10-15-2019

The development and application of functions describing pasture yield responses to phosphorus, potassium and sulfur in Australia using meta-data analysis and derived soil-test calibration relationships

Cameron J P Gourley

David Weaver

Richard J. Simpson

Sharon R. Aarons

Murray M. Hannah

See next page for additional authors

Authors

Cameron J P Gourley, David Weaver, Richard J. Simpson, Sharon R. Aarons, Murray M. Hannah, and Ken I. Peverill

CSIRO PUBLISHING

Crop & Pasture Science, 2019, **70**, 1065–1079
https://doi.org/10.1071/CP19068

The development and application of functions describing pasture yield responses to phosphorus, potassium and sulfur in Australia using meta-data analysis and derived soil-test calibration relationships

Cameron J. P. Gourley[A,B,F], *David M. Weaver*[C], *Richard J. Simpson*[D], *Sharon R. Aarons*[A], *Murray M. Hannah*[A], *and Ken I. Peverill*[E]

[A]Agriculture Research Victoria, Ellinbank Centre, Department of Economic Development, Jobs, Transport and Resources, Ellinbank, Vic. 3821, Australia.
[B]School of Chemistry, Monash University, Clayton, Vic. 3800, Australia.
[C]Department of Primary Industries and Regional Development, 444 Albany Highway, Albany, WA 6330, Australia.
[D]CSIRO Agriculture and Food, GPO Box 1700, Canberra, ACT 2601, Australia.
[E]KIP Consultancy Services, 4 Collier Court, Wheelers Hill, Vic. 3150, Australia.
[F]Corresponding author. Email: Cameron.Gourley@ecodev.vic.gov.au

Abstract. An improved ability to predict pasture dry matter (DM) yield response to applied phosphorus (P), potassium (K) and sulfur (S) is a crucial step in determining the production and economic benefits of fertiliser inputs and the environmental benefits associated with efficient nutrient use. The adoption and application of soil testing can make substantial improvements to nutrient use efficiency, but soil test interpretation needs to be based on the best available and most relevant experimental data. This paper reports on the development of improved national and regionally specific soil test–pasture yield response functions and critical soil test P, K and S values for near-maximum growth of improved pastures across Australia. A comprehensive dataset of pasture yield responses to fertiliser applications was collated from field experiments conducted in all improved pasture regions of Australia. The Better Fertiliser Decisions for Pastures (BFDP) database contains data from 3032 experiment sites, 21 918 yield response measures and 5548 experiment site years. These data were converted to standard measurement units and compiled within a specifically designed relational database, where the data could be explored and interpreted. Key data included soil and site descriptions, pasture type, fertiliser type and rate, nutrient application rate, DM yield measures and soil test results (i.e. Olsen P, Colwell P, P buffering, Colwell K, Skene K, exchangeable K, CPC S, KCl S). These data were analysed, and quantitative non-linear mixed effects models based upon the Mitscherlich function were developed. Where appropriate, disparate datasets were integrated to derive the most appropriate response relationships for different soil texture and P buffering index classes, as well as interpretation at the regional, state, and national scale. Overall, the fitted models provided a good fit to the large body of data, using readily interpretable coefficients, but were at times limited by patchiness of meta-data and uneven representation of different soil types and regions. The models provided improved predictions of relative pasture yield response to soil nutrient status and can be scaled to absolute yield using a specified maximal yield by the user. Importantly, the response function exhibits diminishing returns, enabling marginal economic analysis and determination of optimum fertiliser application rate to a specific situation. These derived relationships form the basis of national standards for soil test interpretation and fertiliser recommendations for Australian pastures and grazing industries, and are incorporated within the major Australian fertiliser company decision support systems. However, the utility of the national database is limited without a contemporary web-based interface, like that developed for the Better Fertiliser Decisions for Cropping (BFDC) national database. An integrated approach between the BFDP and the BFDC would facilitate the interrogation of the database by advisors and farmers to generate yield response curves relevant to the region and/or pasture system of interest and provides the capacity to accommodate new data in the future.

Additional keywords: better fertiliser decisions for pastures, fertiliser, pasture growth response.

Received 11 February 2019, accepted 14 June 2019, published online 15 October 2019

Introduction

On-farm management of fertiliser is of major economic significance to Australian grazing industries, when both expenditure on fertiliser and the higher farm productivity enabled by fertiliser use are considered. Fertilisers containing P, K and S continue to be a key requirement for the Australian grazing industries. However, increased community concerns about excess nutrients and impacts on water quality means that farmers and service providers need to have access to, and use, the best possible information regarding optimum nutrient management practices for environmental as well as productivity benefits.

As late as the 1960s, fertiliser recommendations were mostly based on the district-level advice because there was little or no capacity for farmers to access site-specific criteria (e.g. soil tests) to assess the nutrient requirements of individual paddocks (Reuter *et al*. 1995). Reuter *et al*. (1995) reported that high rates of superphosphate application were recommended typically for newly cleared land (e.g. 210–420 kg superphosphate/ha.year) with the rate of application being reduced to a 'maintenance' level once ~110 kg P/ha had been applied. Maintenance rates were expected to equal P removed in farm products, P lost by leaching and runoff and P 'immobilised' in the soil (Barrow 2015).

Even when soil testing became available to all farms from the 1970s, soil test targets for fertiliser use were not generally promoted. This may have been, in part, because critical soil test concentrations were known to differ with soil type (e.g. Rudd 1972) and hence rates of fertiliser application were often formulaic. For example, P-fertiliser rates were typically based on an early maintenance rate of 1 cwt superphosphate/acre (125 kg superphosphate/ha), but this was often applied annually, biennially or less frequently irrespective of the P status of a soil or whether available-P concentrations needed to be maintained or increased.

Assessment of P, K and S fertility status by soil testing is now widely accepted and is a major tool in providing fertiliser advice for crops (Speirs *et al*. 2013) and pasture (Simpson *et al*. 2015). The bicarbonate extraction procedure of Olsen (Olsen *et al*. 1954), further modified by Colwell (Colwell 1963), are the most recognised P soil test methods. Colwell K (Colwell 1963) and KCl-40 S methods (Blair *et al*. 1991) are most commonly used for K and S (Rayment and Lyons 2011).

The fertiliser advice provided to farmers has been underpinned by soil test calibrations relating soil nutrient levels to plant yield response and estimation of threshold soil test values. The concept of critical soil nutrient thresholds for near-maximum pasture production was recognised in numerous early studies of pasture responses to fertiliser application (e.g. P: McLachlan 1965; Rudd 1972; Spencer and Glendinning 1980; Yeates 1993; Gourley and James 1997; Angell 1999; Holford and Crocker 1988; Reuter *et al*. 1995; K and pH: Peverill *et al*. 1999; Gourley 1989; S: Blair *et al*. 1991). These largely regional- or state-based studies were often climate and soil type specific. Limited site numbers associated with many of these experiments often did not provide enough data or site diversity to enable the determination of universal response functions. Critical values varied between soil types and soil characteristics making it difficult to define universally-relevant soil test benchmarks from field experiment data (Bowden and Bennett 1975; Montgomery and Rubenis 1978).

The compilation of a large number of fertiliser response studies and their derived critical values (thresholds for critical values ranged from 50–90%) by Peverill *et al*. (1999) was a significant contribution to improving the standardisation of soil test interpretation for a broad range of Australian pastures and crops. However, key questions relating to the interpretation of soil tests remained, such as our ability to differentiate critical P, K and S soil test levels across regions and soil types. The demand for improved scientific evidence justifying fertiliser use, and therefore improved national soil test interpretation standards, was driven by increased scrutiny of environmental implications of fertiliser inputs, ongoing economic pressures facing pasture-based industries, improvements in soil test analytical techniques and technological advances in nutrient management and decision support systems for soil nutrient management. A more tailored approach to nutrient management, based on the best available information for soil test targets, a greater understanding of fluxes of nutrients on farms and potential nutrient loss processes and pathways will lead to improved nutrient efficiency on farm and hence the best return on fertiliser investment, as well as reduced risk of losses of nutrients to the environment (Gourley and Weaver 2012; Melland *et al*. 2008).

The collation, review and standardisation of field-based pasture yield and P, K and S fertiliser application experiments, undertaken between 1955 and 2006, resulted in the comprehensive national Australian database – Better Fertiliser Decision for Pastures (BFDP, Gourley *et al*. 2007). A similar approach was developed to improve the prediction of pasture yield response to nitrogen fertiliser applications for Australian pastures (Gourley *et al*. 2017). This paper describes the subsequent meta-analysis, developed response functions, model refinement and determined critical soil test values for the major P, K and S soil tests used for pastures in Australia. We also highlight the application of these functions and critical values which enable farmers and advisors to adopt a targeted approach to soil nutrient management for improved pastures.

Materials and methods

Collation of national datasets

A national team of scientists and fertiliser agronomists from all states of Australia identified and collated a comprehensive set of Australian pasture production fertiliser response data from around 650 pasture fertiliser experiments conducted between 1955 and 2006 from all major pastoral regions in Australia (Fig. 1). Sources of this information included peer-reviewed scientific publications, government and industry reports as well as unpublished data.

These field-based experiments varied from short-term single-site experiments to national studies involving multiple site and multi-year assessments. Most experiments were of a simple design involving the measurement of pasture DM yield response to surface-applied P, K and/or S fertiliser to an existing pasture, usually on a commercial dairy, sheep or beef farm with stock excluded during the growth assessment period.

