Closing the nitrogen supply and demand gap using legume residue combined with fertiliser nitrogen input

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Abstract
In low-rainfall wheat cropping systems, low crop uptake of nitrogen (N) has been linked to asynchrony in soil-N supply through mineralisation. This is especially true on sandy soils of SE Australia which have a low-N supply capacity. When N released from soil and residues is insufficient, and/or the timing of biological supply is not well matched with crop demand, manipulating N supply using fertiliser applications becomes vital to achieve yield potential. The aim of this study was to measure the timing of N supply with crop N uptake for wheat following wheat-residues and wheat following lupin-residues under two N fertiliser rates in a low-rainfall sandy soil environment. In each residue-type site, plants and deep soil samples to rooting depth were collected at sowing and at 5 key wheat growth stages. Plants were analysed for N content, above-ground biomass and grain yield at maturity. All soil samples were analysed for gravimetric water content and mineral-N. The combination of lupin residues with a high fertiliser N rate increased soil mineral-N at the time of high demand, promoted plant growth and wheat N uptake. In a dry season, the additional N supplied as fertiliser at early stages was a key input to support an increase in wheat yield potential. Responses in N uptake throughout the growing season indicate that there remains a demand for fertiliser N following legume-N residue in this environment, but fertiliser N inputs remain risky as indicated by the lack of significant yield increase in a low rainfall growing season.

Key Words
Soil N supply, crop N demand, yield potential, legume residues, low rainfall

Introduction
Managing in-crop mineral-N availability using N fertilisation and legume crop residues has the potential to close N-derived wheat (*Triticum aestivum* L.) yield gaps by improving N use efficiency, especially for south eastern (SE) Australian sandy soils with low N-supply capacity (Gupta et al. 2011). Mineralisation of soil N supplies about 70 % of wheat N uptake in Australia (Angus 2001). However, low crop uptake of N remains a concern in the dry environments of SE Australia and has been attributed to asynchrony in soil mineral-N supply via mineralisation (Hoyle and Murphy 2011). This study is focused on the semi-arid Mallee region of SE Australia where N fertiliser rates are typically low and opportunities for late season application can be limited by a lack of rainfall events. As a result it is difficult to develop suitable N management strategies, leading to uncertainty for farmers when deciding on fertiliser N applications (Monjardino et al. 2013).

Recent studies in Mallee environments demonstrated that the inclusion of a legume break crop increased the subsequent wheat yield (McBeath et al. 2015), due to greater N cycling and supply, and reduced soil-borne diseases (Gupta et al. 2011). Narrow-leaf lupins (*Lupinus angustifolius*) are a major N_2 fixing, dryland crop in Australia, and are frequently grown on sandy soils (Unkovich et al. 2010). Lupins grown in rotation with wheat have contributed to higher wheat yields by replenishing the soil organic N reserves through modest N release from lupin stubble decomposition (Evans et al. 2001), but the asynchrony of mineral-N supply and wheat demand is still evident in dry conditions. When the N released from soil and residues is insufficient, and/or the timing of biological supply is not well matched with crop demand, then manipulating N supply with fertiliser becomes vital to achieve yield potential (Gupta et al. 2011; Hoyle and Murphy 2011). In Mallee environments, the period between the growth stages (GS) of stem extension and anthesis (GS30-65, Zadoks et al. 1974) is known to be critical in terms of water and N supply for reducing wheat yield variation (Sadras et al. 2012). Therefore, in situations of low N fertility, early supplementation with N fertiliser is needed to ensure adequate crop establishment and early development (Poole and Hunt 2014). There remains a gap in understanding the synchrony between N supply from crop residues combined with N fertiliser inputs in relation to the timing of crop N uptake (crop biomass and biomass N) at key GSs in low-rainfall environments. The aim of this study was to measure the timing of soil N supply with crop N uptake for wheat following lupins and wheat following wheat under two N fertilisation rates in a low-rainfall Mallee sand to evaluate the role of these N input strategies in closing the wheat N supply-demand gap.

