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The effect of stubble on nitrogen tie-up and supply – The Mallee experience

Authors: Vadakattu Gupta[1], John Kirkegaard[2], Therese McBeath[1], Rick Llewellyn[1], Stasia Kroker[1], Steve Szarvas, Bill Davoren[1], Willie Shoobridge[1], Alan Richardson[2]
[1]CSIRO Agriculture & Food Waite campus, [2] CSIRO Agriculture & Food Canberra
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Key Messages

- Cereal stubble should be thought of as a source of C for microbes, not as a source of N for crops. In the Mallee under no-till systems, only 1-2% of the N requirement of wheat crops is derived from the previous wheat stubble.
- N tie-up in cropping soils is only a temporary constraint as the immobilised N will be released through microbial turnover, generally later in the crop season in spring.
- N tie-up by cereal residue is not just a problem following incorporation – it also occurs in surface-retained and standing-stubble systems.
- Management of tie-up is reasonably straightforward – supply more N (5 kg N for each t/ha of cereal residue) and supply it early to avoid impacts of N tie-up on crop yield and protein.
- Deep-banding N can improve the N uptake, yield and protein of crops, especially in stubble-retained systems.

Background

Carbon availability along with soil moisture are the most limiting constraints of microbial functions in low organic matter Mallee soils. Previous research in the Mallee has shown that the management of biologically available C is the key to improving biological functions including those involved in N mineralisation and availability. Crop residues are one of the major sources of C for soil biota therefore stubble retention can provide benefits through changes in soil physical, chemical and biological properties which influence carbon turnover, nutrient generation and subsequent availability of nutrients to crops (Gupta and Roget, 2008). Although stubble retention benefits are expected to be realised in all soil types, the magnitude and nature of change in biological functions can vary depending on type and timing of stubble management and is influenced by soil type and environmental factors (e.g. rainfall).

Most dryland farmers in the Mallee retain all, or most of their crop residues to protect the soil, retain soil moisture and maintain soil fertility in the long term. However, a pro-active and flexible approach to stubble management that recognises and avoids situations in which stubble can reduce productivity or profitability makes sense and has been promoted as part of the GRDC Stubble Initiative (Gupta et al., 2016; Swan *et al*., 2017). One such situation is where large amounts of retained stubble, especially high C:N ratio cereal stubble, "ties-up" soil N leading to N deficiency in the growing crop that may reduce yield. The timing, extent and consequences of N tie-up are all driven by variable weather events (rainfall and temperature) as well as soil and stubble type, so quite different outcomes may occur from season to season and in different paddocks (Gupta, 2016). In this paper we review in simple terms the process of N tie-up (immobilisation) and mineralisation, to understand the factors driving it. We then provide the results from a 3-year field experiment at Karoonda and other examples from experiments in the southern NSW (both long-term and short-term) that serve to illustrate the process, and the ways in which the negative consequences can be avoided while maintaining the benefits of stubble.

N cycling processes and controlling factors

Nitrogen mineralised from the soil organic matter and crop residues makes a substantial contribution (~50%) to crop N uptake (Angus and Grace, 2017; Gupta, 2016). The rate and timing of N mineralisation regulates plant available mineral N levels in soils and the release of mineral N in soil is regulated by the processes associated with microbial turnover (Figure 1). Microbial activities are also responsible for the conversion of fertilizer N into plant available forms.

