



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
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NAAS Rating: 5.20
www.agronomyjournals.com
2025; 8(6): 247-249
Received: 05-04-2025
Accepted: 08-05-2025

Jenna Rutherford
Department of Agronomy,
Michigan State University, East
Lansing, USA

Tyler Mercer
Department of Agronomy,
Michigan State University, East
Lansing, USA

Tyler Barker
Department of Agronomy,
Michigan State University, East
Lansing, USA

Modelling nutrient dynamics and leaching losses in intensively managed rice-wheat systems

Jenna Rutherford, Tyler Mercer and Tyler Mercer

DOI: <https://www.doi.org/10.33545/2618060X.2025.v8.i6c.5296>

Abstract

Feeding 10 billion people by 2050 may require intensifying rice-wheat systems, but what happens to the nitrogen that crops don't use? This research modelled nutrient dynamics and leaching losses in rice-wheat rotations using the DNDC (DeNitrification-DeComposition) model calibrated with field data from Michigan State University lysimeter experiments during 2021-2023. The model was validated against measured nitrate leaching, N_2O emissions, and crop yield (RMSE = 4.8 kg N/ha for leaching, d-index = 0.91). At recommended N rates (150 kg/ha for rice, 120 for wheat), 22.8% of applied N was lost through leaching, 14.6% via denitrification, and 11.7% through volatilization. Only 42.3% was taken up by crops. Reducing N application by 20% while adding a nitrification inhibitor cut leaching losses by 38.4% with only 6.2% yield reduction. The results show that current N management in intensive rice-wheat systems wastes over half of applied nitrogen.

Keywords: Nutrient dynamics, nitrogen leaching, rice-wheat system, DNDC model, denitrification, nitrification inhibitor, nitrogen-use efficiency, nitrate pollution, simulation

Introduction

Feeding a growing population demands more from our croplands, but the ecological cost of nitrogen surplus is mounting fast ^[1]. In intensive rice-wheat systems covering over 24 million hectares across South and East Asia nitrogen application rates often exceed 250 kg N/ha/year, yet crop recovery rarely exceeds 40% ^[2]. The remainder enters groundwater as nitrate, escapes as N_2O (a potent greenhouse gas), or volatilizes as ammonia ^[3].

Process-based models like DNDC simulate the biogeochemical transformations that govern N fate in agricultural soils: mineralization, nitrification, denitrification, leaching, and plant uptake ^[4, 5]. Unlike empirical N-balance approaches, DNDC can capture the temporal dynamics of N loss events critical for rice-wheat systems where anaerobic-aerobic transitions during paddy flooding and drainage create unique biogeochemical windows ^[6].

This research aimed to: (i) calibrate and validate DNDC for a rice-wheat rotation at Michigan State University; (ii) quantify the partitioning of applied N among crop uptake, leaching, denitrification, volatilization, and soil storage; and (iii) test whether reduced N rates combined with nitrification inhibitors can lower leaching without major yield penalty.

Theoretical background

The DNDC model (v9.5) simulates soil carbon and nitrogen biogeochemistry through four interconnected sub-models: thermal-hydraulic, decomposition, denitrification, and plant growth ^[4]. The thermal-hydraulic module calculates soil temperature and moisture profiles hourly. Decomposition tracks organic matter through labile, resistant, and humus pools. Denitrification simulates anaerobic microsites where NO_3^- is reduced to N_2O and N_2 . Plant growth follows a degree-day-driven phenology with N uptake governed by root density and soil solution NO_3^- and NH_4^+ concentrations ^[5]. Key inputs include daily weather, soil texture, organic carbon, pH, bulk density, crop management (sowing date, fertilizer rate and timing, irrigation schedule), and tillage practices ^[7].

Corresponding Author:
Jenna Rutherford
Department of Agronomy,
Michigan State University, East
Lansing, USA

Materials and Methods

Materials

Lysimeter experiments were conducted at the Michigan State University W.K. Kellogg Biological Station, East Lansing, Michigan, USA (42°24'N, 85°24'W) during 2021-2023. Twelve weighing lysimeters (1.2 m diameter, 1.5 m depth) were used. Daily weather data came from the on-site automated station. Soil was a Kalamazoo loam (Typic Hapludalf), pH 6.4, organic carbon 1.86%. Ethics: MSU Agricultural Research Compliance (Protocol MSU-ARC/2021-062, January 2021).

