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Soil nitrogen—crop response calibration relationships and criteria for winter cereal crops grown in Australia

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Abstract. More than 1200 wheat and 120 barley experiments conducted in Australia to examine yield responses to applied nitrogen (N) fertiliser are contained in a national database of field crops nutrient research (BFDC National Database). The yield responses are accompanied by various pre-plant soil test data to quantify plant-available N and other indicators of soil fertility status or mineralisable N. A web application (*BFDC Interrogator*), developed to access the database, enables construction of calibrations between relative crop yield ($(Y_0/Y_{max}) \times 100$) and N soil test value. In this paper we report the critical soil test values for 90% RY (CV90) and the associated critical ranges (CR90, defined as the 70% confidence interval around that CV90) derived from analysis of various subsets of these winter cereal experiments.

Experimental programs were conducted throughout Australia's main grain-production regions in different eras, starting from the 1960s in Queensland through to Victoria during 2000s. Improved management practices adopted during the period were reflected in increasing potential yields with research era, increasing from an average Y_{max} of 2.2 t/ha in Queensland in the 1960s and 1970s, to 3.4 t/ha in South Australia (SA) in the 1980s, to 4.3 t/ha in New South Wales (NSW) in the 1990s, and 4.2 t/ha in Victoria in the 2000s. Various sampling depths (0.1–1.2 m) and methods of quantifying available N (nitrate-N or mineral-N) from pre-planting soil samples were used and provided useful guides to the need for supplementary N. The most regionally consistent relationships were established using nitrate-N (kg/ha) in the top 0.6 m of the soil profile, with regional and seasonal variation in CV90 largely accounted for through impacts on experimental Y_{max}. The CV90 for nitrate-N within the top 0.6 m of the soil profile for wheat crops increased from 36 to 110 kg nitrate-N/ha as Y_{max} increased over the range 1 to >5 t/ha. Apparent variation in CV90 with seasonal moisture availability was entirely consistent with impacts on experimental Y_{max}. Further analyses of wheat trials with available grain protein (~45% of all experiments) established that grain yield and not grain N content was the major driver of crop N demand and CV90.

Subsets of data explored the impact of crop management practices such as crop rotation or fallow length on both pre-planting profile mineral-N and CV90. Analyses showed that while management practices influenced profile mineral-N at planting and the likelihood and size of yield response to applied N fertiliser, they had no significant impact on CV90. A level of risk is involved with the use of pre-plant testing to determine the need for supplementary N application in all Australian dryland systems. In southern and western regions, where crop performance is based almost entirely on in-crop rainfall, this risk is offset by the management opportunity to split N applications during crop growth in response to changing crop yield potential. In northern cropping systems, where stored soil moisture at sowing is indicative of minimum yield potential, erratic winter rainfall increases uncertainty about actual yield potential as well as reducing the opportunity for effective in-season applications.

Additional keywords: barley, critical range, critical test, cropping system, direct drill, fertiliser experiment, incubation test, organic carbon, wheat, soil type, texture, total nitrogen, zero till.

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Introduction

Throughout Australia, the majority of cropped soil has been and continues to be used for cereal production. In southern Australia, pasture legumes traditionally played a vital role in supplementing cereal nitrogen (N) supplies (Greenland 1971; Clarke and Russell 1977) following their introduction into cropping rotations post World War II, and contributed to arresting the decline in cereal yields that was occurring with continuous fallow–wheat rotations

(Donald 1967). In contrast, cereal production systems that developed in northern Australia have relied heavily on the inherent high N fertility status of soils in areas that previously supported native grassland or brigalow (*Acacia harpophylla*) scrub. In the absence of any rotation with legume pastures, continuous cropping with cereals led to the eventual decline in N fertility (Hallsworth *et al*. 1954; Dalal and Probert 1997) for all but the most fertile soils, as was evidenced by declines in cereal yield and grain protein and an inverse association between response in wheat yield to applied N and grain protein level of unfertilised crops (Strong 1981; Holford *et al*. 1992).

Use of fertiliser N for cereal production in Australia received considerable impetus during the 1960s, when the much lower price of imported urea made N fertiliser application an economic proposition. There was extensive research into the use of N fertiliser for wheat production in the various cropping regions (Russell 1963, 1967; McClelland 1970; Rasmussen *et al*. 1971; Taylor *et al*. 1974; Strong *et al*. 1978) to assess profitability of applying N fertiliser to dryland wheat crops. Application of N was a significant component of the National Soil Fertility Project in the 1970s (Colwell 1977), particularly in Victoria and New South Wales (NSW). This early research was focussed on assessing climatic, cultural and edaphic factors and analysis of a variety of soil N tests from a range of soil depths for prediction of a likely grain response to N fertiliser, with research generally conducted by state-based research groups.

In Western Australia (WA) and parts of South Australia (SA), soil testing is impeded in many cereal production areas by the nature of soils that dominate. Sandy-textured soils, which frequently contain a significant proportion of gravel or sheet limestone, make sampling beyond the surface layer impracticable and possibly irrelevant for mobile forms of N such as nitrate. As a consequence, the focus of WA research on N fertiliser use was to develop simulation models (e.g. NP Decide; Burgess 1988) which describe soil and fertiliser N transformation and its movement in soil and uptake by the cereal crop. However, many wheat and barley experiments were conducted over many years where potential measures of crop-available N were determined on soils to a depth of 0.45 m, including nitrate-N and ammonium-N concentrations (mg/kg), and soil total N%.

Multi-rate N fertiliser experiments with wheat were conducted in the more remote Western Downs (1975–77) and Central Highlands (1974–76) of Queensland (Strong *et al.*1978) and also during 1985–89 in northern NSW (Holford and Doyle 1992; Doyle 1994). The heavy-textured soils that dominate northern cereal regions enabled easy soil sampling to depths of up to 1.2 m. Hence, measures of water and crop-available N, primarily nitrate-N supply, were readily obtained before crop sowing. Many other soil parameters were determined on surface and subsoil layers as a means of soil characterisation. Soil testing for a variety of crop-available N measures was a primary focus of these experimental programs, with measures including nitrate-N mass (kg N/ha) to 1.2 m as well as soil total N%, soil organic carbon (C)% and laboratory measures of mineralisable N under aerobic or anaerobic conditions determined on the top 10 cm soil layer.

Research in the early 1990s in SA on supplementing N supplies to wheat and barley crops followed the development of a diagnostic tool based on nitrate content of cereal basal stems to detect N deficiency in wheat crops (Papastylianou 1984; Elliott *et al*. 1987) and barley crops (Elliott *et al*. 1993). This research was concentrated on relating crop response to applied N to a variety of measures of crop-available soil N (Xu *et al*. 1996*b*), including the mass of soil nitrate-N (kg N/ha) to soil depths as great as 0.6 m, combined soil ammonium-N and nitrate-N mass, soil total N% and a laboratory measure of aerobic N mineralisation. Results of these experiments and soil measures were used in the development of a decision support system (DSS) called TOPNRATE that enabled N fertiliser to be recommended on the basis of a soil test (Xu and Elliott 1993). Another DSS enabled use of soil organic C% to guide N fertiliser management for dryland cereal cropping (Payne and Ladd 1993) and formed the basis of the ‘N calculator’.

McDonald (1989) foreshadowed that there would be a need for the more regular and greater use of N fertiliser in Australian wheat production as grain production systems intensified and native fertility reserves were exploited. Industry statistics illustrate these changes. Since the late 1980s, winter cereal production has increased by >50%, with most of that increase occurring by the late 1990s before reaching a plateau, while fertiliser N use more than doubled over the same period (Lake 2012). The increase in production has come primarily through increasing cropped area, due primarily to reduced use of pasture rotations, with the proportionally greater increase in N fertiliser use also reflecting a reduced frequency of legume species in crop rotations and leys (Rovira 1994; Hooper *et al*. 2003; Edwards *et al*. 2012). Growers and advisors wishing to make decisions about increasingly costly fertiliser N investments face a sequence of decisions, including: (*i*) whether fertiliser N is needed; (*ii*) if so, how much is needed to meet a target yield and protein content with minimum financial risk; and (*iii*) what is the most efficient and cost-effective N application strategy to achieve that objective.

Pre-season soil sampling has traditionally been used to indicate likely fertiliser N responsiveness, and N fertiliser experiments conducted within the three cereal regions of Australia (northern, southern and western) provide an extensive source of crop response and pre-planting soil test information. These data have been included in an Australian database (BFDC National Database; Watmuff *et al*. 2013; Dyson and Conyers 2013) developed to enable a range of soil tests to be evaluated as means of determining the need for supplementary inputs of major plant nutrients (N, phosphorus (P), potassium (K) and sulfur (S)) as fertilisers for grain crops grown throughout Australia. This paper presents results of interrogations of these historical fertiliser experiments to assess the effectiveness of various pre-plant soil testing methods and analytical approaches to determine whether N fertiliser is required in winter cereal crops. It also explores the impact of other management factors (rotation history, fallow length) on both the decision to apply N fertiliser and the likely responsiveness of the crop to applied N.

Materials and methods

Nitrogen response data from >1300 wheat and ~120 barley experiments that have been conducted since 1958 within five Australian states are recorded in the BFDC National Database (Table 1). Unfortunately, many experiments that were conducted

Table 1. Number of wheat and barley experiments conducted in various Australian states by decade and reported in the BFDC National Database in which yield response to applied nitrogen was evaluated

State	1958–70		1971–1980		1981–1990		1991–2000		2001–2011	
	Wheat	Barley	Wheat	Barley	Wheat	Barley	Wheat	Barley	Wheat	Barley
NSW[A]	71	0	100	2	95	0	56	5	9	6
Qld	189	0	75	0	13	0	11	0	0	0
SA	33	0	7	8	64	45	48	40	5	3
Vic.	60	0	47	4	2	2	21	2	23	0
WA	0	0	133	0	38	1	197	0	18	0

[A] Includes ACT.

in the late 1950s and 1960s are not included, as detailed results from these experiments were never maintained following extensive reporting (Russell 1963, 1964, 1967; McClelland 1970; Taylor *et al*. 1974, 1978). That was not always the case, as other experimental programs that were carried out at that time in Queensland (Strong *et al*. 1978) and NSW (Holford *et al*. 1992) by public and private agencies, often in collaborative efforts, and others done since that time (Strong 1981; Holford and Doyle 1992; Xu *et al*. 1996*a*) are included. Details of the criteria for experiments to be accepted into the BFDC National Database are provided in Watmuff *et al*. (2013). Most of these experiments have enabled response to applied N to be evaluated against one or several common N soil tests.

