. Only class A trials were used in this study to derive the critical concentrations and confidence intervals for wheat, whereas all treatment series were used for barley.

Methods developed for recording data into the BFDC National Database, and obtaining soil test calibrations and accompanying statistics using the *BFDC Interrogator*, are described in full by Watmuff *et al*. (2013) and Dyson and Conyers (2013). All P sorption tests were converted to equivalent PBI values using equations provided in Watmuff *et al*. (2013). Where soil sampling was to 7.5 cm, values were converted to equivalent levels in 0–10 cm using the algorithm described by Watmuff *et al*. (2013). Where available, metadata on soil pH, texture, crop stress, crop yield, stored profile soil water, PBI and growing season rainfall were recorded.

Relative yield *v.* soil test value calibration curves were constructed by the *BFDC Interrogator* using the algorithm described by Dyson and Conyers (2013). From the fitted regression, critical values corresponding to 80, 90, and 95% of maximum relative yield (Y_{max}) plus associated 95% confidence intervals for these values were reported by *BFDC Interrogator*. In addition, the calculated correlation coefficient (*r*) for each relationship indicated the goodness of fit of the regression to the data. In *BFDC Interrogator*, $r > 0.2$ was adopted as a default limit for plotting the critical values for a minimum of eight data points. In the present study, we generally achieved *r*-values of >0.6 and mostly used $r \sim\geq 0.4$ as a minimum threshold for establishing the critical values. The *BFDC Interrogator* also reports the 70% confidence interval at 90% relative yield and the slope of the fitted regression between 50 and 80% of Y_{max} as a measure of the responsiveness of crop yield to increased soil P.

Based on initial examination of the fitted regressions, low yield and crop stress filters were applied to screen out treatment series with low soil test values and Y_{max} >90%, plus those with high soil P value and Y_{max} <90%. Subsequently, the treatment series were partitioned by soil type using the Australian Soil Classification (ASC) (Isbell 2002), pH($CaCl_2$) (referred to as pH_{CaCl2}), surface soil texture, PBI, time (eras), growing season rainfall, or profile soil water content.

A selection of independently collected class B treatment series was used to test the accuracy of the critical concentrations and confidence intervals estimated from the class A datasets. Accuracy was assessed by scoring the percentage of treatment series for a particular selection of soils where a soil test value above the critical concentration correctly predicted relative yield >90 or 95% and where a soil test value below the critical concentration correctly predicted a relative yield <90 or 95% of maximum.

Results

Overview of treatment series used

Entries in the BFDC National Database cover trials over seven decades, with the highest numbers per decade in 1960–69 for wheat (Table 1) and in 1990–99 for barley (data not

Table 1. Numbers of phosphorus experiments with wheat and barley entered in BFDC National Database by decade when experiments were conducted

Decade	All	NSW[A]	Qld	SA	Tas.	Vic.	WA
1950s	20	20	0	0	0	0	0
1960s	640	172	171	166	12[B]	43	76
1970s	399	126	89	33	12[B]	65	74
1980s	287	101	2	112	0	0	72
1990s	184	32	0	89	0	2	61
2000s	232	73	2	34	0	30	93
2010+	14	3	0	7	0	1	3
Total	1776	528	264	441	24	141	379

[A] Includes one treatment series for the Australian Capital Territory in the 1970s.

[B] Exact dates of treatment series not known but they were conducted in the 1960s and 1970s (L. Sparrow, pers. obs.).

shown). A large proportion of the P treatment series from Queensland came from studies conducted in the 1960s, and very few since 1979, so the Vertosol dataset was dominated by experiments during earlier eras of cropping. Only 24% of the treatment series for P were gathered since 1990, an era of cropping when the use of varieties with high yield potential (and higher water-use efficiency) (see Fig. 1), herbicides for weed control, early sowing with minimum tillage, and crop residue retention have become common practice.

Eighty per cent of the treatment series for wheat and 90% for barley were classified as class A trials (see *Materials and methods*) compared with the 80% average for the whole database (Watmuff *et al*. 2013).

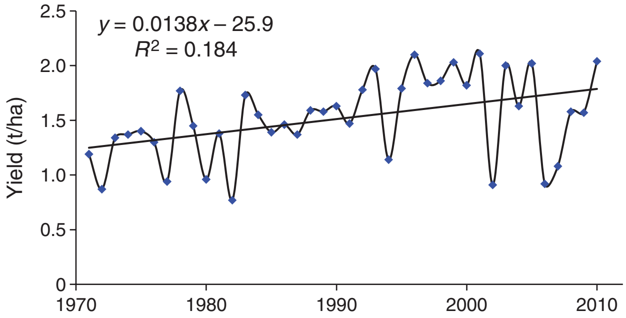

Fig. 1. Mean Australian wheat yields for planting seasons 1971–2010. Source: ABARES (2011).

Yield level

Across the Australian grain growing regions, mean wheat yield has been ~1 t/ha in 8 of the last 40 years, during extreme droughts (Fig. 1). Hence, we used 1 t/ha as a filter for screening out treatment series with low maximum yield. For treatment series with yield <1 t/ha, there was either no relationship between Y_{max} and Colwell-P, or the relationship fitted had a lower critical concentration than for the remainder of the treatment series (Appendix 1). The one exception was the Supracalcic Calcarosol Sub-order, which had similar critical P concentrations of ~49 (confidence interval 37–66) mg/kg for the <1 t/ha treatment series and for the higher yielding treatment series (Appendix 1; Table 2). Indeed for the Supracalcic Calcarosol treatment series in the BFDC National Database, average yield was low and none of the yields exceeded 1.55 t/ha. For Colwell-P, the <1 t/ha filter accounts for 7% of treatment series; 70% of the treatment series had maximum yield 1–3 t/ha, while only 24% had maximum yield >3 t/ha. The effect of wheat yield on critical P concentrations was explored for soil types with sufficient data. In Chromosols, there was no shift in the critical P concentrations between sites with yield >2 t/ha *v.* >1 t/ha (Table 3). Similarly, in Red Sodosols, Calcarosols, and Vertosols, selecting only treatment series with yield >1.5 or >2 t/ha compared with yield >1 t/ha had no significant effect on the critical P concentration for wheat. In Red Chromosols, treatment series with yield >3 t/ha still produced a critical P concentration that was not significantly different to selection of yield >2 or >1 t/ha (data not shown).

Table 2. Critical phosphorus concentrations (mg/kg; CC) and confidence intervals (CI) at 80, 90, and 95% of maximum yield for wheat grown on soils of various Australian Soil Classification Orders and Sub-orders

r, Goodness of fit of the soil test calibration curve; slope RY, slope of fitted curve between 50 and 80% of maximum yield. All Colwell-P values were for 0–10 cm, but in the cases where sampling was for 0–7.5 cm, an adjusted value was calculated as described in *Materials and methods*. The actual sampling depths are shown for each Soil Order or Sub-Order

Soil Order or Sub-order	Soil depth (cm)	No. of trials	80%		90%		95%		*r*	Slope RY	Filter applied
			CC	CI	CC	CI	CC	CI			
Calcarosol except Supra- and Hyper-calcic	0–10	134	15	12–19	20	16–25	25	19–32	0.37	2.4	>1 t/ha
Supracalcic Calcarosol	0–10	21	35	21–57	47	24–92	57	24–140	0.38	0.97	Nil[A]
Yellow, Brown and Grey Chromosol	0–10	43	16	15–18	20	18–22	22	20–25	0.84	4.3	pH >4.3
Red Chromosol	0–7.5 + 0–10	96	19	16–22	25	20–32	31	24–41	0.52	2.3	>1 t/ha, no severe stress, pH >4.3
Kandosol	0–7.5 + 0–10	70	19	16–22	25	21–30	31	25–38	0.68	3.3	>1 t/ha, no severe stress, pH >4.3
Dermosol	0–10	12	17	10–26	22	14–35	27	16–46	0.66	Poorly defined	>1 t/ha, no severe stress
Brown, Yellow and Grey Sodosols	0–7.5 + 0–10	34	17	14–21	21	17–27	25	19–33	0.74	4.3	>1 t/ha no severe stress, pH >4.3
Red Sodosols	0–10	29	19	15–24	27	20–36	35	24–49	0.76	2.8	>1 t/ha, no severe stress, pH >4.3
Yellow, Red and Brown Tenosol	0–10	38	17	14–20	21	18–26	25	20–31	0.76	4.0	>1 t/ha, pH >4.3
Grey Tenosol	0–10	22	16	13–19	20	16–25	23	18–30	0.81	4.3	>1 t/ha, pH >4.3
Grey Vertosol	0–7.5 + 0–10	54	12	8–16	16	12–21	19	15–26	0.46	4.8	>1 t/ha no severe stress
Black and Brown Vertosol	0–7.5 + 0–10	99	12	10–14	19	16–22	26	22–31	0.73	3.9	>1 t/ha

[A] The yield filter (>1 t/ha) was removed for this soil type since there was no fit of the *BFDC Interrogator* regression function to the filtered data.

