Productivity – sustainability trade-offs are mitigated through optimized nitrogen banking strategies

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Abstract

In dryland grain cropping systems of Australia, nitrogen (N) deficiency accounts for ~ 40% of the wheat yield gaps. Nitrogen banking strategies that match soil N supply to crop N demand have the potential to reduce these yield gaps and potentially reverse declines in soil organic carbon (SOC) and soil N stocks. Here, we identify optimal N banking strategies at a national level that minimise trade-offs between productivity (grain yield and crop gross margin) and negative environmental outcomes (N_2O and GHG emissions). We simulated ten N banking scenarios across nine soil types. Different SOC fractions and crop-fallow rotations were compared to national average N fertilizer specific to each soil type and production region. N banking scenarios were simulated by balancing soil mineral N at sowing with fertiliser N to meet different levels of annual N supply or N bank levels. The optimal N bank averaged 150±12, 180±9 and 207±4 kg N ha^{-1} in low, medium and high rainfall environments with large variability across initial SOC content and soil types. On average this equates to 38 – 92 kg N ha^{-1} of fertilizer needed to maintain soil mineral N stocks and productivity. The optimal N bank target was predicted to reach long-term N balance when inputs and outputs were approximately equal, even though soil C was still predicted to be declining irrespective of the production environments. Thus, this study demonstrated that optimized N banking strategies that take cognisance of soil, and seasonal climatic boundaries have the potential to mitigate yield gaps while balancing productivity- sustainability trade-offs in dryland cropping systems.

Keywords

APSIM, crop rotations, diversification, rotations, yield gap.

Introduction

Nitrogen (N) banking is a long-term nitrogen management strategy aimed at improving the practical implementation of seasonal N fertilizer inputs. This approach sets a consistent target N budget for each year's crop that can be met from the soil or fertiliser inputs, and this is applied every year without adjustment based on seasonal predictions. This approach is expected to supply sufficient N for crops to meet water-limited yield potential in better seasons without the need to tactically adjust throughout the year, and accounts for recycling or recovery of excess N from lower yielding seasons that will contribute to N supply in subsequent years (Flohr et al., 2024; Meier et al., 2021). We know that this N bank target can vary significantly across environments based on their yield potential. This strategy is being tested experimentally across the nation; hence, we need to determine this target value in new environments.

This modelling analysis aims to predict optimal N bank strategies for a range of experimental locations distributed nationally and examine how this might differ between different environments, soil types common in that region and across different starting soil organic carbon (OC) levels. While N banking is only one of the strategic N management options that are being tested across the country, it is the system for which there is the least information and understanding. Subsequent analysis will compare a range of N management decisions for their capacity to generate better yield and profit outcomes across the wide range of environments spanning Australia's grain production regions.

Methods

Long-term simulations

This study is a simulation analysis that uses the APSIM Next Generation (APSIMX) farming systems modelling framework (Holzworth et al., 2018) to simulate a range of N banking strategies for long-term wheat - fallow rotations across the wheat belt of Australia (Figure 1a). There were 10 N bank levels simulated from 30 – 400 kg N ha^{-1} using weather data from Patched Point data weather stations (Jeffrey et al,. 2001) for the period 1991 – 2022 following a common equilibration period of 20 years. These N bank levels were simulated on the most common soil types found in in a 50 km radius around each weather station according to the Australian Soil Resource Information System (ASRIS) (Johnston et al. 2003). The initial

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soil labile organic carbon content was also set to five different levels (0.6, 0.9, 1.2, 1.5 and 1.8%) to explore how this influenced N bank targets. The APSIMX manager rules were used to simulate water-limited yields except for the additional annual fertiliser application in various sites. The sites were grouped into three production environments based on average long-term growing season rainfall (April – Oct). These were low rainfall (< 250 mm), medium rainfall (250-325 mm) and high rainfall (>325 mm) environments. At each location, different wheat cultivars were used to capture common practice in the region and includes Beaufort, Trojan, Axe and Revenue to match different sowing windows and environments with different growing-season lengths.