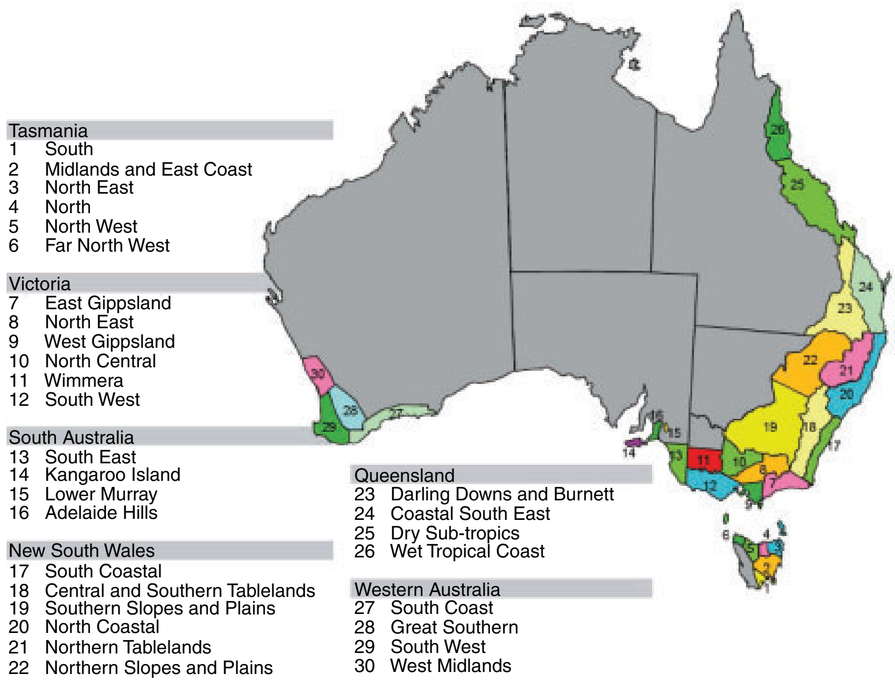

Fig. 1. Improved pasture grazing regions of Australia, segmented by climate, pasture type and irrigation.

Experiments had to meet strict design, data collection and quality criteria to be included in the analysis. This included adequate replication, a zero application (control) and a high application treatment of P, K and S, with evidence that all other nutrients were present at sufficient levels so as not to limit pasture growth.

A Microsoft Excel template used in the data collation process provided a standard format for field and laboratory data entry, and for site meta-data such as soil description and classification, location, experimental design, soil sampling depth, other soil and plant tests, climatic data and animal measurements. Templates were accompanied by a Microsoft Word document describing experimental aims, nutrient application rates, form of applied nutrient, number of replicates, experimental design and field methodology including harvesting techniques.

Many collated datasets presented data from several experiment sites or covered more than one trial year or more than one nutrient under investigation. Numerous datasets had multiple harvests while others had one harvest or a composite dry matter yield from multiple harvests. To simplify interpretation, each pasture dry matter (DM) harvest was treated as a separate experiment for an individual site and year (nutrient site year).

The data were adjusted to standardised units and compiled in a specifically designed national database (Microsoft Access), where the data could be explored and interpreted. Where necessary, the soil test analysis was adjusted to correspond to a standardised sample depth of 10 cm, using the algorithm described by Coad *et al.* (2010). All soil P sorption measures were transformed into an equivalent Phosphorus Buffering Index (PBI) (Burkitt *et al.* 2002) value as described by Watmuff *et al.* (2013). Skene K (Skene 1956) and Exchangeable K values were converted to estimated Colwell K values (conversion factor Skene K:Colwell K 1 : 1; exchangeable K : Colwell K 390 : 1; Gourley 1999) and all compiled data was used to derive relationships for Colwell K and relative yield (RY) for national, state, region, cation exchange capacity class and soil textural classes.

The final sets of raw data used for the meta-analysis were derived from 248 independent sources of experimental data ultimately compiled within the BFDP database (Gourley *et al.* 2007). The collated datasets provided 21 918 rows of data, from 3032 experiment sites and 5548 nutrient site years. An additional 400 dataset files were documented and archived but not processed for statistical analysis. The dataset therefore serves as an ongoing resource for information about pasture–fertiliser response experiments, and with new technology the capacity to accommodate new data in the future.

Prediction of relative yield response to P, K and S fertiliser applications

Where there was sufficient data, pasture DM yield in response to a range of applied P, K and S fertiliser rates was described using a modified Mitscherlich equation (Ozanne *et al.* 1969, 1976) of the form:

$$y = \alpha(1 - \beta * \exp(-\lambda x)) + \varepsilon \qquad (1)$$

where y is pasture DM yield (kg ha^{-1}), N is rate of nutrient P, K or S applied (kg ha^{-1}), α, β and λ are coefficients, and ε is error. The coefficient α determines the maximum attainable yield, β determines the proportion of this maximum yield present at 0 applied P, K or S, and λ is commonly referred to as the curvature, or c coefficient, as it determines the curvature of the response function. Estimated coefficients were plotted against meta-data to identify relationships between them, which were then used to expand Eqn 1. Values of λ were considered a reliable estimate of the curvature of the response curve where α was within 20% of the observed maximum yield and β had a value of at least 0.20.

Where there were insufficient data to fit a curve (e.g. with 2 or 3 rates of P, K or S) or curve fitting did not converge, relative yield (RY) was calculated for data as:

$$RY = \frac{\text{Pasture yield with no nutrient applied}}{\text{Maximum pasture yield when non-limiting nutrient is applied}} \times 100 \quad (2)$$

where the numerator and denominator are mean values. This formula was used because it guaranteed a result while maximising stability (i.e. good precision). It is a conservative method in that it tends to overestimate actual RY in cases where associated nutrient rates may not have resulted in the effective maximum response.

These two approaches were used to determine the RY for each trial site and related to the associated initial soil test value. The use of RY rather than absolute response overcomes differences in pasture yield between experiments and locations due to the effects of climate, season and growth period (Bowden and Bennett 1975). Negative as well as positive responses were included, to avoid any bias.

Only experiments that used the following Australian soil tests: Olsen and Colwell P; Colwell, Skene and exchangeable K; and CPC and KCl-40 S, were analysed because there were insufficient data to analyse less commonly used tests. The relationship between RY and associated soil test measure (e.g. Colwell P, Olsen P, Colwell K, CPC S and KCl-40 S) was determined using a modified Mitscherlich equation:

$$RY = 100 \times (1 - \exp(-c \times ST)) \quad (3)$$

where c is a regression coefficient that defines the curvature of the response and ST is soil test measure.

Effect of region, soil texture and PBI class

Soil test–pasture response relationships were determined for all national datasets, or differentiated by state, region, soil texture, PBI and cation exchange capacity categories. There were insufficient metadata to further differentiate the responses with respect to pasture species, pasture composition, and grazing enterprise.

The response relationships were compared statistically, and significant differences were identified. An F-test was used to determine if the individual region, soil texture and PBI class relationships were significantly different from the pooled relationship using the method described by Ratkowsky (1983). Where no statistical differences occurred, data were pooled to increase the precision of the final response relationship and were therefore deemed to be applicable across all pooled data. All statistical analyses were performed using the GENSTAT statistical package (Rothamsted Experimental Station, Lawes Agricultural Trust, Harpenden, UK). Once the optimum soil test–pasture response function for each soil test was developed, critical soil test values at 95% RY for P, K and S were determined.

In addition to developing soil test–pasture response relationships, the derived critical soil test values for P were compared with previous response relationships and critical values (Yeates 1993; Weaver and Reed 1998; Angell 1999; Moody 2007) developed in a limited geographical scope. Soil test–pasture response relationships were further adjusted to account for these previous response relationships, particularly where there were environmental implications from fertiliser use (Windsor *et al*. 2010). Response curves derived from Yeates (1993) for pure subterranean clover stands required that ammonium oxalate extractable Fe (Tamm 1922) ranges were converted to PBI using the transfer function provided by Weaver and Wong (2011). The critical Colwell P values from Moody (2007) were adjusted from 90% RY to 95% RY by multiplying the 90% RY values by 1.3, the ratio of 95% RY to 90% RY using Eqn 3 for any value of c.

Results

Although the key data relating to initial soil test level (i.e. Colwell P, Olsen P, Colwell K, Skene K, exchangeable K, CPC S, KCl-40 S), experiment location (i.e. national, state, region), experimental design, replication and pasture yield measurements were key requirements for the acceptance of any dataset, paucity in additional metadata relating to soil and site characteristics such as pasture species, botanical composition, irrigation practices and grazing management, did not enable additional data segmentation. A summary of the different soil fertility tests used across Australia at a state and national level, the number of experiment site years of data collected and collated in the relational database is presented in Table 1.

Olsen P

Olsen P is the second most common soil P test in Australia and is routinely used in Victoria and Tasmania. A total of 566 experiment site years of data were collected and collated to derive a national Olsen P pasture yield response relationship and critical soil test value (Table 1).

There were no significant differences between the Olsen P soil test–pasture response relationships when differentiated according to state, region, soil texture and PBI categories. There was no consistent trend of increasing critical value with

Table 1. The number of experiment site years of data collated for various soil tests across States and nationally

	Tas.	NSW	Vic.	SA	WA	Qld	National
Olsen P	0	66	395	70	35	0	566
Colwell P	532	269	420	548	430	45	2244
Bray1P	0	87	91	30	0	1	209
Bray 2P	0	60	39	0	26	21	146
Lactate P	0	66	91	0	0	0	157
Fluoride P	0	60	0	0	0	0	60
HCl Extr. P	0	0	39	0	0	0	39
Kerr/Von Stieglitz P	0	0	0	0	0	35	35
Morgan P	0	0	91	0	0	0	91
Egner P	0	0	91	0	0	0	91
Colwell K	512	128	277	19	164	10	1110
Skene K	0	0	104	0	26	0	130
Exch. K	0	114	94	1	0	9	218
CPC S	0	83	167	0	0	11	261
KCl-40 S	0	24	0	33	1	0	58
MCP S	0	0	89	29	0	7	125

increasing clay content, however, the sand textural class had a lower critical Olsen P value (11–14 mg/kg). In contrast, clay loams had an estimated critical value of 36 mg/kg, though the range was large and the r^2 value was only 0.085. The undifferentiated dataset (Fig. 2) was therefore used to derive a response relationship with a 95% critical Olsen P value of ~15 mg/kg (Table 2), with an overall r^2 value of 0.199

Colwell P

The Colwell soil test is the most common P soil test in Australia and is the standard in all states except Victoria. The Colwell P data consisted of 2244 experiment site years of data, nearly 50% of all collected soil test data (Table 3). There were no statistically significant differences between the Colwell P–pasture response relationships when differentiated by state, region or soil texture.