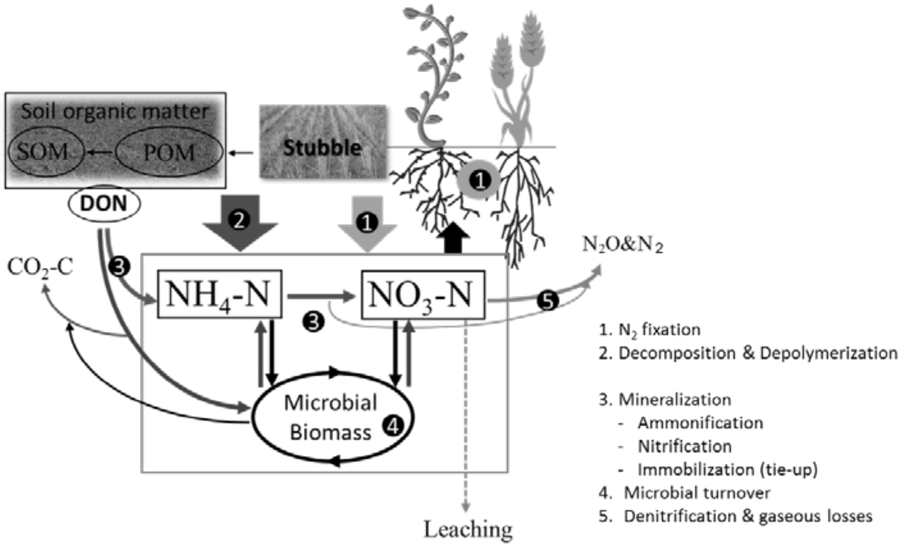

Figure 1*. Biological processes involved in nitrogen cycling that influence plant available nitrogen levels in soil. SOM – soil organic matter, DON – dissolved organic nitrogen, POM – particulate organic matter (Gupta, 2016).*

The process of N tie-up and release (N-Immobilisation and Supply)

Farmers are always growing two crops – the above-ground crop (wheat, canola, lupins etc) is obvious, but the below-ground crop (the microbial biomass, MB) are always growing as well; and like the above-ground crop they need water, warm temperatures and nutrients to grow (there's as much total nutrient in the microbes/ha as in the mature crop, and 2/3rds are in the top 10cm of soil!). There are two main differences between these two "crops" – firstly the microbes can't get energy (carbon) from the sun like the above-ground plants, so they rely on crop residues as the source of energy (carbon). Secondly, they don't live as long as crops – they can grow, die and decompose again ("turnover") much more quickly than the plants – maybe 2-3 cycles in one growing season of the plant. The microbes are thus immobilising and then mineralising N as the energy sources available to them come and go. In a growing season it is typical for the live microbial biomass to double by consuming carbon in residues and root exudates – but they need mineral nutrients as well. Over the longer-term the dead microbe bodies (containing C, N, P, S) become the stable organic matter (humus) that slowly releases fertility to the soil. In the long-term, crop stubble provides a primary C-source to maintain that long-term fertility, but in the short-term the low N content in the cereal stubble means microbes initially need to use the existing soil mineral N (including fertiliser N) to grow, and compete with the plant for the soil N.

Microbial biomass in soil

Soil microbial biomass (MB) is a store-house for nutrients, changes in the amount of MB due to management and seasonal variation can exert a significant impact on microbial immobilisation and net N mineralisation. In Australian agricultural soils, MB-C accounts for 1.5 to 3.0% of soil organic C and MB-N 2-5% of total N. The amount of MB varies with soil type and agro-ecological region (Table 1), and is influenced by crop rotation, tillage and stubble management practices that influence microbial populations and the quantity and quality of residues. For example, MB is generally higher after legume and canola crops compared to cereal crops. MB-C:N ratio generally varies between 6.5 and 9 and a wide MB-C:N ratio is shown to be associated with cereal crop residues and rhizosphere soils. Due to the short turnover time of MB in Australian soils, it may only act as a short-term reservoir for nutrients and as a biocatalyst for soil organic matter cycling and N release, in particular *in-crop* N mineralisation.

As microbial turnover and associated N mineralisation-immobilisation balance is influenced by seasonal conditions, estimation of N supply potential at the beginning of a crop season should include the amount of N in MB and the N that can be mineralised from SOM and crop residues (Gupta 2016, McBeath et al., 2015a). Additionally, management practices that increase the size of the MB pool and modulate its turnover could assist with the synchronisation of N mineralisation to crop demand. For example, higher N mineralisation after a legume crop is related to higher MB, whereas greater microbial turnover after canola also contributes to higher N mineralisation (Gupta, 2016).