Economic calculations and assumptions
Annual gross margins (GM) were calculated for each N bank strategy outlined above. Variable input prices assumed were the same as those assumed in prior N bank analyses (see Meier, Hunt, and Hochman (2021)) and these were held constant across all sites. N fertiliser as Urea including freight was costed at \$1.08 kg^{-1}, and this varied based on N inputs used. Other variable costs were \$32 ha^{-1} for farm operations, seed cost was \$28 ha^{-1} and application of sprays and fertilisers was set to \$103 ha^{-1}. Wheat grain price was \$245 t^{-1} on farm and freight and levies of \$24 t^{-1}. Grain revenue was also reduced by 1% for levies and insurance.

$$GM(\$\ ha^{-1}) = \big((\text{yield (t } ha^{-1}) \times \text{grain price (\$ } ha^{-1})) - (\text{Fertiliser (kg } ha^{-1}) \times \text{urea price (\$ } t^{-1}) + \text{total variable cost (\$ } ha^{-1})\big)$$

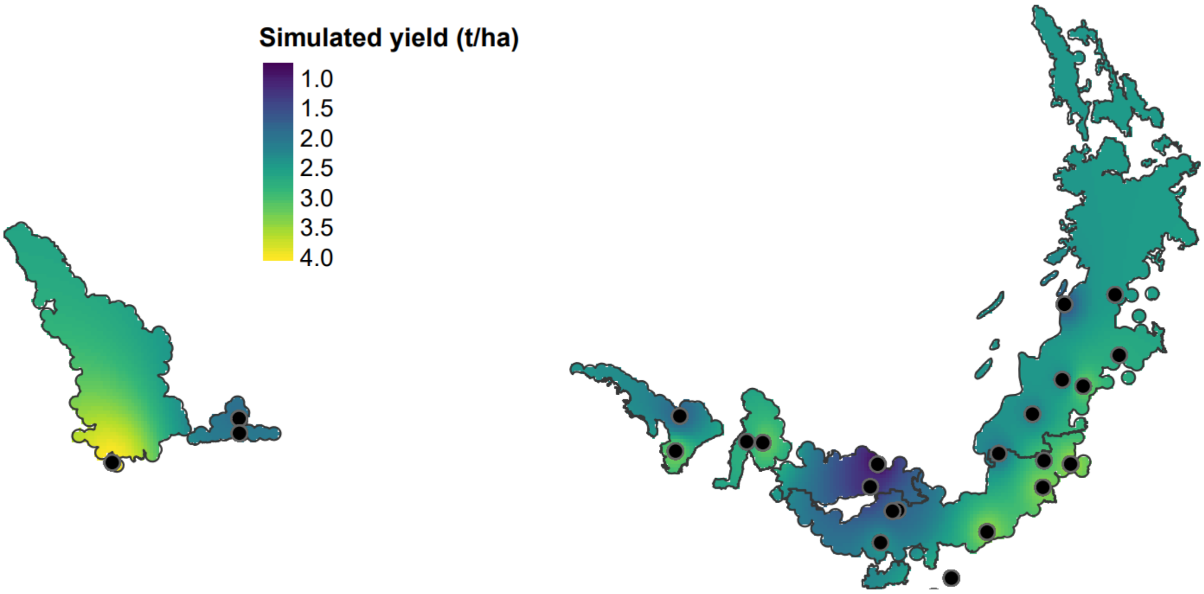

Figure 1. The spatial distribution of N banking experimental sites (points) and average simulated grain yield (t ha^{-1}) for the pre-experimental modelling.

Results

System productivity and seasonal response
The average simulated water-limited yields varied considerably across production environments (Figure 1). On average, yield was 2-fold higher in high rainfall environments (mean = 3.5 t ha^{-1}) than in low rainfall environments (mean = 1.6 t ha^{-1}). To demonstrate how the N bank targets can be estimated, Figure 2 shows the quadratic relationship of average grain yield in response to increasing N bank targets (i.e. soil mineral N and balanced by fertiliser inputs). The optimal N bank targets increased linearly with increasing growing season rainfall indicating high rainfall environments were more responsive to N supply (either through soil mineral N or fertiliser).