Soil tests for nitrogen

Experiments in the BFDC National Database have used a variety of methods to determine available N reserves before sowing. These include: (*i*) the mass of plant-available N (kg N/ha) measured as concentrations of nitrate-N, ammonium-N, or mineral-N (nitrate-N + ammonium-N) and converted to absolute amounts by use of a measured or estimated bulk density in each soil layer; (*ii*) the concentration of plant-available N forms listed above in (*i*) but unable to be converted to a mass due to difficulties in acquiring bulk density data; and (*iii*) measures of soil organic C (%), soil total N (%), or mineralisable N released during soil incubation (for a specified duration and temperature) to indicate potential plant-available N supply. Because of the quantitative requirement for N exhibited by grain crops, measures of the mass of plant-available N (kg N/ha) are believed by many advisers to be most beneficial to guide future crop N requirements. Nitrate-N, or in some regions mineral-N, expressed as kg/ha in the root-zone, has now become the standard measure of available soil N used in decisions on the N fertiliser requirements of a planned crop (Edwards and Herridge 1998). In northern soils, where levels of ammonium-N are usually very low (<2 mg/kg) and quickly transformed to nitrate (Strong and Cooper 1992), quantities of nitrate-N at sowing or before sowing are used. In some southern production areas, measures of the concentration (mg/kg) of mineral-N or nitrate-N alone have been used extensively to guide application of N fertiliser (Xu *et al*. 1996*b*).

All of the above N soil tests, determined across the full range of Australian cropping soils, are available in the BFDC National Database and so a comparative evaluation of these tests to guide future application of N fertilisers to wheat and barley crops can be made.

Soil sampling

Experiments contained in the BFDC National Database currently only contain data on soil sampling undertaken before or at planting. The time of sampling has varied between programs and regions, but was generally within 3 months of sowing. Sample depths were more variable, ranging from surface layers (0–0.1 or 0–0.15 m) to varying fractions of the crop rooting depth (i.e. to 0.3, 0.45, or 0.6 m, or, mainly in the northern grains region, to 0.9 or 1.2 m). In situations where the mass of available N has been determined, depth increments are able to be summed to produce a profile total (kg N/ha) to the depth of sampling.

In order to compare responses between northern and southern production regions, we have used a common sampling depth of 0.6 m to compare the efficacy of pre-plant soil testing in determining the need for N fertiliser application. However, more intensive exploration of the optimum sampling depth has been undertaken within production regions where data are available. Unfortunately, this has not always been as thorough as desirable, as data from some experiments have only been retained as profile totals (i.e. nitrate-N in 1.2 m) rather than as individual depth increments.

Statistical analyses

Watmuff *et al*. (2013) describe the development and use of a tool, the *BFDC Interrogator*, which allows users to generate specific soil test calibration relationships between any soil test and relative yield (%RY) of crop response: $\%RY = (Y_0/Y_{max}) \times 100$, where Y_0 is the yield with no added nutrient and Y_{max} is the maximum yield achievable by the addition of sufficient nutrient.

The algorithm developed by Dyson and Conyers (2013) describing the calibration is the back-transform of the linear regression:

$$\ln(\text{soil test value}) = a + b \times \text{arcsine}\left((\%RY/100)^{0.5}\right) \quad (1)$$

Developing a calibration relationship is a two-stage process. The mean ln(soil test value) and correlation coefficient (*r*) are extracted from the above regression on the raw soil test values and RYs. The raw soil test values are then adjusted or linearised (Dyson and Conyers 2013) using these two parameters and the above regression (Eqn 1) is repeated for the adjusted soil test values.

This analysis enables the critical concentration and critical range to be determined for any specified %RY. Critical soil test value at 90%RY (CV90) and its critical range (CR90, the 70% confidence interval) were selected to describe an appropriate target soil test value or range. The CR90 for contrasting datasets can be compared to determine the statistical significance of any apparent differences in CV90, i.e. $P < 0.1$. These outputs of the *BFDC interrogator*, derived from calibrations between responses of wheat or barley crops to a variety of N soil tests for specified soil depths and contrasting management systems, are presented and discussed in the light of their use to guide N fertiliser application to these crops.

Protocols used to interrogate the BFDC Database

Typical interrogation pathways used to explore the wheat and barley experiments are illustrated in Fig. 1. Initial selections in the *Interrogator* include 'Annual trials'—nutrient (N), crop (wheat or barley), as well as other options such as soil type according to the Australian Soil Classification (ASC; Isbell 2002), state (NSW, Queensland, SA, Victoria, or WA), experimental year and farming system. Experiments that are selected can be further filtered as shown in Fig. 1. Outputs of the *Interrogator* so achieved generated data presented in this paper.

Interrogations were used to explore the following aspects: (*i*) the most effective soil tests and sampling depths for reliably indicating a need for N fertiliser application in wheat and barley at national and state levels; (*ii*) the influence of crop demand for N (indicated by crop yield potential, i.e. Y_{max}, and also grain protein concentration, kg N/t grain) on CV90 and CR90 (the importance of grain protein (≤11% and >11.5%) as a modifier of CV90 was considered within broad yield classes (i.e. 1–2 or 2–4 t/ha) to avoid confounding of the two components of N demand); (*iii*) relationships between in-crop rainfall (a potential surrogate for crop size and hence N demand) and CV90 were explored for wheat and barley crops in SA and wheat crops in Queensland; (*iv*) the effect of other management factors (rotations in SA and fallow length in Queensland) on the CV90 and CR90, and on the magnitude of yield response to applied N; and (*v*) the effect of variation in rainfall between pre-plant sampling and fertiliser application at sowing on the determination of calibration criteria for crops in Queensland.

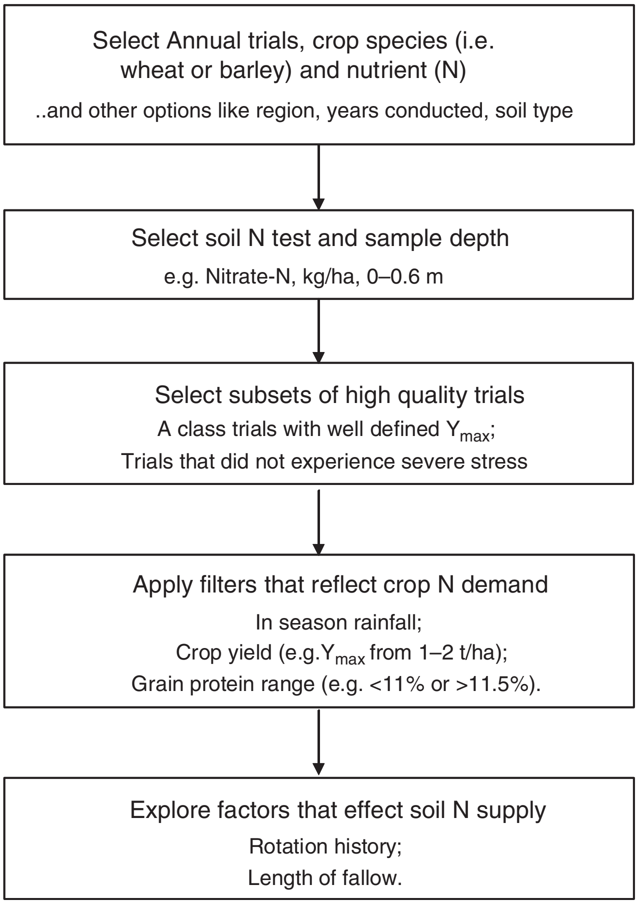

Fig. 1. Description of the interrogation process used to develop relationships between relative yield or yield response to applied fertiliser and N soil test values for subsets of the experimental data contained in the BFDC National Database.

Results

Predicting the need for nitrogen from pre-plant soil tests

The combination of sampling depth and mineral N measurement that provided the most extensive set of data across grains regions was the mass of nitrate-N to 0.6 m (kg N/ha), which is available from 315 experiments conducted across four states covering both northern and southern cereal growing regions of Australia. Unfortunately, data from NSW experiments could not be included in this analysis as only cumulative totals to 1.2 m depth were available. Relationships between this pre-plant measure of available N and relative yields of wheat and barley crops are shown in Fig. 2.

The critical soil test value at 90% RY (CV90) for wheat (49 kg N/ha nitrate-N to 0.6 m, with a quite narrow CR90 of 45–53 kg nitrate-N/ha) at a national level is dominated by data from experiments in Queensland and SA. When this dataset is disassembled on the basis of regional studies, some differences are evident. The lowest CV90 for wheat (44 kg nitrate-N/ha to 0.6 m) was derived from Queensland crops (193 experiments), with this value somewhat lower than the CV90 for wheat crops from SA (56 kg nitrate-N/ha to 0.6 m) and Victoria (62 kg nitrate-N/ha to 0.6 m). The CR90 values for datasets from both Queensland (40–49 kg nitrate-N/ha) and SA (51–61 kg nitrate-N/ha) were quite narrow and this contrasted strongly with the data from Victoria. The yield range in the smaller number of experiments from Victoria was much wider than for other states, with many high-yielding experiments producing Y_{max} in excess of 4 or 5 t/ha, contrasting with about half the experiments that were much lower yielding with an average Y_{max} of <3 t/ha. This wide range in Y_{max} among the experiments from Victoria, combined with a high proportion of moderately responsive sites with high soil tests, has contributed to the wider CR90. The *r* values for these relationships were typically 0.51–0.55 for all except the data from Victoria, where *r* was only 0.35

In the smaller barley dataset (Fig. 2) there was less variability evident between the full set and subsets based on either malting or feed barley. The CV90 of all barley nationally was 58 kg nitrate-N/ha to 0.6 m, with a relatively wide CR90 of 48–70 kg nitrate-N/ha. This relationship was improved simply by specifying whether the barley grain produced was targeting feed (61 kg nitrate-N/ha to 0.6 m, with a CR90 of 54–68 kg nitrate-N/ha) or malting quality

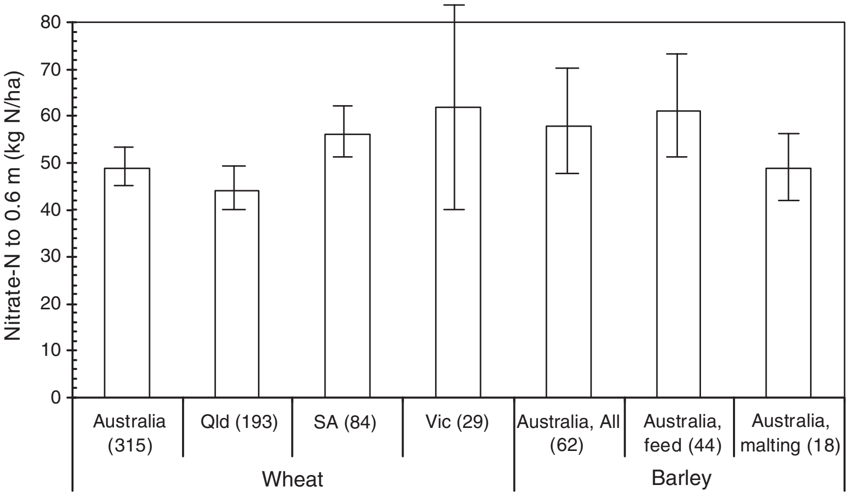

Fig. 2. Critical soil test value at 90% relative yield (CV90) of soil nitrate-N (kg/ha) to 0.6 m for wheat and barley crops Australia-wide, or for wheat experiments within individual Australian states. The number of treatment series used to create each calibration is in parentheses. Capped vertical lines indicate the critical range (CR90, defined by the 70% confidence interval) around each CV90.