Table 1. *Amount of microbial biomass carbon and N supply and immobilisation potentials in the surface 0-10 cm of agricultural soils from the different cropping regions of Australia (Gupta 2016).*

Location	Soil type	MB-C	N immobilization potential[&]	N supply potential[$]
		kg C / ha	kg N / ha	
Waikerie/Karoonda, SA	Sand and sandy loam	150 - 300	15 - 25	10 - 35
Streaky Bay, SA	Calcarosol - sandy loam	210 - 400	15 - 30	20 - 50
Minnipa, SA	Calcarosol - loam	560 - 710	40 - 51	42 - 56
Appila, SA	Loam	450 - 585	32 - 42	35 - 45
Kerrabee, NSW	Loam	420 - 525	30 - 40	35 - 50
Millewa, NSW	Sandy loam	150 - 310	11 - 22	14 - 31
Condobolin, NSW	Sandy loam	240 - 585	17 - 42	20 - 45
Horsham, Vic	Sandy loam	140 - 230	12 - 24	10 - 16
Horsham, Vic	Clay	546 - 819	39 - 59	52 - 72
Wongan hills, WA	Loamy sand	250 - 350	18 - 25	25 - 40

[&] N immobilisation potential is estimated assuming an average 50% increase of MB during a growing season.

[$] N supply potential is calculated from N in MB plus N mineralization measured in a laboratory aerobic-incubation assay.

A worst-case scenario

The background discussed above helps to understand the process of immobilisation, when and why it happens, and how it might be avoided or minimised. Imagine a paddock on 5th April with 3t/ha of undecomposed standing wheat stubble from the previous crop after a dry summer. A 30mm storm wets the surface soil providing a sowing opportunity. Fearing the seeding equipment cannot handle the residue, but not wanting to lose the nutrients in the stubble by burning, the residue is mulched and/or incorporated into the soil. A canola crop is sown in mid-April with a small amount of N (to avoid seed burn) and further N application is delayed until bud visible due to the dry subsoil.

In this case, the cereal stubble (high carbon and low nitrogen – usually ~90:1) is well mixed through a warm, moist soil giving the microbes maximum access to a big load of carbon (energy) – but not enough N (microbe bodies need a ratio of about 7:1). The microbes will need all of the available N in the stubble and the mineral N in the soil and may even break-down some existing organic N (humus) to get more N if they need it (so carbon is lost from the soil!). The microbes will grow rapidly, so when the crop is sown there will be little available mineral N - it's all “tied-up” by the microbes as they grow their population on the new energy supply. Some of the microbes are always dying as well but for a time more are growing than dying, so there is “net immobilisation”. As the soil cools down after sowing, the “turnover” slows, and so is the time taken for more N to be released (mineralised) than consumed (immobilised) and net-mineralisation is delayed. Meanwhile - the relatively N-hungry crops, in particular a canola crop, is likely to become deficient in N as the rate of mineralisation in the winter is low. This temporary N-deficiency if not corrected or avoided, may or may not impact on yield depending on subsequent conditions.

Based on the simple principles above, it's relatively easy to think of ways to reduce the impact of immobilisation in this scenario:

(1) The stubble load could be reduced by grazing or burning (less C to tie up the N but loss of C for biological activity)
(2) If the stubble was from a legume or canola rather than cereal (crop sequence planning) it would have lower C:N ratio and tie up less N.
(3) The stubble could be incorporated earlier (more time to move from immobilisation to mineralisation before the crop is sown), however excessive tillage accelerates C turnover.
(4) N could be added during incorporation (to satisfy the microbes and speed up the "turnover")
(5) More N could be added with the following crop at sowing (to provide a new source of N to the crop and microbes), and this could be deep-banded (to keep the N away from the higher microbe population in the surface soil to give the crop an advantage)
(6) A different seeder could be used that can handle the higher residue without incorporation (less N-poor residue in the soil)
(7) A legume could be sown rather than canola (the legume can supply its own N, can emerge through retained residue and often thrives in cereal residue).

