Quantifying sources of N inefficiency in Mediterranean semi-arid cropping systems

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Abstract
Most dryland growers in Australia retain all or most of their crop residues to protect the soil from erosion and improve soil water balance but retaining stubbles with high C:N ratio can decrease nitrogen (N) availability to crops and nitrogen-use efficiency (NUE). A simulation experiment was conducted using different N application rates (0, 25, 50, 75, 100, 150 and 200 kg N/ha) over 27 years at four locations (Mildura, Birchip, Longerenong and Lake Bolac) in Victoria, Australia to capture interactions between sites and seasons, with and without retention of crop residues to investigate how residue retention influences NUE. Immobilization of nitrogen was the biggest source of inefficiency at all simulated sites at rates of N fertilizer application likely to be used by growers. Leaching became a bigger source of inefficiency at Mildura due to low soil water holding capacity, but only at rates of fertilizer application much higher than would be commercially applied. At all simulation sites, immobilization started to decline above annual additions of 50 kg N/ha at Mildura, 75 kg N/ha at Birchip and 200 kg N/ha at Lake Bolac and Longerenong. At all sites, C:N ratio of stubbles decreased with increasing N rates which reduces the immobilization of N. This research shows that NUE could be improved by reducing immobilization, and further research is necessary to evaluate strategies to minimise immobilization of N.

Key Words
APSIM, N-immobilization

Introduction
Nitrogen (N) is an essential element and the most limiting nutrient for crop production in most of the world's agricultural areas (Ågren *et al.* 2012). Dryland crop growers in Australia prefer to retain the crop residues to protect soil from erosion(Freebairn and Wockner 1983), improve soil water balance and increase soil fertility in the long term (Kirkegaard *et al.* 2018). Wheat and barley are the dominant grain crop species grown in Australia, which typically produce stubble with high C:N ratios of ~80. Retention of high C:N ratio stubbles can change N dynamics and consequently decrease nitrogen-use efficiency (NUE) compared to older farming systems where stubbles were removed by grazing and burning.

From the middle of the 20th century, most of Australian's wheat was grown in rotation with legume pastures, and soil N was replenished by biological N_2 fixation. The supply of N from pastures for the following wheat crop was a major factor in the low use of N fertilizer in Australian wheat production (McDonald 1989). There was a shift from grazing to cropping in the mid1990s due to the higher profitability of cropping after the wool price collapsed in 1991. With an ongoing shift to continuous cropping, grain production and maintenance of soil organic matter became increasingly reliant on applications of N fertiliser and yields of many crops are currently N-limited (Hochman and Horan 2018). As with crop production systems globally, increasing crop yields in south eastern Australia will require increasing inputs of fertiliser N (Hochman and Horan 2018).

Cropping systems models which are able to simulate crop growth and soil N processes accurately can be a useful tool to better understand farming systems (McCown *et al.* 1996). This allows simultaneous evaluation of all sources of N inefficiency, conducted over multiple sites and seasons, and imposition of many experimental treatments to assess the impact on N efficiency.

We applied the Agricultural Production System SIMulator (APSIM) to quantify the relative importance of immobilization, denitrification and leaching as sources of N inefficiency in wheat-based farming systems in western Victoria. We conducted simulations over 27 years at four locations across a rainfall gradient, with and without retention of crop residues to capture interactions between site and season, and how the influence of residue retention on NUE.

Methods

Site description

APSIM 7.9 was used to model soil water, N dynamics and crop growth to quantify different sources of N inefficiency given different N fertilizer rates and stubble retention practices. We considered four different sites (Mildura, Birchip, Longerenong and Lake Bolac) which are located in the state of Victoria and vary in soil type and the amount of annual rainfall they receive (Figure 1). The soil types were selected from APSoil (www.apsim.info) to be representative of each region, and were a Calcarosol with light-textured (sandy to loamy) surface at Mildura (Werrimul No 097), Calcarosol with heavier-textured (clay loamy-clay) surface at Birchip (Jil Jil No573), Grey Vertosol at Longerenong (Horsham No1008) and a Brown Sodosol (sandy clay loam) at Lake Bolac (Lake Bolac No914). The APSIM modules used in the study were NWHEAT, SOILWAT, SOILN, RESIDUE and MANAGER. All of these modules are well validated for wheat growth and development and simulation of soil water and N dynamics (Luo *et al.* 2014).

Crop production was simulated from 1 January 1980 until 31 December 2016 and the first ten years of the simulation were discarded to remove effects of model initialisation. The time period used for analysis (1990-2016) coincides with the break-point in water-limited potential yields identified by Hochman *et al.* (2017). climate data for each location were obtained from the SILO website (https://legacy.longpaddock.qld.gov.au/silo/).