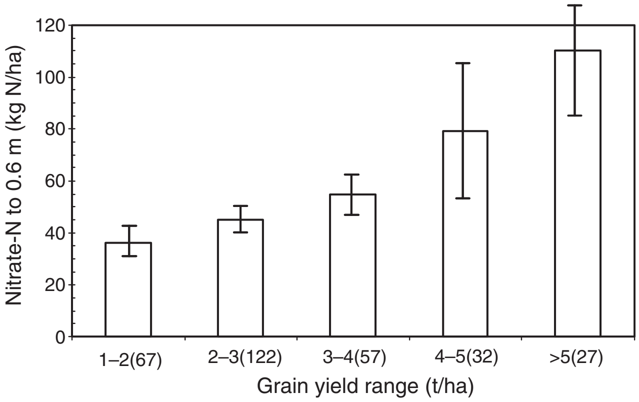

Fig. 3. Critical soil test value at 90% relative yield (CV90) of soil nitrate-N (kg/ha) to 0.6 m for Australia-wide wheat crops segregated into categories of trial maximum yields (Y_{max}): 1–2, 2–3, 3–4, 4–5, >5 t/ha. The number of treatment series used to create each calibration is in parentheses. Capped vertical lines indicate the critical range (CR90, defined by the 70% confidence interval) around each CV90.

(49 kg N/ha nitrate-N to 0.6 m, with CR90 of 42–58 kg nitrate-N/ha).

Influence of crop demand for nitrogen

Filtering all Australian wheat crops by Y_{max} obtained in each experiment, using increments of 1 t/ha between 1 and >5 t/ha, showed the very strong impact of crop demand through Y_{max} on CV90 (Fig. 3). At the lowest Y_{max} (1–2 t/ha), CV90 was 36 kg nitrate-N/ha to 0.6 m, with this value rising steadily to 110 kg nitrate-N/ha for Y_{max} >5 t/ha. The same effect of increasing Y_{max} on CV90 evident at the national scale was also observed within each state-based dataset (data not shown). In SA and Queensland there was good agreement between CV90 values for experiments with similar Y_{max} (e.g. for Y_{max} 1–2 t/ha, CV90 in SA was 31 kg nitrate-N/ha and in Queensland was 36 kg nitrate-N/ha; for Y_{max} 3–4 t/ha, CV90 in SA was 60 kg nitrate-N/ha and in Queensland was 64 kg nitrate-N/ha). In Victoria there were fewer experiments to work with, but 45% of experiments (13) recorded Y_{max} >4 t/ha with CV90 of 94 kg nitrate-N/ha to 0.6 m, whereas the other 16 experiments in which Y_{max} was <4 t/ha had a much lower CV90 of 47 kg N/ha to 0.6 m.

A similar trend was evident in barley when the dataset was subdivided into Y_{max} categories with roughly similar entries. Here, CV90 increased from 48 kg nitrate-N/ha in 0.6 m for Y_{max} <3.1 t/ha, to 65 kg N/ha in 0.6 m for Y_{max} 3.1–4.02 t/ha and 62 kg N/ha in 0.6 m for Y_{max} >4.02 t/ha (data not presented). The limited number of experiments for barley did not allow an exploration of these effects within the feed and malting crop categories.

The exploration of effects of grain protein on CV90 was somewhat limited as only 45% of the wheat experiments in the BFDC National Database have data on both grain protein and yield. As a result, the assessment of any modifying effects of grain protein on CV90 required broader yield (Y_{max}) categories than used in Fig. 3. Instead, effects in crops of 1–2, 2–4 and >4 t/ha were considered (Table 2). Critical values for all available experiments were derived (regardless of whether protein data were available), and then experiments were partitioned within these yield categories into those in which grain protein was ≤11% and >11.5% without N fertiliser application (i.e. the Y_0 condition).

The predominant impact of differences in crop yield was again evident, with CR90 increasing from 27–39 kg nitrate N/ha in 0.6 m for 1–2 t/ha crops, to 42–51 and 74–110 kg nitrate N/ha in 0.6 m for 2–4 and >4 t/ha crops, respectively. Although there was a smaller number of experiments for which grain protein data were available, the similarity in the analyses suggests that the above relationships were primarily driven by crops in which protein was <11% (i.e. where yields were limited by N availability; Strong and Holford 1997). Significant

Table 2. Critical soil test value at 90% relative yield (CV90), critical range (CR90) and correlation (*r*) value of soil nitrate-N (kg/ha) to 0.6 m for Australia-wide wheat crops that were segregated by trial maximum yield (Y_{max}) into categories of 1–2, 2–4 and >4 t/ha

Within each Y_{max} category, CV90 was determined from all available trials regardless of whether protein data were unavailable (NA), or for subsets of the experiments where grain protein data were available and were either <11% or >11.5% in the unfertilised treatments

Yield class	Grain protein	No. of treatment series	CV90	CR90	*r*
1–2 t/ha	NA	102	32	27–39	0.36
	<11%	9	No relationship derived		
	>11.5%	21	No relationship derived		
2–4 t/ha	NA	196	46	42–51	0.51
	<11%	52	53	45–62	0.33
	>11.5%	29	No relationship derived		
> 4 t/ha	NA	58	91	74–110	0.7
	<11%	42	76	66–88	0.6
	>11.5%	5	No relationship derived		

relationships could not be developed between RY and soil test for crops where protein was >11.5%, which is consistent with the expectation that these crops did not suffer yield limitations due to lack of available N.

Relationships between in-crop rainfall and CV90 were explored for wheat crops in Queensland and wheat and barley crops in SA (Fig. 4). Increasing in-crop rainfall created only small increases in CV90, and these increases were consistent with increases in the average Y_{max} in each category. For Queensland wheat crops, CV90 increased slightly, from 39 to 44 kg nitrate-N/ha, as in-crop rainfall increased from <150 to 150–200 mm, but then progressively declined to 41 kg nitrate-N/ha and then to 35 kg nitrate-N/ha in 60 cm as in-crop rainfall increased to 200–250 mm and then >250 mm, respectively. These patterns were mirrored by changes in average Y_{max} for experiments experiencing these in-crop rainfalls. As rainfall increased, Y_{max} initially increased from 1.72 to 2.51 t/ha, then plateaued at 2.53 t/ha before declining to 2.22 t/ha when rainfall was >250 mm However, in SA, the CV90 for wheat crops grown in seasons with in-crop rainfall <350 mm was 53 kg nitrate-N/ha in 0.6 m, compared with 61 kg nitrate-N/ha when rainfall was >350 mm. This was consistent with an increase in average Y_{max} from 2.84 to 3.89 t/ha. Similarly for barley in SA, CV90 increased from 54 kg nitrate-N/ha for seasons with <300 mm of in-crop rainfall to 63 kg nitrate-N/ha in seasons where in-crop rainfall was >300 mm, while average Y_{max} increased from 3.13 to 4.12 t/ha.

Other sampling depths and nitrogen analyses

The BFDC National Database contains records of experiments in which direct measurement of available N was undertaken over different sampling depths (from 0–0.1 to 0–1.2 m), using mineral-N (nitrate-N + ammonium-N) rather than simply nitrate-N and either recorded as concentrations or converted to mass using bulk density measurements. The impacts of these differences in available N measurement on the ability of pre-plant soil samplings to determine the need for fertiliser N application are explored in Fig. 5 and Table 3 and below.

In northern regions, where the predominant clay soil profiles are deep and water accumulated over the summer fallow and stored in the subsoil is critical to successful winter cereal crop production, it has been suggested that testing soils deeper than 0.6 m for mineral-N reserves may be of even greater benefit for winter cereal crops. It has been assumed that these greater sampling depths will be necessary to account for the situations where significant quantities of mineral-N may be moved deep into the subsoil when excessive rainfall is received during fallow periods. However, calibrations shown in Fig. 5 suggest that while the CV90 increases significantly with sampling depth for soils of

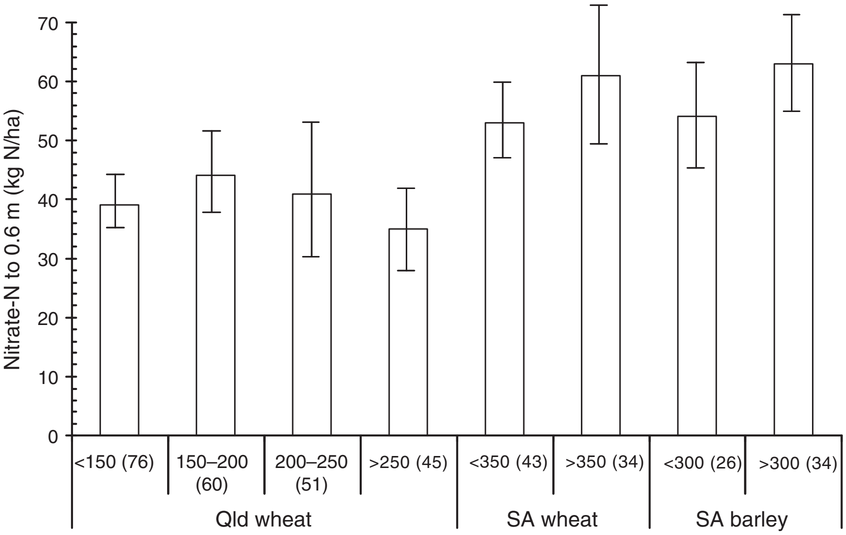

Fig. 4. Impact of in-crop rain (mm) on critical soil test value at 90% relative yield (CV90) of soil nitrate-N to 0.6 m for wheat crops in Queensland, and wheat and barley crops in South Australia. Critical ranges (CR90, defined by the 70% confidence interval around each CV90) are displayed as capped vertical lines, and numbers of treatment series are shown in parentheses.