Trade-offs between productivity and environmental outcomes
In addition to the production outcomes, a critical question with the strategic N management option like N banking is how this influences the overall N inputs required, N losses, cycling of N over seasons, and overall system N and C balance. We evaluated these trade-offs (Figure 3) based on seven metrics including grain yield, gross margins, N balance (where positive is 'N building' and negative is 'N mining'), net global warming potential (GHG) from soil-based emissions of N_2O and changes in stored SOC ('Abatement' or

‘Emissions’), and N fertiliser applied to the crop (‘Fertiliser’). On average, 39 kg N $ha^{-1}yr^{-1}$ additional fertiliser is needed to maintain optimal N bank targets in the low rainfall environments, while 92 kg N ha^{-1} yr^{-1} is needed in the high rainfall environments in addition to soil supply depending on the initial labile OC content (Figure 3). This was associated with higher yield, gross margins and slightly higher CO_2 emissions. Medium rainfall environments tend to maintain greater CO_2 abatement, lower emissions and lesser N mining compared to low and high rainfall environments.

The optimal N bank target was predicted to reach long-term N balance when inputs and outputs were approximately equal, even though soil C was still predicted to be declining irrespective of the production environments. Finally, a question about these longer-term strategies is their capacity to increase N losses. At least in this scenario, these values are low and a high proportion of the added N is retained. Nonetheless, the nitrous oxide (N_2O) emissions are significant contributors as a potent greenhouse gas. As N supply increases the lower soil C reduction is sufficient to offset the higher N_2O emissions, until a yield starts to plateau.