Table 3. Effects of minimum yield on critical soil phosphorus concentrations (mg/kg; CC) and confidence intervals (CI) corresponding with 90 and 95% of maximum yield (Y_{max}) of wheat in Chromosols (all Sub-orders except Red Chromosol), Red Sodosols, Calcarosols (all Sub-orders except Hypercalcic and Supracalcic), and Vertosols (Grey Sub-order, and remaining Sub-orders)

r, Goodness of fit of the soil test calibration curve; slope RY, slope of fitted curve between 50 and 80% of maximum yield

Soil Order or Sub-order	No. of treatment series	90%		95%		*r*	Slope RY	Y_{max} criteria
		CC	CI	CC	CI			
All Chromosols except Red	111	19	16–22	23	19–28	0.78	2.4	>1 t/ha
	54	18	14–24	23	17–30	0.78	2.6	>2 t/ha
Red Sodosol	32	28	21–38	36	25–52	0.74	1.8	>1 t/ha
	28	26	21–34	34	25–46	0.80	2	>1.5 t/ha
Calcarosol except Supracalcic or Hypercalcic Sub-orders	134	20	16–25	25	19–32	0.37	2.4	>1 t/ha
	78	22	17–27	26	20–35	0.44	2.3	>2 t/ha
Grey Vertosol	69	15	12–19	19	15–24	0.47	2.8	>1 t/ha
	50	16	14–19	19	16–23	0.55	2.9	>2 t/ha
Vertosol (except Grey Vertosol Sub-order)	104	19	16–22	25	21–30	0.71	3	>1 t/ha
	89	19	16–22	25	21–30	0.73	3.1	>2 t/ha

Table 4. Critical concentrations (mg/kg; CC) and confidence interval (CI) for Colwell-P soil test (0–10 cm depth) partitioned by samples taken 1958–93 and 1994–2011 for all soils across Australia or for Western Australian (WA) soils only

Critical values were calculated at 80, 90, and 95% of the relative grain yield. Treatment series with <1 t/ha and severe crop stress were excluded from the analysis; *r*, goodness of fit of soil test calibration curve; slope RY, slope of fitted curve between 50 and 80% of maximum yield

Era	No. of treatment series	80%		90%		95%		*r*	Slope RY
		CC	CI	CC	CI	CC	CI		
1958–80	665	15	14–16	20	19–22	25	23–28	0.57	3.8
1981–93	246	15	14–17	20	18–22	24	22–27	0.68	4.3
1995–2011	231	20	16–24	26	22–31	31	25–38	0.35	1.6
WA only 1958–94	187	11	10–13	14	12–17	17	14–20	0.65	3.1
WA only 1995–2011	107	18	16–21	22	20–26	26	23–30	0.57	2.0

Era when phosphorus trials were conducted

Considering all wheat treatment series with Y_{max} >1 t/ha and no report of severe crop stress, there were lower critical Colwell-P values at 90% of maximum yield for experiments conducted before 1995 than for those conducted in 1995–2011. The same trend was evident for the critical P concentration at 95% of Y_{max}, although the confidence intervals overlapped (Table 4). For the treatment series from WA only, where there was a rapid shift towards minimum tillage commencing around 1990 (1992, 15% adoption; present, >90% adoption; Llewellyn *et al.* 2012), the difference between eras was more pronounced and there was no overlap between confidence intervals for critical concentrations at Y_{max} of 80, 90, or 95% (Table 4). However, because most of the P treatment series in the BFDC National Database were for experiments conducted before 1990, this limited the extent to which the earlier eras could be ignored in deriving critical concentrations. In particular, for Vertosols, most of the data were from Queensland, gathered during 1960–79, and this represents a bias in the data available. By contrast, in an examination of the critical soil P test values for cereal, lupin, and canola crops in WA, Anderson *et al.* (2013*a*) exclusively focussed on treatment series from 1994 onwards.

Soil types

There were sufficient treatment series to determine critical soil P concentrations for wheat on Calcarosols, Chromosols, Dermosols, Kandosols, Tenosols, and Vertosols but not on Ferrosols, Podosols, or Rudosols (Table 5). In general, critical P concentrations corresponding with 95% of Y_{max} increased in the sequence: Grey Vertosol < Yellow, Brown, and Grey Chromosols; Grey Tenosol < Calcarosol; Black and Brown Vertosols < Dermosol; Yellow, Brown, and Red Tenosols < Brown, Yellow, and Grey Sodosols < Kandosol; Red Chromosol < Red Sodosol < Supracalcic Calcarosol (Table 2). However, given the magnitude of the confidence intervals, not all of these differences were significant. At 90% of Y_{max}, critical concentrations were lower by 2–8 mg P/kg and confidence intervals were narrower than at 95% of Y_{max}. In general, the lower confidence limit for the critical concentration at 95% of Y_{max} corresponds approximately with the critical concentration at 90% of Y_{max}. At 90% of Y_{max}, the limits of the critical interval were generally no more than 20–30% greater or lesser than the critical concentration. At 80% of Y_{max}, critical concentrations were mostly in the range 11–20 mg/kg, and only the extreme differences (Vertosols *v.* Supracalcic Calcarosols) were significantly different from the remainder of soils. Within most of the ASC groups, splitting of the treatments series based on Sub-orders improved the goodness of fit, reduced the size of the confidence interval, and resulted in groups with more distinctive critical soil P concentrations.

On Calcarosols, the relationship between relative wheat yield and soil P level was improved by removing the treatment series for Hypercalcic and Supracalcic Sub-orders from the dataset analysed (Table 2). The separation of Hypercalcic and Supracalcic Sub-orders from the remainder of Calcarosols is

Table 5. Numbers of class A treatment series for Calcarosol, Chromosol, Dermosol, Kandosol, Tenosol, and Vertosol Orders or Sub-orders of the Australian Soil Classification available in the BFDC National Database to estimate critical concentrations for wheat

See *Materials and methods* for definition of class A treatment series

ASC Order or Sub-order	NSW	Qld	SA	Tas.	WA	Vic.	Australia
Calcarosol (except Supracalcic Sub-order)	4	0	158	0	4	25	191
Supracalcic Calcarosol	0	0	25	0	0	0	25
Chromosol (Yellow, Brown, Grey Sub-orders)	6	0	14	0	103	3	126
Red Chromosol	60	17	56	0	10	38	181
Dermosol	11	0	4	0	0	2	17
Kandosol	59	0	4	0	83	0	146
Sodosol (except Red Sodosol Sub-order)	21	0	31	0	13	2	67
Red Sodosol	12	0	15	0	15	0	42
Tenosol	0	5	23	0	86	0	114
Grey Tenosol	0	0	0	0	48	0	48
Unknown	219	0	64	24	29	20	356
Vertosol (Black, Brown, Red Sub-orders)	100	191	12	0	0	1	304
Grey Vertosol	44	50	0	0	0	28	122
Others (Ferrosol, Rudosol, Kurosol, Podzol)	2	1	2	0	0	2	7

consistent with their much higher levels of carbonate, including high topsoil carbonate in the profiles (Isbell 2002). Even so, the goodness of fit was inferior to that of most other soil groups (Table 2). In Supracalcic Calcarosols, the critical P concentration (and confidence interval) at 90% of maximum yield, 47 (24–92) mg/kg (Table 2), was over twice as high as that of the remaining Calcarosols, 20 (16–25) mg/kg, but the relationship was poorly defined. There was no relationship between Y_{max} and Colwell-P in the 0–10 cm layer for Hypercalcic Calcarosols, and inclusion of this Sub-order of Calcarosols with Supracalcic Calcarosols decreased the goodness of fit of the relationship (data not shown).

Red Chromosols had a critical P concentration (and confidence interval) of 25 (20–32) mg/kg at 90% of maximum yield compared with values of 20 (18–22) mg/kg in the remaining Chromosols (Tables 2, Fig. 2). The confidence interval for Red Chromosols was relatively large and overlapped that for the remaining Chromosols. By contrast, there was no distinction between critical P concentrations for Grey and Brown Chromosols and no fit of the data just for Yellow Chromosols due to insufficient sites (data not shown). For the Red Chromosol treatment series, improvement in the goodness of fit of the soil test calibration curve, and a small decrease in the confidence interval, was obtained by filtering out sites with low pH_{CaCl2} (<4.3). When the Colwell-P was below the critical concentration of 25 mg/kg, there was a high frequency of treatment series with >0.25 t/ha yield increase from P fertiliser application (Fig. 3).

