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Combined application of nitrogen and phosphorus to enhance nitrogen use efficiency and close the wheat yield gap on varying soils in semi-arid conditions

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Abstract

A primary driver of the wheat yield gap in Australia and globally is the supply of nitrogen (N) and options to increase N use efficiency (NUE) are fundamental to closure of the yield gap. Co-application of N with phosphorus (P) is suggested as an avenue to increase fertiliser NUE, and inputs of N and P fertiliser are key variable costs in low rainfall cereal crops. Within field variability in the response to nutrients due to soil and season offers a further opportunity to refine inputs for increased efficiency. The response of wheat to N fertiliser input (0, 10, 20, 40 and 80 kg N ha^{-1}) under four levels of P fertiliser (0, 5, 10 and 20 kg P ha^{-1}) was measured on three key low rainfall cropping soils (dune, mid-slope and swale) across a dune-swale system in a low rainfall semi-arid environment in South Australia, for three successive cropping seasons. Wheat on sandy soils produced significant and linear yield and protein responses across all three seasons, while wheat on a clay loam only produced a yield response in a high rainfall season. Responses to P fertiliser were measured on the sandy soils but more variable in nature and a consistent effect of increased P nutrition leading to increased NUE was not measured.

KEYWORDS
dryland, fertiliser responsiveness, nutrition

1 | INTRODUCTION

Nitrogen (N) is known to be a leading cause of wheat yield gaps in Australian cropping systems (Hochman & Horan, 2018), and Cui et al. (2014) argue that closing the gap between actual and attainable N use efficiency (NUE) is an important target in the goal of closing yield gaps. Further to this, a recent review of Duncan, O'Sullivan, Roper, Biggs, and Peoples (2018) finds that the key to increasing NUE potentially lies with co-application of other macronutrients, in particular phosphorus (P). Because of the water-driven riskiness of crop production in low rainfall environments, inputs of organic matter and fertiliser nutrients both tend to be low (Sadras, 2002). As a result, N and P remain the most limiting and expensive nutrients in low rainfall cropping systems. There is a high level of variation of soil types and as a result soil fertility over relatively short distances (Rab et al., 2009), lending this environment to significant adoption of soil-specific management of nutrient inputs (Robertson et al., 2012). Optimisation of nutrient input according to soil type for the balance between profit maximisation and risk minimisation remains a challenge (Hoffman, Llewellyn, Davoren, & Whitbread, 2017; Monjardino, McBeath, Brennan, & Llewellyn, 2013). A significant proportion of Australian low rainfall cropping occurs on a dune-swale landscape with high levels of variation in soil type but relatively small shifts in elevation (Hoffman et al., 2017; Rab et al., 2009; Whitbread, Hoffman, Davoren, Mowat, & Baldock, 2017). The heavier textured soils in this landscape tend to be loams in the surface with a higher cation exchange capacity, but with heavier texture with depth, often associated with subsoil constraints which hinder crop production and as a result lower nutrient extraction in lower rainfall seasons (Hoffman et al., 2017). With consistent inputs of fertiliser in past seasons, at times in excess of replacement levels, P fertility in particular has accumulated to some extent in these soils (Latta, Mock, & Smith, 2008). On the sandier soil types which have lower organic matter (OM), cation exchange capacity and clay content, the higher leaching losses of N and less sorption sites for the retention of P results in lower accumulation of N and P, and these soils tend to be less fertile than the loams (McBeath, Gupta, Llewellyn, Davoren, & Moodie, 2015a).

Soil biological activity modulates the resupply capacity of nutrients both in terms of amount and timing of nutrient release for plant uptake (Ladd, Oades, & Foster, 1996). In low rainfall cropping soils, the availability of N can limit microbial processes related to decomposition and carbon (C) turnover from soil OM and recent crop residues (Gupta, Rovira, & Roget, 2011). Soil microbial communities have been found to be sensitive to N, P, K and S fertilisation causing changes in composition and/or activities with responses varying based on soil type, cropping system and rate and frequency of application (Allison & Martiny, 2008). The response of the biological components of the system to fertiliser input can be a major determinant of the impact of that fertiliser input.

It is often assumed that there will be a positive synergy for grain yield and NUE when N and P are applied together in low fertility situations, and this synergy has been demonstrated several times in Australian cropping systems (Alston, 1980; Armstrong, Millar, Halpin, Reid, & Standley, 2003; Brennan & Bolland, 2009; Colwell, 1963a; Duncan et al., 2018; Holford, Doyle, & Leckie, 1992; Officer, Dunbabin, Armstrong, & Norton, 2008). Brennan and Bolland (2009) measured an increased demand for N with increasing levels of P input at seven sites across three seasons for both wheat and canola grown on sands in Western Australia. However, the synergy between N and P input does not always occur, depending on the inherent fertility and crop responsiveness to N and/or P (Haileselassie, Habte, Haileselassie, & Gebremeskel, 2014; Lester, Birch, & Dowling, 2008). A further key co-limitation for NUE is the growing season rainfall (Cossani, Slafer, & Savin, 2010). Fertiliser NUE is strongly linked with the availability of water and responsiveness is, as a result, cropping season dependent (Hancock, McNeill, McDonald, & Holloway, 2011). On the other hand, while crop responses to P input have been linked to seasonal conditions (McBeath, McLaughlin, Kirby, & Armstrong, 2012), the response to P fertiliser tends to be considered to be more temporally stable than crop response to N (Lambert, Lowenberg-DeBoer, & Malzer, 2006).

While there is evidence to suggest that intensive crop production on the sandy soil types in this low rainfall environment respond well to increased inputs of N (McBeath, Gupta, Llewellyn, Davoren, & Moodie, 2015a; Monjardino et al., 2013; Whitbread, Davoren, Gupta, Llewellyn, & Roget, 2015), the potential for the application of P fertiliser to influence NUE of wheat in different soil types and seasons has not been explored. The aims of this study were to measure the effect of repeated additions of a range of doses of fertiliser N and P on closure of the wheat yield gap through increased wheat yield and NUE under varying soil types and growing seasons.