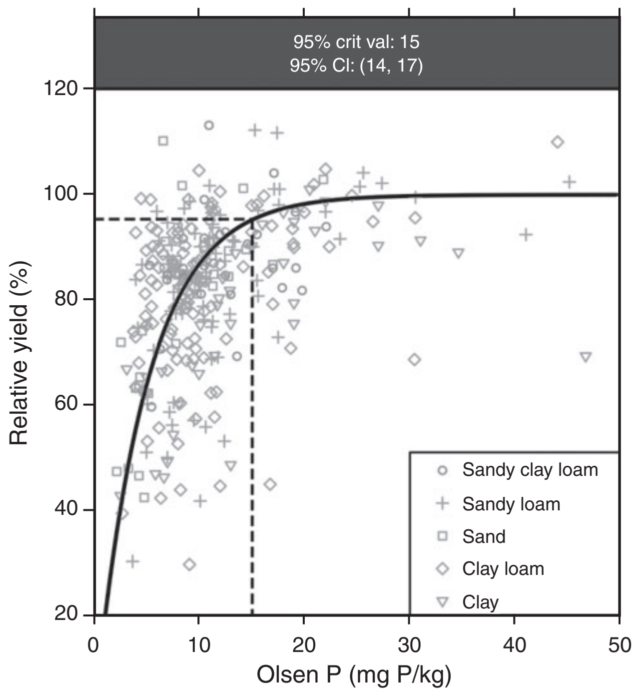

Fig. 2. The relationship between relative yield (RY %) and Olsen P soil test value from nationally collated experiments, showing the soil texture class for individual field experiments. The critical Olsen P soil test value at 95% RY is indicated by the dashed line and shown in the panel header along with 95% confidence interval (CI).

Table 2. The 95% critical Olsen P soil test value and equation describing the relationship between Olsen P soil test value and pasture DM relative response (RY %)

Critical value (mg/kg)[A]	95% confidence interval[B]	Number of experiments	Equation RY (%)[C] =
15	14–17	303	100 × (1 – exp (–0.202 × Olsen P))

[A]Soil test value at 95% of predicted relative yield.
[B]95% Chance that this range covers the critical soil test value.
[C]exp = Euler's constant (~2.71828).

The national data relating Colwell P to RY resulted in a critical Colwell P value of 35 mg/kg, with an r^2 of 0.477. Differentiating by soil texture revealed very small differences in derived critical values, and no clear trend of increasing critical value with increasing clay content. (Table 3). Sandy loams (41 mg/kg) and Clay loams (39 mg/kg), were the only exceptions, and these values are not substantially different from the critical value derived for the national dataset. These results challenge the previously held view that critical Colwell P levels increase with increasing soil clay content.

Differentiating Colwell P critical values with PBI

A total of 605 Colwell P experiment site years of data were partitioned into 12 overlapping PBI classes to increase statistical power (Fig. 3). A highly significant ($P < 0.01$) curvilinear relationship was determined between the estimated critical Colwell P values at 95% RY and mean PBI value for each designated PBI class (Eqn 4; Fig. 4). The relationship between the critical Colwell P and designated PBI range enables the estimation of a critical Colwell P value for 95% RY when the PBI of a soil is known (Table 4).

$$\text{Critical Colwell P} = 19.6 + 1.1 \times \text{PBI}^{0.55} (r^2 = 0.92) \quad (4)$$

Additionally, the regression *c* coefficients (Fig. 4) were correlated with the mean PBI in each range (Eqn 5), enabling RY to be described as a continuous function of PBI and Colwell P (Eqn 6). The advantage in such an approach is that there is no restriction to 95% of RY as specified in Fig. 4 and Table 4. Lower or higher yield targets can be estimated dependent on PBI and Colwell P values:

$$c = -0.196 + 0.046 \times \text{PBI}^{0.179} (r^2 = 0.94) \quad (5)$$

$$\text{RY} = 100 - 100 \times \exp((-0.196 + 0.046 \times \text{PBI}^{0.179}) \times \text{Colwell P}) \quad (6)$$

The relationship used to predict Colwell P from PBI values for 95% RY (Eqn 4) indicated that the critical Colwell P never falls below 20 mg P/kg (Fig. 5). A comparison of critical Colwell P values for Moody (2007) and Yeates (1993) to those derived from Eqn 6 indicate a wider range of *c* coefficients for soils with low PBI, and lower critical Colwell P values than that derived by Gourley *et al.* (2007) (Fig. 5). For example, critical Colwell P values of 0–20 mg P/kg are reported by Moody (2007) and

Table 3. Colwell P 95% critical soil test levels (mg/kg) and 95% confidence intervals, number of experiments and r squared value, differentiated by soil textural classes

Category	Critical value	95% Confidence interval	Number of experiments	r^2
National	35	34–36	879	0.477
Volcanic clay[A]	–	–	9	–
Clay	35	34–37	75	0.558
Clay loam	39	37–40	185	0.265
Sandy clay loam	41	38–43	39	0.351
Sandy loam	35	34–36	282	0.453
Sand	34	33–35	286	0.477

[A]Insufficient data to derive response relationship.

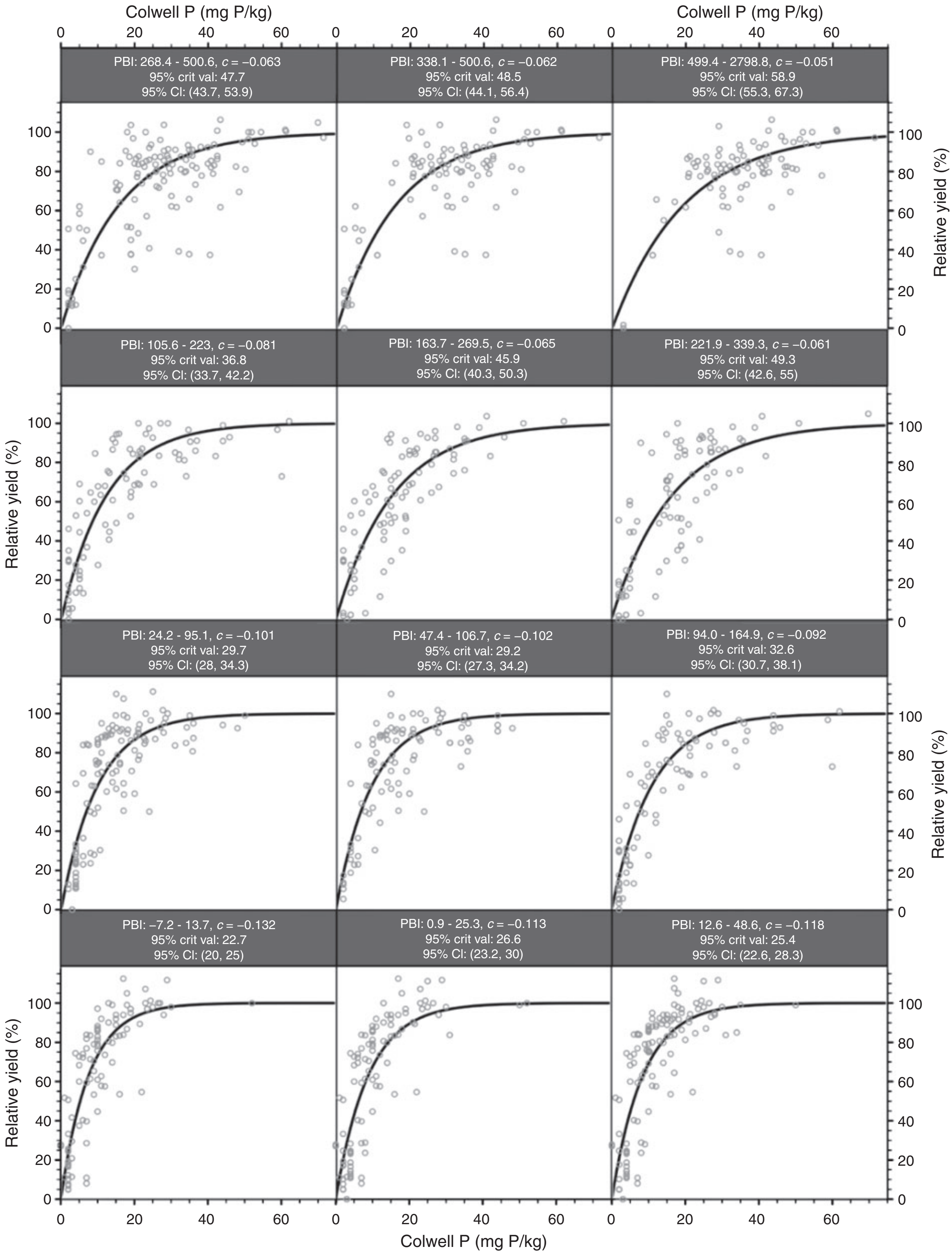

Fig. 3. The relationship between relative yield (RY %) and Colwell P soil test for overlapping PBI ranges. Critical value for 95% RY, 95% confidence interval (CI) and *c* coefficient shown for each PBI range in the panel header.

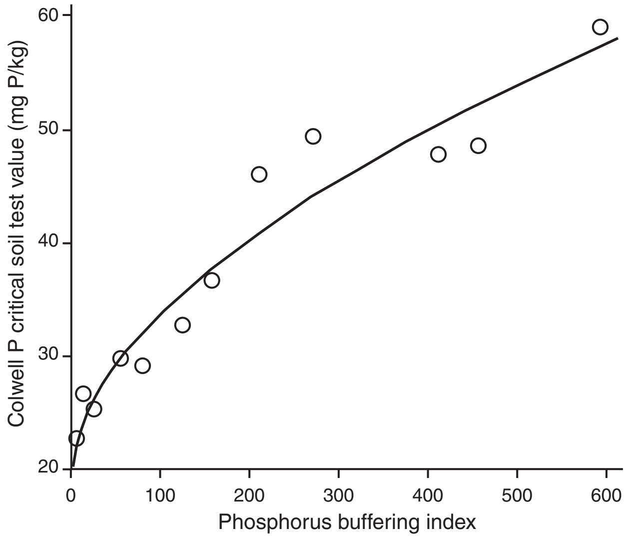

Fig. 4. Relationship between Colwell P critical soil test value for 95% relative yield (RY%) and phosphorus buffering index value (mean values within a range). $r^2 = 0.92$.

Yeates (1993) when PBI < 15 (Fig. 5), compared with a minimum Colwell P of 20 mg P/kg using Eqn 4, or a minimum of 15.3 mg P/kg using Eqn 6. These reports indicate greater responsiveness of low PBI soils (<15) to P additions and the need to refine critical Colwell P values for soils with PBI <15 (Yeates 1993; Angell 1999; Moody 2007; Bolland *et al*. 2010; Windsor *et al*. 2010).