For Kandosols, the critical P concentration at 90% of Y_{max}, derived from 70 treatment series, was 25 (confidence interval 22–30) mg/kg in the 0–10 cm layer (Table 2). Removal of Red Kandosols improved the *r*-value for the relationship but did not alter the estimated critical concentration or confidence interval (data not shown). The critical Colwell-P concentrations in Kandosols were comparable to those in the Red Chromosols.

Red Sodosols had higher critical P concentrations than the remaining Sodosols (Yellow, Brown, and Grey Sub-orders), although the confidence intervals overlapped (Table 2, Fig. 2). Overall, Red Sodosols had higher critical P concentrations than all other soils apart from the Supracalcic Calcarosols, while for the remaining Sodosols critical P concentrations were comparable to those for Kandosols and Red Chromosols.

Tenosols, which were mainly found in WA (Table 5), were split into Grey and other Tenosols (Yellow, Brown, and Red) to improve the goodness of fit of the soil test calibration curve (Table 2). Filtering data to remove treatment series with pH_{CaCl2} <4.3 improved the goodness of fit and reduced the confidence interval but, for the Yellow, Brown, and Red Tenosols, increased the critical P concentration from 17 (confidence interval 13–23) to 23 (20–27) mg/kg. Lower critical concentrations were found for Grey Tenosols, although the confidence intervals overlapped with those of other Tenosols (Table 2). Yellow, Brown, and Red Tenosols had critical P concentrations similar to the Dermosols and the Yellow, Brown, and Grey Sodosols, whereas for Grey Tenosols, critical Colwell-P concentrations were most similar to Yellow, Brown, and Grey Chromosols. In Grey Tenosols, when Colwell-P concentrations were less than the critical concentrations at 90 or 95% of Y_{max}, a yield increase of >0.3 t/ha was generally obtained from P fertiliser application (Fig. 3). For other Tenosols, at less than the critical Colwell-P concentration (23 mg/kg), there was a high frequency of >0.2 t/ha yield increase for treatment series from P fertiliser application.

The Vertosols had the lowest critical Colwell-P concentrations of all the Soil Orders. The relationships between relative yield of wheat and soil P levels improved when Grey Vertosols were separated from the remaining Sub-orders of Vertosols (Black, Brown, Red; Table 2). Although the confidence intervals did overlap, the critical value for Grey Vertosols was lower, at 15 (12–19) mg/kg, than for the Black, Brown, and Red Vertosols, at 19 (16–22) mg/kg. The Grey Vertosols had the lowest critical Colwell-P concentrations of all soils examined, whereas the values for Black and Brown Vertosols were comparable to the Grey Tenosols. In the Black and Brown Vertosols, treatment series generally had a yield increase of >0.2 t/ha from P fertiliser application when Colwell-P was below the critical concentration of 19 mg/kg (Fig. 3).

Rainfall and stored soil water

Rainfall during the growing season had no effect on critical Colwell-P concentrations in Black and Brown Vertosols

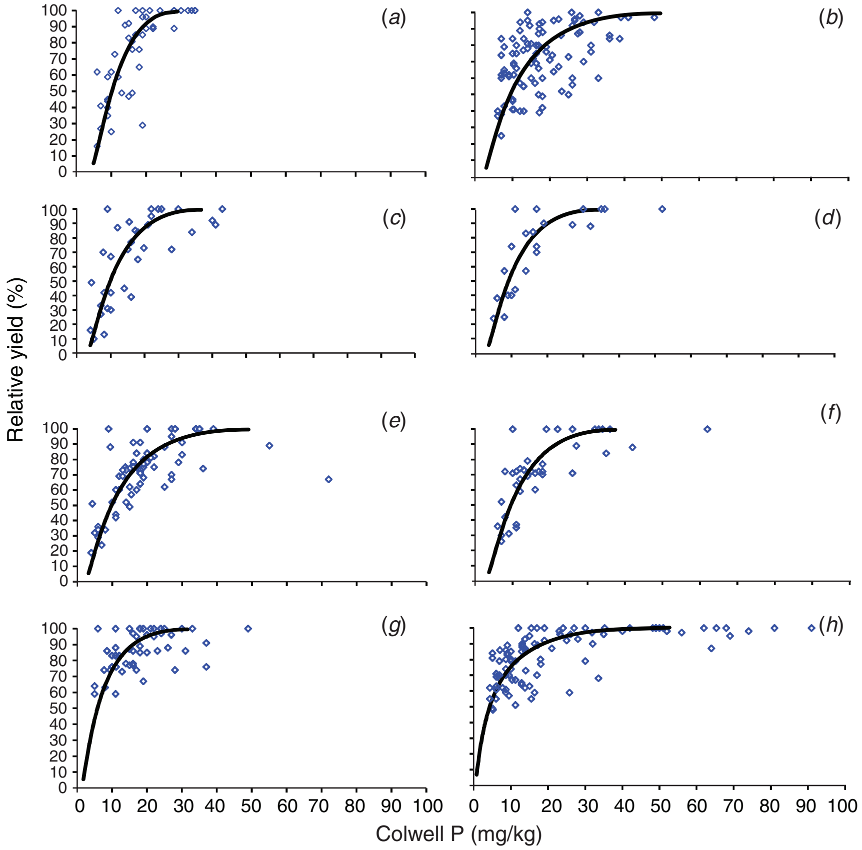

Fig. 2. Relationships between relative grain yield of wheat (as a percentage of maximum) and Colwell extractable P in 0–10 cm depth for the following soils: (*a*) Chromosols (Yellow, Grey, Brown), (*b*) Red Chromosol, (*c*) Sodosols (Grey, Yellow, Brown), (*d*) Grey Tenosol, (*e*) Kandosols, (*f*) Tenosols (Yellow, Brown, Red), (*g*) Grey Vertosols, (*h*) Black and Brown Vertosols. See Table 2 for correlation coefficients of soil test calibration curves fitted and the critical concentrations and their confidence intervals for each figure part.

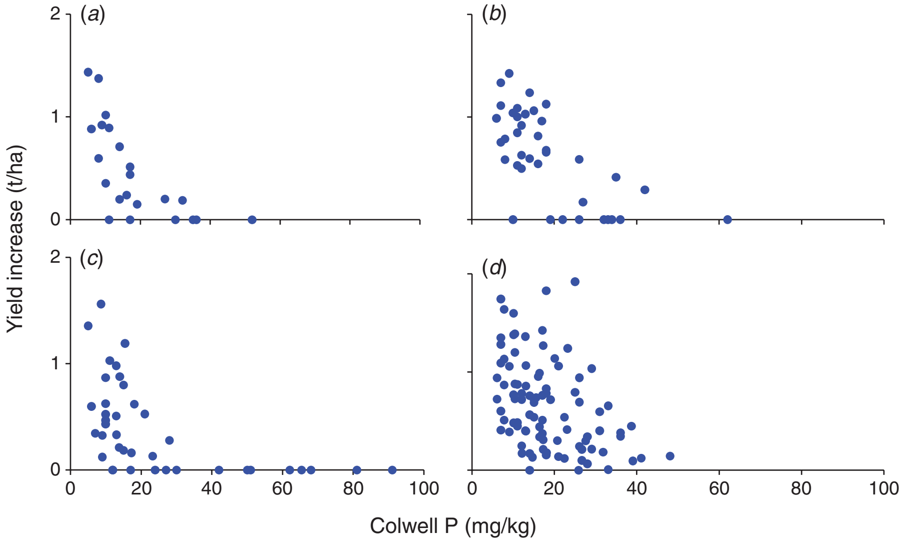

Fig. 3. Relationships between grain yield increase of wheat (t/ha) with P fertiliser addition and Colwell extractable P in 0–10 cm depth for the following soils: (*a*) Grey Tenosol, (*b*) Tenosols (Yellow, Brown, Red), (*c*) Black and Brown Vertosols, (*d*) Red Chromosol.