2 | MATERIALS AND METHODS

2.1 | Site characteristics

The fertiliser experiments were implemented in a typical dune-swale system with three key soil types in the same field at Lowaldie (S 33°59.616, E 136°19.915) 20 km North East of Karoonda, SA. The soil types were a dune on a deep sand (Arenic Luvisol), a mid-slope with sandy over clay loam (Luvic Calcisol) and a swale on clay loam over clay (Luvic Sodic Calcisol) classified according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2014); herein referred to as the dune, mid-slope and swale soils. The transition in elevation across this landscape was only 2 m (dune at 71.3 m, mid-slope at 71.9 m and swale at 70.2 m). Bulk density was measured in situ according to the procedure outlined by Burk and Dalgliesh (2008). Soils were sampled in transects across each field replicate (block) with six replicate cores. The soil cores were subsampled to depths of 0–0.1, 0.1–0.6 and 0.6–1.0 m, and samples were returned to the laboratory and thoroughly mixed prior to sub-sampling for nitrate and ammonium N analysis. The remainder of the sample was oven-dried at 40°C for one week. The soils were sieved and ground by mortar and pestle and then analysed for a range of chemical properties that regulate soil fertility. Soil electrical conductivity (EC) was measured in a 1:5 soil: water suspension while pH was measured in a 1:5 soil: 0.01 M calcium chloride solution (Rayment & Lyons, 2011). Boron concentration was determined by the hot calcium chloride extraction (Rayment & Lyons, 2011). Exchangeable sodium percentage (ESP) was calculated following measurement of cation exchange capacity using 0.1 M ammonium chloride with 0.1 M barium chloride extractant (method 15E1) outlined in Rayment and Lyons (2011). Organic carbon (C) was measured according to the Walkley Black method (Rayment & Lyons, 2011; Walkley & Black, 1934). Topsoil samples (0–0.1 m depth) were also analysed for Colwell-extractable potassium and P (Colwell, 1963b; Rayment & Lyons, 2011), extractable sulphur using 0.25 M potassium chloride at 40°C (Blair, Chinoim, Lefroy, Anderson, & Crocker, 1991), diffusive gradients in thin-films for P (DGT P) according to Mason, McNeill, McLaughlin, and Zhang (2010) and P buffering index according to Burkitt, Moody, Gourley, and Hannah (2002). Soil nitrate N and ammonium N were analysed at 0–1.0m according to Method 7C2b (Rayment & Lyons, 2011). The soil nitrate N and ammonium N were converted to kg ha^{-1} value using the corresponding soil type and depth bulk density value and the sum of the nitrate and ammonium N represented the mineral N (kg ha^{-1}) which was summed to 1 metre depth using the value for each sample depth.

TABLE 1 Soil profile bulk density (BD), clay content, cation exchange capacity (CEC), mineral nitrogen (N), Colwell-extractable phosphorus (P), phosphorus buffering index (PBI), Colwell extractable potassium (K), potassium chloride extractable sulphur (KCl-40 S), organic carbon (OC), electrical conductivity (EC), pH, exchangeable sodium percentage (ESP) and calcium chloride extractable boron ($CaCl_2$ B) of the dune, mid-slope and swale measured prior to sowing of crops in 2010

Depth m	BD gcm^{-3}	Clay % $w\ w^{-1}$	CEC Meq $100g^{-1}$	Mineral N Kg ha^{1}	Colwell P mg kg^{-1}	PBI	Colwell K mg kg^{-1}	KCl–40 S mg kg^{-1}	OC % $w\ w^{-1}$	EC1:5 dS m^{-1}	$CaCl_2$ pH 1:5	ESP % w w^{-1}	$CaCl_2$ B mg kg^{-1}
Dune													
0–0.1	1.34	3	2.83	24	21	6	75	4.2	0.54	0.045	5.9	2.8	0.68
0.1–0.2	1.45	3	2.28	13	11	6	27	2.0	0.26	0.030	6.1	2.6	0.54
0.2–0.4	1.59	3	1.77	14	5	9	55	1.2	0.11	0.030	6.5	5.1	0.42
0.4–0.6	1.59	12	8.57	10	2	28	170	2.5	0.06	0.150	8.5	13.9	3.45
0.6–0.8	1.67	21	14.05	9	2	71	254	6.0	0.07	0.230	8.4	17.4	8.31
0.8–1.0	1.76	[a]	16.98	9	[a]	[a]	305	11.9	0.08	0.350	8.5	22.3	12.51
Mid-slope													
0–0.1	1.66	3	2.8	32	21	7	121	4.1	0.54	0.064	5.3	2.5	0.53
0.1–0.2	1.67	3	1.86	12	9	2	69	1.8	0.15	0.039	6.2	3.8	0.37
0.2–0.4	1.62	12	4.42	22	4	12	118	1.7	0.08	0.065	8.0	17.0	1.64
0.4–0.6	1.62	23	14.55	10	13	34	285	6.7	0.06	0.368	8.9	23.6	10.18
0.6–0.8	1.59	30	19.30	13	[a]	88	365	12.2	0.08	0.496	8.9	25.4	14.49
0.8–1.0	1.68	[a]	21.41	14	2	[a]	410	17.3	0.06	0.592	8.9	29.5	18.11
Swale													
0–0.1	1.50	8	6.08	15	38	28	309	5.9	0.97	0.112	5.9	6.1	0.74
0.1–0.2	1.69	24	16.16	8	10	46	230	11.5	0.50	0.368	8.4	13.4	3.26
0.2–0.4	1.70	30	24.26	11	4	105	243	53.0	0.40	0.848	8.7	26.1	13.09
0.4–0.6	1.70	34	24.20	8	3	91	293	108.2	0.18	1.136	8.7	35.3	19.84
0.6–0.8	1.72	35	20.98	8	[a]	64	323	105.8	0.13	0.976	8.2	42.7	18.51
0.8–1.0	1.56	[a]	19.22	6	[a]	[a]	320	112.9	0.11	0.896	6.5	46.8	13.93

[a]Missing value.