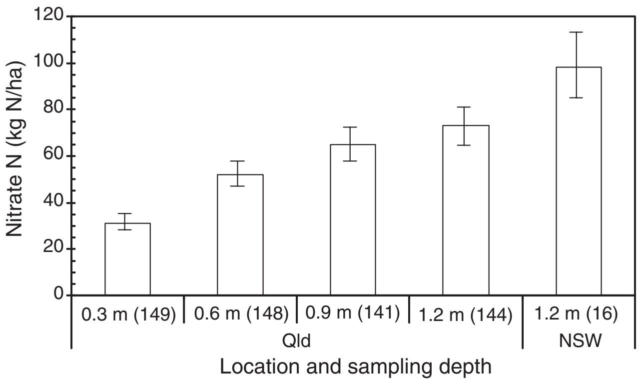

Fig. 5. Critical soil test value at 90% relative yield (CV90) of soil nitrate-N (kg/ha) derived from pre-plant soil sampling to depths of 0.3, 0.6, 0.9 and 1.2 m for wheat crops on the Darling Downs of Queensland and for New South Wales to 1.2 m. Critical ranges (defined by the 70% confidence interval around each CV90) are displayed as capped vertical lines, and the numbers of treatment series are shown in parentheses.

the Darling Downs Region of Queensland, there is little difference in the accuracy of predictions of pre-plant soil samples from 0.3 to 1.2 m in determining likely fertiliser N responsiveness. The *r* value for each sampling depth was consistently between 0.6 and 0.66, while the critical ranges were similarly narrow relative to the respective critical values. The apparently higher CV90 recorded for NSW experiments sampled to 1.2 m was consistent with a greater proportion of higher yielding experiments conducted under improved management systems. The average Y_{max} in the NSW studies was 4.3 t/ha, compared with only 2.2 t/ha in the Queensland studies.

The impacts of sampling depth and of measuring either nitrate-N or mineral-N, using either the quantity of available N (kg/ha) or the average concentration over the depth increment (mg/kg), are explored for wheat and barley experiments from SA that were conducted in the period 1990–92 (Table 3). The data show that for these soils and cropping systems, there is no real difference in the accuracy of predicting the need for fertiliser N application using CV90s developed from different profile depths (0.1–0.6 m), measurement of nitrate-N or total mineral-N, and use of weighted profile concentrations or calculated mass of nitrate- or mineral-N.

Where only very shallow soil sampling (0–0.1 m) is possible before the break of the sowing season, there is a significant amount of data relating available N concentrations (either nitrate-N or total mineral-N) or surrogates for available N, such as organic C and total N, in these surface layers. Critical values developed for each of these measurement methods are shown in Table 4. Although these relationships can be developed, in most instances the *r* values are relatively low (typically 0.2–0.4) and the CR90s are quite wide, suggesting these shallow measurements usually are unable to accurately predict the need to apply N fertiliser to maximise crop yield.

Impacts of management factors on critical nitrogen soil test value and the likely response to nitrogen

The impact of management factors such as fallow length and rotation history on both critical soil test N and the magnitude of yield responses to applied N fertiliser are explored in two examples: (*i*) from Queensland wheat crops to look at the impact of fallow length (Fig. 6), and (*ii*) from SA wheat crops to examine the effect of rotation history (Fig. 7).

The experiments from Queensland were partitioned into those in which the preceding fallow period could be described as 'short' (<7 months) or 'long' (>8 months). Each category comprised two subgroups: the 'short fallows' consisted of double-crop situations (fallows <3 months) as well as what was effectively annual winter cropping (fallows <7 months); the 'long fallows' contained fallows of 8–12 months (typically transitioning from a summer to a winter cropping pattern) and >12 months (where a lack of accumulated soil moisture or planting rain reduced crop frequency). Both short and long fallows produced similar CV90 (47 and 42 kg nitrate-N/ha in 0.6 m) and overlapping CR90 (41–53 and 35–50 kg nitrate-N/ha, respectively), suggesting fallow length had little impact on CV90 for predicting N fertiliser needs. However, when the average yield responses to N fertiliser for these two contrasting fallow lengths are considered for soil test values below the lower confidence limit (i.e. <41 and <35 kg nitrate-N/ha to 0.6 m, respectively), short-fallow experiments produced much larger average yield

Table 3. Critical soil test value at 90% relative yield (CV90) and critical range (CR90), number of experiments, and correlation (*r*) value for nitrate-N (mg/kg or kg/ha) and mineral-N (kg/ha) from sampling depths of 0.1, 0.2, 0.4, or 0.6 m as predictors of N fertiliser response of South Australian wheat and barley crops grown in 1990–92

Depth (m)	Nitrate-N								Mineral-N			
	(mg/kg)				(kg/ha)				(kg/ha)			
	No.	CV90	Range	*r*	No.	CV90	Range	*r*	No.	CV90	Range	*r*
						Wheat						
0.1	89	13	11–15	0.52	89	18	16–21	0.53	62	24	22–27	0.59
0.2	86	11	9.7–12	0.57	88	30	27–34	0.58	66	40	37–43	0.63
0.4	85	8.3	7.5–9.2	0.56	87	46	42–50	0.56	65	58	54–63	0.57
0.6	80	6.8	6.1–7.5	0.56	84	56	51–61	0.52	66	72	66–78	0.49
						Barley						
0.1	76	18	16–21	0.62	71	27	24–31	0.59	55	30	25–36	0.45
0.2	72	14	13–16	0.59	68	38	34–41	0.65	55	41	37–46	0.58
0.4	65	9.4	8.5–10	0.57	65	50	46–54	0.62	53	55	50–62	0.53
0.6	61	7.3	6.5–8.2	0.55	61	58	52–64	0.58	49	67	59–76	0.52

Table 4. Critical soil test value at 90% relative yield (CV90) and critical range (CR90), number of experiments, and correlation (*r*) value for shallow samples (0–0.1 or 0–0.15 m) measuring nitrate-N or total mineral-N (nitrate-N + ammonium-N) concentrations, organic C, or total N for dominant soil types in Western Australia, Queensland, New South Wales, South Australia, and Victoria

State/soil type (no. of expts)	Depth	CV90 (CR90)	*r*
	Nitrate N (mg/kg)		
Vic. (127)	0–10 cm	6.8 (4.5–10)	0.22
NSW (204)	0–10 cm	11 (9.4–13)	0.29
SA (91)	0–10 cm	14 (12–17)	0.41
	Nitrate-N + ammonium-N (mg/kg)		
WA (337)	0–15 cm	15 (13–16)	0.27
	Organic C (%)		
Qld Grey Vertosols (51)	0–10 cm	0.93 (0.73–1.2)	0.3
SA Sodosols (28)	0–10 cm	1.2 (0.9–1.5)	0.49
WA Tenosols (105)	0–10 cm	0.83 (0.59–1.2)	0.3
WA Chromosols (97)	0–10 cm	0.91 (0.67–1.2)	0.33
	Total N (%)		
Qld Grey Vertosols (50)	0–10 cm	0.09 (0.069–0.12)	0.34
SA Chromosols (32)	0–10 cm	0.11 (0.1–0.134)	0.44

increases (1.06 t/ha) than long-fallow experiments (0.41 t/ha). The greater yield response for the short-fallow experiments where soil test N was less than the lower boundary of CR90 would be expected to require a larger quantity of supplementary N than for the equivalent long-fallow experiments. This contention is supported by a lower average soil test value for short-fallow (21 kg/ha nitrate-N to 0.6 m) than long-fallow (29 kg/ha nitrate-N to 0.6 m) experiments in those data subsets.

In the SA example, experiments were conducted on fields that had previously grown a cereal, grain legume, or annual pasture and these produced similar CV90 (51, 57 and 58 kg nitrate-N/ha in 0.6 m, respectively) and overlapping CR90 (45–58, 47–69 and 40–84 kg nitrate-N/ha, respectively), suggesting rotation history had only a minor impact, if any, on CV90 for predicting the need for fertiliser N. However, when the average yield responses to N fertiliser in these three situations are considered, for soil test values less than the lower confidence limit (i.e. 45, 47 and 40 kg nitrate-N/ha, respectively), the average response following a cereal in the rotation was 0.93 t/ha, compared with the average yield increase of 0.53 t/ha following a grain legume and 0.34 t/ha following annual pasture (see Fig. 7 for responses following cereal and grain legume). Given the relationship between crop yield and N demand discussed earlier, this greater yield response in cereal rotations would imply a greater N fertiliser requirement. This fertiliser N requirement would be further increased by the lower average soil test N recorded in the cereal rotations. For situations where the soil test value was less than the lower boundary of CR90 in the two rotational systems, pre-plant N averaged 29 and 39 kg nitrate-N/ha to 0.6 m for the legume and cereal rotations, respectively.

Risks associated with pre-plant soil testing to guide nitrogen fertiliser application at or before sowing

There are several practical difficulties with using soil samples collected up to 3 months before sowing to guide N fertiliser applications that are made at or before sowing. Perhaps the most obvious of these are uncertainties about occurrence of a sowing rainfall event in the planting window, and then seasonal yield potential. These are especially relevant in southern Australia and WA, where in-season rainfall is the prime determinant of crop yield potential and, hence, likely N demand. However, even in northern Australia—where soil water-holding capacity can be large, deep sowing can be used to place seed in moist soil, and yield potential is strongly influenced by moisture stored during the preceding fallow—there are risks associated with pre-plant soil sampling and N application. Soil or fertiliser N may be lost due to excessively wet weather, and an example of this is provided in Fig. 8, where contrasting results were obtained from the application of N fertiliser to fields with a similar range in available N (kg nitrate N/ha in 0–0.6 m) in consecutive growing seasons on the Darling Downs of Queensland.

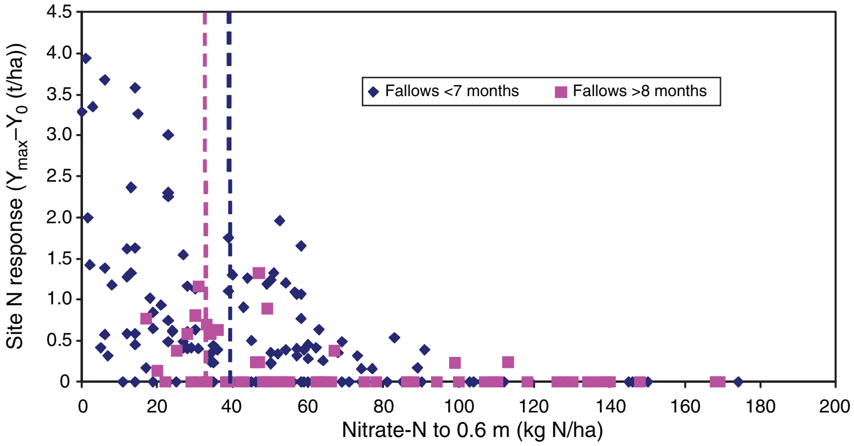

Fig. 6. Quantitative yield response to applied N fertiliser ($Y_{max} - Y_0$ t/ha) as a function of nitrate-N kg/ha to 0.6 m measured before planting for wheat crops grown in Queensland in fields with contrasting fallow lengths. Short fallows were defined as <7 months after harvest of the preceding crop (i.e. <3 months and 3–7 months), while long fallows were defined as >8 months (including fallows >12 months). Dashed lines represent the lower boundary of the 70% confidence interval (CR90).