Table 6. Colwell-P soil test (mg/kg; 0–10 cm) critical concentrations (confidence intervals in parentheses) at 90 and 95% of maximum yield for Queensland wheat crops grown on Black or Brown Vertosols with various ranges of growing season rainfall

r, Goodness of fit of the soil test calibration curve; slope RY, slope of fitted curve between 50 and 80% of maximum yield

Growing-season rainfall filter	No. of treatment series	90%	95%	*r*	Slope RY
None	187	25 (22–28)	34 (30–38)	0.64	2.5
<150 mm	61	25 (20–31)	32 (26–40)	0.67	Poorly defined
150–200 mm	51	26 (20–34)	35 (28–46)	0.62	2.1
200–250 mm	34	27 (20–36)	37 (27–49)	0.65	1.7
>250 mm	37	24 (17–33)	33 (25–44)	0.57	2.0

Table 7. Colwell-P soil test (mg/kg; 0–10 cm) critical concentrations (confidence intervals in parentheses) for 90 and 95% of maximum yield of Queensland wheat crops grown on Black or Brown Vertosols with above or below 250 mm of stored soil water at sowing

r, Goodness of fit of the soil test calibration curve; slope RY, slope of fitted curve between 50 and 80% of maximum yield

Stored soil water (mm)	No. of treatment series	90%	95%	*r*	Slope RY
<250 mm	139	22 (19–26)	31 (27–36)	0.64	2.1
>250 mm	42	34 (29–41)	43 (35–52)	0.74	2.5

(Table 6) or in Grey Vertosols (data not shown). However, partitioning of series according to soil profile water at sowing gave rise to different apparent critical P concentrations for wheat on Black and Brown Vertosols (Table 7). With <250 mm of stored soil water, the critical concentration was 31 (confidence interval 27–36) mg/kg, compared with 43 (35–52) mg/kg with >250 mm stored water. The apparent effect of increased stored water may be due to higher yield obtained, although these experiments were conducted when long fallows (more stored water) were prevalent, and these are known to depress the population of mycorrhizal spores and thus increase dependence of the crop on applied P (Thompson 1990).

Soil texture

The reporting of soil texture in the metadata was limited to <40% of treatment series and resulted in insufficient treatment series with which to systematically examine texture effects on critical concentrations. Considering all the Yellow, Brown, and Grey Chromosols, the critical concentration was 25 (confidence interval 19–33) mg/kg, whereas for just the sand-textured profiles of this soil group, the critical concentration was 19 (12–27) mg/kg. By contrast, for Red Chromosols there was no difference between the critical P concentrations in the sandy loam texture class compared with all the treatment series for this soil group.

In Kandosols, gravel can represent a high proportion of the soil mass in the root-zone, but the soil P test was conducted only on the fine (<2 mm) fraction. However, gravel percentage was not reported in the metadata; hence, its influence on critical P concentrations, which is discussed below, could not be assessed.

Phosphorus sorption

Testing the effect of PBI on critical P concentrations was constrained by the limited number of treatment series with measured PBI, especially for soils with extremely low or high PBI (Table 8). For ‘very very low’ to ‘low’ PBI classes (Moody 2007), change in PBI had no effect on the critical Colwell-P concentration for wheat. When PBI was rated extremely low or moderate, there were insufficient treatment series to fit a soil test calibration curve. There were insufficient data in the BFDC National Database for soils across a wide range of PBI to examine its effects on critical Colwell-P concentrations.

Validation of estimated critical concentrations

In general, there was no significant difference between critical values and confidence intervals for the classes A + B compared with class A treatment series only for wheat (Table 9). However, since the class B treatment series represented datasets independent from the class A treatment series, they were used to test the validity of the estimated critical concentrations derived from class A treatment series for wheat. For many soils, there were sufficient class A treatment series to estimate critical concentrations and confidence intervals (Table 2) but insufficient class B data to test the accuracy of these estimates. Nevertheless, for Black and Brown Vertosols, Grey Vertosols, Red Chromosols, Yellow, Brown and Grey Chromosols, Calcarosols, Supracalcic and Hypercalcic Calcarosols, Grey Tenosols, and Yellow, Brown and Red Tenosols, it was possible to test the accuracy of the critical concentrations at 90 and 95% of Y_{max}. While filters were used to establish the most reliable critical concentrations, they were not applied for

Table 8. Effect of phosphate buffer index (PBI) class on critical concentrations (mg/kg; CC) and confidence intervals (CI) of Colwell-P for wheat at 90 or 95% of maximum yield

Treatment series were filtered to remove severe stress, yield <1 t/ha and pH_{CaCl2} <4.3. PBI classes as defined by Moody (2007). Class A and B treatment series are both included (see *Materials and methods* for definitions of classes). Soils sampling depth 0–7.5 cm (adjusted) plus 0–10 cm. *r*, Goodness of fit of soil test calibration curve; slope RY, slope of fitted curve between 50 and 80% of maximum yield

PBI class (range)	No. of treatment series	90%		95%		*r*	Slope RY
		CC	CI	CC	CI		
Extremely low (<15)	5					No fit	
Very very low (15–35)	31	20	15–25	24	17–32	0.62	4.2
Very low (36–70)	94	22	17–28	27	20–36	0.49	3.6
Low (71–140)	62	23	18–29	29	22–39	0.6	3.3
Moderate (141–280)	21					No fit	

Table 9. Effect of selecting either class A treatment series only or class A + B treatment series on critical concentrations (mg/kg; CC) and confidence intervals (CI) corresponding with 80, 90, and 95% of maximum yield of wheat for selected Soil Orders or Sub-orders

Soil samples from 0–7.5 or 0–10 cm depth. *r*, Goodness of fit of the soil test calibration curve; slope RY, slope of fitted curve between 50 and 80% of maximum yield. See *Materials and methods* for definitions of classes of treatment series

Soil Order or Sub-order	No. of trials	80% CC	80% CI	90% CC	90% CI	95% CC	95% CI	*r*	Slope RY	Treatment series
All Sodosol	107	21	17–25	28	22–36	34	26–46	0.55	1.8	A + B
	93	21	17–27	29	22–38	35	26–48	0.55	1.8	A only
All Chromosol except Red Chromosol	121	14	12–16	18	15–22	22	18–27	0.73	2.2	A + B
	114	13	11–16	18	15–22	22	17–27	0.66	2.0	A only
Grey Vertosol	102	13	10–16	17	14–21	21	17–27	0.41	2.3	A + B
	69	11	9–15	15	12–19	21	16–27	0.36	2.4	A only

Table 10. Accuracy of prediction of crop relative yield by pre-plant soil phosphorus test

Accuracy was measured by scoring the number of treatment series for a particular selection of soils where a soil test value above the critical concentration correctly predicted relative yield above the yield threshold (90 or 95% of maximum) and where a soil test value below the critical concentration correctly predicted a relative yield below the yield threshold (90 or 95% of maximum). Only class B treatment series were used. No yield filters were applied since the use of the critical concentration as a prognostic test for P deficiency occurs before planting the crops when yield outcome is unknown. For critical concentrations and confidence intervals applied for each soil see Table 2. LCI, Lower end of confidence intervals; CC, critical concentration; UCI, upper end of confidence interval

Soil type	Yield threshold (% of maximum)	No. of treatment series	% Correct prediction Overall	<LCI	LCI CC	CC UCI	>UCI
Black and Brown Vertosol	95	182	76	87	50	50	81
	90	182	84	84	73	42	92
Grey Vertosol	95	36	61	100	100	40	27
	90	36	53	100	67	25	59
Red Chromosol	95	37	68	93	83	25	63
	90	37	62	82	67	25	67
Calcarosol (Calcic or Lithocalcic Sub-orders)	95	22	77	100	80	0	50
	90	22	64	71	67	33	67
Supracalcic or Hypercalcic Calcarosol	95	9	33	–	100	0	0
	90	9	11	–	0	0	17
Grey Tenosol	95	9	33	67	–	0	20
	90	9	22	33	–	–	17
Yellow, Brown and Red Tenosol	95	11	91	100	100	50	–
	90	11	82	100	–	0	50
Summary	95	306	72	91	72	36	70
	90	306	72	83	68	31	80

predicting the accuracy of the critical concentrations. The reasoning behind this was that a soil test is conducted before the crop is grown, and hence, the P fertiliser decision based on the soil analysis is made before the seasonal conditions affecting yield are known.

Overall, 72% of the Colwell soil P analyses correctly predicted whether yield would be depressed by P deficiency (Table 10). For Vertosols, Red Chromosols, and Calcarosols, for which the most treatment series were available, the accuracy of the critical Colwell-P concentration was 53–84%, but over two-thirds of the data were from Vertosols. For Grey Tenosols and Supracalcic Calcarosols, the accuracy of the prediction of Y_{max} from the critical concentration was poor, possibly because insufficient numbers of treatments series were available for each of these soils.

Barley

For barley, the critical P concentrations increased in the order: Grey Vertosol < Chromosols and Sodosols < Calcarosols < Ferrosols (Table 11). The Red Chromosol Sub-orders may have higher critical P concentrations than do other Chromosols (30 *v.* 26 mg/kg), but the confidence intervals of the two groups substantially overlapped. Indeed, for each of the soil groupings used, there were wide confidence intervals, suggesting that additional filters would be useful to apply, but the lack of treatment series for barley usually precluded further partitioning of the dataset in the way done with wheat.