The dune and mid-slope had lower organic carbon, cation exchange capacity, Colwell P and K and extractable S than the swale soil, but P, K and S were not below critical values for deficiency (Anderson, Peverill, & Brennan, 2013; Brennan, Bolland, & Ramm, 2013; Moody, 2007; Table 1). The soils had a neutral surface pH with alkaline subsurface layers. The ESP exceeded 15% at 60 cm depth in the dune, 40 cm in the mid-slope and 20 cm in the swale while boron exceeded 15 mg kg^{-1} at 80 cm in the mid-slope and 40 cm in the swale, both levels anticipated to have a negative effect on crop root extraction of water (Table 1). The swale was saline from 20 cm depth, and the mid-slope was moderately saline from 60 cm depth, also anticipated to have a negative effect on wheat crop productivity (Peverill et al., 1999; Table 1).

The climate at this site is semi-arid with an annual average rainfall of 337 mm and average April to October cropping season rainfall of 237 mm (Figure 1). The 2010 cropping season had above average rainfall (342 mm), 2011 had below average cropping season rainfall (203 mm) but above average annual rainfall (505 mm) due to record summer rainfall events, and 2012 was an average cropping season (258 mm) with a dry finish (Figure 1).

2.2 | Experimental design

A wheat (*Triticum Aestivum*) crop was sown in May of each cropping season 2010–2012 following opening rains of at least 20 mm. All plots were sown with a 7-row plot seeder with narrow points (50 mm wings) and press wheels spaced 0.23 m apart with each plot 1.6 m wide and 20 m long. There were 20 fertiliser treatments which included every combination of four rates of P (0, 5, 10 and 20 kg P ha^{-1} applied as triple superphosphate) and five rates of N (0, 10, 20, 40, and 80 kg N ha^{-1} applied as Urea). All fertiliser treatments were applied at sowing with the fertiliser applied approximately 4 cm below the seed except the 80 kg N ha-1 treatment involved the application of 40 kg N ha^{-1} at sowing and 40 kg N ha^{-1} at growth stage 31 (Zadoks, Chang, & Konzak, 1974). The highest N rate treatment was split due to concerns about fertiliser toxicity, particularly in the sandy soil types. The in-season N application involved topdressing of the plots using the seeder equipment with the tynes removed to ensure an even distribution of urea across the plot. The experiments were laid out in a completely randomised block design with 3 replicates, and the design was applied three times to the dune, mid-slope

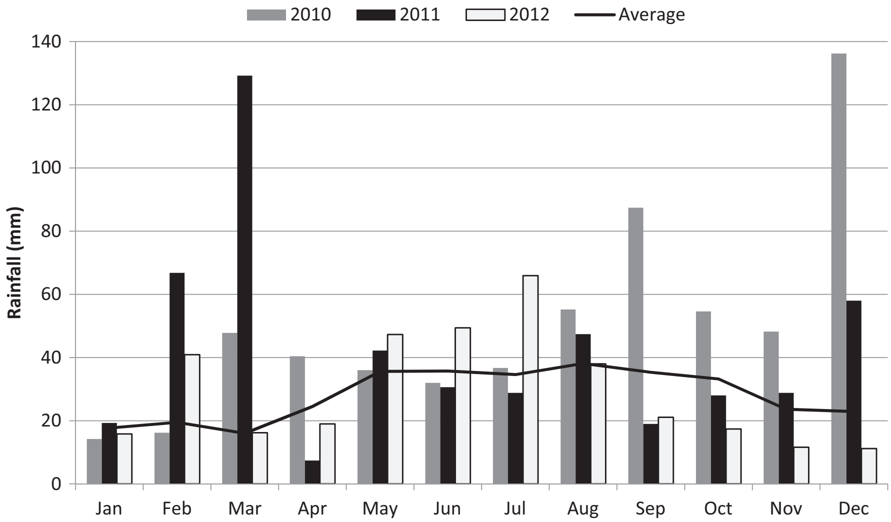

FIGURE 1 Site monthly rainfall relative to average rainfall for 2010–2012

and swale soil types. The fertiliser treatments were repeated in 2010, 2011 and 2012 with the same treatment applied to the same plots each year and crops sown with knife points in-between previous crop rows to retain stubble.

2.3 | Crop management

The wheat cultivar selected in each growing season was rotated to minimise pressure on weed and disease management. Wheat was sown at 70 kg ha^{-1} with *cv.* Correll grown in 2010 and rotated to cv. Mace in 2011 after yellow leaf spot build up in 2010, and rotated from *cv.* Mace to *cv.* Kord CL Plus® in 2012 to enable weed pressure to be maintained at low levels and to ensure stripe rust remained at low levels. All plots received sulphur applied as gypsum (100 kg ha^{-1}; 12% w w^{-1} S content) spread before sowing and in-crop foliar applied trace element fertilisers ($ZnSO_4{\cdot}7H_2O$ at 1.9 kg ha^{-1}, $MnSO_4{\cdot}H_2O$ at 3 kg ha^{-1} and $CuSO_4{\cdot}5H_2O$ at 0.4 kg ha^{-1} in 100 L ha^{-1} water) in every growing season to ensure nutrients other than N and P were not limiting. Crop plots were maintained in-season with the aim of minimising any impact of weeds and disease (e.g. *Pyrenophora tritici-repentis*). This was successfully achieved through the use of a range of common herbicides and limited use of fungicides applied equally across all soil types.

2.4 | In-season measurements

A minimum of eight surface soil samples (0–0.1 m depth) were collected using a 3.5 cm diameter corer, from adjacent to the previous crop row 1 week prior to sowing, and bulked to create a single sample per plot for analysis. In addition, a soil core to 1 m depth was taken prior to sowing in each year of the experiment for each replicated plot in a subset of treatments. Samples were taken from the position of the current season crop row, representing the resources available to the current crop. The cores were divided into depths of 0–0.1, 0.1–0.6 and 0.6–1.0 m and thoroughly mixed prior to sub-sampling for measurement of water content and nitrate and ammonium N analysis according to the procedures described above. Soils at 0–0.1 m depth were dried at 40°C for one week and then ground (mortar and pestle) and sieved (<2 mm) for P analysis according to the procedures described above. Plots were machine harvested at maturity to measure grain yield. Dried wheat grain samples (≈12% w w^{-1} moisture) were analysed for protein using a FOSS® (model Infratec Sofia) NIR analyser calibrated against a subset of samples measured on a Formacs® HT series Combustion TOC/TN analyser with a high-temperature furnace system.