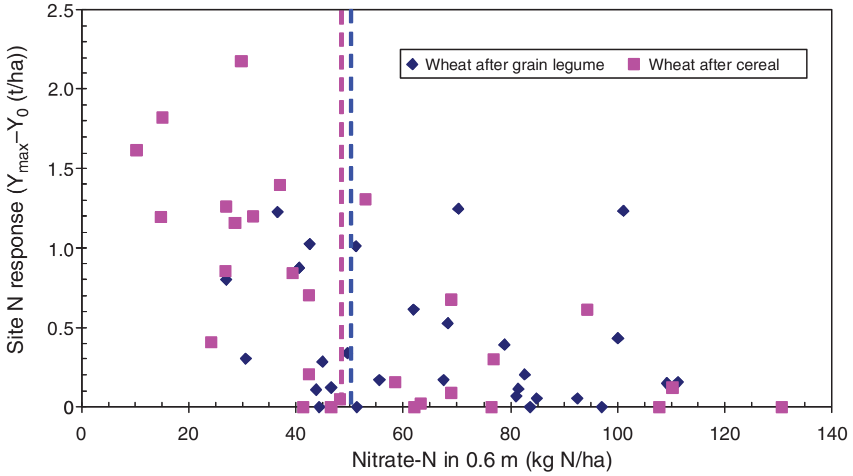

Fig. 7. Quantitative yield response to applied N fertiliser ($Y_{max} - Y_0$ t/ha) for wheat crops in South Australia grown in fields where the previous crop was either a grain legume or a cereal crop, plotted as a function of nitrate-N kg/ha to 0.6 m measured at planting. Dashed lines represent the lower boundary of the 70% confidence interval (CR90).

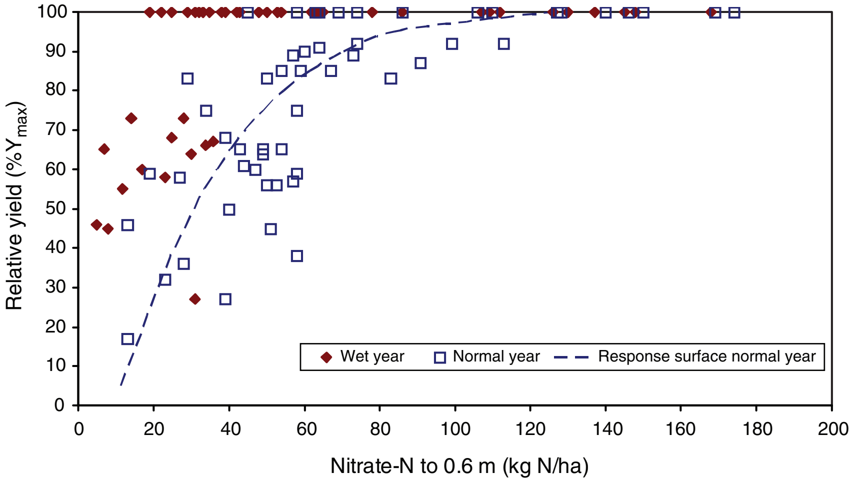

Fig. 8. Relationships between nitrate-N kg/ha to 0.6 m determined from a pre-plant soil test and relative yield of wheat crops grown in consecutive growing seasons in Queensland. Experiments were conducted in 1965, a wet year when heavy rain (130–150 mm) fell between soil sampling and sowing, and 1966, a year of normal (30–50 mm) rainfall during the same period. In 1965, no relationship was obtained between pre-plant soil test and relative yield, whereas a good relationship existed for 1966.

In 1965, soil sampling and fertiliser N application were undertaken 9–10 weeks before sowing, after which an extended wet period occurred in which 130–150 mm of rain fell on already wet soil profiles. For experiments conducted during this season, no relationship could be found between pre-plant soil test value and crop response to N fertiliser; responses to applied N were recorded only on sites where pre-plant N was exceptionally low (<35 kg N/ha), and average Y_{max} across the 48 experiments that year was only 1.8 t/ha. Findings from the 54 experiments conducted in the following season (1966) were in direct contrast to the results in 1965. In 1966, soil sampling and fertiliser application were undertaken closer to sowing (5–6 weeks prior) and there was <45 mm of rain in the intervening period (i.e. an effective planting rain). In this season there was a well-defined relationship between soil test and relative yield ($r = 0.77$), a well-defined CV90 value (71 kg nitrate N/ha in 0–0.6 m) and a range in yield responses to applied N that were consistent with the measured available N in the pre-plant soil sampling. The average Y_{max} in that season was 2.8 t/ha.

Discussion

The cost of N fertiliser inputs dominates fertiliser budgets for both winter and summer cereal crops across Australia (ABARES 2011), with application rates typically based on a matrix of fertiliser and grain prices, yield expectations/seasonal outlook, and an understanding of the available N supply in the soil profile (Angus 2001). The large number of wheat, and to a lesser extent barley, N response experiments currently in the BFDC National Database has provided an unparalleled opportunity to explore the impact of various measures of available N supply, determined by pre-plant soil testing, on response to applied N. The critical soil test values (CV90) and ranges (CR90) derived from these analyses can be used to develop a solid base upon which seasonal outlook, input costs and grain prices can be integrated to optimise returns from N fertiliser investment.

Major limitations in conducting these analyses were the disparities in reporting of available N and soil sampling depths (concentrations or quantities, in profile layers or summed across a profile to the crop rooting depth). The most extensively utilised reporting and sampling methods (kg nitrate-N/ha to 0.6 m) allowed a combined assessment of <25% of wheat experiments and ~50% of barley experiments nationally (Fig. 2). While this assessment suggested slightly higher CV90 for barley than wheat (i.e. 58 *v.* 49 kg nitrate-N/ha in 0.6 m), these national assessments masked significant variability between states/regions for wheat and between crop types (malting *v.* feed) for barley. Most of the variability in CV90, and indeed the apparent differences between localities/states (and crop types, in the case of barley), were consistent with differences in crop yields in the various experimental programs that were conducted in quite discrete eras during the past 50 years. As illustrated for wheat (Fig. 3) and discussed in the case of barley, increasing yield potentials (Y_{max}), indicative of greater crop N demand, had a major impact on CV90. In the case of wheat, CV90 increased from 36 to 110 kg nitrate-N/ha to 0.6 m as Y_{max} increased from 1–2 to >5 t/ha, while for barley CV90 increased from 48 to 65 kg nitrate-N/ha to 0.6 m as Y_{max} increased from <3 to >4 t/ha.

The earliest wheat experiments were conducted in Queensland during the 1960s and 1970s (Strong *et al*. 1978; Strong 1981), producing an average Y_{max} of 2.17 t/ha. Subsequent research in SA was conducted during the 1980s (Elliott *et al*.1987; Xu and Elliott 1993) with an average Y_{max} of 3.42 t/ha, whereas the most recent wheat research in Victoria was conducted during the 2000s and had an average Y_{max} of 4.21 t/ha. Considerable changes in cereal crop management practices have occurred during that time, with issues such as stubble retention, reduced tillage, or direct drill as well as much improved varieties contributing to increased yield potential and system water-use efficiency. The regional differences in potential yields and CV90 were therefore at least partly due to differences in crop management, with the research programs spanning conventional tillage systems in Queensland through to direct drill, stubble-retained systems on permanent beds in Victoria. The increase in potential yields represented by these eras are consistent with the increase in CV90 from 44 (Queensland) to 62 (Victoria) kg nitrate-N/ha to 0.6 m (Fig. 2).

The apparent differences in CV90 between regions in Fig. 2 were effectively eliminated when comparisons were conducted on discrete yield classes across the regions. The most detailed contrasts were possible for data from experiments in SA and Queensland, where for experiments with Y_{max} of 1–2 t/ha the respective CV90s for SA and Queensland were 31 and 36 kg nitrate-N/ha, and for experiments with Y_{max} of 3–4 t/ha the respective CV90s were 60 and 64 kg nitrate-N/ha. This consistency in CV90 between diverse climatic zones and differing soils is encouraging in terms of developing widely applicable soil test guidelines to determine the need for N fertiliser applications.

Further evidence of consistency in CV90 was obtained from the comparison of management systems in Queensland and in SA shown in Figs 6 and 7. Differing fallow lengths in Queensland (Strong *et al*. 1978) or crop rotations in SA (Xu *et al*.1996*b*) had no significant impact on CV90 and, hence, on the decisions about whether N fertiliser was required in each system within those regional programs. The differences between the CV90s for wheat in each region (42–47 kg nitrate-N/ha in Queensland and 51–58 kg nitrate-N/ha in SA) were consistent with different average Y_{max} between the experiments (i.e. average Y_{max} of 2.1–2.3 t/ha in Queensland *v.* 3.1–3.8 t/ha in SA). However, while there was consistency between CV90s for different management system, there were clearly significant impacts of those management systems on soil test N determined pre-planting and on the yield response to applied N where available N was less than the lower boundary of CR90. Average nitrate-N to 0.6 m (kg N/ha) increased from 52 kg N/ha in short fallows to 75 kg N/ha after a long fallow in Queensland, and from 53 kg N/ha in fields following a prior cereal crop to 67 kg N/ha following a grain legume and 73 kg N/ha following a grass–legume pasture in SA. There was also a clearly higher proportion of fields that were responsive to N fertiliser application in the short fallows *v.* long fallows in Queensland (Fig. 6) and in the cereal *v.* the legume rotation in SA (Fig. 7). However, even with the higher soil N status in long fallows (Queensland) or legume and pasture rotations (SA), soil test N was less than the lower boundary of CR90 in 22% (long fallow) and 27% (legume) to 42% (pasture) of experiments, and N fertiliser responses would be expected. The variability in nitrate-N to 0.6 m recorded in experiments conducted with the same fallow length (Fig. 6) or crop rotation (Fig. 7) clearly show that using 'average' effects of management to estimate available N would greatly increase the risks of either under- or over-application of N fertiliser. These data clearly illustrate the importance of soil testing as well as information on management and expected Y_{max}, to determine an appropriate N fertiliser response.