Discussion

Representativeness of soil P tests

Soils types, classified by the ASC, were a primary factor in distinguishing critical P concentrations, as they were in the last major study of critical soil P concentrations for crops in Australia (Moody and Bolland 1999). In decreasing order of prevalence, the major ASC Soil Orders for wheat available in the BFDC National Database were: Vertosol > Calcarosol > Chromosol > Tenosol > Kandosol > Sodosol > Dermosol. All other ASC Orders were represented by too few samples to be analysed

Table 11. Critical Colwell-P concentrations (mg/kg; CC) and 95% confidence intervals (CI) for barley corresponding to 80, 90, and 95% of maximum relative yield

r, Goodness of fit of the soil test calibration curve; slope RY, slope of fitted curve between 50 and 80% of maximum yield. Soil depth was 0–10 cm

Soil Order or Sub-order	No. of treatment series	80%		90%		95%		*r*	Slope RY
		CC	CI	CC	CI	CC	CI		
Black, Brown, and Grey Vertosol	11	13	8–23	17	12–25	21	14–29	0.63	Not defined
Chromosol and Sodosol	43	15	12–18	22	17–28	28	21–38	0.78	3.5
Brown and Red Chromosol	31	17	13–21	25	18–35	33	22–49	0.78	2.9
Calcic and Hypercalcic Calcarosol	13	31	24–39	34	26–44	36	27–48	0.57	6.0
Red Ferrosol	28	54	39–75	76	50–120	96	55–170	0.44	1.0

separately, although 21% of treatment series had no reported ASC group. For barley, only Red and Brown Chromosols, Vertosols, Hypercalcic Calcarosols, and Red Ferrosols had sufficient treatment series to estimate critical concentrations. The distribution of soils on which cereals are grown reflects regional geology (McKenzie *et al*. 2004). Calcarosols were predominantly in SA, Vertosols were mostly in Queensland and NSW, while WA had most of the Tenosols. Grain-production regions of northern NSW and Queensland are chiefly represented by heavy-textured soils that dominate in this usually low winter rainfall zone. However, within other states there may be notable gaps in the soils and regions represented. For example in WA, Anderson *et al*. (2013*a*) noted that there were few P-response treatment series for wheat in the Northern Agricultural Region. Moody and Bolland (1999) report on experiments that fill some gaps, such as for Ferrosols with wheat, but the number of treatment series is insufficient for *BFDC Interrogator* analysis. The gaps identified will be important for locating future trials.

Improving reliability of critical soil P test

In the present study, we have focussed on refining critical P concentrations and decreasing the range of the confidence interval of the estimated value. However, the greatest source of variation in soil P tests generally arises from the method and representativeness of soil sampling in the field (Brown 1999). Factors affecting the collection of a representative soil sample for P analysis include the number of subsamples composited, depth of sampling (e.g. Bolland and Brennan 2006) especially for no-till wheat, spatial variation in Colwell-P including location of previous fertiliser bands (Bolland and Brennan 2006), and time of year (Brown 1999). Best practice for soil sample collection needs to be followed in order to ensure that the soil P test for the site can be validly compared with other values in the database. Brown (1999) described methodologies that should be followed when collecting representative soil samples for chemical analysis. Quality control and quality assurance of laboratory results is also crucial for the validity of soil P test interpretation. Adherence to published methods for soil P testing (e.g. Rayment and Lyons 2011) provides confidence that soil P results from different laboratories and from samples collected in different years are indeed comparable. Laboratories that routinely and successfully participate in proficiency testing programs offered by the Australasian Soil and Plant Analysis Council (ASPAC; see www.aspac-australasia.com/index.php/lab-proficiency) provide a greater level of confidence in the accuracy of the laboratory determination of P.

Prior to this study, the most comprehensive assessment of critical soil P concentrations for wheat was that compiled by Moody and Bolland (1999). The purpose of that review was to assemble from regional studies the reported critical concentrations associated with 90% of maximum yield. Data were assembled from both published and unpublished sources but the critical P concentration was generally estimated by authors who contributed the data. The key difference with the present study is that a consistent methodology has been applied to estimating Y_0 and Y_{max}, and a standardised regression function applied to all treatment series. Where filters have been applied, these are explicit in the findings reported. Moreover, all the data used in the analysis are accessible to other registered users of *BFDC Interrogator*, and hence, the analysis is repeatable and assumptions used in the present study can be tested for validity in particular regional circumstances. Further treatment series will be added to the BFDC National Database over time meaning that critical concentrations will need to be periodically updated.

Another key advance in the present analysis is that confidence intervals are reported for the calculated critical concentrations. In plant analysis, several authors have advocated for the use of critical ranges rather than critical values (e.g. Dow and Roberts 1982; Wei *et al*. 1998). It is argued that a critical concentration implies a level of precision in the estimated value that is not justified by the variability of the field environment or the variability associated with the sample collection. The present analysis and the *BFDC Interrogator* tool provides for the first time an explicit statement about the level of confidence that should be attached to the critical concentration. This approach appears to overcome many of the drawbacks identified by Jordan-Meille *et al*. (2012), who assembled soil P test calibrations for 18 European counties. Jordan-Meille *et al*. (2012) commented on the lack of standardisation in methods used to derive critical concentrations for P in Europe and the lack of access to original data, which made it difficult to synthesise results from different studies and across different countries.

In establishing reliable critical P concentrations from the BFDC National Database, the criteria we applied were: maximising goodness of fit, minimising the size of the confidence interval, and decreasing the number of plotted treatment series with either false negative (high Y_{max} but low soil P) or false positive (low Y_{max} but high soil P) relationships between yield and soil test P. Low yield or crop stress (commonly due to drought) limits the demand for all nutrients,

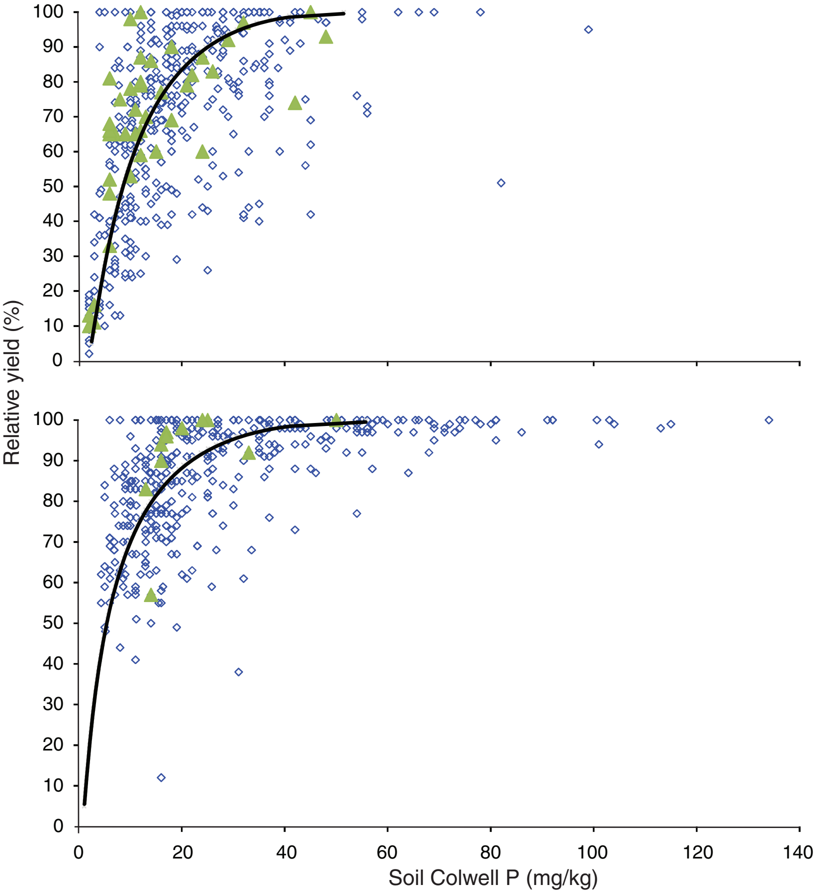

Fig. 4. Relationships between relative yield (as a percentage of maximum for each treatment series) and Colwell extractable P (0–10 cm) for barley (▲) *v.* wheat (◇) on: Chromosol and Sodosol profiles (upper panel) and on Vertosol profiles (lower panel).

and hence for such crops, it is common to achieve a high relative yield even with low soil P levels (e.g. Fig. 4). In the present study, we have addressed this phenomenon and its effect on the calculated critical P concentration by excluding treatment series with yield <1 t/ha and those with severe crop stress. Improved *r*-values and decreased confidence intervals were generally obtained from this screening, and plots of Y_{max} *v.* Colwell-P had fewer false negative results. Severe crop stress was used as a filter for the same reason. Overall ~7% of data points had yield <1 t/ha. It could be argued that 1 t/ha is an arbitrary minimum yield threshold. When we varied the threshold from 1 to 1.2 or 1.3 t/ha, there was little improvement in the goodness of fit of the regression, or change in the critical P concentration itself or the size of the confidence interval (data not shown). Nevertheless, for regional application of the *BFDC Interrogator* to generate relevant critical concentrations, a different yield filter could be used. We suggest that the 0–20 percentile range for yields for that region, denoting severe stress, might be a suitable threshold to apply in the first instance.