Consequently, Eqn 6 was further modified (Eqn 7), based either on published models or models fitted to reported critical values for soils with PBI < 15 (Yeates 1993; Angell 1999; Moody 2007; Bolland *et al*. 2010; Windsor *et al*. 2010). The result is a close correlation with the initial critical Colwell P values (Eqn 4), except where PBI < 15 (Fig. 5), and where Colwell P values <20 should be expected. Equation 7 can also be modified to estimate a target Colwell P value based on a known PBI and a target RY (Eqn 8).

$$\text{RY} = 100 - 100 \times \exp((-0.196 + (0.045 - 0.227 \times \exp(-0.201 \times \text{PBI})) \times \text{PBI}^{0.179}) \times \text{Colwell P}) \quad (7)$$

$$\text{Colwell P} = \ln\left(\frac{\text{RY} - 100}{-100}\right) / (-0.196 + (0.045 - 0.227 \times \exp(-0.201 \times \text{PBI})) \times \text{PBI}^{0.179} \quad (8)$$

Other soil phosphorus tests

Pasture harvest data related to other soil P tests were also collated including Bray1 (209 experiment site years) and Bray2 (146 experiment site years), lactate (157 experiment site years), fluoride (60 experiment site years), HCl extractable (39 experiment site years), Morgan (91 experiment site years), Kerr and Von Stieglitz test (35 experiment site years) and Egner (91 experiment site years) (Table 1). Many of these tests were associated with a small number of regionally and soil type specific studies with limited scope for further data analysis and extrapolation to other sites or regions. Consequently, calibrations were not determined between RY and these historical soil tests which are rarely used today.

Table 4. Phosphorus buffering index (PBI) categories and corresponding Colwell P 95% critical soil test values

PBI category		Critical value (mg/kg) for mid point of PBI category (range)[A]
≤ 5	Extremely low	10 (9–12)
>5–10	Very low	15 (12–17)
>10–15	Low	20 (17–21)
>15–35	Moderately low	26 (21–28)
>35–70	Medium	29 (28–31)
>70–140	Moderately high	33 (31–35)
>140–280	High	39 (35–42)
>280–840	Very high	55 (42–68)
≥ 840	Extremely high	n/a[B]

[A]Critical Colwell P value at the midpoint of PBI class. Values in parentheses are critical Colwell P values at the lowest and highest PBI values within the range.
[B]Insufficient data to derive a response relationship.

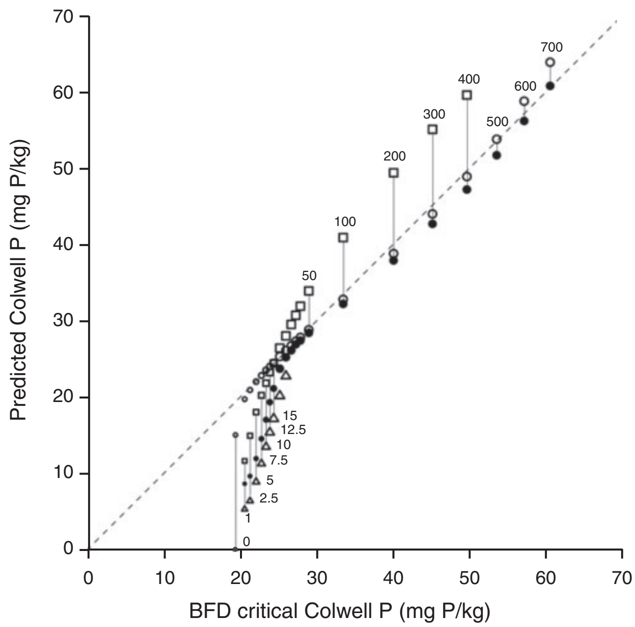

Fig. 5. Predicted Colwell P values compared with BFD critical values from Eqn 4 for (○) Eqn 6, (□) Moody 2007, (●) Eqn 7, (△) Yeates 1993. Dashed line = 1 : 1. Vertical lines span the Colwell P for different predictions, connecting points of the same phosphorus buffering index values (labelled).

Potassium soil tests

Various soil K extractants have been used and advocated by soil testing laboratories across Australia. Many of these tests are strongly correlated and appear to extract similar levels of soil K (Gourley 1999). Colwell K was the more commonly used soil K test nationally, with 1110 experiment site years collated within the BFDP database, while Skene K (130 experiment site years), and exchangeable K (218 experiment site years) were also routinely used. In total 1458 K fertiliser experiment site years were collated. Most of the data came from Victoria (335 experiment site years), followed by Tasmania which provided (60 experiment site years) and WA (45 experiment site years). There were very few, if any data provided from the remaining states (NSW 4 experiment site years, SA 1 experiment site year, and Qld 0 experiment site years).

When the combined national K soil test dataset, with all soil K data converted to Colwell K values, was used to derive a response relationship (Table 5) a critical 95% Colwell K value of 169 mg/kg was estimated. There were no statistical differences ($P > 0.05$) in the Colwell K – RY relationships when the data were differentiated according to state, region and cation exchange capacity classes. However, when the national K soil test data were differentiated into five soil texture classes based on clay percentage (sand, sandy loam, sandy clay loam, clay loam, clay) the Colwell K – pasture response relationship did show significant dependence ($P < 0.05$) on soil texture (Fig. 6; Table 5), with an increasing soil test K requirement with increasing clay content. There were insufficient data to define a response relationship for the clay texture class.

Table 5. The Colwell K 95% critical soil test values and 95% confidence intervals, number of experiments, r-squared value, and the relationship between Colwell K soil test value and pasture DM relative yield (RY %) differentiated by soil textural classes

Soil texture	Critical value (mg/kg)[A]	95% confidence interval[B]	Number of experiments[C]	r^2	Equation RY (%)[D] =
Sand	126	109–142	50	0.47	100 × (1 – exp (–0.024 × Colwell K))
Sandy loam	139	126–157	122	0.47	100 × (1 – exp (–0.022 × Colwell K))
Sandy clay loam	143	127–173	75	0.29	100 × (1 – exp (–0.021 × Colwell K))
Clay loam	161	151–182	194	0.47	100 × (1 – exp (–0.019 × Colwell K))

[A]Soil test value at 95% of predicted maximum pasture yield.
[B]95% chance that this range covers the critical soil test value.
[C]Clay sites (4) not included.
[D]exp = Euler's constant (approx. 2.71828).

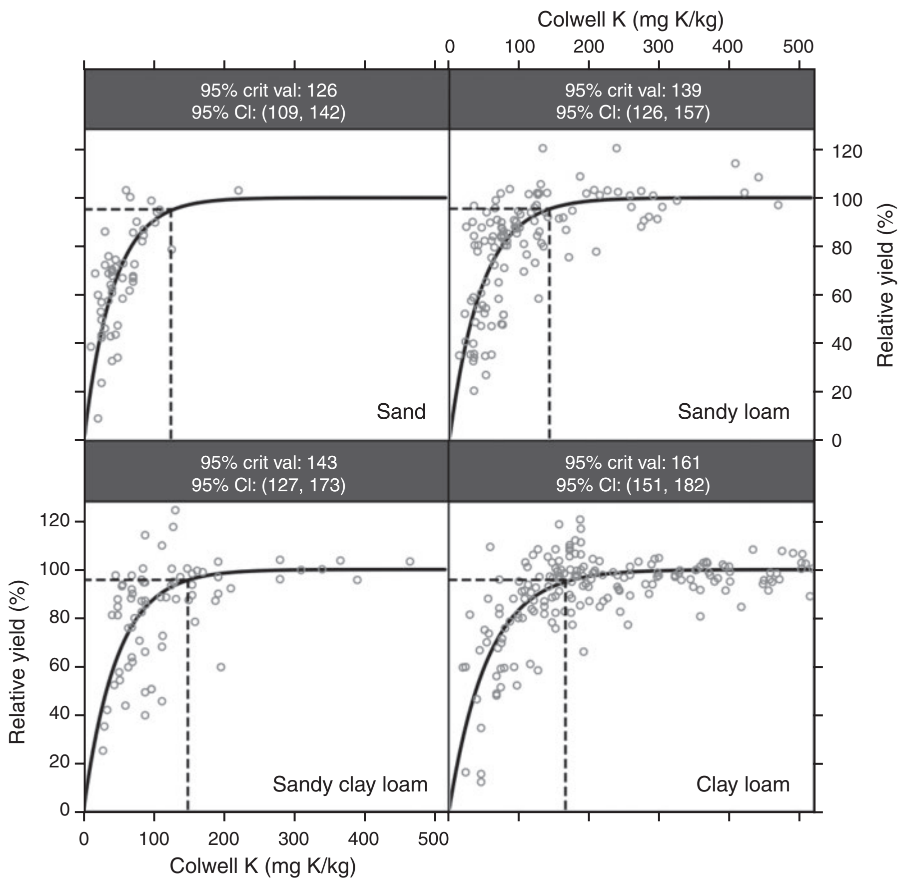

Fig. 6. The relationship between relative yield (RY %) and Colwell K soil test value for four soil texture classes. The critical Colwell K soil test values at 95% RY are indicated by the dashed lines and shown in the panel header along with 95% confidence interval (CI) for each soil texture class.

Sulfur soil tests

Fewer S fertiliser–pasture yield field experiments were conducted compared with P or K, most likely due to the historical and widespread use of superphosphate which often provided adequate S for plant growth. The three main soil S tests collated within the BFDP database were MCP (calcium phosphate), CPC S (calcium phosphate plus charcoal; Peverill and Briner 1974) and KCl-40 (potassium chloride; Blair *et al*. 1991). In total 444 experiment site years of S soil test and pasture yield data were collated across all states of Australia (Table 1). Of this total, 261 sets included data relating to the CPC S test, 125 related to the MCP S test and 58 related to the KCl-40 S test. The calibration of the KCl-40 S test was further limited to work undertaken in SA (33 experiment site years) and the central tablelands of NSW (24 experiment site years) with one site in WA.

The CPC and KCl-40 S tests are poorly correlated (Peverill and Briner 1974; Lewis 1999) and therefore experiment data using these separate soil S tests could not be pooled. Moreover, the use of each S soil test tended to be regionally specific, and most S experiments were conducted on clay loam or sandy loam soils. As the CPC S test was a modified and improved version of the MCP S test (Peverill and Briner 1974) only CPC S calibrations were determined.