Grain protein concentration was another factor considered likely to influence the N demand per t grain, and thus potentially impact on CV90. The impact of this factor in wheat was explored in Table 2. Experiments were considered within yield categories regardless of whether protein data were available, and then partitioned into grain protein ≤11% or >11.5%. The expectation was that protein <11% was indicative of situations where yield was limited by inadequate N supply (Russell 1963), whereas protein levels >11.5% were unlikely to respond to N fertiliser (Strong and Holford 1997). Although the investigation was limited by the paucity of experiments with both protein and yield data, results of our analysis were consistent with those expectations, as experiments in which grain protein was >11.5% contributed little to the development of relationships between relative yield and soil test N pre-plant, presumably because yields in those experiments were not limited by N availability. This analysis gave us some confidence that crop yield potential (Y_{max}) was clearly the dominant factor affecting CV90, and if there were any changes in CV90 in response to grain protein they were not strong enough to be identified from the inherent variability between experiments within the yield categories.

Given the strong relationship between crop N demand and CV90, it was logical to explore the impact of soil or seasonal factors that would be expected to impact on Y_{max}, and hence CV90. In rainfed cropping systems in Australia, seasonal yield potential is primarily driven by the crop's available water supply. In temperate, Mediterranean-like climates of southern Australian and WA, this is determined primarily by the winter and spring rainfall received during crop growth, and stored soil water generally has a negligible impact on overall crop water supply. In southern regions this has largely resulted from the decline in the frequency of use of fallowing, which was used as a means of conserving water in the soil from one winter season for crop growth in the subsequent winter period (French 1978). In western regions, the primarily light-textured soils, which have only a small capacity to store moisture, further limit the value of fallowing to accumulate soil water. Using SA data as a case study for southern production systems, we were able to show a modest influence of in-crop rainfall on CV90 for both wheat and barley crops (Fig. 4). The increase in CV90 from 53 to 61 kg nitrate-N/ha in 0.6 m for wheat crops in SA as in-crop rainfall increased from <350 to >350 mm was accompanied by a rise in average Y_{max} from 2.84 to 3.89 t/ha. Similarly for barley, CV90 increased from 54 to 63 kg nitrate-N/ha for an in-crop rainfall increase from <300 to >300 mm, with an accompanying increase in average Y_{max} from 3.13 and 4.12 t/ha.

The subtropical regions of northern Australia provide a marked contrast to southern and western regions, as soil water stored during a fallow plays a much greater role in production of the dryland cereal crop, particularly for winter cereals, which usually receive only modest in-crop rainfall. Rain during the summer fallow in Queensland and northern NSW represents the majority of the annual rainfall, with falls often occurring in intense rainfall events. This fallow rainfall, combined with predominantly heavy-textured Vertosols capable of storing $\geq$200 mm plant-available soil moisture in the rooting depths of most winter cereal crops (Webb *et al*. 1997), provides the capacity to accumulate significant proportions of the water supplies for northern winter cereals. Using experiments from Queensland in this analysis, we again showed changes in CV90 that were consistent with changes in Y_{max}, but in this case the response to increasing in-season rainfall fluctuated from increases to decreases in Y_{max} (Fig. 4). This variable response to in-season rainfall is attributed to the greater reliance on subsoil moisture reserves to support crop growth and yield in those soils and environmental conditions. Growers would not plant without the presence of significant profile moisture reserves, and the planting decisions would have been more conservative (i.e. required a greater proportion of profile recharge) in the era when this research was conducted (V. French, pers. comm.). The rise in average Y_{max} of ~0.8 t/ha (i.e. from 1.7 to 2.5 t/ha) that occurred as in-crop rainfall increased from <150 mm to 150–200 mm was accompanied by an increase in CV90 for wheat crops from 39 to 44 kg nitrate-N/ha in 0.6 m. However, subsequent in-season rainfall increases produced a plateau and then subsequent decline in the average Y_{max}, which was 2.5 t/ha for 200–250 mm rainfall and 2.2 t/ha for rainfall >250 mm, with these changes in Y_{max} accompanied by a progressive decline in CV90 to 41 kg nitrate-N/ha and then to 35 kg nitrate-N/ha in 0.6 m. The negative impact of increasing in-crop rainfall in Queensland experiments is consistent with the relatively slow internal drainage rates of heavy Vertosols, and thus a propensity to waterlog and to potentially lose N via denitrification under wet conditions (i.e. a soil profile at or near field capacity, in addition to significant in-crop rainfall, especially early in the growing season). Significant losses have been recorded even when waterlogging only occurs for short periods (Islam 1992; Avalakki *et al*. 1995).

Collectively, data from these analyses show a fairly consistent increase in CV90 of 6–9 kg nitrate-N/ha to 0.6 m as average Y_{max} increased by 1 t/ha, regardless of production region. This quantum of change in response to an increase of 1 t/ha in Y_{max} was consistent with the change in the lower boundary of the CR90 for wheat yields increasing from 1–2 to 2–3, 3–4 and 4–5 t/ha (Fig. 3), with the increase being 9, 8 and 9 kg nitrate-N/ha to 0.6 m for each 1 t/ha yield increase. The increase to the >5 t/ha category was much larger (30 kg/ha), but this and the 4–5 t/ha category had the smallest number of experiments and widest CR90. Unfortunately, a similar analysis could not be conducted for barley due to insufficient data.

For the bulk of this paper, a 0.6 m sampling depth was used as a standard in both southern and northern Australia. However, there is little evidence from our analyses that 0.6 m is the optimum sampling depth in either region. Data in Fig. 5 suggest that while CV90 and CR90 increase significantly with sampling depth for northern soils (Darling Downs of Queensland), there is little difference in the accuracy of predictions of likely fertiliser N responsiveness (*r* values 0.6–0.66) for sampling depths of 0.3, 0.6, 0.9, or 1.2 m. A similar lack of clarity with respect to optimum sampling depth is evident in data presented for SA wheat and barley crops (Table 3). While CV90 values change with sampling depth (increasing quantities (kg/ha) or decreasing average concentrations (mg/kg) of mineral-N as sampling depth increases), there is little difference in the accuracy of predicting the need for N fertiliser application for soil sampling depths of 0.1, 0.2, 0.4, or 0.6 m, or indeed in the measurement of either nitrate-N only or both nitrate-N and ammonium-N (mineral-N) using either mass (kg/ha) or the average concentration (mg/kg) over the depth increment.

Collectively, both results suggest that within each region there were strong correlations between available N concentrations in successive soil layers, which is consistent with observations made by other authors (e.g. Xu *et al*. 1996*a*). However, the data for nitrate-N concentrations in the 0–0.1 m layers shown for WA, SA, and NSW in Table 4 suggest that the consistency in CV90 values that was evident between regions for 0.6 m sampling depths (Fig. 2), especially within yield categories, is less evident in shallower sampling depths. There was also a much lower level of confidence in CV90 values derived from these shallow sampling depths (low *r* and wide CR90), with the resulting increased level of uncertainty about N fertiliser decisions limiting the value of these shallow pre-plant soil tests. There was little obvious benefit from the inclusion of ammonium-N with nitrate-N (i.e. mineral-N) in the ability to predict N fertiliser requirement, and there was no suggestion that other surrogates for available N (organic C or total N; Tables 3 and 4) were as useful as direct measurement of nitrate-N alone. There did, however, appear to be potential to use organic C as a filter to improve relationships between soil test N and relative yield. Although no useful calibrations were revealed for wheat crops, barley experiments in SA did reveal higher CV90s for nitrate-N (kg/ha) to 0.2, 0.4, or 0.6 m on soils with a high organic C content (>1.4%). Unfortunately, there were insufficient data to explore these relationships within yield categories, given the over-riding influence of Y_{max}/N demand on CV90, and the recognised role played by soil organic matter in background fertility and soil health. This aspect may be more fully explored with additional data added to the database.

In most grain growing regions of Australia, some form of N-budgeting approach that balances N supply against estimated crop N demand is commonly used to estimate fertiliser N requirements, with assumptions formalised in decision support software such as N Calculator (Payne and Ladd 1993; Baldock 2005), Smart N Decisions (Cox 2009), or Yield Prophet (Hunt *et al*. 2006). These tools rely on balancing estimates of N supply (current levels of available N and likely in-season N mineralisation from residues or soil organic matter) with crop N demand (grain yield and protein content, adjusted for crop N-uptake efficiency, and the partitioning of crop N between biomass and grain). All such tools rely on a measure of available N in the soil, which in the analyses in this paper have been derived from soil samples collected at or before planting, and provide reliable estimates of the need for supplementary N fertiliser. However, while pre-plant profile sampling is relatively easy in some soil types and regions (e.g. Vertosols in the northern region), there are practical difficulties in conducting profile assessments in some southern and western areas. Collecting a profile sample when soils are dry and set hard during autumn, or from profiles that contain gravel or sheet limestone in relatively shallow profile layers, can be difficult or even impossible. If samples may only be collected to very shallow depths (0.1–0.2 m) before sowing rains, the ability of these shallow samples to accurately predict N fertiliser requirements for the subsequent crop is quite poor (Table 4).

In such situations, some growers (and advisors) are adopting a strategy of using the shallow soil sample (i.e. 0.10 or 0.15 m) pre-planting as an interim measure to determine whether fertiliser N is needed before the late tillering phase of crop development. Crop or further soil sampling can be undertaken to ascertain supplementary N needs when a more accurate seasonal yield target may be evident or improved soil moisture facilitates profile sampling. Such an approach provides dual benefits of having a clearer picture of seasonal yield potential at the time when the bulk of N application is being considered, and also minimising the risk of N losses by using split N applications to better synchronise N supply with crop demand during the season (Elliott *et al*. 1987; Angus 2001). The more reliable in-season rainfall environment in southern and western production regions allows such in-season N management to be conducted with some certainty, and recent reports (e.g. Norton 2012) illustrate that there is little risk of yield penalties arising from delaying application of at least part of the N application until later in the growing season.

Perhaps the greatest difficulty in achieving improved N management lies in estimating expected crop yield and, hence, N demand. While this is especially relevant for situations typical of much of southern Australia and WA, where in-crop rainfall is a major determinant of crop yield, it also applies to the northern region where stored soil water at planting is often a very conservative estimate of crop yield potential. The level of sophistication in predicting crop yield potential varies from grower/adviser estimates to district or regional forecasts based on rainfall records and seasonal forecasts, and simulation modelling. Regardless, there are still significant risks of under- or over-estimating yields and, hence, crop N demands, especially if seasonal yield potential is estimated before sowing and fertiliser N is applied at that time. In an effort to reduce these risks, many southern and western region growers have adopted a conservative approach to N fertiliser applications, applying low rates at or before sowing and supplementing this with additional N applied in-crop (Norton *et al*. 2009). While such an approach can utilise pre-plant soil testing to assess starting levels of available N, and there are tools such as traditional tissue sampling or more sophisticated in-crop canopy reflectance indices (Rodriguez *et al*. 2006) to determine crop N status at key seasonal growth stages, the challenge remains to determine the optimum supplementary N rates needed to meet crop N demand at those stages in the growing season. Unfortunately, there are no data available in the BFDC National Database to explore the potential of shallow soil tests to predict early-season N demand, or indeed to define the relationship between a mid-season soil N sampling, relative yield and N fertiliser requirements. If in-season N management strategies for winter cereals in southern and western cropping regions are to be further refined, such relationships will need to be developed.