In modern farming systems, where stubble is retained on the surface and often standing in no-till, control-traffic systems, less is known about the potential for immobilisation. In GRDC-funded experiments as part of the Stubble Initiative (CSP187, CSP00174, MSF 00003, BWD00024), we have been investigating the dynamics of N in stubble-retained systems. Here we provide examples from recent GRDC-funded experiments in at Karoonda (SA), Horsham (Vic), Temora and Harden (southern NSW), and discuss the evidence for the impact of immobilisation and provide some practical tips to avoid the risks of N tie-up.

Cereal stubble isn't a major source of N for crops – Tracing N from previous cereal crop stubble

Studies at 3 sites in southern Australia (Karoonda, Temora and Horsham) have tracked the fate of the N in wheat stubble to determine how valuable it is for succeeding wheat crops under Australian systems. Stubble labelled with ^{15}N (a stable isotope that can be tracked in the soil) was used to track where the stubble N went.

At the Karoonda experimental site (at Lowaldie, North East of Karoonda, SA), the 2-year continuous wheat experiment was conducted on the dune (sand) with different stubble management treatments using the ^{15}N wheat stubble grown at the site during 2014. The trials were generally sown at the end of May in each year using knife points with 50 Kg/ha DAP and 24 kg/ha Urea placed below the seed (N20, P10). Results from the analysis of soils (sowing and harvest), crop residues and plant and grain samples have indicated (Figure 2) that, of the 12 kg/ha of N contained in 2.5 t/ha of retained wheat residue retained in 2014, only 0.75 kg/ha N (5%) was taken up by the first (following) wheat crop (representing 1.2 % of crop requirement); and 0.4 kg/ha N (3.5%) was taken up by the second wheat crop (1% of crop requirement).

The majority of the N after two years remained in the soil organic matter pool (5.5 kg N/ha or 45%) and some remained as undecomposed stubble (20% or 2.4 kg N/ha). Thus, we can account for around 73% of the original stubble N in crop (8.5%), soil (45%) and stubble (20%) with 26.5% unaccounted (lost below 50 cm and/or denitrified). Similarly, N in cereal stubble represented only 6% and 1.1% of crop requirements over two years at Temora (7.6% Year 1; 4.4% Year 2) and at Horsham (3% Year 1; 2.5% Year 2), respectively. In similar work carried out in the UK which persisted for 4 years, crop uptake was 6.6%, 3.5%, 2.2% and 2.2% over the 4 years (total of 14.5%), 55% remained in the soil to 70 cm, and 29% was lost from the system (Hart *et al*., 1993).