Insufficient data were available to investigate whether soil S test–pasture production response relationships differed between soil texture, states or regions. The nationally combined S soil test–pasture response relationships for CPC S, had a critical 95% value of 3 mg/kg, whereas for the KCl-40 S soil test, the critical 95% value was 8 mg/kg (Fig. 7; Table 6).

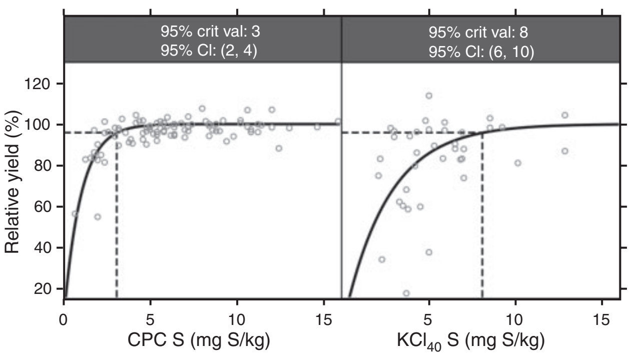

Fig. 7. The relationship between relative yield (RY %) and soil test value for CPC S and KCl-40 S tests. The critical S soil test values at 95% RY are indicated by the dashed lines and shown in the panel header along with 95% confidence interval (CI).

Discussion

Strengths and limitations of the meta-analysis

The BFDP national database of pasture yield responses to soil nutrient status – as measured by soil test P (Colwell P, Olsen P), K (Colwell K) and S (KCl-40 S, CPC S) – is the first collation of national experiment data enabling the determination of response functions and critical nutrient concentrations, applicable to most soil types in southern Australia. The data utilised in the model development represent a comprehensive historical collation of 3032 experiment site years of data where experiments were established with individual pursuits in mind, most likely without thought of aggregation. The response functions and critical extractable nutrient concentrations are widely accepted and incorporated within fertiliser company guidelines and decisions support systems (https://www.fertilizer.org.au/Fertcare). Rapid industry uptake of the PBI test (Burkitt *et al*. 2002, 2008), which allows critical Colwell P values to be estimated for soils differing in PBI and the realisation that K benchmarks could be defined for soils grouped by texture class were also fundamental to this outcome.

A similar meta-analysis of 2255 field trials from experiments conducted over 50 years has also been undertaken to define the relationships between pasture production and soil P and K in New Zealand (Edmeades *et al*. 2006). The response functions and critical soil test values are used extensively by industry as the basis of fertiliser decisions for improved pasture in New Zealand.

The derived mathematical models summarise the data as they were available. There may be bias through over-representation in some regions and under representation in others (i.e. paucity of Olsen P data in NSW and Queensland, dominance in Victoria), whereas non-uniformity of management protocols among trials created analysis and interpretational challenges. Furthermore, yield responses may have varied between regions due to rainfall distribution, differences in the dominant pasture species (e.g. different legumes, annual and/or perennial grasses), latitudinal changes (e.g. between Tasmania and Queensland), and dryland and irrigation regions. Insufficient metadata was available to establish whether these exogenous factors would further differentiate the soil test–pasture growth relationships.

Notwithstanding these possible limitations with the data available, soil test–pasture yield response functions and soil nutrient critical values for commonly used soil tests are now available to fertiliser company decision support systems, advisors and farmers and it is feasible for them to set targets for available-nutrient concentrations that are appropriate for the soils they are managing. For P it is now possible to more accurately estimate the amounts of P to apply to achieve a

Table 6. The CPC and KCl-40 S 95% critical soil test values and 95% confidence intervals, number of experiments, state contributing experiment data, and relationship between CPC and KCl-40 S soil test value and pasture DM relative yield (RY %)

Sulfur test	Critical value (mg/kg)[A]	95% confidence interval[B]	Number of experiments	State[C]	Equation RY (%)[D] =
CPC	3	2–4	94	Vic, NSW, Qld	100 × (1 – exp (–1.014 × CPC S))
KCl-40	8	6–10	37	NSW, SA	100 × (1 – exp (–0.388 × KCl-40 S))

[A]Soil test value at 95% of predicted maximum pasture yield.
[B]95% chance that this range covers the critical soil test value.

specified increase in soil test P using relationships developed between fertiliser application rate, change in soil test P concentration and PBI (Burkitt *et al*. 2002, 2008), for the maintenance of a desired soil test P concentration using estimates of P loss from the soil (P that is accumulated or leached) and via animals (P transferred to camps or removed in products) (Cayley and Kearney 2000; Cayley and Quigley 2005), and to plan the capital investment in soil P fertility and its likely rate of financial return (Simpson *et al*. 2009). Diversity in the soil P status and P-sorption chemistry of farm paddocks can now be accommodated in these calculations (Burkitt *et al*. 2001).

Critical soil test values

The critical soil test values for temperate pasture production in southern Australia presented in this paper are defined as the extractable-nutrient concentration of topsoil (0–10 cm depth) that supports 95% RY, similar to that used for soil test yield responses for Australian cropping systems (Speirs *et al*. 2013). The critical values are estimates derived by measuring the growth response to a limiting nutrient generally from a grass–legume pasture dependent on the fixation of atmospheric nitrogen by its clover component. In many cases, it is the critical soil nutrient requirement of the clover that essentially determines pasture nutrient requirements because they typically have higher P (Ozanne *et al*. 1969, 1976; Helyar and Anderson 1971; Jackman and Mouat 1972; Hill *et al*. 2010; Sandral *et al*. 2019), K (Hunt and Wagner 1963; Bolton and Penny 1968; Brockman *et al*. 1970; Simpson *et al*. 1988; Bolland *et al*. 2002) and S (Gilbert and Robson 1984; Warman and Sampson 1994; Tallec *et al*. 2008) requirements than grasses in the sward. For the determination of a particular critical nutrient requirement, other nutrients, soil physical and/or soil chemical conditions must be non-limiting for pasture growth. The successful use of critical nutrient concentrations to manage pasture growth, therefore, requires that similar conditions occur in farm paddocks, or that other limiting factors will be corrected concurrently (e.g. Trotter *et al*. 2014).

An assumption of the critical nutrient concept is that limiting available nutrients are found predominantly in the uppermost layer of the soil profile enabling estimates to be based on soil sampled from the 0–10 cm topsoil layer. This assumption is reasonable for available-P, the most common limiting nutrient in many southern Australian virgin soils, due to the moderate to high P-sorption capacity of these soils. For example, it is often reported that, when fertiliser is applied, 70–85% of change in soil P occurs in the top 10 cm of the soil, with the remaining change confined to the 10–20 cm layer even after very long periods of continuous P-fertiliser application (e.g. Schefe *et al*. 2015; Simpson *et al*. 2015). However, this assumption may break down in light-textured soils with very low P-buffering capacity (e.g. PBI <15), where soil P can leach from the uppermost soil layer (e.g. Lewis *et al*. 1981; Ritchie and Weaver 1993) and in soils where K and S have accumulated below the topsoil layer (e.g. Wong *et al*. 2000; Bolland and Russell 2010). Under these circumstances critical topsoil nutrient benchmarks may be less reliable indicators of pasture yield potential, and consideration should be given to soil sampling to an appropriate depth or using a combination of soil and plant testing (Bolland and Russell 2010).

Phosphorus

Despite the large variation associated with the nationally derived relationship between pasture RY and Olsen P (Fig. 2), the determined 95% critical value of 15 mg P/kg was the same value previously determined for dryland and irrigated Victorian pastures (Montgomery and Rubenis 1978; Gourley and James 1997) and also consistent with a previously proposed critical value of 20 mg P/kg for 7.5 cm sampling depth for subterranean clover pasture in NSW (Spencer *et al*. 1969). More recent experiments have also found that there was no pasture production response to soil Olsen P values above currently recommended optimum concentrations of 13–16 mg/kg (Cotching and Burkitt 2011; Aarons *et al*. 2015*a*; Simpson *et al*. 2015; Sandral *et al*. 2019).

The use of a nationally derived Olsen P–RY function appears justified as there were no statistical differences determined when the Olsen P datasets were differentiated by soil texture or PBI class, and is supported by earlier attempts at refining Olsen P recommendations for pastures in Victoria (Gourley and James 1997). The Olsen P soil test relies on a 30-min extraction period, which may limit the proportion of measured P that is strongly held by soil (Rayment and Lyons 2011). This is in contrast with the Colwell P soil test with a 16-h extraction procedure (Rayment and Lyons 2011) and the recognition that Colwell P soil test concentrations will include a proportion of P strongly held by soil and not available to plants during the immediate growing season (Moody 2007).

A similar extensive meta-analysis undertaken in New Zealand found that the response function for Olsen P was similar for all major soil groups, and when adjusted for the difference in sampling depth (75 mm) the derived critical value (95% of RY) for Olsen P was 20 mg/kg (Edmeades *et al*. 2006). Unfortunately, similar comparisons of the national relationships for soil test K and S between New Zealand and Australia could not be made due to differences in standard soil analysis methods.

Extension of critical soil test phosphorus estimates to soils with very low phosphorus buffering

Prior to the widespread adoption of PBI in Australia, other approaches to account for soil type dependent critical Colwell P values were used. For example, in Western Australia (WA), ammonium oxalate extractable iron (Tamm 1922) was commonly used to classify soils according to their potential to adsorb P (Yeates 1993; Weaver and Reed 1998; Angell 1999). The ammonium oxalate extractable iron classes and associated critical Colwell P values previously in use in WA provide greater sensitivity for soils with low P retention and is consistent with lower critical Colwell P values for soils with lower PBI suggested in models developed by Moody (2007). Development of critical Colwell P values for sandy soils with low P retention was undertaken because of the environmental sensitivity of the Swan Coastal Plain region of WA where significant offsite water quality problems occur from P runoff (Hodgkin and Hamilton 1993). The soil test response functions developed in WA showed a dependence on P sorption but had a greater emphasis at the low end of the P sorption spectrum, thus providing greater sensitivity.

Empirical relationships between ammonium oxalate extractable iron and PBI (Bolland and Windsor 2007; Weaver and Wong 2011), along with existing ammonium oxalate extractable iron classes justified the partitioning of PBI <15 into pragmatic 0–5, 5–10 and 10–15 ranges (Bolland *et al*. 2010). Additionally, the minimum critical Colwell P values advocated by BFD (20 mg P/kg; Fig. 5; Eqn 4) was more than double that of existing critical Colwell P values for pure subterranean clover (Yeates 1993) based on a trial program for coastal plain sandy soils in WA. Hence PBI classes and critical Colwell P values were further modified (Table 4) to cater for these poor sandy soils where PBI <15 (Bolland *et al*. 2010; Summers and Weaver 2011). The differentiated Colwell P response functions account for 56% of the variation, a similar range to that reported by Bell *et al*. (2013) for cereal crop responses.