To determine if there were cumulative effects of the fertiliser treatments on soil biological properties, a subset of treatments were analysed for soil biological properties were analysed in the 2012 growing season using the 0–0.1 m depth pre-sowing soil samples. Soil samples were pre-incubated for 48 hr at 25°C after adjusting the soil moisture to field capacity (7.5% and 11.0% w w^{-1} for the dune and swale samples, respectively). Samples were analysed for chemical (dissolved organic C and mineral N), biochemical (microbial biomass, MB) and biological activity (C and N mineralisation potential) properties. Microbial biomass C was measured using the chloroform-fumigation extraction method as per Sparling, Gupta, and Zhu (1993). Pre-incubated soils were extracted with 2 M KCl (1:3 soil to KCl ratio) for mineral N levels. For carbon (POC) and N (PMN) mineralisation potential measurements, 100 g of each soil was incubated (aerobic) in a closed 500 ml glass jar with 15 ml of 1 M NaOH at 25°C for 21 days. Mineral N levels measured at the start and end of the incubation were used to calculate PMN. Mineral N (ammonium and nitrate N) in the extracts was analysed as per the method by Rayment and Lyons (2011). CO_2-C trapped in the alkali trap was estimated using a double end point titration (Gupta, Roper, Kirkegaard, & Angus, 1994). Nitrogen supply potential was calculated assuming that all of the PMN and 50% of MB-N from microbial turnover and faunal-predation would be available for plant uptake (McBeath, Gupta, Llewellyn, Davoren, & Whitbread, 2015b). Dissolved organic C in the 0.5 M K_2SO_4 extracts (1:3 soil to extractant ratio) were measured using the previously mentioned TOC/TN analyser.

2.5 | Nitrogen use efficiency and recovery

Simple equations were used for a partial derivation of NUE and apparent N recovery by grain as described by Duncan et al. (2018). The x of the term Nx refers to the fertiliser N applied while N0 refers to the treatment with no fertiliser N applied.

$$\text{NUE}\left(\frac{\text{kg grain}}{\text{kg N}}\right)=\frac{\text{yield N}x-\text{yield N0}}{\text{fertiliser N}}$$

$$\text{N Recovery}\left(\frac{\text{kg grain N}}{\text{kg N}}\right)=\frac{\text{grain N}x-\text{grain N0}}{\text{fertiliser N}}$$

2.6 | Yield gap analysis

Water-limited wheat yield potential (with no N limitation) was modelled for each of the three soil types in the 2010–2012 growing seasons using the Agricultural Production Systems Simulator (APSIM v. 7.7) (Holzworth et al., 2014). These modelled yields were compared with the highest wheat yield achieved experimentally. The APSIM modules utilised in the analysis were Wheat (wheat crop growth and development), SoilWat (soil water balance), SoilN (soil N dynamics), SurfaceOM (surface residue dynamics) and Manager (management rules) as described by Hunt and Kirkegaard (2011). The measured site characteristics including the chemical properties, crop lower limit and drained upper limit were used to parameterise the model which allows the estimate of yield potential to factor in the effect of constraints to crop water use. The use of APSIM for the simulation of wheat response to soil water and N has been widely tested and validated in Australian cropping systems (Hunt & Kirkegaard, 2011; Probert, Dimes, Keating, Dalal, & Strong, 1998; Sadras & Rodriguez, 2010; Verburg, Bond, & Hunt, 2012; Whitbread et al., 2017). The fit of modelled versus actual data for wheat yield at Karoonda and on the same soil types (R^2 = 0.84, RMSE = 0.3 t ha^{-1}) has been previously demonstrated in Monjardino et al. (2013). The weather data were obtained from an onsite weather station, and missing data points were patched with data from the SILO Patched Point Dataset for the nearby Australian Bureau of Meteorology at Karoonda (station 025006). The APSIM-Manager rules used were based on a sowing on the same day that the field experiment was sown in 2010–2012. Nitrogen was applied as urea at 150 kg N/ha to attain an N unlimited yield. Soil water and N were reset to pre-sowing soil test values on the date that the soil test was taken. The surface OM was reset to 1.5 t ha^{-1} with a C:N of 80 at the same time. The yield gap was calculated as the N unlimited yield minus the highest attained yield for each growing season.

2.7 | Statistical analysis

All data were statistically analysed with Genstat V13® Software. The initial analyses were analyses of variance carried out in GenStat for each year and each variable, where the treatment formula was Pol (N;1) * Pol (P;1), which partitions the main effects of N and P into linear and deviation from linear components and also assess how the interaction partitioned. The replicates were removed with a block statement. Those analyses showed that the effects of the fertiliser were mainly linear responses, and interactions between N and P were expected to be mainly reflected in the linear by linear component. A series of simple linear regressions were then performed where the slope was a measure of the responsiveness of the relevant measure to the amount of N or P applied. The intercept was an estimate of the measure in the absence of any N or P. A repeated measure assessment was carried out where the years were considered as subplots. That analysis was a useful approximation for the interaction with year as that analysis assumes all the correlations of the residuals among the years were similar but that condition was not always met. Two other methods were tried for the assessment of the repeated measures; multivariate analysis of variance, where each year was treated as a separate variable but the output was difficult to interpret and considering the mean across the three years and the trends within a plot—that formulation gave useful results but it was difficult to summarise. The use of the split plot in time was therefore used to assess the means of across treatments and across times.