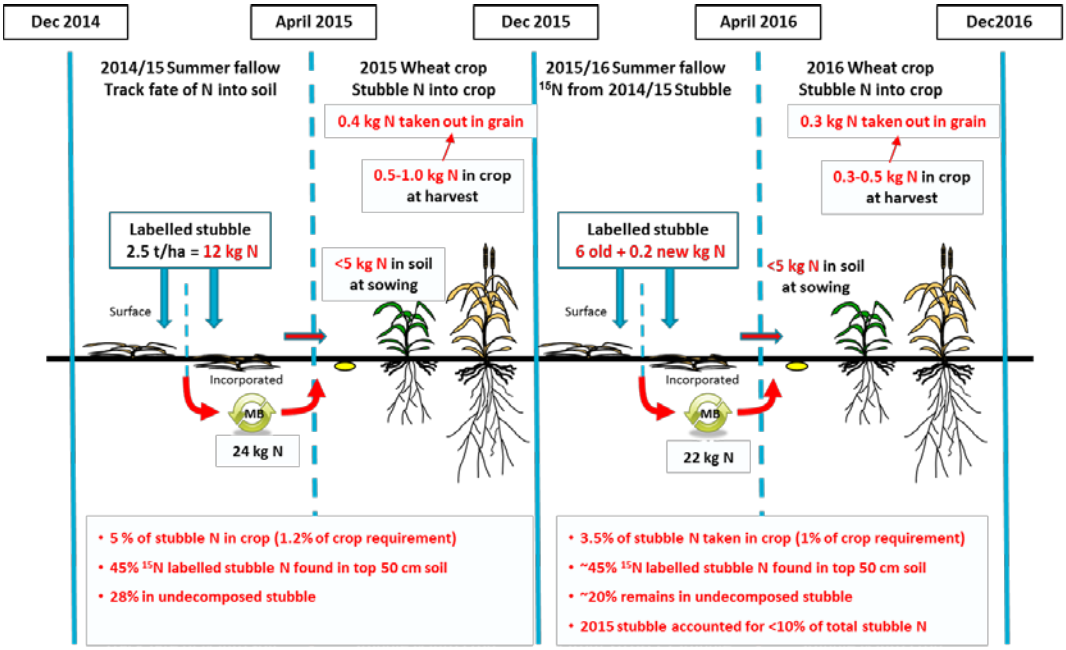

Figure 2. *The fate of the N contained in retained wheat stubble over two years in successive wheat crops following the addition of 2.5 t/has of wheat stubble containing 12 kg/ha N. The successive crops took up 5% (0.75 kg N/ha) and 3.5% (0.4 kg N/ha) of the N derived from the original stubble representing only 1.2% and 1% of the crops requirements. Most of the stubble N remained in the soil (45%) or was lost (27%). MB – total amount of N (kg/ha) in the MB in the surface 10 cm soil.*

The main point from the above evidences is that the N in cereal stubble represented only a small percentage of crop requirements over two years and takes some time to be released through the microbial biomass and organic pool into available forms and losses can occur during the process. Therefore, cereal stubble is not a major source of N, instead a source of C for biological activity. In the lower rainfall cropping regions, microbial turnover of C and N from residues is influenced by stubble retention practices and environmental conditions (rainfall; duration of wet and warm soil conditions). Results for soils at sowing indicated that stubble retention generally increased dissolved organic C (DOC) levels in the soil and *Standing* and *Incorporated* stubble treatments significantly increased MB C and MB N compared to *No-Stubble (cut low and removed)* and *Surface (cut low and retained)* stubble (Gupta et al. 2016).

Can stubble really reduce yield significantly in no-till systems – and is N-tie up a factor?

Harden long-term site (experiences from Southern NSW; Kirkegaard et al. 2018)

In a long-term study at Harden (28 years) the average wheat yield has been reduced by 0.3 t/ha in stubble retained *vs* stubble burnt treatments, but the negative impacts of stubble were greater in wetter seasons (Figure 3). Nitrogen tie-up may be implicated in wetter years, due to higher crop demand for N and increased losses due to leaching or denitrification, but significant differences in the starting soil mineral N pre-sowing were rarely found. For many years, N tie-up was not considered as an issue (though insufficient measurements to confirm it). In 2017, two different experiments in sub-plots at Harden investigated the potential role of N tie-up in the growth and yield penalties associated with stubble. A crop of wheat (cv. Scepter) was sown on 5 May following a sequence of lupin-canola-wheat in the previous years. In both the stubble-retained and stubble-burnt treatments we compared the 100 kg N/ha surface applied with 100 kg/N deep-banded below the seed. The pre-sowing N to 1.6 m was 166 kg N/ha in retained and 191 kg N/ha in burnt but was not significantly different.