Methods

Study site characterisation and treatments

The experiment was conducted in 2015 in a field at Lowaldie (33°59.616S, 13°619.51E), South Australia, on a deep sandy soil (Kandosol; Isbell 2002) with residues from the 2014 cropping season. Each residue-type comprised 8 microplots (each of 1.7 m wide x 6 m long) and, due to their physical separation, each residue-type was analysed separately. The experimental site for each residue-type had a randomised design with 2 N fertiliser strategies: low-N (20 kg N/ha) and high-N (55 kg N/ha) fertiliser input with 4 replicates. Wheat (cv. Mace) was sown at 70 kg/ha on 21/5/15. Potassium sulfate was spread prior to sowing at 33 kg/ha in all plots to supply effective rates of 6 kg S/ha and 14 kg K/ha. Fertilisers were applied at sowing, banded below the seed as 50 kg/ha of di-ammonium phosphate (includes 10 kg P/ha) and 24 kg of urea. The high-N treatment received an extra 76 kg/ha of urea on 16/6/15, when the crop was at GS12, to avoid any potential fertiliser toxicity associated with applying the whole dose at sowing. The climate is Mediterranean-type with a mean annual rainfall of 352 mm, 67% of which occurs during the wheat growing season (236 mm). The growing season rainfall (May-Nov) was below average (decile 3) with a total of 195 mm rainfall. The soil at both residue-type sites was characterised using the methods described in McBeath et al. (2015). The soil had a neutral to alkaline pH increasing at depth with, a low cation exchange capacity and organic carbon, but moderate levels of available phosphorus (25 mg/kg), potassium (100 mg/kg) and sulphur (3.5 mg/kg). The EC was low throughout the profile (<900 μS/cm), but exchangeable sodium (> 6%) was likely to restrict crop productivity below 40 cm depth, and boron (> 15 mg/kg) below 80 cm (Peverill et al. 1999) (Table 1).

Table 1. Soil profile physical and chemical properties of the site. BD=bulk density, C=carbon, EC=electrical conductivity, CEC=cation exchange capacity, ESP=exchangeable sodium percentage.

Depth (cm)	BD (g/cm^3)	Sand (%)	Organic C (%)	pH1:5 ($CaCl_2$)	EC1:5 (μS/cm)	CEC (meq/100g)	ESP	Boron (mg/kg)	C:N Ratio
0-10	1.49	96	0.6	6.1	25.3	3.1	0.7	0.5	12:1
10-20	1.50	97	0.3	6.3	38.0	3.3	2.7	0.5	
20-40	1.64	97	0.2	6.3	29.2	6.7	3.8	1.8	
40-60	1.71	93	0.1	6.5	59.6	14.2	8.2	8.7	
60-80	1.73	79	0.2	7.3	156.5	19.3	22.1	13.0	
80-100	1.78	57	0.1	8.2	246.0	22.0	23.0	17.3	

Soil water, mineral-N and wheat N uptake at key growth stages

Plant and deep soil samples were collected prior to sowing and at 5 key growth stages: GS14/22, GS31, GS39, GS65, and GS99 (Figs.1, 2). Four replicates of wheat plant samples were collected in harvested areas of 0.5 m^2 to determine total above-ground biomass and grain yield at maturity (dry matter basis). Plants were oven dried, ground, sieved, and analysed for total N (Leco). N uptake (stubble and grain) were determined by the total N % in each fraction multiplied by the biomass weight, and converted to kg N/ha. Deep soil cores to 100 cm depth in 6 increments were collected prior to sowing and at maturity. In-crop soil cores were collected up to the maximum rooting depth at each GS; namely, 40 cm at GS14/22, GS31, and GS49; and 60 cm at GS65. All soil samples were analysed for gravimetric water content and mineral-N (nitrate-N + ammonium-N). Soils were extracted by shaking with 2 mol/L KCl (soil:solution ratio 1:3) on an orbital shaker for 1 h, filtered through Whatman No.1, and analysed colorimetrically on the extracts (Miranda et al. 2001). The plant available water (PAW) was calculated as the actual water content - water held at the crop lower limit. The yield potential (kg/ha) was calculated as: (water use-110 mm) x 22 kg/ha/mm (Sadras and Angus 2006) where water use=growing-season rainfall (mm) + PAW at sowing (mm)-PAW at harvest (mm).