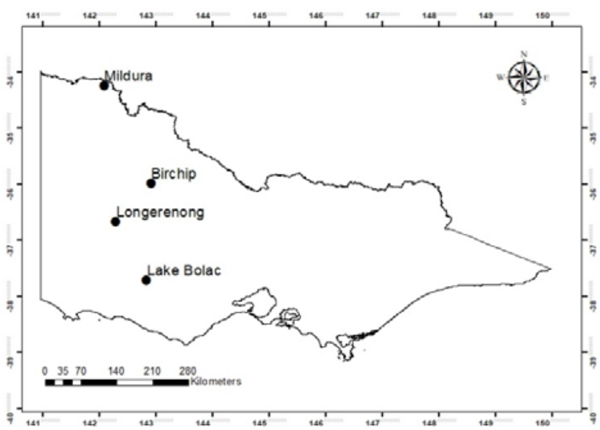

Figure 1. The location of experimental sites in Victoria, Australia

Parameters used for simulations included the fertilizer type (urea-N) which was incorporated to the soil at sowing at all sites, the sowing date was 1 May, the cultivar was early-mid, the row spacing was 250 mm, the sowing density was 150 plants/m^2 and grain yields are reported at a moisture content of 12%. Treatments in the simulation experiment were seven N rates (0, 25, 50, 75, 100, 150 and 200 kg/ha N) which were added at sowing for the purposes of simplification, and two stubble treatments (retention versus burning) which were applied in a factorial combination. Stubbles were 'removed' by resetting surface organic matter to 0 kg/ha on 1 January in each year of the simulation. In the retained treatment, stubbles accumulated were only reduced through natural decay. The maximum soil depth was 1.3 m for all sites deep.

Results

Retaining stubble increased immobilization substantially at all sites but this varied with N rate. At all sites immobilization initially increased with increasing N rate, but then declined once N inputs exceeded offtake (Figure 2). Immobilization was the biggest source of N inefficiency when stubble was retained at all sites except Mildura (Calcarosol), where leaching was greater at high N rates (Figure 3). However, immobilization was greater than leaching at the levels of N application likely to be used by growers in this environment (25-50 kg/ha N). Denitrification was a substantial loss at Longerenong and Lake Bolac where stubble was retained, and N application exceeded 150 kg/ha.

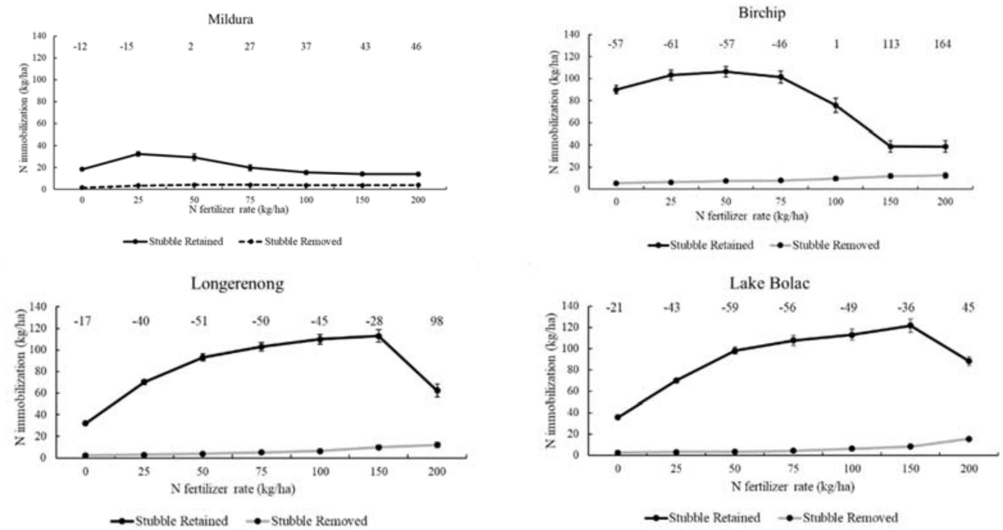

Figure 2. Mean annual N immobilization at different N rates and with stubble (removed or retained). Numbers at the top of the graph are the N balance (fertiliser input – offtake in grain, leaching and denitrification) in kg/ha of the retained treatment.