Deep-banding the N fertiliser had no impact on crop biomass or N% at GS 30, but increased both the biomass and N content of the tissue at anthesis more in the retained-stubble than in burnt stubble (Table 2). Retaining stubble decreased biomass overall but not tissue N. N uptake (kg/ha) at anthesis was significantly increased by deep-banding in both stubble treatments, however the increase was substantially higher in the stubble-retain treatment than in the burn treatment (38 kg N/ha *cf* 15 kg N/ha).

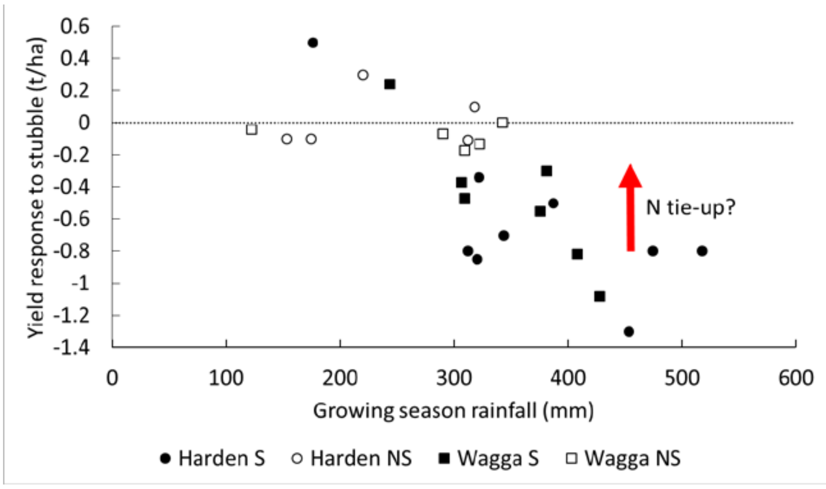

Figure 3: *Effect of retained stubble on wheat yield is worse in wetter seasons at the Harden (circles) and Wagga (squares) long-term tillage sites. Open symbols where difference between retain and burnt were not significant (NS), solid where significant (S).*

The overall impact of deep-banding on yield persisted at harvest, but there was no effect, nor interaction with stubble retention, presumably due to other interactions with water availability. However, the fact that deep-banding N has had a bigger impact in the stubble retained treatment during the growing season provides evidence of an N-related growth limitation related to retained stubble. It's appearance at anthesis, and not earlier, presumably reflects the high starting soil N levels which were adequate to support early growth but the cold dry winter generated N deficiencies as the crop entered the rapid stem elongation phase. The increased protein content related to both burning and deep-banding and its independence from yield, suggest a N deficiency effect throughout the growing season generated by stubble retention.

Table 2: *Effect of surface-applied and deep-banded N on wheat response in stubble-burnt and stubble-retained treatments at Harden in 2017 (Kirkegaard et al. 2018).*

Treatment		**Anthesis**			**Harvest (@12.5%)**	
Stubble	**100 N**	**Biomass (t/ha)**	**Tissue N (%)**	**N Uptake (kg N/ha)**	**Yield (t/ha)**	**Protein (%)**
Retain	**Surface**	8.1	1.1	91	4.5	9.3
	Deep	9.1	1.4	129	5.1	10.2
Burn	**Surface**	8.9	1.2	104	4.5	10.3
	Deep	9.5	1.3	119	5.0	10.8
LSD (P<0.05)	***Stubble***	*0.6*	*ns*	*ns*	*ns*	*0.8*
	N	*0.2*	*0.1*	*8*	*0.2*	*0.4*
	Stubble x N	*0.6*	*0.2*	*12*	*ns*	*ns*

Mallee Experiments

Five years of experiments across the Mallee environment (Karoonda, Loxton and Ouyen), have investigated the