3 | RESULTS

3.1 | Grain yield response

All the highly significant wheat yield responses to N and P inputs (p < 0.001) were with the main effects rather than the interactions, and as a result, the responses are represented using simple linear regressions (Figure 2). In no case was there a significant linear–linear interaction between N and P for yield. The slope of the regressions on yield was used to describe the responsiveness to nutrient input (kg ha^{-1} yield per kg ha^{-1} N or P input) (Figure 3). The crops on sandy soil types were more responsive to N inputs compared with the swale soil type across all seasons. Yields were not maximised at 80 kg N ha^{-1} input on the sandy soil types. The only season in which yield on the swale was positively responsive to N inputs was in the high-yielding season of 2010, with no response in 2011 and 2012 (Figure 3). Similarly, the only season in which the swale was responsive to P inputs was in 2010, with no significant response in 2011 and 2012. Wheat on the sands was more responsive to P inputs, with some variation around the level of responsiveness (both between the two sands and between seasons) (Figure 3). The seasonal difference in responsiveness had components of the cumulative effects of N inputs and the climatic effects influencing water-limited yield potential. A test of whether the season or year of the experiment influenced the crop responsiveness to N or P showed a between-year effect on responsiveness of grain yield to N for all soil types (Figure 3, p < 0.05, SED between responsiveness slopes is 3.62) but not for P (p > 0.05).

3.2 | Grain protein

There were grain protein responses to N input, with the highest level of N input achieving the highest protein result in all seasons

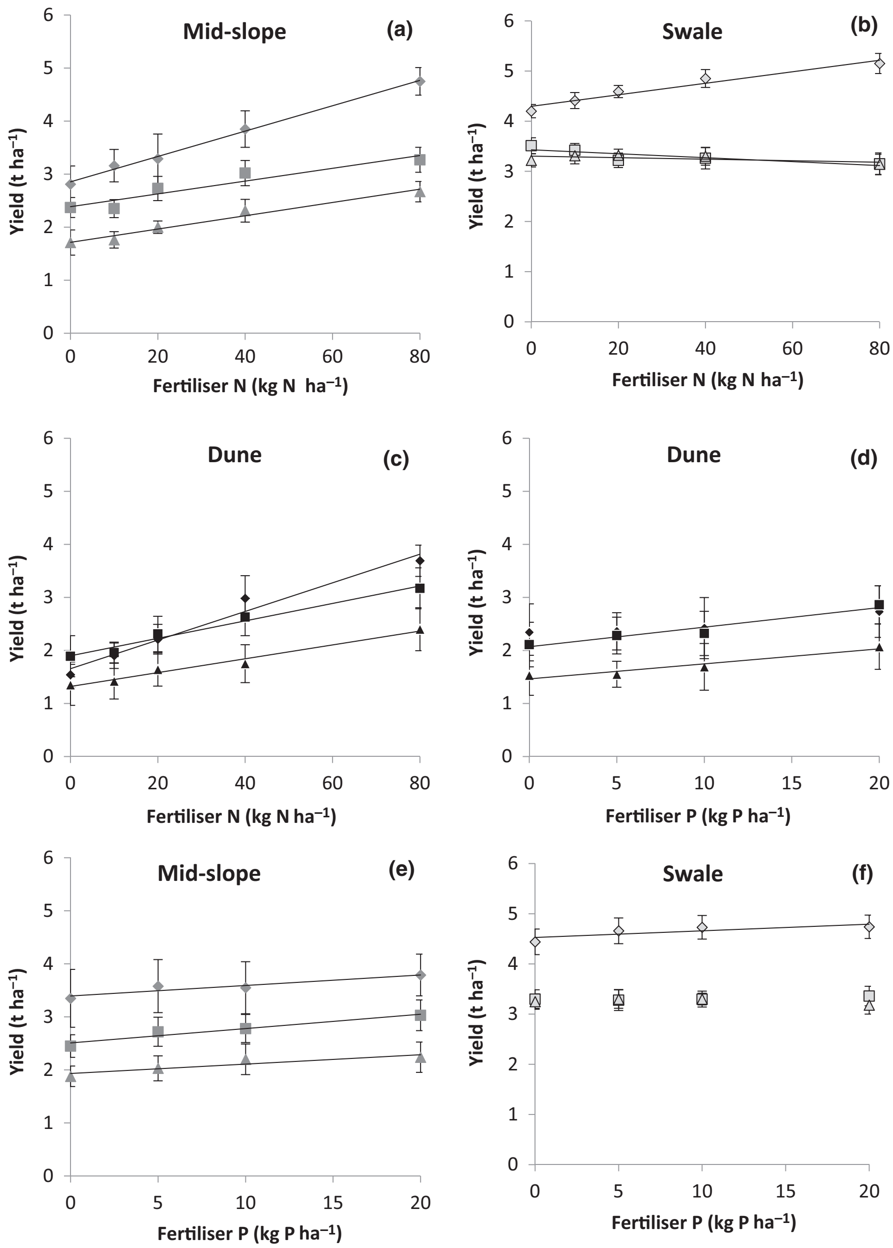

FIGURE 2 Mean grain yield ± standard error in response to additions of N (kg ha^{-1}) as the average of the yield response to all levels of P on the dune (a), mid-slope (c) and swale (e) and in response to additions of P (kg ha) as the average of the yield response to all levels of N on the dune (b), mid-slope (d) and swale (f) soil types across the 2010–2012 growing seasons where 2010 is represented by a diamond, 2011 by a square and 2012 by a triangle. Where the linear regression was significant ($p < 0.05$), it is drawn on the figure and the standard error of the slope and of the difference between slopes is given in Figure 3

(Table 2). The response to N was averaged across all levels of P input as there was no significant effect of P input on protein. The swale soil, which was the least grain yield responsive to N input, was the most grain protein responsive to N input (Figure 4) and accumulated the highest protein levels in almost all scenarios (Table 2).

3.3 | Soil chemical and biological fertility

Sampling of pre-sowing mineral N did not indicate any clear trends in response to the level of N input from the previous season (Table 3). Analysis of mineral N levels within sampled layers did not indicate that any leaching had occurred within the top metre of the profile, with most mineral N stratified in the top 20 cm of the soil profile (data not shown). Despite responses to P fertiliser input on the sandy soil types, soil test values for extractable P were in excess of the predicted critical requirement, where the critical value for Colwell P is 10–17 mg kg^{-1} (Moody, 2007) and DGT P is 66 μg L^{-1} (Mason et al., 2010), and the P input level did not consistently influence the soil test level (Table 3).