In the northern region soils and climate, testing soils for water and available N to at least 0.6 m at or before planting would seem to be warranted. However, given that mineral-N reserves below 60 cm may be of even greater benefit if a significant amount of nitrate-N is moved deep into the subsoil due to an excessively wet summer fallow (e.g. the recent 2010–11 and 2012–13 summers), further assessment of the optimum sampling depth in these soils may be warranted.

Northern region growers still face risks in using pre-sowing soil testing and fertiliser application to meet crop N demands. While the greater reliance on stored soil moisture tends to give growers in this region an (albeit conservative) estimate of seasonal yield potential at or before planting, growers are still reliant on seasonal forecasts to determine the additional yield potential from in-season rainfall, and hence the additional N fertiliser requirement. Unfortunately, most parts of the region do not have the range of risk minimisation strategies available to them that southern or western growers have, as in-crop rainfall events are few and difficult to forecast. As a result, in-crop N applications are even riskier than applications before sowing. The most likely outcome of attempts to split N applications under these conditions is positional unavailability of the in-season N application in dry topsoil or volatilisation losses due to an absence of adequate rain after fertiliser application, although recent studies (Schwenke *et al*. 2012) have suggested that the risk of significant volatilisation losses from topdressed N applications may be lower than previously estimated. There are also both productivity and economic risks arising from poor recovery of both soil and fertiliser N due to denitrification caused by excessive rainfall and periodic waterlogging, either before sowing or in the early stages of crop growth, before N has been accumulated in plant biomass (e.g. the 1965 season shown in Fig. 8). In 1965 much of the available N supply (nitrate-N to 0.6 m) determined several weeks before expected crop sowing was lost during significant waterlogging events associated with prolonged autumn and early winter rainfall. More recent fertiliser experiments have demonstrated the likely impact of such rainfall events on the loss of N fertiliser applied before sowing (Strong and Cooper 1992; Strong *et al.* 1992).

Conclusions

The extensive range and number of N fertiliser response experiments contained in the BFDC National Database has provided an excellent opportunity to explore the value of pre-plant soil testing in determining the need to apply fertiliser N. The experiments, conducted over a period of >40 years, from different regional programs conducted in different eras, have no doubt been influenced by improvements in crop management and genetics that have occurred over this period. These improvements are presumed to be at least partly responsible for the observed differences in average Y_{max} between regions and eras. However, the strong influence of crop yield (as a surrogate for N demand) on CV90, below which fertiliser N responses are expected, has allowed a combined analysis of the disparate datasets to be conducted with considerable success. As the number of more recent N fertiliser experiments being incorporated in the database increases, the reliability of this analysis under modern farm management practices can be tested further.

The analyses conducted using nitrate-N to 0.6 m in this paper have provided a consistency in CV90 and CR90 values within ranges of defined crop yield potentials across diverse northern and southern cropping systems for wheat, and also a fairly consistent step-change in critical ranges as crop yield potentials increase (i.e. 8–10 kg nitrate-N/ha to 0.6 m for each 1 t/ha yield increase for yield classes of 1–2 up to 4–5 t/ha). The analyses have suggested that apparent effects of seasonal factors (e.g. in-crop rainfall) on CV90 are entirely consistent with effects on crop yield potentials (i.e. Y_{max}), and that within regions, management factors such as crop rotation or fallow length, while affecting the available N reserves, have little impact on those critical values. It has also shown that yield, rather than grain protein, is the dominant factor affecting N demand and, hence, variation in CV90, and that once grain protein values exceed 11.5% there is generally no useful relationship between pre-plant soil test and relative grain yield (i.e. crops were able to access adequate available N for that yield potential).

Collectively, these findings suggest that accurate seasonal forecasts of crop yield potentials, and hence the ability to predict N demand, hold the keys to successful use of pre-plant soil tests to predict fertiliser N response. In cropping systems such as those in northern Australia, where at least some indication of base yield potential can be derived from profile moisture reserves at or before sowing, these predictions have a greater degree of reliability. The difficulty in these systems is responding to better than expected seasons and higher yield potentials, given the variable in-season rainfall and hence opportunities to recover in-season N applications.

The greatest uncertainty around pre-plant soil testing to guide crop N applications at or before planting is in systems where crop performance is based almost entirely on in-crop rainfall, and profile soil sampling is difficult before the onset of seasonal rainfall and planting (e.g. in western and some southern areas). The compensation in these regions tends to be the greater frequency and predictability of in-season rainfall events that allows opportunities to split N applications during the growing season and so respond to changing crop yield potentials. Further development of such strategies would require an assessment of the N required at or before sowing to allow the crop to reach a suitable growth stage when in-season N can be applied, and then sufficient plant or soil data to allow an assessment of the quantity of fertiliser N required to match the N demand at these later growth stages. Currently, there are limited data to develop or test such relationships, but assessments of available N within the rooting depth, either from pre-plant or in-season soil testing, will form part of any such decisions.

Additional data for oilseeds and summer cereal crops

In addition to the winter cereals, the BFDC national database also contained experiments which recorded yield responses to applied nitrogen (N) fertiliser for other important crops grown in Australia. Analyses of experiments for oilseed and summer cereal crops catalogued in the database are reported in Appendix 1.

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Appendix 1. Soil nitrogen – crop response calibration relationships and criteria for oilseeds and summer cereal crops grown in Australia

Introduction

In addition to the winter cereals, the BFDC national database also contained experiments which recorded yield responses to applied nitrogen (N) fertiliser for other important crops grown in Australia. Analyses of experiments for oilseed and summer cereal crops catalogued in the database are reported here rather than as a separate paper due to the relatively limited number of experiments for individual crops compared to winter cereals.

Materials and methods

The number of experiments within the BFDC database for N responses in oilseeds and summer cereals is relatively small with only 340 experiments or about 7% of the total catalogued (Table 1). Of these 340 experiments, most are for canola and rapeseed (both *Brassica napus*). Table 1 also shows that there is a wide range in soil tests used for estimating soil N and in the layers of soil sampled. This severely restricted the ability to filter the database with very specific criteria (e.g. soil type, rainfall zone, production range) because the dataset rapidly diminished to below the minimum criteria (<9 data points) for developing critical values (Dyson and Conyers 2013).

Table 1. Datasets for N responses in the BFDC database for oilseeds and summer cereals

	Number of experiments	Regional distribution (by states of Australia)	N soil test used most frequently in the database
		Summer cereal crops	
Maize	17	Queensland (QLD)	Nitrate (0–120 cm, kg/ha)
Sorghum	72	New South Wales (NSW), Northern Territory, QLD	Nitrate (various depth increments, mg/kg)
		Oilseed crops	
Canola	212	Western Australia (WA), NSW	Mineral N^{A} (0–15, 15–30, 30–45 cm, mg/kg) Nitrate, Ammonium (mg/kg); Nitrate, Mineral N (kg/ha); Org C, Total N (%) × depths (0–10, 0–15, 0–30, 0–60, 0–90, 10–30 or 30–160 cm)
Rapeseed	21	South Australia (SA)	Nitrate, anaerobic ammonium, Org C, C/N, total N (0–10 cm)
Mustard	9	NSW	Nitrate, Mineral N (0–10 cm, mg/kg)
Peanuts	0		
Safflower	1	NSW	Nitrate (0–10 cm, mg/kg)
Sunflower	9	NSW	Nitrate (0–30 cm, kg/ha)
Soybean	1	NSW	Mineral N (0–10 cm, kg/ha)
Flax/linola/linseed	4	NSW	Mineral N (0–10, 10–30, 30–160 cm, kg/ha)

[A] Mineral N for this appendix is ammonium N plus nitrate N.

The approach to searching the BFDC database and analysing the relationships between crop yield and soil test value was the same as that taken with winter cereals using the curve fitting procedure outlined in Watmuff *et al.* (2013) based on the statistical procedures developed by Dyson and Conyers (2013).

Results

Oilseed crops

There were either no data or insufficient data to meet minimum criteria for deriving critical values for linseed/linola/flax, peanuts, safflower, soybean or sunflower.

There were also insufficient data for separate searches with either rapeseed or mustard alone. Therefore, data for canola, rapeseed and mustard (*Brassica juncea*) were combined as one crop type (*Brassica* spp.) because of their genetic and agronomic similarity.

The largest dataset for *Brassica* spp. was the nitrate + ammonium N (mg/kg) soil test (mineral N) in either the 0–15, 15–30, 30–45 or 0–45 cm soil layers, with the latter consisting of the average of the three 15 cm depth increments at each site. These experiments were conducted with canola in WA in the late 1990s on sandy or duplex soil types (Chromosols, Kandosols, Tenosols and Sodosols (Isbell 2002)). Even though this dataset contained a very discrete set of experiments, a critical soil test value was still poorly defined (see Fig. 1 for the 0–15 cm layer) for each of the 3 layers sampled or the composite 0–45 cm layer (Table 2).

The critical value for mineral N to achieve 90% relative grain yield (CV90) was estimated at 35 mg/kg for the 0–15 cm soil horizon but with a wide critical range (CR90) of 22–56 mg/kg. The comparable figures for the 15–30, 30–45 and 0–45 cm layers were 18 mg/kg

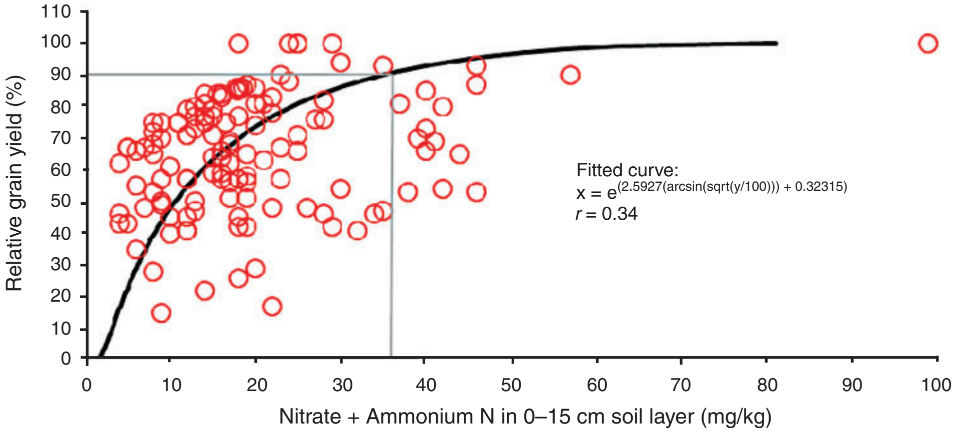

Fig. 1. Relationship between mineral N in 0–15 cm soil layer and grain yield response of canola to N fertiliser from all experiments conducted in WA.