Statistical analysis

For each residue-type the effect of time and N rate treatments on each measured variable (e.g. soil mineral-N, plant biomass) was analysed using ANOVA for repeated measures designs with linear mixed effects models (lme) in R (2014), with time and N rate as fixed effects, and the replicate as a random effect. Where ANOVA results showed a significant effect of the time*N rate, the differences between pairs of treatments were compared with DGC test (p<0.05) (Di Rienzo et al. 2002). Paired t tests (p<0.1) were performed between N rates on the measured variables at harvest.

Results and Discussion

Wheat following lupin showed a clear response in plant growth to a higher N rate at advanced growth stages as the plant biomass was 2.5 fold higher with the high N rate at GS65 (Fig 1a) which can be attributed to a higher N uptake (Fig 1b). Soil profile mineral-N in the rooting depth decreased with time following crop growth patterns, illustrating the soil N supply-plant demand relationship (Fig. 1c). Higher soil mineral-N up to rooting depth (0-40 cm) was observed at GS49 with the low N rate (Fig. 1c), and at GS65 there were found higher soil ammonium-N up to rooting depth with the low N rate (data not shown), corresponding with the lower levels of biomass production. Overall there was increased utilisation of soil mineral-N to meet plant demand at the high N rate. The majority of the mineral-N appeared to be depleted between tillering and booting (GS14/22 and GS49), and depletion was faster in the high-N treatment where N uptake was greatest (Angus 2001; Hoyle and Murphy 2011).

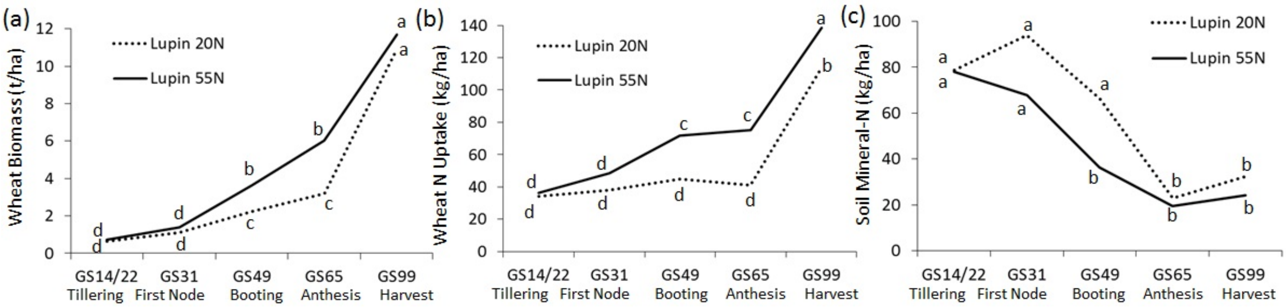

Fig. 1. Wheat following lupin plant biomass (a), plant N uptake (b), and sum of soil mineral-N to rooting depth (c) at different growth stages. Sum of soil mineral-N up to 40 cm at GS14/22, GS31, and GS49; and up to 60 cm at GS65 and GS99. Growth stages with different letters indicate significant differences of the mean ($p<0.05$). 20N=20 kg N/ha, 55N=55 kg N/ha.

Wheat following wheat-residues showed no response in plant growth and N uptake with a higher N rate (Fig. 2 a, b). It could be inferred that there were other factors (such as root disease incidence) inhibiting a response to the increased input of N fertiliser that might have been resolved in the lupin break site (McBeath et al. 2015). Therefore in the higher fertiliser N treatment, soil mineral-N remained high at GS49 (Fig. 2c), especially at depth (20-40cm) (paired t test, p=0.08) possibly due to leaching (data not shown).