Applying a filter for low pH also improved the goodness of fit and decreased the confidence interval by removing false positive points. Low pH may be associated with Al toxicity, which limits root growth and hence restricts P uptake (Slattery *et al.* 1999). At these sites, even with soil P levels above the critical concentration (or even above the upper confidence limit), low Y_{max} was obtained. It may be possible to increase Y_{max} on such sites by increased rates of P fertiliser, but a better investment for grain growers is to apply lime to treat soil acidity. It is possible that with a larger dataset it could be shown that higher critical soil P concentrations apply to such acid soils, but we recommend that the focus of attention should be on treating acidity in the first instance. We used pH_{CaCl2} <4.3 as the acidity filter, since this is commonly used as a pH threshold for Al toxicity (Slattery *et al.* 1999). However, the pH threshold for wheat cultivars may vary, and the threshold for barley is generally higher (Slattery *et al.* 1999). In principle, a different pH filter could apply to a particular region's cropping system, but presently we had insufficient metadata to test this. In addition, manganese toxicity or molybdenum deficiency may be the main acidity constraints in some soils and this might warrant a higher pH filter (Slattery *et al.* 1999).

Existing literature usually sets critical P concentrations at 90% of Y_{max} (e.g. Moody and Bolland 1999). However, *BFDC Interrogator* also provides critical concentrations corresponding with 80 or 95% of Y_{max}. With Colwell-P, the upper confidence limit for the critical concentrations corresponding with 90% of Y_{max} was a similar value to the critical concentration associated with 95% of Y_{max}. The choice of which level of Y_{max} to apply for setting a critical concentration depends on the production system and the level of risk acceptable to a grower. In a reliable, high-rainfall zone or, indeed, with irrigation (which is uncommon for wheat in Australia), the upper confidence limit of the critical concentration associated with 95% of Y_{max} may be an appropriate target Colwell-P concentration, since the risk of lost yield from inadequate P may greatly exceed the risk of no return from the P fertiliser investment in the year of application due to low yield. By contrast, in low-yielding and unreliable rainfall zones, the critical concentration at 80% of Y_{max} provides guidance that may be useful to growers seeking to minimise costs of P fertiliser when the likelihood of profit from the investment is low.

The *BFDC Interrogator* can be used to re-examine published estimates of the critical P concentrations. For example, Holford and Cullis (1985) concluded that the critical value (90% Y_{max}) was 25 ± 4 mg/kg for the Colwell soil P test on a 0–10 cm soil sample. The treatment series within the *BFDC Interrogator* for the NSW wheatbelt covering a similar area (approximately bounded by the Murray River in the south, and Cootamundra in the north) gave a critical value for Colwell-P of 27 (20–36) mg/kg over 126 experiments with a soil pH_{CaCl2} of <5.6. This was consistent with the value reported by Holford and Cullis (1985).

In the northern NSW Slopes and Plains, the previously reported critical Colwell value ranged from 30 mg/kg (Holford and Doyle 1992) to 57 mg/kg (Holford and Cullis 1985). The latter and higher estimate was derived from a selection of 39 of 49 sites reported by Colwell and Esdaile (1968) and Colwell (1977). Based on all 49 sites, which have been entered in the BFDC National Database, the critical value for Colwell-P estimated by *BFDC Interrogator* was 25 (18–34) mg/kg, suggesting that the value of 57 mg/kg based on 39 of the sites was misleading.

The data of Doyle (1977) examined the N and P responses of wheat at 141 sites in northern NSW during 1974 and 1975. Response in grain yield to P application varied with soil pH, and Doyle (1977) concluded that grain yield responses to added P fertiliser ceased when Colwell soil P reached ~72 mg/kg at a soil pH_{H2O} of 6.5. Data from 61 of Doyle's sites were recovered but did not satisfy criteria for the class A treatment series in the BFDC National Database; only 21 sites were entered as class B treatment series. However, using the maximum average yields of the 61 sites, the critical Colwell-P concentration at 90% of Y_{max} was ~29 mg/kg. The mean pH_{H2O} of the known 61 sites was 6.54. The *BFDC Interrogator*, using class A treatment series only (i.e. independent dataset), produced a critical Colwell-P concentration of 30 (23–39) mg/kg at 90% of Y_{max} for the same region, which matches with 29 mg/kg for the entire dataset of Doyle (1977).

Critical Colwell-P concentrations quoted by Moody and Bolland (1999) for Queensland Vertosols also compare favourably with the values shown in Table 2. For Grey Vertosols of the Maranoa Region, a concentration of 15 mg/kg and confidence interval of 12–19 mg/kg agrees with previously quoted critical concentrations of 10–20 mg/kg. Similarly, for Black and Brown Vertosols of the Darling Downs Region, a critical concentration of 19 mg/kg and confidence interval of 16–22 mg/kg falls within previously quoted critical range of 15–24 mg/kg.

Factors affecting critical soil P test concentrations and confidence intervals

Era

Reuter *et al*. (1995) reported that Colwell-P in the 0–10 cm layer of soil was higher under no- till than under conventional cultivation. White (1990) reported a similar effect for three WA soils where direct drill (knifepoints) and zero tillage (disc openers) methods of seed and fertiliser placement were instituted. Indeed, within 3 years of adopting minimum tillage, stratification of Colwell-P in the surface 0–10 cm was measurable. This reflects both shallow placement of P fertiliser by drilling with the seed, and the lack of mixing by tillage (Chen *et al*. 2009). Across the whole BFDC National Database, considering all soils, the critical Colwell-P concentrations appeared to be higher in post-1994 treatment series than in the treatment series for earlier eras (1958–80 or 1981–93). This suggests either greater demand for extractable P or decreased P availability to crops. Yield level of wheat crops >1 t/ha had no significant effect on the estimated critical concentration for Colwell-P in the present study, so that the change in critical concentration may not be related to plant demand except at the very low yield levels. It is more probable that under minimum tillage, P availability to roots has declined. Chen *et al*. (2009) argued that under the rainfed conditions for wheat in Australia, the frequent drying of topsoil would limit root access to the P, which is increasingly stratified close to the soil surface under minimum tillage.

The implications of these findings are several-fold. First, some caution needs to be exercised with datasets, such as the Black and Brown Vertosols, derived largely from earlier eras. Where there are knowledge gaps for the recent era, additional experiments should be a priority to establish appropriate soil test critical concentrations for use in current fertiliser decision-making. Provided the following 'rule-of-thumb' is applied with caution when making P fertiliser decisions, critical Colwell-P concentrations derived in the pre-1990s era may be increased by up to 6 mg/kg to account for the combination of practice changes that have occurred over time, particularly the adoption of minimum tillage and the surface stratification of P that follows.

Soil properties

Water repellence is widespread in many cropping soils with low clay content in the surface horizon, particularly in WA and SA (Cann 2000). According to Dr J. W. Bowden (pers. comm.), significant areas of gravel soils (which are commonly Kandosols) in the high-rainfall zone (500–700 mm) of the WA grain-belt express severe water repellence, and respond to added P fertiliser even when soil Colwell-P concentrations are well above the apparent critical concentration. As with acidity (see above), it could be argued that these soils should be treated as having much higher critical P concentrations, and further evidence gathered to quantify the appropriate value, but more logically the focus should be placed on alleviating the primary constraint of water repellence. If effective technologies exist to do so, the latter approach should be a more cost-effective investment for grain growers than increased P fertiliser.

Soil tests are conducted on the <2 mm fraction of soils after sieving to remove coarse particles such as gravel (Rayment and Lyons 2011). For most soils, this method of sample preparation has no consequence apart from producing a more homogenous sample that minimises subsampling errors in the laboratory. However, on highly weathered land surfaces in southern Australia, a high proportion of the soil mass may be coarse gravel of ferruginous origin (McKenzie *et al*. 2004). Similarly, on Supracalcic and Hypercalcic Calcarosols, gravel-size calcite may account for a significant portion of soil mass (Isbell 2002). In some grain-cropping soils, gravel may comprise up to 60% of soil mass that is sieved out before analysis. A high soil P test value for gravel-rich soils may be misleading, since it represents a smaller P store available to plant roots than in a soil with low or zero gravel content. Moreover, the gravel not only dilutes the available P store, but the P sorption capacity of ferruginous gravel may be appreciable as is the capacity of calcite to cause precipitation of soluble P. On an Arenic Orthic Tenosol, increased gravel percentage in the sample was reported to increase the critical Colwell-P concentration from 10 mg/kg (no gravel) to 22 mg/kg (30–50% gravel) (Moody and Bolland 1999). Further investigation is needed to determine whether interpretation of the soil P test values for predicting crop response could be improved by consideration of the gravel percentage in soils submitted for P analysis. In addition, consistent reporting of the gravel content and PBI along with Colwell-P levels in soils may provide a more confident prediction of P availability to crops on gravel-rich soils.