In general, the amount of MCB, mineral N levels, PMC and NSP was higher in the swale compared to the dune in the final year of the experiment (Table 4). On the dune, the DOC was highest while MBC was lowest at the highest level of fertiliser input (Table 4). Generally, there were significantly positive relationships between MBC and PMC ($R^2 = 0.68$; $p < 0.01$) and PMN ($R^2 = 0.47$; $p < 0.05$). Additionally, in the Swale soils, PMN levels were significantly correlated to DOC concentrations in soil ($R^2 = 0.98$; $p < 0.01$).

3.4 | Nitrogen use efficiency, nitrogen recovery and yield gap analysis

Nitrogen use efficiency and apparent N recovery (which incorporates N accumulated in protein) both showed an interaction between

N and P treatment. In the sandy soil types, at each level of P input NUE tended to decrease with increasing inputs of N but there was not a significant shift in NUE between inputs of 40 and 80 kg N/ha. However, at N input greater than 10 kg N ha^{-1} the apparent recovery of N in grain did not diminish with increasing N input, indicating that the crop was responsive to increasing N input through yield and protein (Table 5). The effect of the level of P input on NUE was more difficult to describe as it varied significantly between soils and seasons (Table 5).

Water-limited yield potential with no limitation to N or P supply was estimated using APSIM and the yield gap between the water-limited yield potential and the maximal experimental yield was calculated (Table 6). The yield gap was proportionally larger on the sandy soil types across all seasons. The negative yield gap for the swale in 2012 indicates that the modelled effect of subsoil constraints (according to their effect on crop lower limit when characterised) on crop yield in a dry season was greater than the actual effects. The season with the highest yield potential (2010) also had the highest level of NUE and N recovery (Table 6).

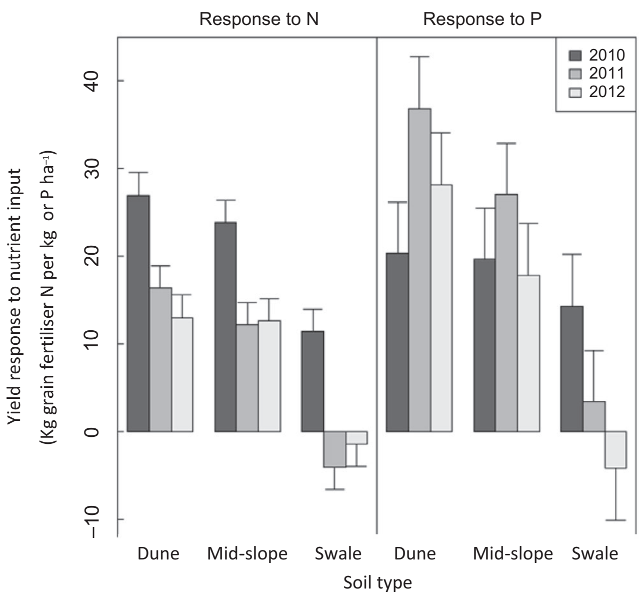

FIGURE 3 Grain yield response (kg ha^{-1}) per unit fertiliser (a) N or (b) P kg ha^{-1} input on the dune, mid-slope and swale soil types across the 2010–2012 growing seasons. Error bars represent the standard error of the responsiveness slope and the standard error of the difference between slopes is 2.56

4 | DISCUSSION

Wheat yield responses to N inputs up to 80 kg N ha^{-1} were consistently achieved in the sandy soil types for the growing seasons 2010–2012. The linear nature of the sandy soil yield response (Figure 2), combined with a yield gap in the order of 15%–30% (Table 6), and a lack of protein response to increasing inputs of N (Figure 4) indicates that the yield maximising level of N supply was not reached (Angus & Fischer, 1991) and that responses might be expected at rates in excess of 80 kg N ha^{-1}. Input levels greater than 80 kg N ha^{-1} are considered well in excess of the level of risk growers would be willing to take in this region (Monjardino et al., 2013). This risk aversion is in part driven by a range of other constraints to production including soilborne diseases such as rhizoctonia root rot (*Rhizoctonia solani*) which has been shown to contribute to yield reductions in cereal crops in the cropping soils of this region (Gupta et al., 2012).

Approximately 20–25 kg N ha^{-1} is required to produce 1 tonne of wheat grain, and with a NUE in the order of 40%–50%, approximately 40 kg N ha^{-1} from soil and fertiliser origin is required to produce 1 tonne of grain (Fageria, Baligar, & Allan Jones, 2010). The pre-sowing soil mineral N levels when combined with fertiliser N input in the sandy soil types (highest N input treatment had N available of 116–139 kg N ha^{-1}) should have been adequate to produce wheat yields in excess (≈ 2.9–3.5 t ha^{-1}) of those achieved in most cases (Table 3; Figure 2). However, there was temporal variation in the level of responsiveness to N input on the sandy soils with responsiveness ranging from 12–27 kg grain kg N^{-1} fertiliser input (Figure 3). While temporal variation in response to N inputs is expected (Lambert et al., 2006), the inability of the wheat crop to reach N limited yield potential where supply was adequate suggests that there are likely to be other factors limiting roots accessing mineral N and limiting fertiliser use efficiency (Sadras & Rodriguez, 2010). This temporal variation in responsiveness could have been more thoroughly explored had in-season biomass

TABLE 2 Protein (% w w^{-1}) response to additions of nitrogen (N, 0–80 kg N ha^{-1}) on the dune, mid-slope and swale soil types in 2010, 2011 and 2012

	Dune			Sand over clay			Swale		
N input (kg ha^{-1})	2010	2011	2012	2010	2011	2012	2010	2011	2012
N 0	11.28	11.54	11.16	11.12	12.32	11.77	9.19	13.12	10.69
N 10	11.22	11.97	11.62	11.26	12.31	11.64	9.38	13.55	11.27
N 20	10.90	11.80	11.68	10.84	11.97	11.44	9.26	13.91	11.96
N 40	10.98	11.92	11.64	11.20	13.32	12.13	9.86	14.65	13.12
N 80	11.42	12.80	11.90	11.71	13.75	12.86	11.23	14.72	14.15

Note: Protein data within an N input level are the average of all rates of P input. For all soils and seasons, the effect of N input had $p < 0.05$ and the standard error of the slope and of the difference between slopes is given in Figure 4.