Refinement of PBI ranges and critical Colwell P values for soils with PBI <15 has important economic and environmental consequences. In south-west WA for example, 20% of soils fall into the PBI <15 category, compared with <1% of soils on Australian dairy farms in this group (Weaver and Wong 2011). A PBI category of <15, or minimum critical Colwell P values of 20 mg P/kg are not refined enough in areas where there is significant environmental sensitivity, and where it is difficult to achieve and maintain Colwell P values of 20 mg P/kg because of the low P sorption in these soils (Ritchie and Weaver 1993). For example, only 25% of soil samples collected on the Swan Coastal Plain in south-west WA from 2009–2019 with a PBI < 15 exceed a Colwell P of 20 mg P/kg compared with 62% of samples with PBI >15 exceeding critical Colwell P values for 95% RY. This disparity exists even in the face of traditional fertiliser practice of 1 bag superphosphate/acre • year (125 kg superphosphate/ha • year) on soils with PBI <15. It would therefore be remiss to adopt a critical Colwell P value of 20 mg P/kg in the PBI <15 category when it (1) is not consistent with previously reported lower critical values (Yeates 1993; Moody 2007; Bolland *et al.* 2010) derived for clover which has a higher P requirement than ryegrass; (2) would place unnecessary economic pressure on growers attempting to achieve and maintain such critical values; (3) would exacerbate existing environmental pressure on sensitive waterways (Hodgkin and Hamilton 1993); and (4) would not be consistent with the nutrient stewardship goals of the national Fertcare program (https://www.fertilizer.org.au/Fertcare). Moreover, when PBI is <15 P may move readily to depth in the soil profile and an extensive re-think of soil sampling strategies and fertiliser choice (e.g. slower release) may be required. The refined mathematical models therefore fall pragmatically between the estimated critical Colwell P values for Moody (2007) and Yeates (1993) when PBI < 15 (Fig. 5; Eqns 7, 8), otherwise they coincide closely with Eqn 4.

Potassium

In a large calibration study involving over 40 sites in south-west Western Australia, Cox (1974) compared K soil tests involving HCl, NH_4OAc, $CaCl_2$, and $NaHCO_3$ extractants and concluded that all the tests were highly correlated, with none statistically better than the other in predicting yield response of pasture. In a collation of K soil test calibration studies undertaken in Australia, Gourley (1999) also concluded that despite the different analytical extractants used, a similar but broad critical value (95% of RY) range of 100–250 mg K/kg could be used.

Although previous interpretation of soil test K critical values levels often varied with soil texture, for example 100 mg/kg for pastures on sandy soils and 120 mg/kg for pastures on loams and clays (Skene 1956), other studies were unable to differentiate soil K test critical values by soil texture (Spencer and Govaars 1982; Gourley 1989). The texture differentiated Colwell K soil test and pasture RY relationships identified here has refined these general recommendations. The derived critical values (95% of RY) for Colwell K range from 126 to 161 mg/kg for pastures grown on sand and clay loam soils respectively.

Sulfur

The development of national soil S test and pasture RY relationships were limited by a smaller number of experimental sites when compared with soil test P and K, the dominance of the CPC S soil test (experiment site years of data: CPC S = 261, MCP S = 125, KCl-40 S test = 58), limited regional locations for specific soil S tests, and soil types dominated by clay loams. In earlier work, Lewis (1999) was unable to determine different soil S test targets from different extraction methods and recommended a critical range of 5–10 mg/kg for pastures irrespective of which soil S test was used.

In this study we propose a CPC S soil test critical value (95% of RY) of 3 mg/kg and for the KCl-40 S soil test, a critical value (95% of RY) of 8 mg/kg. Peverill and Briner (1974) had previously recommended a critical value (95% of RY) for the CPC S soil test of 5.4 mg/kg for pastures. Blair *et al*. (1991) recommended a critical value (95% of RY) for the KCl-40 S soil test of 6.5 mg/kg for pastures, but this was determined from a 7.5 cm soil sampling depth. The higher critical value determined for the KCl-40 S soil test compared with the CPC S soil test in our study is consistent with the earlier work by Spencer *et al*. (1969), who reported higher extraction concentrations for the heat soluble procedure compared with the phosphate extraction method. The national KCl-40 S critical value of ~7 mg/kg recommended for wheat and canola (Anderson *et al*. 2013), is similar to the critical value of 8 mg/kg estimated in this study but is confounded by a 30 cm sampling depth of soils for these crops. Anderson *et al*. (2013) further recommended that when soil sampling to determine extractable soil S for crops, samples should be collected at intervals to a minimum depth of 30 cm. Although pasture root systems are generally more limited to the surface soil, the potential stratification of S is a potential factor responsible for the variability in RY responses collated (Fig. 4).

The KCl-40 test has become the national standard soil S test across all regions of Australia for both pastures and crops (Rayment and Lyons 2011), but these results suggest that additional pasture field calibration studies that broaden the applicability and validate the current response functions and critical values for soil S tests are warranted.

Application of soil test benchmarks

Lean *et al*. (1997) outlined the continued importance of maintaining investment in soil fertility for farm profitability and describe the risk of a downward spiral in the viability of farm businesses if essential nutrient inputs that underpin productivity are cut. The resultant critical soil test benchmarks developed in the present study, indicating the nutrient level that corresponds with 95% RY, enable the farm manager to set a soil test target for fertiliser management that suits the production goals of the farm enterprise. Soil test targets that are lower than the critical benchmark can be expected to result in a stock carrying capacity that is lower than the potential maximum, and targets that are higher are unlikely to support farther gains in production (Carter and Day 1970; Curll 1977; Lloyd Davis *et al*. 1998; Cayley *et al*. 1999). Success is achieved by also commencing a program of regular soil testing to monitor changes in nutrient availability (e.g. Simpson *et al*. 2009).

A 25-year-long farm-level example of soil nutrient monitoring in the Bookham Agricultural Bureau's fertiliser demonstration trial (Graham 2006) and a recent replicated, long-term (20 year) fertilised grazing experiment (Simpson *et al*. 2015) have tested the practice of soil-test guided management of nutrients (e.g. Gourley *et al*. 2007; Five Easy Steps Decision tool, Simpson *et al*. 2009). These studies reiterated that fertilising to concentrations above the derived critical soil test P concentration does not increase production, and fertilising to keep soil test P within a target range improves the cost-effectiveness of fertiliser use. Many shorter-term and smaller-scale field studies also support the derived soil test critical values, notably addressing P and K (e.g. Cotching and Burkitt 2011; Aarons *et al*. 2015*a*; Simpson *et al*. 2015; Sandral *et al*. 2019). Moreover, higher soil test P concentrations are associated with greater and unnecessary rates of P accumulation in the soil (Simpson *et al*. 2014, 2015) and incur larger risks of P loss to waterways (Melland *et al*. 2008; Gourley and Weaver 2012).

A clear lesson from data emerging from the widespread use of soil testing is that there is a wide range in the nutrient status of pasture soils, and that within-farm variation can be as large as between-farm variation (Weaver and Wong 2011; Trotter *et al*. 2014; Aarons et al. 2015*b*; Gourley *et al*. 2015). Advancements in spatially-defined soil test data enable the generation of nutrient distribution maps applicable at a range of scales (e.g. subpaddock, paddock, farm, catchment), which can greatly improve targeted nutrient applications for improved pastures.

Even when soil test monitoring consistently reveals that the nutrient status of a paddock could be improved, it can still be a leap of faith for many landowners to begin a program for capital increase in soil fertility or alternatively to reduce fertiliser inputs, either because of cost or risk aversion. In the first instance, the large extra investment in fertiliser to increase soil fertility and the even larger investment in additional livestock to utilise additional pasture growth requires a high level of confidence that the critical nutrient benchmarks are 'true'. Although it is recognised that the current critical values are based on an historical collection of many experiments, local supporting evidence may be lacking. The more recently developed BFDC database (Speirs *et al*. 2013) and its consensus nutrient guidelines for crops address this issue by a data interface that allows users to drill down to district-level data within the database that underpins critical nutrient benchmarks (Watmuff *et al*. 2013). This is reinforced by the refinement of critical Colwell P values for PBI <15 reported here. The earlier development of the BFDP database does not have such an interface. The unification of these databases with similar user-accessibility is needed.

It would be foolhardy to believe that local, regional and national response function assessments such as these will be absolutely correct. Further monitoring of soil nutrient availability using standard soil tests, steady increases in stocking rate in line with growth of additional pasture, continued soil testing and sound forward planning are all essential follow-up steps to protect and check any fertiliser investment strategy. Nevertheless, objective fertiliser and stocking rate investment planning is now feasible at a regional and national level. This is well recognised, with the fertiliser industry and other related stakeholders having incorporated these derived soil test pasture DM response relationships within currently used fertiliser decision support systems as well as using this information within training programs for their advisor and farmer networks. Moreover, the national Fertcare program currently uses these soil test pasture DM response relationships as the benchmark for comparison of soil test recommendations from all fertiliser companies and advisors seeking Fertcare accreditation, and in support of its nutrient stewardship goals.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

Funding support for the Better Fertiliser Decisions for Pastures project was provided by Agriculture Victoria Research, Dairy Australia, Meat & Livestock Australia, Land and Water Australia, National Land and Water Resources Audit, Fertiliser Australia, Canpotex, Incitec Pivot, CSBP, Impact Fertilisers, Hifert, South Australia Research and Development Institute, EPA Victoria, New South Wales Agriculture, Department of Agriculture West Australia, Queensland Department of Primary Industries, Tasmanian Institute Agricultural Research, University of New England and CSIRO. A nation-wide team assisted in the compilation of field data from across Australia. Project team members included Jeff Kraak, Garry Kuhn, Ed Pol, Digby Short, Peter Flavel, Andrew Speirs, Jonnie White, David Orr, Jenny Collins, Malcolm McCaskill, Andrew Smith, Joe Jacobs, Peter Sale, Doug Newton, Mark Conyers, Graham Crocker, Mike Bolland, Phil Moody, Kevin Lowe, Rob Chattaway, Lucy Burkitt, Leigh Sparrow, Nigel Fleming, Dale Lewis, Doug Reuter and Denis Elliott. The authors would especially like to thank Tom Davison and Cameron Allan for their commitment to developing national soil test standards and assistance in coordinating industry funding, Nick Drew for the strong engagement with the fertiliser industry, and Ivor Awty for his essential contribution to collating data and creating and managing the national database. Richard Simpson was funded by the Australian Government Department of Agriculture (Rural R&D for Profit Program), Meat and Livestock Australia, Dairy Australia and Australian Wool Innovations Ltd. Farmer members of the Monaro Farming Systems group and Phil Graham are thanked for access to their unpublished soil test data.