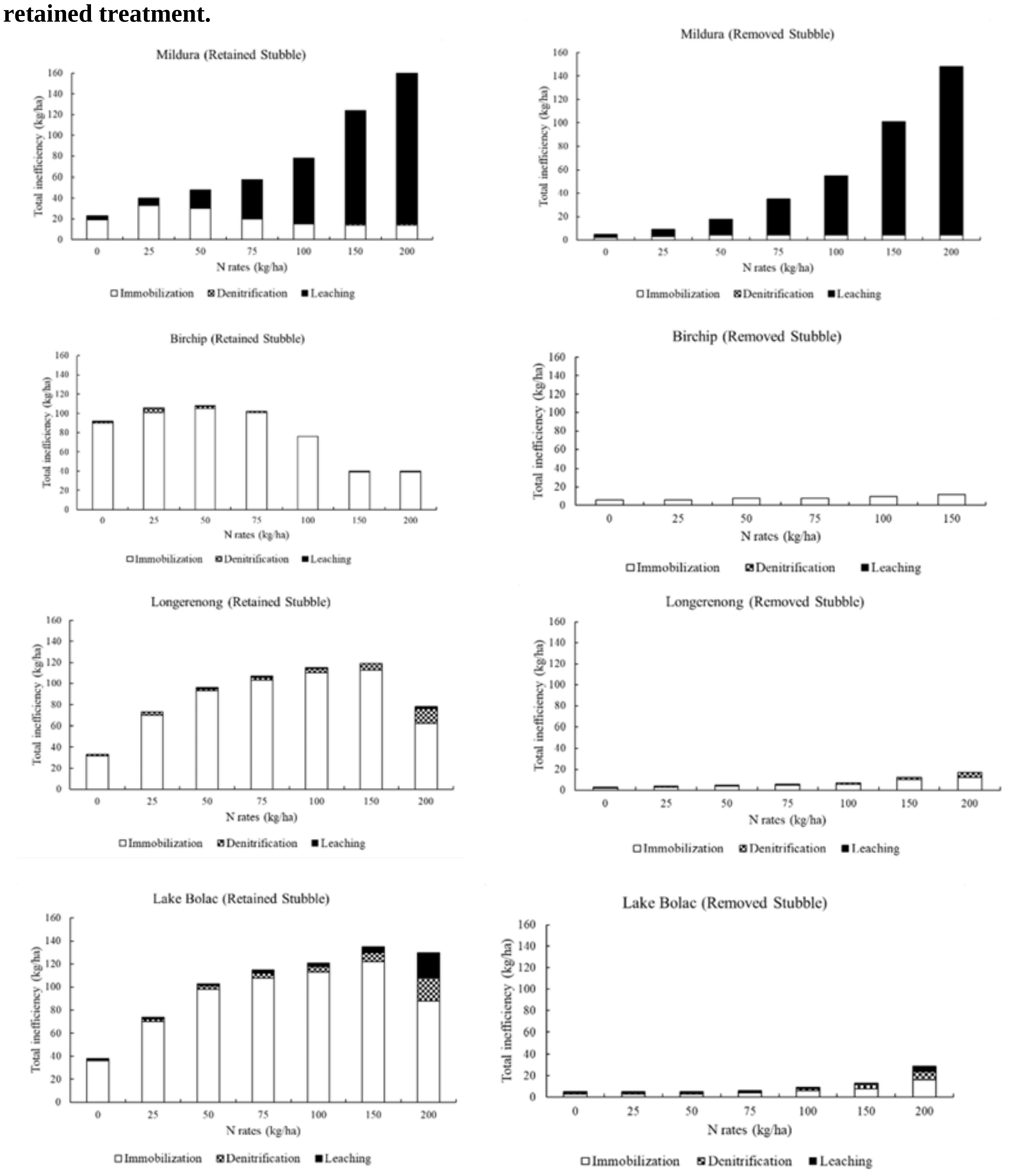

Figure 3. The proportion of N inefficiencies at different N rates and with stubble removed or retained.

Discussion

The APSIM simulation suggested that immobilization at all sites initially increased with increasing N rates which was due to increasing carbon inputs as crop biomass increased. However, immobilization started to decline after a level of N input that coincided with attainment of a neutral N balance (N inputs equal N offtake in grain). The C:N ratio of stubbles at all sites decreased with increasing N rates (data not shown) which reduced immobilization.

Immobilization of fertilizer N is a source of N inefficiency and can negatively impact on crop production when it exceeds mineralisation rate during critical periods of crop growth. However, it is also necessary for maintenance of soil organic matter. Nitrogen immobilization is not strictly speaking a loss, since the N is stored in the soil organic matter and can be mineralised and taken up by later crops. However, because the half-life of immobilised N is decades (Angus and Grace 2017), it is an agronomically important source of inefficiency.

Whilst denitrification was considerably at high N rates in high-rainfall environments (Figure 3), immobilization was still the biggest source of inefficiency. Volatilization is another source of inefficiency but was not studied here as it is not a process simulated by APSIM. All N was applied at sowing and incorporated which is a simplification not strictly representative of grower practice but would mean that volatilization losses would be negligible.

Given that immobilization is the biggest source of inefficiency in Victorian cropping systems with retained stubble, fertiliser NUE will be increased by management strategies that reduce immobilization. This could include deferring N fertiliser applications to coincide with the period of rapid crop uptake, deep and in-crop mid-row banding (Angus and Grace 2017) or choosing to grow species (e.g. canola) which can suppress immobilization (Ryan *et al.* 2006). These strategies should be evaluated in field experiments to allow the most cost-effective combination to be adopted by growers.

Conclusion

Immobilization of N is the largest source of N inefficiency in stubble-retained cropping systems in Victoria at levels of N input currently used by farmers. Further research is necessary to evaluate management strategies to reduce immobilization of N.

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