Between the different N rates, there were no differences in the grain yield within each residue-type. However, wheat yields after lupin exceeded 3 t/ha (min-max range 2.8-4.5 t/ha) indicating a legume-break effect (McBeath et al. 2015); whereas wheat after wheat had a mean yield of 1.3 t/ha (min-max range 0.9-1.8 t/ha). The actual wheat yield after lupin as % of yield potential was higher (paired t test, p=0.08) with the high-N than with the low-N rate (116% vs. 90 %). The actual yields of wheat following wheat-residues were similar between the N rates and were only 37 % of the yield potential.

The improved plant growth and N uptake of wheat following lupin might have been due to the break-crop effect which increased N uptake from the legume-derived N supply (Gupta et al. 2011; Peoples et al. 2015). At sowing time soil mineral-N up to 60 cm depth was 50 kg/ha after lupins and 30 kg/ha after wheat evidencing the N release from legumes through mineralisation over the fallow. At GS12/22 the soil mineral-N was 1.9 fold higher on lupin (78 kg/ha) compared with wheat residues (42 kg/ha), providing a high-N environment at tillering. The magnitude of the difference in plant performance may be also explained by the load and quality of the residue-types since the biomass N in lupin and wheat stubble at sowing was on average 66 (±19.3) and 21 kg/ha (±3.5) respectively. Similar values of N in lupin biomass were reported for low-rainfall sandy environments (Evans 2001; Unkovich et al. 2010).

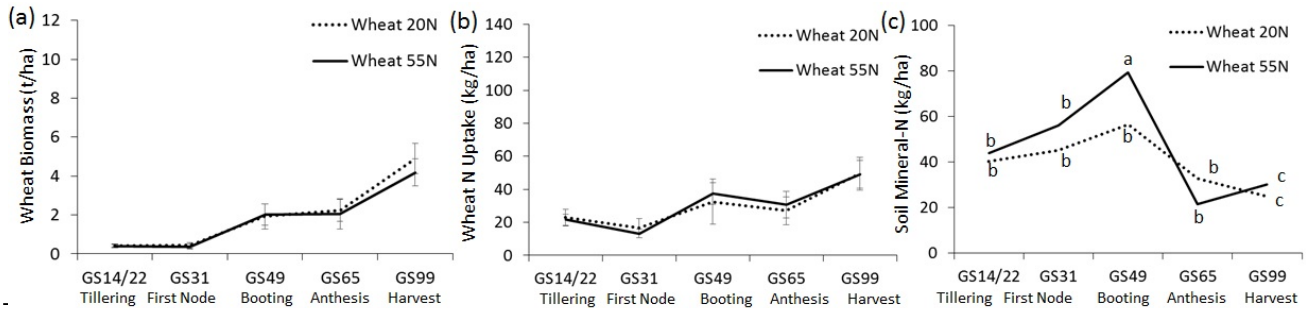

Fig. 2. Wheat following wheat plant biomass (a), plant N uptake (b), and sum of soil mineral-N to rooting depth (c) at different growth stages. Sum of soil mineral-N up to 40 cm at GS14/22, GS31, and GS49; and up to 60 cm at GS65 and GS99. For (a) and (b) error bars indicate standard deviation of the mean. Growth stages with different letters (c) indicate significant differences of the mean ($p<0.05$). 20N=20 kg N/ha, 55N=55 kg N/ha.

Conclusion

The combination of lupin residues with a high fertiliser N rate increased soil mineral-N at the time of high demand and promoted plant growth and wheat N uptake, resulting in a more rapid depletion of soil mineral-N. In a dry season, this did not translate into a significant yield effect but did increase the wheat yield potential. Responses in N uptake throughout the growing season indicates that there remains a demand for fertiliser N following legume-N residue in this environment, but fertiliser N inputs remain risky as indicated by the lack of significant yield increase in a low rainfall growing season.

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