References

Aarons SR, Goudy A, Heaven M, Phillips L, Mele P, Campbell R (2015*a*) Sustaining productive dairy soils – soil and pasture response to P and K. Final project report to Dairy Australia. Report number C00000600.

Aarons SR, Gourley CJP, Hannah MC (2015*b*) Between and within paddock soil nutrient, chemical variability and pasture production gradients in grazed dairy pastures. *Nutrient Cycling in Agroecosystems* **102**, 411–430. doi:10.1007/s10705-015-9714-5

Anderson GC, Peverill KI, Brennan RF (2013) Soil sulphur crop response calibration relationships and criteria for field crop grown in Australia. *Crop & Pasture Science* **64**, 523–530. doi:10.1071/CP13244

Angell KW (1999) Fertilisers for pastures on sandy soils of the Swan Coastal Plain. Bulletin 4357, Agdex 540, Agriculture Western Australia.

Barrow NJ (2015) Soil phosphate chemistry and the P-sparing effect of previous phosphate applications. *Plant and Soil* **397**, 401–409. doi:10.1007/s11104-015-2514-5

Bell MJ, Moody PW, Anderson GC, Strong W (2013) Soil phosphorus – crop response calibration relationships and criteria for oil seeds, grain legumes and summer cereal crops grown in Australia. *Crop & Pasture Science* **64**, 523–530. doi:10.1071/CP13244

Blair G, Chinoim N, Lefroy R, Anderson G, Croker G (1991) A soil sulphur test for pastures and crops. *Soil Research* **29**, 619–626. doi:10.1071/SR9910619

Bolland MDA, Russell WK (2010) Changes in chemical properties of 48 intensively grazed, rain-fed dairy paddocks on sandy soils over 11 years of liming in south-western Australia. *Australian Journal of Soil Research* **48**, 682–692. doi:10.1071/SR07026

Bolland MDA, Windsor DP (2007) Converting reactive iron, reactive aluminium, and phosphorus retention index (PRI) to the phosphorus buffering index (PBI) for sandy soils of south-western Australia. *Australian Journal of Soil Research* **45**, 262–265. doi:10.1071/SR07026

Bolland MDA, Cox WJ, Codling BJ (2002) Soil and tissue tests to predict pasture yield responses to applications of potassium fertiliser in high-rainfall areas of south-western Australia. *Australian Journal of Experimental Agriculture* **42**, 149–164. doi:10.1071/EA01060

Bolland MDA, Russell B, Weaver DM (2010) Phosphorus for high rainfall pastures. Bulletin 4808. Department of Agriculture and Food Western Australia. Available at: https://researchlibrary.agric.wa.gov.au/bulletins/59/.

Bolton J, Penny A (1968) The effects of potassium and magnesium fertilizers on yield and composition of successive crops of ryegrass, clover, sugar beet, potatoes, kale and barley on sandy soil at Woburn. *The Journal of Agricultural Science* **70**, 303–311. doi:10.1017/S0021859600012624

Bowden JW, Bennett D (1975) The 'Decide' model for predicting superphosphate requirements. In 'Proceedings of Symposium Phosphate in Agriculture'. November 1974'. Australian Institute Agricultural Science (Victorian Branch). 6.1–6.36.

Brockman JS, Shaw PG, Wolton KM (1970) The effect of phosphate and potash fertilizers on cut and grazed grassland. *Journal of Agricultural Science, Cambridge* **74**, 397–407. doi:10.1017/S0021859600023042

Burkitt LL, Gourley CJP, Sale PWG, Uren NC, Hannah MC (2001) Factors affecting the change in extractable phosphorus following the application of phosphatic fertiliser on pasture soils in southern Victoria. *Australian Journal of Soil Research* **39**, 759–771. doi:10.1071/SR00069

Burkitt LL, Moody PW, Gourley CJP, Hannah MC (2002) A simple phosphorus buffering index for Australian soils. *Australian Journal of Soil Research* **40**, 1–18.

Burkitt LL, Sale P, Gourley CJP (2008) Soil phosphorus buffering measures should not be adjusted for current phosphorus fertility. *Australian Journal of Soil Research* **46**, 676–685. doi:10.1071/SR06126

Carter ED, Day HR (1970) Interrelationships of stocking rate and superphosphate rate on pasture as determinants of animal production. I. Continuously grazed old pasture land. *Australian Journal of Agricultural Research* **21**, 473–491. doi:10.1071/AR9700473

Cayley JWD, Kearney GA (2000) Profitable use of phosphorus fertiliser for temperate pastoral Australia. In 'Proceedings of the Australian Society for Animal Production. Vol. B'. (Ed. GM Stone) pp. 191–194. (ASAP: Melbourne)

Cayley J, Quigley P (2005) Phosphorus for sheep and beef pastures. Department of Primary Industries, Victoria. Available at: http://agriculture.vic.gov.au/agriculture/farm-management/pastures/phosphorus-sheep-and-beef.

Cayley JWD, Kearney GA, Saul GR, Lescun CL (1999) The long-term influence of superphosphate and stocking rate on the production of spring-lambing Merino sheep in the high rainfall zone of southern *Australian Journal of Agricultural Research* **50**, 1179–1190. doi:10.1071/AR98198

Coad JR, Burkitt LL, Gourley CJP (2010) Influence of sample depth on extractable nutrient concentrations, pH and phosphorus buffering index of pasture soils in south-eastern Australia. *Australian Journal of Soil Research* **48**, 355–360. doi:10.1071/SR09104

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**, 190–198. doi:10.1071/EA9630190

Cotching WE, Burkitt LL (2011) Soil phosphorus effects on ryegrass (*Lolium perenne* L.) production on a Hydrosol in Tasmania. *New Zealand Journal of Agricultural Research* **54**, 193–202. doi:10.1080/00288233.2011.591809

Cox WJ (1974) The use of a soil test for predicting the potassium need of pasture. In 'Proceedings of the Australian Soil Science Conference'. Melbourne, Vic. pp. 24–28. (University of Melbourne: Melbourne)

Curll ML (1977) Superphosphate on perennial pastures. I. Effect of a pasture response on sheep production. *Australian Journal of Agricultural Research* **28**, 991–1005. doi:10.1071/AR9770991

Edmeades DC, Metherall AK, Waller JE, Roberts AHC, Morton JD (2006) Defining the relationship between pasture production and soil P and the development of a dynamic P model for New Zealand pastures: a review of recent developments. *New Zealand Journal of Agricultural Research* **49**, 207–222. doi:10.1080/00288233.2006.9513711

Gilbert MA, Robson AD (1984) Studies on competition for sulfur between subterranean clover and annual ryegrass. I. Effect of nitrogen and sulfur supply. *Australian Journal of Agricultural Research* **35**, 53–64. doi:10.1071/AR9840053

Gourley CJP (1989) Predicting the responsiveness of pasture to potassium fertilizer in Victoria. *Australian Journal of Experimental Agriculture* **29**, 377–382. doi:10.1071/EA9890377

Gourley CJP (1999) Potassium. In 'Soil analysis: an interpretation manual'. (Eds KI Peverill, LA Sparrow, DJ Reuter) pp. 229–239. (CSIRO Publishing: Melbourne, Vic.)

Gourley CJP, James GS (1997) Predicting the response of irrigated perennial pasture to superphosphate. *Australian Journal of Soil Research* **35**, 301–312. doi:10.1071/S96061

Gourley CJP, Weaver DM (2012) Nutrient surpluses in Australian grazing systems: management practices, policy approaches, and difficult choices to improve water quality. *Crop & Pasture Science* **63**, 805–818. doi:10.1071/CP12154

Gourley CJP, Melland AR, Waller RA, Awty IM, Smith AP, Peverill KI, Hannah MC (2007) Making better fertiliser decisions for grazed pastures in Australia. Victorian Government Department of Primary Industries, Melbourne. Available at: http://www.asris.csiro.au/downloads/BFD/Making%20Better%20Fertiliser%20Decisions%20for%20Grazed%20Pastures%20in%20Australia.pdf.

Gourley CJP, Aarons SR, Hannah MC, Dougherty WJ, Burkitt LL, Awty IM (2015) Soil phosphorus, potassium and sulphur excesses, regularities and heterogeneity in grazing-based dairy farms. *Agriculture, Ecosystems & Environment* **201**, 70–82. doi:10.1016/j.agee.2014.12.010

Gourley CJP, Hannah MC, Chia KTH (2017) Predicting pasture yield response to nitrogenous fertiliser in Southern Australia using a meta-analysis derived model, with field validation. *Soil Research* **55**, 567–578. doi:10.1071/SR17032

Graham RP (2006) Bookham grazing demonstration results. In 'NSW DPI Sheep Conference'. pp. 211–216. (Orange Agricultural Institute: Orange, NSW)

Helyar KR, Anderson AJ (1971) Effects of lime on the growth of five species, on aluminium toxicity, and on phosphorus availability. *Australian Journal of Agricultural Research* **22**, 707–721. doi:10.1071/AR9710707

Hill JO, Simpson RJ, Ryan MH, Chapman DF (2010) Root hair morphology and mycorrhizal colonisation of pasture species in response to phosphorus and nitrogen nutrition. *Crop & Pasture Science* **61**, 122–131. doi:10.1071/CP09217

Hodgkin EP, Hamilton BH (1993) Fertilizers and eutrophication in southwestern Australia: setting the scene. *Fertilizer Research* **36**, 95–103. doi:10.1007/BF00747579

Holford I, Crocker G (1988) Efficacy of various soil phosphate tests for predicting phosphate responsiveness and requirements of clover pastures on acidic tableland soils. *Soil Research* **26**, 479–488. doi:10.1071/SR9880479

Hunt OJ, Wagner RE (1963) Effects of phosphorus and potassium fertilizers on legume composition of seven grass-legume mixtures. *Agronomy Journal* **55**, 16–19. doi:10.2134/agronj1963.00021962005500010007x

Jackman RH, Mouat MCH (1972) Competition between grass and clover for phosphate. I. Effect of browntop (*Agrostis tenuis* Sibth.) on white clover (*Trifolium repens* L.). Growth and nitrogen fixation. *New Zealand Journal of Agricultural Research* **15**, 653–666. doi:10.1080/00288233.1972.10421622

Lean GR, Vizard AL, Webb Ware JK (1997) Changes in productivity and profitability of wool-growing farms that follow recommendations from agricultural and veterinary studies. *Australian Veterinary Journal* **75**, 726–731. doi:10.1111/j.1751-0813.1997.tb12256.x

Lewis DC (1999) Sulphur. In 'Soil analysis: an interpretation manual'. (Eds KI Peverill, LA Sparrow, DJ Reuter) pp. 221–228. (CSIRO Publishing: Melbourne, Vic.)