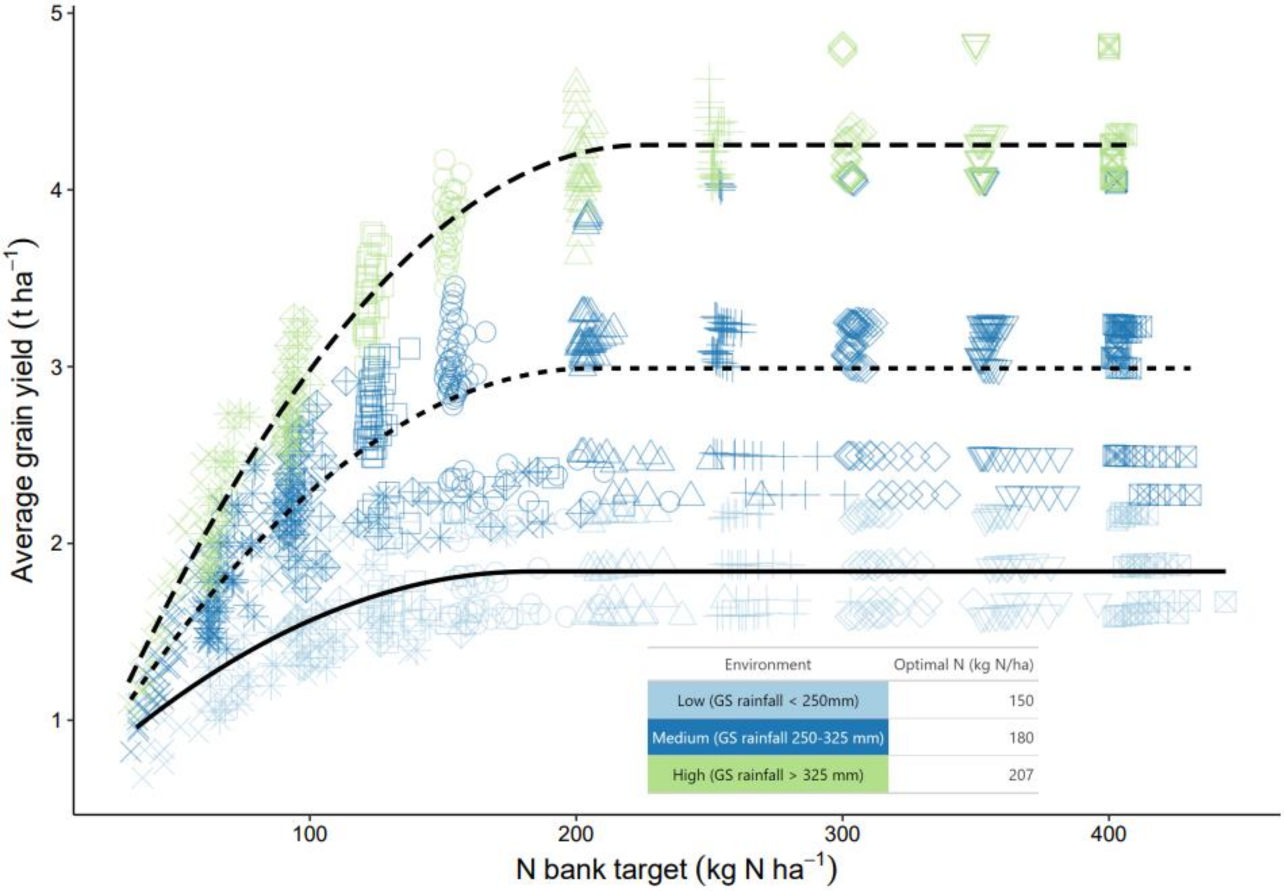

Figure 2. A quadratic-plateau relationship between average simulated grain yield (t ha^{-1}) and mean N bank target (kg N ha^{-1}) across the three production environments. Optimal N bank target for each environment is provided as inset for a long-term wheat-fallow rotation.

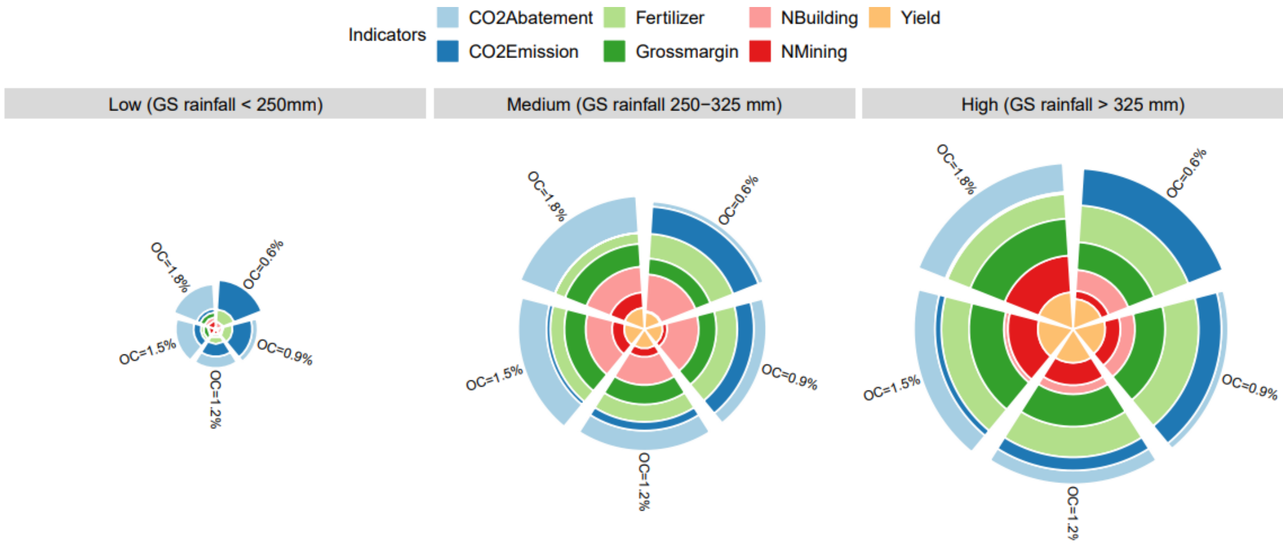

Figure 3. Trade-offs between productivity (yield and gross margin), fertiliser and environment outcomes (N building, N mining, CO_2 abatement or emission) across different initial labile OC levels for a long-term wheat-fallow rotation.

Conclusion

Developing a robust N fertiliser strategy is critical to maximising seasonal yield potential while avoiding long-term carbon decline and mitigating risks of N losses. Tactical N budgeting in the face of uncertain seasonal outcomes is tricky and has high information demands to make helpful predictions of seasonal yield potential. Longer-term strategic approaches such as N banking can be simpler and have advantages of incurring costs following higher profit years but have higher risks of N losses. Further work will examine how this approach compares to other decision-making strategies over the long-term and across different production environments.

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