(14–25), 13 mg/kg (10–18) and 21 mg/kg (16–29), respectively. As is obvious in Figure 1 and from the wide CR90 for each CV90, there were many situations (as represented by individual data points on the graph) which do not lie close to the fitted line. This suggests that the calculated CV90 does not accurately predict N deficiency for many individual situations in this dataset.

This general dataset was then filtered using several criteria to test whether subsets of these data could be identified which had more usable estimates of CV90 with narrower CR90. The most effective filters were soil type (for maximum yields above 1.2 t/ha) and maximum grain yield, with CV90 and CR90 presented in Table 2 for two soil layers.

Table 2. The critical value and critical range of mineral N (mg/kg) for 90% relative yield of canola derived for two soil layers. Results are shown for subsets of the available data based on soil type, organic carbon (max grain yield >1.2 t/ha) or maximum grain yield

Filter (No. expts)	0–15 cm		0–45 cm	
	Critical value	Critical range	Critical value	Critical range
		Soil type^{A}		
All (117)	40	24–66	23	16–33
Chromosols (30)	NR^{B}		NR^{B}	
Kandosols (33)	57	24–130	31	17–60
Tenosols (52)	35	21–59	20	16–23
		Organic carbon in 0–15 cm layer (%, Heanes 1984)		
All (117)	40	24–66	BFDC Interrogator can only filter for characteristics in the same soil layer as the soil test	
Less than 1.0 (77)	33	12–92		
1.0 – 2.0 (31)	58	11–300		
Greater than 2.0 (9)	47	28–76		
		Maximum grain yield (t/ha)		
All (128)	35	22–56	21	16–29
Less than 1.2 (11)	19	9–43	15	7–31
1.2 – 1.7 (45)	NR		NR	
1.7 – 2.2 (43)	38	19–74	22	14–35
Greater than 2.2 (29)	45	15–140	25	11–60

[A] Australian Soil Classification (Isbell 2002).

[B] Dataset did not meet minimum criteria in the BFDC interrogator so no response curve was fitted.

Although CV90s appeared different for Kandosols and Tenosols, the CR90s around each CV90 were so large and overlapping that there was little justification for supporting different critical values between these two soil classifications. Equally, there was a trend of increasing CV90 as maximum grain yields increased, but the relationships were not tight (as reflected in the large critical ranges for each critical value). Critical values were lower when mineral N concentrations were averaged over all three soil layers sampled compared to just the topsoil (0–15 cm) and the relationships were generally tighter (smaller critical ranges) but still wide (Table 2).

The influence of soil organic carbon % (as a surrogate for mineralisable N) on CV90 was tested by filtering the general dataset into three ranges of organic carbon (Table 2). However, there did not appear to be any consistent effect of organic carbon on CV90 and CR90s were wide for all organic carbon bands.

Any further filtering of these subsets of data generally resulted in minimum criteria not being met so no response curves (and hence critical values) could be derived.

The rest of the *Brassica* spp. data were from clusters of unrelated experiments conducted in NSW and SA (see Table 1). A wide range of soil N tests were conducted on these experiments at various sampling depths. Few of these tests and sampling depths were common to many experiments (all were different to the large WA dataset), which severely hampered interrogations of the database.

The only critical value which could be developed from this collection of 104 experiments from SA and NSW was for nitrate N (mg/kg) for the 0–15 cm layer. The CV90 was 8 mg/kg with a CR90 of 4–17 mg/kg.

Summer cereals

Data for sorghum and maize in the BFDC database were derived from experiments conducted in Qld, NSW or the NT.

Soil nitrate N (mg/kg) in the 0–10 cm surface soil layers predicted N deficiency in sorghum with a reasonable degree of precision (see Fig. 2). The CV90 was 10 mg/kg with a relatively narrow CR90 of 7–14 mg/kg. The relationship was similar but not as precise for the same soil test taken over 0–15 cm (CV90 of 7 mg/kg and CR90 of 3–15 mg/kg) even though these data came from different experiments. Similar relationships existed for nitrate N (mg/kg) sampled from deeper soil layers (0–30, 30–60, 60–90, 90–120 and 0–120 cm) with CV90s of about 3–4 mg/kg for each of these layers and CR90s of 2–7 mg/kg.

Soil tests other than nitrate N taken from the topsoil layers had no predictive value for indicating likely N deficiency.

Approximately 50% of the sorghum experiments had maximum yields >4 t/ha, and when this subset of experiments was compared to the whole set, the CV90 derived from the 0–10 cm soil test was higher (13 mg nitrate N/kg) than that derived from the whole population (i.e. 10 mg/kg). There was, however, still significant overlap in CR90 for the >4 t/ha subset (10–17 mg/kg) with that for the whole population (7–14 mg/kg). Note that a response curve could not be generated for experiments with maximum yields <4 t/ha because the data did not satisfy minimum criteria.

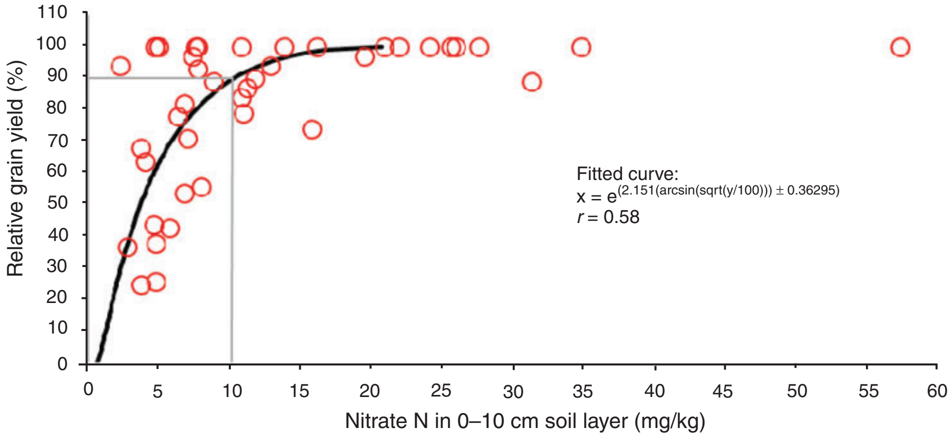

Fig. 2. Relationship between the concentration of nitrate N in 0–10 cm soil layer and response in grain yield of sorghum to N fertiliser from all experiments.

Only 17 experiments with maize conducted in Qld have been entered into the BFDC database. Soil nitrate N (kg/ha), sampled to the bottom of the root zone (0–120 cm), had some predictive value for maize. However, the derived CV90 (160 kg/ha) had a wide CR90 of 91–280 kg/ha, making the estimate of little practical value. While part of the problem was the small number of experiments upon which the analysis could be conducted, another key limitation was the fact that all experiments had relative yields less than or equal to 90% of maximum (i.e. no clear plateau could be determined). The CV90 was therefore an estimate at the very edge of the dataset, which is reflected in the wide critical range.

Discussion

Interrogating the BFDC database to develop critical soil N levels had limited value for oilseed and summer cereal crops grown in Australia. Low numbers of experiments (less than 10% of the total number in the database) for many crops and differing soil N tests (type of test and depth of soil sampling) prevented the development of precise estimates of CV90, or even the derivation of any response relationships.

However, effective interrogations were possible for *Brassica* crops (canola, mustard and rape) although even then searches using combined data for all species were necessary in many cases. It was also possible to derive estimates of CV90 for sorghum and maize.

It was not possible to critically compare the value of different soil N tests for oilseeds or summer cereals as predictive tools for N deficiency because the datasets were either too small, the soil layers sampled too inconsistent or there were insufficient numbers of experiments which had multiple soil tests recorded, or a combination of any of these three.

The most populous and coherent dataset for this appendix was for the concentration of mineral N taken at various soil depths for canola grown in WA. Critical values for mineral N (mg/kg) in surface soil (0–15 cm) varied with productivity and soil type. As maximum yields increased from less than 1.2 t/ha to more than 2.2 t/ha, CV90 for mineral N increased from 19 to 45 mg/kg, which is consistent with an increased demand for N to support the increasing biomass production.

An aggregated mineral N test (mg/kg) to 45 cm showed similar trends to the test taken to only 15 cm but was less sensitive to both soil type or productivity and had a higher level of precision (as evidenced in smaller critical ranges for each critical value). This makes the deeper test more attractive for general use because interpretation is less sensitive to the environment in which the canola will be grown. However, despite generally better estimates of available N from this aggregated assessment, critical values were still too large (CR90 often covered a 2–3 fold range) to recommend the test as a reliable prognostic tool for N deficiency in canola, even in WA. Filtering by organic carbon as a surrogate for mineralisable N provided no improvement to the uncertainty of the mineral N test alone.

The number of *Brassica* spp. experiments outside of WA was about half of those conducted in WA and were far more fragmented in terms of tests conducted and layers sampled. As a consequence, few CV90 estimates could be derived with any confidence. A CV90 of 8 mg nitrate N/kg in the top 15 cm of soil was derived for *Brassica* spp. from all experiments conducted in SA and NSW. This value is difficult to reconcile with a CV90 of 40 mg mineral N/kg for the same soil layer for canola in WA, especially given that the data from SA and NSW were from heavier soil types than in WA.

Despite this apparent lack of precision with mineral or nitrate N in surface soils for predicting N deficiency in *Brassica* spp., this test holds some promise for sorghum. A CV90 of 10 mg nitrate N/kg with a CR90 of only 7–14 mg/kg appears to be quite a robust prognostic indicator for this test under Australian rainfed conditions. However, quantitative determinations using the same test taken over the whole root zone (mg/kg over 0–120 cm) were even more precise, with a CV90 of 4 mg nitrate N/kg and a CR90 of 3–6 mg/kg. Hibberd *et al*. (1986) published a critical value of less than 50 kg nitrate N/ha in the top 80 cm for sorghum grown on Vertosols which is consistent with interpretations from the BFDC database. However, comparisons could not be made directly due to differences in depth increments sampled and the need to convert nitrate N tests in BFDC from mg/kg to kg/ha using an estimated bulk density.

A comparison could not be made with maize because for that crop, nitrate N (mg/kg) was not recorded for the experiments in the database. However, a relationship was derived for soil nitrate N (kg/ha) to 120 cm but the uncertainty around the estimated critical value was still too wide for the test to have much commercial value. While difficult to make direct comparisons, the derived CV90 of 160 kg/ha appears similar to those published for maize by Strong and Mason (1999).

No further filtering of the data for oilseeds or summer cereals was possible due to lack of numbers or inconsistent soil testing approaches.

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