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A paradigm shift in nitrogen management: In-silico insights into biological nitrification inhibition in farming systems

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Abstract: Retaining nitrogen (N) in soils in the form of ammonium (NH_4^+) by inhibiting nitrification has been proposed as a strategy to reduce N losses from gaseous emissions and nitrate (NO_3^-) leaching. Biological nitrification inhibition (BNI) involves the release of natural metabolites from crop roots, offering a sustainable alternative to synthetic nitrification inhibitors. The biological nitrification inhibitors (BNIs) are released directly into the rhizosphere during crop growth providing a more sustained and spatio-temporally distributed inhibitory effect on nitrification. However, BNI effectiveness varies based on crop species, and interactions with soil and climatic factors. Therefore, a systems modelling approach could provide an insight into BNI potential in different cropping systems. We developed a BNI model suitable for integration into farming systems models to simulate BNI release and bioactivity in the context of cropping systems, that allows evaluating the plausible benefits from BNI in cropping systems. The integrated BNI functionality into APSIM offers a systematic framework for evaluating BNI impacts on N cycling, loss and crop productivity in cropping systems. The model scripts are adaptable to other mechanistic models that represent nitrification, root growth and C and N cycling processes.

Keywords: *Adaptation, APSIM, nitrous oxides, root exudations, uncertainty analysis*

1. INTRODUCTION

Nitrogen (N) is essential for crop productivity but is frequently lost from agroecosystems through gaseous emissions (NH_3, N_2O, N_2), nitrate (NO_3^-) leaching, and runoff, contributing to low N use efficiency (NUE). These losses are primarily driven by NH_3 volatilization and microbially mediated nitrification and denitrification processes. Nitrification is the process of microbial conversion of ammonium (NH_4^+) to NO_3^- prior to denitrification of NO_3^- to N_2O. Thus, regulating soil nitrification presents a promising avenue to improve N within the cropping systems. Biological nitrification inhibitors (BNIs), which are natural metabolites released by the roots of certain plants provide a unique mechanism for mitigating N losses, as they are released directly into the rhizosphere during crop growth and can offer a more sustained and spatially distributed inhibitory effect on nitrification. Yet their release rates, persistence, and bioactivity vary with genotype, soil bio-physical conditions, climate, and management, making their real-world performance highly context-dependent. This study integrated a novel BNI subroutine into the Agricultural Production Systems sIMulator (APSIM) (Holzworth et al. 2018), enabling simulation of BNI exudation, bioactivity, persistence, and impacts on N cycling in the broadacre cropping systems of Australia.

2. METHODOLOGY AND RESULTS

The first phase of this integrated modelling involved the development of model conceptualisations of the BNI release mechanism, fate and persistence in soil, bioactivity and consequent interaction with environment and crop management. To do this, we reviewed available evidence on BNI literature based on the following prepositions 1) BNI release vary with plant growth stages and resource availability, 2) BNI fate and persistence in soil depends on their mobility, i.e., hydrophilic or hydrophilic 3) bioactivity of the BNI depends on their interactions with biophysical factors. We integrate these dynamics with current APSIM modelling capability. Table 1 summarises the relative changes (%) in selected environmental and agronomic indicators resulting from the inclusion of BNI in different rotation–region systems, compared with a baseline control scenario without BNI. Across systems, the inclusion of BNI generally resulted in substantial reductions in denitrification with NO_3^- leaching also showing notable decreases in most cases. However, the magnitude of environmental benefits varied with crop type, rotation, and region. In certain systems, small increases in nitrate leaching were observed (e.g., xMz in the North), indicating potential trade-offs under specific environmental and management conditions. These results are subject by the uncertainties in the predictions, especially around magnitude of prediction and process parametrization in APSIM. For example, the lack of agronomic benefits in sorghum despite reduction in N loss is related to the N uptake parametrisation where APSIM-sorghum model allows only NO_3^- uptake such that the reduction in N loss did not translate to increase N uptake as the 'saved' NH_4^+ is not assimilated by the crop.

Table 1 Simulated long-term (1990 – 2023) relative change (%) in environmental (denitrification, N_2O emission, NO_3 leaching) and agronomic (N uptake, biomass, and grain yield) across different cropping systems and BNI compared to a baseline control scenario (BNI-). xW: continuous wheat, xCa_xW: canola – wheat; xMz: continuous maize; xWxxMz: wheat – maize; xSg: continuous sorghum; and xWxxSg: wheat – sorghum rotations

Rotation	Phase	Region	Denitrification	NO_3 Leaching	N_2O emission	N uptake	Biomass	Grain yield
xW	Crop	North	-18.7	-3.7	-22.7	0.6	0.5	1.1
	Fallow	North	2.4	-2.4	1.3			
	Crop	South	-32.4	-1.9	-38.3	0.0	3.2	1.5
	Fallow	South	-7.4	-2.4	-7.5			
	Crop	West	-35.9	-2.6	-43.0	-0.2	0.4	1.4
	Fallow	West	-10.9	-1.6	-11.2			
xCa_xW	Crop	North	-16.8	-2.1	-19.3	1.3	0.7	1.5
	Fallow	North	3.3	-1.3	2.3			
	Crop	West	-28.1	-3.4	-34.0	1.4	2.5	0.2
	Fallow	West	2.2	-1.8				
	Crop	South	-22.9	-2.2	-27.8	1.2	0.8	-0.9
	Fallow	South	0.2	-2.4	0.0			
xMz	Crop	North	-23.3	3.6	-28.1	0.0	-0.3	0.0
	Fallow	North	9.1	1.1	10.2			
xWxxMz	Crop	North	-0.1	0.5	-0.7	0.0	-0.8	-0.9
	Fallow	North	1.2	0.0	1.1			
xSg	Crop	North	-78.3	-55.6	-76.4	-6.2	-2.1	-4.6
	Fallow	North	-78.0	-60.5	-76.8			
xWxxSg	Crop	North	-41.0	-7.1	-41.8	-2.7	1.0	0.8
	Fallow	North	-19.3	-10.0	-19.0			

x–fallow; W– wheat; Ca–canola; Mz–maize; Sg–sorghum.

3. CONCLUSIONS

This study shows that plant root-mediated BNI may be able to reduce in-crop N losses across Australian grains regions, with the greatest benefits in high-loss systems such as continuous wheat and wheat–sorghum in Northern and Western zones. These results highlight the need to consider environmental and economic objectives when evaluating BNI adoption. BNI is best positioned as a targeted strategy for systems with high baseline N losses and crop–soil conditions favouring NH_4^+ uptake. Broader implementation should be integrated with complementary N management practices to minimise trade-offs. Further work should refine BNI trait characterisation, improve model parameterisation, and validate outcomes in field trials to guide region-specific recommendations.

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