Phosphorus sorption

Moody and Bolland (1999) suggested that the critical P concentration in the soil should be adjusted according to its PBI. Gourley *et al*. (2007) also proposed a PBI adjustment for critical P concentrations in pasture soils. The original concept appears to come from Helyar and Spencer (1977) and the original analysis based on five sets of P-response experiments in NSW (Curtis and Helyar 1984). Bolland *et al*. (1994), using 23 mostly sandy soils with low P sorption and no history of P fertiliser application, found a positive relationship between the critical Colwell-P level and the P buffering capacity (PBC) of the soil. However, Bolland *et al*. (1994) noted that the positive relationship was strongly influenced by a few soils with high PBC. Moody (2007) assembled >90 soils from several previous studies across Australia and found critical Colwell-P concentrations for wheat increase with PBI.

There were insufficient data on PBI in the present study to explicitly test for wheat the relationship between critical Colwell-P concentration and PBI; however, soils with the highest critical P concentrations were Red Chromosols, Red Sodosols, and Kandosols, all of which are expected to have high P sorption on account of high Fe- and Al-oxyhydroxide content, although this is not presently evident in the database. Supracalcic Calcarosols, which contain high content of free calcite, also had high Colwell-P critical concentrations, but precipitation reactions of soluble P on calcite rather than P sorption are the main mechanism for reduced P availability (Bertrand *et al*. 2003). By contrast, low critical P concentrations were derived for Grey Tenosols that have very low P sorption (Anderson *et al*. 2013*a*). In barley, very high critical P concentrations were obtained for crops on Ferrosols that are known to have very high P sorption (Moody and Bolland 1999) even though none of the treatment series for wheat or barley on Ferrosols in the BFDC National Database has accompanying PBI data. In the present study, treatment series were dominated by soils in the 'very very low' to 'low' PBI classes. Among these soils, the variation in PBI had no influence on the critical Colwell-P concentration. Similarly, Holford and Cullis (1985) and Bolland *et al*. (1994) suggest that there is little or no relationship between P sorption and the critical P concentration for the Colwell soil P test unless moderate to high PBI values are encountered. The present analysis contradicts the linear adjustment to critical Colwell-P concentrations with increasing PBI as proposed by Moody and Bolland (1999) and as used in studies such as that of Weaver and Wong (2011). We conclude that the BFDC National Database needs increased numbers of sites with PBI values, and more sites with extremely low and moderate–high PBI. Only then can the approach suggested by Moody (2007), which increases critical Colwell-P in a curvilinear relationship to increased PBI, be adequately tested.

Soil test method

Apart from the Colwell extractant for plant-available P, several other extractants were found to be well correlated with Y_{max} (Speirs *et al*. 2013). Critical P concentrations were derived for each of these tests. Many have been used internationally (e.g. Jordan-Meille *et al*. 2012; Kerr and Von Steiglitz 1938) but not as routine tests in Australia, apart from the Olsen-P for mostly dairy pastures and the BSES test, which is still commonly used in Queensland. No single soil P extractant is likely to universally outperform other tests (Moody 2007). For each extractant, the efficacy of the prediction of crop P response is likely to be higher on some soils than on others. For example, Bertrand *et al*. (2003) demonstrated that Colwell and Ca lactate extractants overpredicted the amounts of P available to plants on highly calcareous soils, whereas anion-exchange membrane extractable P was more promising as a predictor of plant-available P on these soils. However, there is substantial inertia in entirely replacing one extractant for another in commercial soil testing laboratories because of the large body of knowledge accumulated for the interpretation of the established test. In the BFDC National Database, Colwell-P information overwhelmingly dominates the available data, and yet even with this extractant, major gaps in the knowledge base were identified. Many laboratories in the USA are switching to the Mehlich 3 extractant as a multi-element extractant to reduce costs of analysis. Where clear relationships can be established between a new extractant and the established extractant, there are fewer impediments to making a switch. Bolland *et al*. (2003), for example, reported that Mehlich 3 extracted similar amounts of P to the Colwell extractant on a range of WA soils and had similar critical concentrations for wheat. A similar approach may have merit for the further development of DGT (diffusive gradients in thin-films) as a routine extractant for soil P availability in Australia (Mason *et al*. 2010).

Crop yield

As discussed above, filtering out treatment series with yield <1 t/ha improved the goodness of fit of relationships and decreased the confidence interval for the P critical concentrations of wheat. However, apart from the 1 t/ha filter, there was no effect of higher yields on critical P concentrations. According to Helyar and Price (1999), potential yield has only a minor effect on critical soil P concentration for wheat. In this respect, P critical concentrations contrast with soil N and K critical concentrations where higher yield generally requires a higher critical soil test value to meet the greater plant nutrient demand (Helyar and Price 1999; Brennan and Bell 2013).

The low-yield treatment series filtered out in developing critical Colwell-P concentrations may nevertheless contain important information for P fertiliser decision-making in low-yield environments such as the Upper Eyre Peninsula. For these regions, yields of ≤1 t/ha should be retained when examining the relationship between Y_{max} and Colwell soil P concentrations, since it is important for the P fertiliser decision to realistically assess the probability of no response when soil P level is low and the crop yield is also low.

Possible confounding factors in response to P

Placement method for P fertiliser is known to influence crop response. Broadcast P has reduced availability to plants, except on Grey Tenosols where post-application rainfall may be sufficient to dissolve fertiliser granules and leach released P into the root-zone (Bolland and Jarvis 1996). By contrast, when the topsoil dries during the growing season, both the P fertiliser placed with the seed and the topsoil P may have reduced availability to plant roots (Jarvis and Bolland 1991). In these situations, placement 5–10 cm below the seed may improve crop response to P fertiliser. Jarvis and Bolland (1991) found that wheat was less responsive to deep-placed P than was lupin, and they attributed this to the acquisition of P earlier in crop growth by wheat than by lupin. Chen *et al*. (2008) used APSIM simulation over 40 years (1957–2006) for Merredin (323 mm annual rainfall) on a duplex soil to determine the seasonal conditions under which a benefit from deep P placement would be observed for wheat yield on a low-P soil. For wheat, placement of P at 8 cm depth consistently improved wheat yield relative to placement at 4 cm; however, further increase in depth of P placement to 14 cm gave no yield response in any year in wheat. Hence, for wheat, current banding practices that place P fertiliser at 5–10 cm and near the seed appear to be optimal for P uptake, and they would not alter the soil P levels expected from a 0–10 cm sampling depth. In the BFDC National Database, there were insufficient treatment series with different placement methods to assess their effect on critical concentrations; however, the effect of P placement method on lupin and canola critical P concentrations is discussed by Bell *et al*. (2013*a*).

Many of the P fertiliser response experiments in the BFDC National Database used single superphosphate (SSP) as the experimental P fertiliser. From the 1980s, a more diverse range of P fertilisers was introduced and now the P fertilisers applied include triple superphosphate, MAP, DAP, and liquid P (ABARES 2011). There are several possible confounding effects of the P fertiliser source on crop responses. The crop yield response attributed to P may, at some sites, have been caused by S or zinc (Zn) contained in SSP (e.g. Riley *et al*. 1992). Similarly, many MAP and DAP products contain micronutrients such as Zn. The N content of MAP and DAP could confound the apparent P response. However, the screening process for data entry into the BFDC National Database involved experienced plant nutritionists who would have identified such confounding factors if they were adequately reported in the metadata available for each trial.

Liquid P fertilisers have proven to be more effective sources of P for cereals on Supracalcic and Hypercalcic Calcarosols (McBeath *et al*. 2007). However, there are few treatment series in the BFDC National Database with which to establish critical concentrations for P response with liquid P. Indeed, even the validity of the Colwell extractant for assessing plant-available P on such calcareous soils has been questioned (Bertrand *et al*. 2003).

Phosphorus-use efficiency varies among wheat cultivars (Osborne and Rengel 2002). Moreover, cultivar variation in tolerance to Al toxicity may affect response to Colwell-P. Current research aims to identify P-efficient germplasm that can be used to improve P-use efficiency of wheat cultivars (e.g. McDonald *et al*. 2010). The successful development and widespread adoption of P-efficient wheat and barley cultivars would necessitate re-examination of the appropriate critical Colwell-P concentrations.

Does barley need different critical values to wheat?