Lewis DC, Clarke AL, Hall WB (1981) Factors affecting the retention of phosphorus applied as superphosphate to the sandy soils in south-eastern South Australia. *Australian Journal of Soil Research* **19**, 167–174. doi:10.1071/SR9810167

Lloyd Davies H, McFarlane JD, de Oliveira OLP, King GW, James JW (1998) A long-term study of superphosphate and stocking rate on sheep production and plant and soil characteristics in central west New South Wales. *Australian Journal of Experimental Agriculture* **38**, 433–439. doi:10.1071/EA97034

McLachlan KD (1965) The nature of available phosphorus in some acid pasture soils and a comparison of estimating procedures. *Australian Journal of Experimental Agriculture and Animal Husbandry* **5**, 125–132. doi:10.1071/EA9650125

Melland AR, McCaskill MR, White RE, Chapman DF (2008) Loss of phosphorus and nitrogen in runoff and subsurface drainage from high and low input pastures grazed by sheep in Australia. *Australian Journal of Soil Research* **46**, 161–172. doi:10.1071/SR07084

Montgomery AJ, Rubenis G (1978) Correlation of soil phosphorus tests with the response of irrigated perennial pasture to phosphorus fertiliser. *Australian Journal of Experimental Agriculture and Animal Husbandry* **18**, 243–248. doi:10.1071/EA9780243

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. doi:10.1071/SR06056

Olsen SR, Cole CV, Watanabe FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. US Department of Agriculture Circular No. 939.

Ozanne PG, Keay J, Biddiscombe EF (1969) Comparative applied phosphate requirements of eight annual pasture species. *Australian Journal of Agricultural Research* **20**, 809–818. doi:10.1071/AR9690809

Ozanne PG, Howes KMW, Petch A (1976) Comparative phosphate requirements of four annual pastures and two crops. *Australian Journal of Agricultural Research* **27**, 479–488. doi:10.1071/AR9760479

Peverill KI, Briner GP (1974) The sulphur status of Victorian grasslands. In 'Proceedings of the 12th International Grassland Congress. Sectional papers: Chemicalization of grassland farming'. Moscow, Russia. (Eds VG Iglovikov, AP Movsisyants) pp. 449–56.

Peverill KI, Sparrow LA, Reuter DJ (1999) 'Soil analysis – an interpretation manual.' (CSIRO Publishing: Melbourne, Vic.)

Ratkowsky DA (1983) 'Non-linear regression modelling: a unified practical approach.' (Marcel Dekker: New York)

Rayment GE, Lyons DJ (2011) 'Soil chemical methods: Australasia.' (CSIRO Publishing: Melbourne, Vic.)

Reuter DJ, Dyson CB, Elliott DE, Lewis DC, Rudd CL (1995) An appraisal of soil phosphorus testing data for crops and pastures in South Australia. *Australian Journal of Experimental Agriculture* **35**, 979–995. doi:10.1071/EA9950979

Ritchie GSP, Weaver DM (1993) Phosphorus retention and release from sandy soils of the Peel-Harvey catchment. *Fertilizer Research* **36**, 115–122. doi:10.1007/BF00747581

Rudd CL (1972) Response of annual medic pasture to superphosphate applications and correlation with available soil phosphorus. *Australian Journal of Experimental Agriculture and Animal Husbandry* **12**, 43–48. doi:10.1071/EA9720043

Sandral GA, Price A, Hildebrand SM, Fuller CG, Haling RE, Stefanski A, Yang Z, Culvenor RA, Ryan MH, Kidd DR, Diffey S, Lambers H, Simpson RJ (2019) Field benchmarking of the critical external phosphorus requirements of pasture legumes for southern Australia. *Crop & Pasture Science* **70**, in press.

Schefe CR, Barlow KM, Robinson NA, Crawford DM, McLaren TI, Smernik RJ, Croatto G, Walsh RD, Kitching M (2015) 100 years of superphosphate addition to pasture in an acid soil – current nutrient status and future management. *Soil Research* **53**, 662–676. doi:10.1071/SR14241

Simpson D, Wilman D, Adams WA (1988) Response of white clover and grass to applications of potassium and nitrogen on a potassium-deficient hill soil. *Journal of Agricultural Science, Cambridge* **110**, 159–167. doi:10.1017/S0021859600079806

Simpson R, Graham P, Davies L, Zurcher E (2009) 'Five easy steps to ensure you are making money from superphosphate. Decision support tool'. (CSIRO & Industry and Investment NSW: Sydney) Available at: https://www.mla.com.au/globalassets/mla-corporate/generic/extension-training-and-tools/5-easy-steps-guide.pdf.

Simpson RJ, Richardson AE, Nichols SN, Crush JR (2014) Pasture plants and soil fertility management to improve the efficiency of phosphorus fertiliser use in temperate grassland systems. *Crop & Pasture Science* **65**, 556–575. doi:10.1071/CP13395

Simpson RJ, Stefanski A, Marshall DJ, Moore AD, Richardson AE (2015) Management of soil phosphorus fertility determines the phosphorus budget of a temperate grazing system and is the key to improving phosphorus-balance efficiency. *Agriculture, Ecosystems & Environment* **212**, 263–277. doi:10.1016/j.agee.2015.06.026

Skene JKM (1956) Soil analysis as an aid to diagnosing deficiencies of phosphorus and potassium. In 'Proceedings Australian Plant Nutrition Conference'. Melbourne. pp. 146–153. (CSIRO: Melbourne)

Speirs SD, Reuter DJ, Peverill KI, Brennan RF (2013) Making better fertiliser decisions for cropping systems in Australia: an overview. *Crop & Pasture Science* **64**, 417–423. doi:10.1071/CP13034

Spencer K, Glendinning JS (1980) Critical soil test values for predicting the phosphorus and sulphur status of subhumid temperate pastures. *Australian Journal of Soil Research* **18**, 435–445. doi:10.1071/SR9800435

Spencer K, Govaars AG (1982) The potassium status of pastures in the Moss vale District, New South Wales. Division of Plant Industry technical paper no. 38. CSIRO, Australia.

Spencer K, Bouma D, Moye DV (1969) Assessment of the phosphorus and sulphur status of subterranean clover pastures. 2. Soil tests. *Australian Journal of Experimental Agriculture and Animal Husbandry* **9**, 320–328. doi:10.1071/EA9690320

Summers R, Weaver D (2011) Soil test and phosphorus rate for high rainfall clover pastures. Department of Agriculture and Food, Western Australia, Perth, Bulletin 4829. Available at: https://www.agric.wa.gov.au/sites/gateway/files/Soil%20test%20and%20phosphorus%20rate%20for%20high%20rainfall%20clover%20pastures%20-%20Bulletin%204829%20%28PDF%201.5MB%29.pdf.

Tallec T, Diquélou S, Lemauviel S, Cliquet JB, Lesuffleur F, Ourry A (2008) Nitrogen : sulphur ratio alters competition between *Trifolium repens* and *Lolium perenne* under cutting: production and competitive abilities. *European Journal of Agronomy* **29**, 94–101. doi:10.1016/j.eja.2008.04.004

Tamm O (1922) Eine Methode zur Bestimmung de der anorganischen Komponente des Bodens. *Meddelanden fran Statens skogsforsoksanstalt Stockholm* **19**, 387–404.

Trotter M, Guppy C, Haling R, Trotter T, Edwards C, Lamb D (2014) Spatial variability in pH and key soil nutrients: is this an opportunity to increase fertiliser and lime-use efficiency in grazing systems? *Crop & Pasture Science* **65**, 817–827. doi:10.1071/CP13449

Warman PR, Sampson HG (1994) Effect of sulfur additions on the yield and elemental composition of red clover and ryegrass. *Communications in Soil Science and Plant Analysis* **25**, 1471–1481. doi:10.1080/00103629409369128

Watmuff G, Reuter DJ, Speirs SD (2013) Methodologies for assembling and interrogating N, P, K, and S soil test calibrations for Australian cereal, oilseed and pulse crops. *Crop & Pasture Science* **64**, 424–434. doi:10.1071/CP12424

Weaver DM, Reed AEG (1998) Patterns of nutrient status and fertiliser practice on soils of the south coast of Western Australia. *Agriculture, Ecosystems & Environment* **67**, 37–53. doi:10.1016/S0167-8809(97)00096-0

Weaver DM, Wong MTF (2011) Scope to improve phosphorus (P) management and balance efficiency of crop and pasture soils with contrasting P status and buffering indices. *Plant and Soil* **349**, 37–54. doi:10.1007/s11104-011-0996-3

Windsor D, Bolland M, Weaver DM, Russell B (2010) Implementing the fertiliser action plan: an industry led approach based on Fertcare. Australian Fertilizer Industry Conference. Gold Coast, Queensland, August 2010. Available at: http://www.fertilizer.org.au/Portals/0/Documents/Conf2010/Fertilizer%20Action%20Plan%20Update%20-%20Windsor%20-%20Paper.pdf?ver=2016-01-29-120300-180.

Wong MTF, Edwards NK, Barrow NJ (2000) Accessibility of subsoil potassium to wheat grown on duplex soils in the south-west of Western Australia. *Australian Journal of Soil Research* **38**, 745–751. doi:10.1071/SR98117

Yeates JS (1993) Changing fertiliser practices. *Fertilizer Research* **36**, 135–140. doi:10.1007/BF00747584