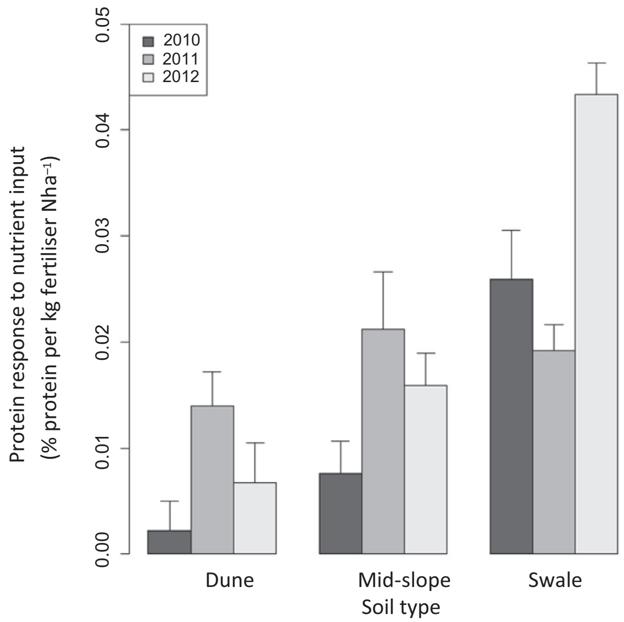

FIGURE 4 Grain protein response (%) per kg ha^{-1} fertiliser N input on the dune, mid-slope and swale soil types across the 2010–2012 growing seasons. Error bars represent the standard error of the responsiveness slope and the average standard error of the difference between slopes is 0.0050

TABLE 3 Pre-sowing soil test values to 1 metre depth for mineral N (kg ha^{-1}) across the three soil types (dune, mid-slope and swale) for extractable phosphorus (P) as Colwell P (mg kg^{-1}) and DGT P (µg L^{-1}) to 0.1 m depth across the three soil types (dune, mid-slope and swale) in 2010, 2011 and 2012

	Dune				Mid-slope				Swale				
N input	**0N**	**20N**	**80N**		**0N**	**20N**	**80N**		**0N**	**20N**	**80N**		**SED**
Mineral N (kg ha^{-1})													
2010	56				101				79				15
2011	34	37	36		40	37	30		48	65	59		7
2012	57	71	70		59	70	93		80	146	142		34
P input	**0P**	**5P**	**10P**	**20P**	**0P**	**5P**	**10P**	**20P**	**0P**	**5P**	**10P**	**20P**	
Colwell P (mg kg^{-1})													
2010	21				21				38				5
2011	23	24	24	24	22	21	20	20	35	34	31	32	2
2012	21	20	22	21	17	20	19	19	33	33	34	34	2
DGT P (µg L^{-1})													
2010	219				237				237				n.s.
2011	210	221	226	250	190	208	187	196	122	114	125	125	16
2012	156	163	170	170	111	123	130	127	144	134	139	148	22

Note: The variation across soil types is approximately constant; therefore, the standard error of difference (SED) for each measurement and year is given; n.s., not significant.

and tissue nutrient concentration been available (Hoogmoed, Neuhaus, Noack, & Sadras, 2018).

Nutrient cycling and availability is regulated by the availability of C for soil microbial biomass and activity in the low organic matter Mallee soils of Southern Australia, and early season immobilisation is likely to be a key factor controlling early crop N supply (Gupta et al., 2011). Any increase in crop biomass and as a result system C inputs due to N and P fertiliser application should have a positive impact on

TABLE 4 The 2012 pre-sowing soil test values to 0.1 m depth for soil biological properties including microbial biomass carbon (MBC), dissolved organic carbon (DOC), potentially mineralisable carbon (PMC) and nitrogen, nitrogen supply potential (NSP) and mineral nitrogen (Min N)

N input (kg ha^{-1})	P input (kg ha^{-1})	MBC (μg C g^{-1})	DOC (μg C g^{-1})	PMC (μg C g^{-1} day^{-1})	PMN (μg C g^{-1} day^{-1})	NSP (μg N g^{-1} day^{-1})	Min N (μg N g^{-1})
Dune							
0	0	174.2 a	62.0 b	4.29	0.49	32.1	9.90
10	5	139.2 bc	59.1 b	5.14	0.49	28.9	9.28
80	5	158.2 ab	66.5 b	3.89	0.33	29.1	12.17
10	20	161.9 ab	60.8 b	4.35	0.41	28.3	8.61
80	20	118.9 c	83.4 a	3.49	0.37	27.1	11.15
Swale							
0	0	191.1	43.7	6.35	0.48	44.8	21.55
10	5	210.6	41.3	4.40	0.39	42.4	19.69
80	5	255.6	51.1	5.56	0.86	59.2	23.85
10	20	240.2	43.9	7.21	0.46	45.7	19.41
80	20	313.8	48.1	7.87	0.66	62.2	26.70

Note: Where the treatment mean is significantly different from another within a soil type, it is annotated with a different letter (p = 0.05).