(i) effect of amount and timing of N fertiliser application according to soil type,
(ii) effect of sowing on previous season's crop row (on or near-row) *vs*. in between rows (inter-row) and
(iii) the response to application of fertiliser with the seed or at depth

on crop performance, N supply capacity and N uptake. Surface soils collected at sowing and in-crop were analysed for MB, mineral N, N supply potential levels (see McBeath et al. 2015-17 Compendium articles for full details).
Sandy soils with low organic matter have lower N supply potential hence any imbalance between mineralisation to immobilisation plays an important role in early season N nutrition of a cereal crop. The immobilisation (tie-up) potential in the surface (0-10 cm) soils at Karoonda range between 15 to 30 kg N/ha which would mean a considerable amount of N from the upfront fertiliser application would be tied-up but would be released later in the season through

microbial turnover. In the sandy soils, MB acts as a buffer or temporary storage pool for nitrate N protecting it against leaching especially in the non-crop season and early crop season, conversely lower MB in the No-stubble treatment would result in greater loss of N in the soil profile. With the higher MB and activity levels, soils on the swale have greater N immobilisation potentials (25-40 kg N/ha) compared to soils on the dune (10-25 kg N/ha), especially in cereal stubble retention systems but they also have higher NSP. While on-row soils have a higher N immobilisation potential (15-25 kg N/ha) compared to off-row soils (10-15 kg N/ha), benefits in terms of crop N uptake have been measured for on-row sown wheat.

Having N fertiliser placed with the seed and 8 cm below (50 kg DAP with seed and 35 kg Urea below) yielded better than all fertiliser 8 cm below the seed at Loxton but not Karoonda in 2017, despite the possibility of a fertiliser toxicity effect of 50 kg DAP/ha with the seed (McBeath et al. 2018). This result, combined with other measured responses to fertiliser placement (2016 and 2017) suggest that placement may be a tool to improve N supply in sands where there is immobilisation pressure.

Overall, the timing of N fertiliser has not had a big impact on yield and there was a notable absence of response to N inputs over the five years of experimentation on the swale soil (including a lack of difference between nil and plus N fertiliser, data not shown) (Table 3). However, there have been a few cases (3 of 10 sand site years) where all N at sowing on sands did generate more yield (in the order of 16-40% more yield). Immobilisation is likely to be proportionally more important on these sands and there are seasonal variables that enhance it's effects. However, the overall season type did not appear to drive the effectiveness of the in-season N application and in all cases the in-season N was applied with impending rainfall.

Table 3. *Wheat Yield (t/ha) in response to time of fertilizer application and season (2010-2014) on different soil types in a dune-swale system in the Mallee region of SA (McBeath et al. 2015).*

Fertilizer Treatment	2010	2011	2012	2013	2014	*Average*
	Swale					
High N upfront[&]	4.3	3.4	3.2	1.3	3.0	*3.04 (4.1%*)*
High N Split[$]	4.0	3.3	2.9	1.4	3.0	*2.8*
	Mid-slope					
High N upfront	3.2	3.8	**2.4**	1.8	3.5	*2.94 (7.3%)*
High N Split	3.1	3.6	**1.7**	1.8	3.5	*2.74*
	Dune					
High N upfront	2.0	**2.9**	1.5	1.6	**2.1**	*2.02 (9.8%)*
High N Split	2.0	**2.5**	1.3	1.6	**1.8**	*1.84*

*Note: Within a season and soil, yield values in response to fertilizer strategies that are significantly different ($P < 0.05$) are shown in bold. * Values in brackets indicate percentage higher than 'High N split' application. [&]40 kg N/ha with 10 kg P/ha applied at sowing, [$]N inputs split (9 kg N/ha at sowing and 31 kg N/ha first node with 10kg P/ha at sowing). The N inputs split treatment received the second application of N at an earlier stage in 2013 and 2014, applied at early tillering.*

In the lower fertility Mallee soils, N tie-up and associated N deficiency could exacerbate effects of soilborne diseases (e.g. rhizoctonia disease), in turn reducing yields hence fertilisation strategies should compensate for N tie-up effects especially in cereal stubble retained systems. However, as stubble retention increases MB and overall N supply potential, long-term stubble management generally improves N supply potential and overall N availability.