Wheat and barley are the two most prevalent grain crops in Australia (12.6 and 4.3 Mha, respectively, grown annually; ABARES 2011). By contrast, the number of P response experiments reported for barley in the BFDC National Database was <10% of the number for wheat. The salient question is whether the critical values for barley are significantly different from those for wheat. If not, then the critical values reported for wheat can be applied as reasonable approximations of those for barley. Even if there is a consistent difference between the two cereals in their critical values on the same soil, the more prevalent wheat experimental records could be used with caution as a benchmark for predicting the likely response of barley to P fertiliser. In addressing the critical P values for pulse, oilseed, and summer cereal crops, with limited numbers of reported P treatment series, Bell *et al*. (2013*a*) used wheat as a benchmark crop for estimating the relative responsiveness to P. Brennan and Bolland (2009) also advocated that critical soil P values for a newly introduced crop, such as canola in the south-west of Australia, should be established by reference to the critical concentrations for the dominant crop of the region, in this case wheat. A more comprehensive discussion of the merits of using soil test critical values for the dominant crop in a region (usually a cereal) as a surrogate for estimating responsiveness of other minor crops to soil P is outlined in Conyers *et al*. (2013).

Our analysis of the BFDC National Database suggested that critical soil P test levels for wheat were similar to those for barley (Tables 5, 7; Fig. 4). However, the barley records are for a limited selection of soils and limited mostly to SA and Tasmania. In SA, the critical concentration associated with 90% of maximum yield was 18 ± 3 mg/kg for barley across a diverse range of soils, which was not significantly different from that for wheat (21 ± 1 mg/kg) (Reuter *et al*. 1995). Average wheat grain yields are slightly lower than average yields for barley (1.56 *v.* 1.72 t/ha; ABARES 2011), but the present study suggests that critical P level was not sensitive to crop yield, except for those crops that have very low yield (<1 t/ha). The barley critical concentrations for Ferrosols may be useful in predicting wheat responses on the same soils, in the current absence of suitable wheat P data.

Gaps in experimental results

The compilation of the experimental records in the BFDC National Database has revealed significant knowledge gaps that limit the range of applications of soil testing for predicting P fertiliser response. Suitable records for oats, triticale, or rye were almost entirely absent. A similar observation about under-representation of pulse and oilseed species in the BFDC National Database has been made by Bell *et al*. (2013*a*) and Conyers *et al*. (2013). In the case of oats, which had an average production area of 0.83–1.24 Mha annually in Australia over the last 7 years (ABARES 2011), this is a major knowledge gap that could be addressed by targeted P-response trials on a selection of important soil types for oats, with wheat included as a benchmark species. Direct comparison of oat and wheat responses to extractable soil P levels at the same site and in the same season would improve the transferability of the oats data by providing access to the larger wheat database for those soils where there are no oats data. Inclusion of rye and triticale in such trials would establish a framework for estimating their likely response to soil P. In general, oats are regarded as requiring lower P fertiliser for maximum yield than wheat (Bolland 1992). Bolland *et al*. (1994) estimated critical Colwell-P concentrations at 50% of Y_{max} for oats and triticale but included no direct comparisons with wheat. Nevertheless, compared with barley, oats had lower critical Colwell-P concentrations at 50% of Y_{max}, whereas values for triticale were comparable to those for barley.

In the present study, metadata was useful for improving the goodness of fit of *BFDC Interrogator* relationships and decreasing confidence intervals associated with the critical concentrations. However, there were inadequate metadata on soil texture, pH, growing season rainfall, gravel content, and PBI to use these in a consistent manner for all queries. The value of future fertiliser response experiments for deriving critical concentrations for soil P could be greatly enhanced by consistently collecting and reporting metadata to improve the accuracy of critical concentrations (e.g. Jordan-Meille *et al*. 2012).

Interrogation pathway

From our examination of the BFDC National Database for soil P tests with winter cereals and the development of critical P concentrations using *BFDC Interrogator*, we suggest principles for interrogation pathways (Fig. 5). The pathway is designed to ensure that key factors affecting critical P concentrations are tested and appropriate filters applied that increase the goodness of fit by the soil test calibration curve and decrease the confidence interval. After first selecting a particular soil test (Colwell is the most likely because of the greater abundance of treatment series), a yield filter should be applied, but the threshold applied here (1 t/ha) can be adjusted for regional circumstances. Soil type is the next major choice, but soil texture or PBI may be alternatives to select if the database allows, because the primary factor that is being selected at this point is probably the P-sorption capacity of the soil. As more data are added to BFDC National Database, PBI may prove more reliable than a soil classification. Finally, there are several options that can be explored to enhance the accuracy of the estimated critical concentration and decrease its confidence interval. Treatment series selected from an era that reflects crop agronomy practices similar to the current system would

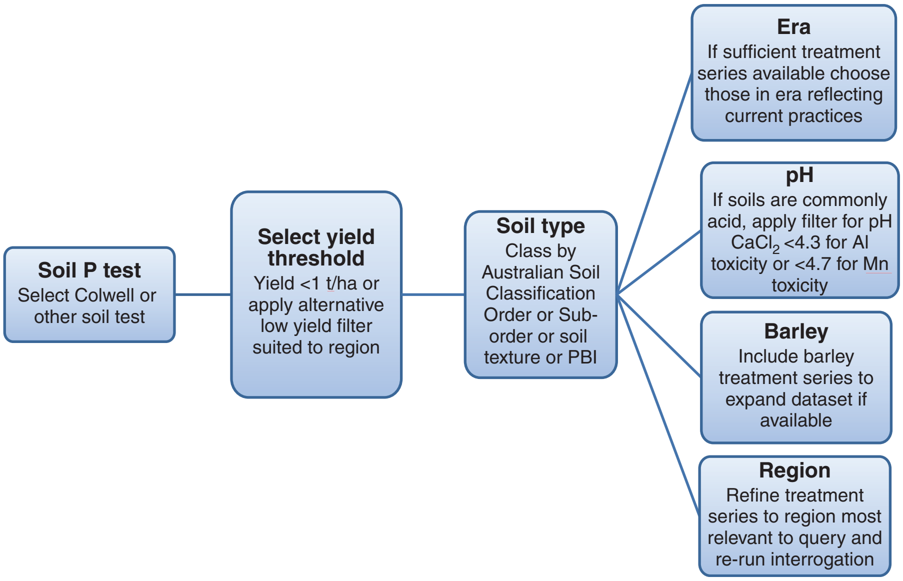

Fig. 5. Schematic of interrogation pathway for obtaining critical P concentrations to apply in a particular situation.

be preferable. For some regions, insufficient modern data are available to have this choice. We found no systematic evidence that barley critical P concentrations were different from those for wheat, so we suggest that where barley treatment series exist for the soil and region of interest, it is justifiable to include both wheat and barley treatment series to increase the number of the data points. Filtering out the acid soils generally improved the goodness of fit and decreased the confidence interval for the Colwell-P critical concentration. We used pH_{CaCl2} >4.3 since this threshold excludes most of the soils where Al toxicity limits P availability and yield potential. However, local variations on the pH filter may be warranted if there is evidence of a more appropriate pH threshold or if more acid-tolerant cultivars are grown. There may be regional differences in critical P concentrations for wheat and barley, and hence where sufficient treatment series are available, selection from the region most relevant to the query may be preferable.

Conclusions

From the present study, an interrogation pathway can be suggested for deriving reliable critical P concentrations with narrow confidence intervals for wheat. Low yield (<1 t/ha was a suitable filter) and severe crop stress treatment series should be removed before estimating the critical P concentration and confidence interval. However, since low yield and severe stress sites typically produced close to maximum yield even at very low Colwell-P concentrations, this needs to be considered in fertiliser decisions based on soil testing for low-yield environments. Variation in yield >1 t/ha had no significant effect on the critical P concentrations. Acidic soils with pH_{CaCl2} <4.3 also decreased the goodness of fit of relationships between yield and soil test P and increased the range of the confidence interval. Soil type based on ASC Orders and Sub-orders produced critical Colwell-P concentrations at 90% of Y_{max} from 15 mg/kg (Grey Vertosol) to 47 mg/kg (Supracalcic Calcarosols), with other soils having values in the range 19–27 mg/kg. The present analysis suggests that the critical P concentrations for wheat and barley on the same soils are comparable. There were insufficient treatment series with extremely low or moderate–high PBI in the database to test the effect of PBI on critical Colwell-P concentration for winter cereals.

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Appendix 1. Plots of relative grain yield (as a % of maximum) versus the Colwell P test for soils when wheat yield was <1 t/ha: (*a*) Grey Vertosol; (*b*) Yellow, Brown and Red Tenosols; (*c*) Calcic Calcarosol; (*d*) Supracalcic Calcarosol