TABLE 5 Nitrogen (N) fertiliser use efficiency (kg grain kg N applied^{-1}) and apparent N recovery from fertiliser (kg N kg N applied^{-1})

	Dune				Mid-slope				Swale			
	0P	5P	10P	20P	0P	5P	10P	20P	0P	5P	10P	20P
NUE (kg grain kg N applied^{-1})												
10N	50	40	41	−59	40	14	30	−26	28	9	10	−2
20N	35	34	13	11	20	13	22	23	9	8	2	0
40N	23	30	23	11	20	26	23	10	14	−1	5	−1
80N	25	10	26	14	17	14	19	15	7	−1	4	−7
SED (NxP)	22				16				8			
Apparent N recovery (kg N kg N applied^{-1})												
10N	0.7	0.8	0.6	−0.5	0.8	0.2	0.5	−0.5	0.2	0.5	0.5	0.2
20N	0.5	0.7	0.1	0.6	0.3	0.3	0.2	0.5	0.1	0.3	0.2	0.2
40N	0.4	0.6	0.4	0.4	0.4	0.6	0.4	0.4	0.4	0.3	0.3	0.3
80N	0.5	0.2	0.5	0.4	0.4	0.3	0.5	0.4	0.3	0.2	0.2	0.2
SED (NxP)	0.5				0.3				0.3			

Note: Within a soil type differences in NUE and N recovery can be separated using the standard error of difference (SED).

size of microbial biomass and associated biological processes such as C and N mineralisation. In addition, fertiliser application can improve the nutritional characteristics of crop residues with ensuing effects on microbial populations and processes in soil, effects which we aimed to measure in the final year of this experiment. On the dune fertiliser application increased C inputs but caused a reduction in MB amount and activity, particularly at the high level of fertiliser input (Table 4). There is potential for the higher rate of fertiliser to have osmotic and ionic effects on microorganisms due to elevated NH_4^+ ion concentrations, particularly in a poorly buffered sand (Rengasamy, 2010). Angus, Gupta, Pitson, and Good (2014) reported a significant reduction in MB in urea and anhydrous ammonia fertiliser bands in two red kandosols, which partially recovered 5 weeks after fertiliser application. They also found significant increases in the DOC concentrations and pH in the fertiliser bands. In the dune, there was significantly higher DOC in the soil at the higher fertiliser rates (Table 4). However, these reductions in MB did not reflect in the N supply potential because N supply potential is a product of both microbial biomass turnover and mineralisation processes (McBeath, Gupta, Llewellyn, Davoren, & Whitbread, 2015b).

In contrast to the sands, the heavier swale soil lacked a grain yield response in two of the three seasons (Figures 2 and 3), but there was a protein response in all three seasons (Table 2; Figure 4) suggesting that the system was still limited for N (Angus & Fischer, 1991). In 2010, the levels of mineral N measured in the swale (Table 3) would not have supported the yields achieved, even when combined with

TABLE 6 For each season, the water-limited yield potential of wheat grain (t ha^{-1}), the yield gap (t ha^{-1}), nitrogen (N) fertiliser use efficiency (kg grain kg N applied^{-1}) and apparent N recovery from fertiliser (kg N kg N applied^{-1}) are presented

Year	Dune	Mid-slope	Swale
Yield potential (t ha^{-1})			
2010	5.26	5.59	5.68
2011	3.88	4.23	3.98
2012	3.06	3.24	2.98
Yield gap (t ha^{-1})			
2010	1.57	0.85	0.53
2011	0.71	0.98	0.47
2012	0.66	0.57	−0.34
Fertiliser NUE (kg grain kg N applied^{-1})			
2010	34	27	17
2011	16	11	−8
2012	12	13	8
SED	4	4	7
Apparent N recovery (kg N kg N applied^{-1})			
2010	0.70	0.56	0.37
2011	0.29	0.28	−0.08
2012	0.20	0.25	0.91
SED	0.08	0.07	0.17

Note: The water-limited yield potential (t/ha) ascertained using APSIM where N and P were not limiting, the yield gap was the water-limited yield potential and the maximal experimental yield measured for a given soil and season (the rate of fertiliser input from which maximum yield was taken was not fixed due to slight negative yield effects of increased N input on the swale soil). For NUE and apparent N recovery, the effect of season can be separated using the standard error of difference (SED).

the highest levels of N input to which the crop did respond, suggesting that in-season mineralisation was an important source of N. The 2010 growing season was characterised by a very high rainfall spring favouring mineralisation. While the biological properties of the swale were not measured in 2010, a comparison of the dune and swale in 2012 suggests that the swale had a higher level of MBC, PMC (microbial activity) and NSP (Table 4) than the dune offering a greater potential supply of N to the crop through mineralisation processes. In subsequent seasons (2011 and 2012), the mineral N levels (Table 3) were adequate or close to adequate for the yield levels achieved (≈3 t ha^{-1}) when combined with some N input.

This experiment provides evidence of the potential benefits of soil-specific management in dune-swale environments. The optimal strategy would involve higher doses of N upfront on sandy soils types and lower upfront doses of N fertiliser on the heavier clay loam supplemented with in-season N fertiliser in seasons of higher rainfall. These findings support the analysis produced in published simulation experiments (Hoffman et al., 2017; Monjardino et al., 2013). It is clear that the sandy soil types were more limited for N supply than for P. There were however instances of a wheat yield response to P, but these were not found to consistently influence NUE and apparent N recovery in contrast with the recent analysis of experiments by Duncan et al. (2018). The yield responses to P were measured despite soil test P values in excess of critical values, and the timing of P response was not clearly linked to a temporal effect supporting the findings of Lambert et al. (2006). Critical soil test P levels have generally been developed in conditions of sufficient N, and the sandy soils in this experiment were N limited even at the highest input of fertiliser N (Peverill et al., 1999). Based on the information available and combined with the stability of the soil test P levels (Table 3), it appears that the soil test P is just one piece of information required in the decision on the optimal rate of P fertiliser in a variable soil environment. There are a range of other factors (e.g. spatial data available, equipment, risk aversion, access to appropriate fertiliser blends to simultaneously vary N and P) to be considered before the case for variable inputs of P fertiliser is compelling (Lowenberg-DeBoer & Aghib, 1999).

5 | CONCLUSIONS

This 3-year study highlighted the potential for variable inputs of N according to soil type in a dune-swale system in the Southern Australian rainfed cropping regions. On the 2 sandy soils, yield responses to N input were still linear at 80 kg N ha^{-1} in all 3 seasons but wheat yield responded to N input on the swale only in a very wet cropping season. Protein response was more consistent across soil types and seasons. Wheat on the sands was more responsive to P inputs than on the swale, with some variation around the level of responsiveness which could not be linked to a cropping season effect or a soil test result. While NUE and apparent N recovery declined at the highest doses of N fertiliser, there was not a clear effect of a crop response to P increasing NUE.

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