Post-sowing N tie-up by retained stubble

The evidence emerging from these studies suggests that even where cereal crop residues are retained on the soil surface (either standing or partially standing) and not incorporated, significant N immobilisation can be detected pre-sowing in some seasons. The extent to which differences emerge are related to seasonal conditions (wet, warm conditions) and to the period between stubble treatment (burning or grazing) and soil sampling to allow differences to develop.

However, even where soil N levels at sowing are similar between retained and burnt treatments (which may result from the fact that burning is done quite late) ongoing N immobilisation post-sowing by the microbes growing in-crop is likely to reduce the N available to crops in retained stubble as compared to those in burnt stubble, especially during the early crop growth period. At the Karoonda site, based on the amount of MB, a 3 t/ha stubble load could cause 19-24 kg N/ha of N tie-up depending upon the seasonal conditions.

Conclusions

In stubble retained systems in the Mallee, cereal stubble contributes only a small percentage (1-2%) of the N requirement for a following cereal crop hence it should mainly be considered as a source of C for soil microorganisms. Our studies have confirmed a risk of N-tie up by surface-retained and standing cereal residues which may occur in-season, in addition to during the summer fallow, and so may not be picked up in pre-sowing soil mineral N measurements. Yield penalties from retained residues especially to successive cereal crops could be reduced by reducing the stubble load or by applying more N (~5kg N per t/ha of cereal residue) and applying it earlier to the following crop. However, it is important to note that stubble provides the much needed C source to soil microorganisms in Australian agricultural soils. Deep placement of the N improved N capture by crops irrespective of stubble management, but was especially effective in stubble-retained situations. Although, N tie-up is a temporary issue, it could be potentially costly as early N supply is important for plant nutrition and health. In summary, N tie-up is an easily managed issue for growers with suitable attention to the management of stubble and N fertiliser.

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References

Angus J, Grace P (2017), 'Nitrogen balance in Australia and nitrogen use efficiency on Australian farms'. Soil Research 55,435-450 http://www.publish.csiro.au/SR/SR16325

Gupta VVSR and Roget DK (2008) Beneficial changes to biological functions through stubble retention and reduced till practices. Proc. of the 10th SANTFA conference 'Got the points –Kick the goals', pp: 38-43.

Gupta VVSR (2016) Factors affecting N supply from soils and stubbles. GRDC Research update held in Adelaide during 9-10th February, Adelaide SA. https://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/02/Factors-influencing-nitrogen-supply-from-soils-and-stubbles

Gupta, VVSR et al. (2016) Nitrogen cycling in cereal stubble retained systems, *MSF Research Compendium 2015. http://www.msfp.org.au/nitrogen-cycling-in-cereal-stubble-retained-systems*

Hart PBS et al. (1993) The availability of the nitrogen in crop residues of winter wheat to subsequent crops. *Journal of Agricultural Science* 121, 355-362. http://agronomyaustraliaproceedings.org/images/sampledata/2017/193_ASA2017_Swan_TonyFinalL.pdf

Kirkegaard et al. (2018) The effects of stubble on nitrogen tie-up and supply. GRDC Wagga Wagga update.

McBeath TM et al. (2015a) Break Crop Effects on Wheat Production across Soils and Seasons in a Semi-Arid Environment. *Crop and Pasture Science*. 66, 566-579.

McBeath TM et al. (2015b) Managing nitrogen nutrition under intensive cropping in low rainfall environments, Australian Agronomy Conference, Hobart, Tasmania.

McBeath TM et al. (2018) Nutritional packages for lighter soils. MSF compendium.

Swan AD et al. (2017) The effect of grazing and burning stubbles on wheat yield and soil mineral nitrogen in a canola-wheat-wheat crop sequence in SNSW. http://agronomyaustraliaproceedings.org/images/sampledata/2017/193_ASA2017_Swan_TonyFinalL.pdf