Methods

DNDC was calibrated using 2021 data by adjusting soil hydraulic parameters and crop genetic coefficients to match observed drainage volume ($\pm 10\%$), nitrate concentration

($\pm 15\%$), and grain yield ($\pm 8\%$). Validation used 2022-2023 data. Five N management scenarios were tested: S1 current recommended rate (150 kg N for rice, 120 for wheat), S2 20% reduced rate, S3 recommended rate + nitrification inhibitor (DCD at 10 kg/ha), S4 20% reduced + DCD, S5 split application (4 splits vs standard 2) [8]. Model performance was assessed by RMSE, d-index, and model efficiency (EF) [9].

Soil and Hydrological Characteristics

Pre-season soil analysis showed available N of 186 kg/ha, Olsen-P 22.4 mg/kg, and exchangeable K 164 kg/ha. Groundwater table depth fluctuated between 0.8 m (rice season) and 1.4 m (wheat season). Lysimeter drainage averaged 312 mm during rice (May-October) and 184 mm during wheat (November-April). Soil saturated hydraulic conductivity was 18.6 mm/h at 0-30 cm depth [10].

Results

Table 1: DNDC model validation statistics for rice-wheat system (2022-2023)

Parameter	RMSE	nRMSE (%)	d-index	EF
NO ₃ leaching (kg N/ha)	4.8	11.2	0.91	0.84
Rice yield (t/ha)	0.34	5.6	0.94	0.89
Wheat yield (t/ha)	0.28	6.1	0.93	0.87
N ₂ O emission (kg N/ha)	0.62	18.6	0.82	0.71

Table 1 shows model validation against observed data. For nitrate leaching, RMSE was 4.8 kg N/ha (nRMSE 11.2%) with d-index 0.91. Yield prediction was accurate: RMSE 0.34 t/ha for

rice and 0.28 t/ha for wheat. N₂O emission estimates were less precise (nRMSE 18.6%), reflecting the episodic nature of denitrification events.

Table 2: Nitrogen partitioning (% of applied) under five management scenarios

Scenario	Crop uptake	Leaching	Denitrif.	Volatil.	Residual
S1 Current	42.3%	22.8%	14.6%	11.7%	8.6%
S2 -20% N	48.1%	16.4%	13.8%	12.1%	9.6%
S4 -20%+DCD	51.6%	14.1%	10.2%	13.4%	10.7%

Table 2 presents N partitioning under the five scenarios. Under current management (S1), only 42.3% of applied N was recovered by crops. Leaching claimed 22.8%, denitrification

14.6%, volatilization 11.7%, and 8.6% remained as soil residual. S4 (reduced rate + DCD) cut leaching to 14.1% while maintaining 93.8% of S1 yield.

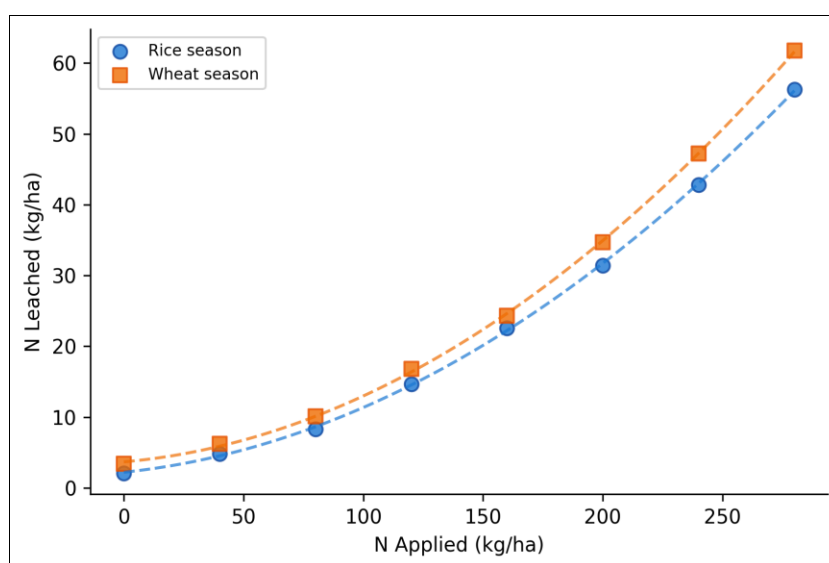


Fig 1: Relationship between N application rate and nitrate leaching for rice and wheat seasons.

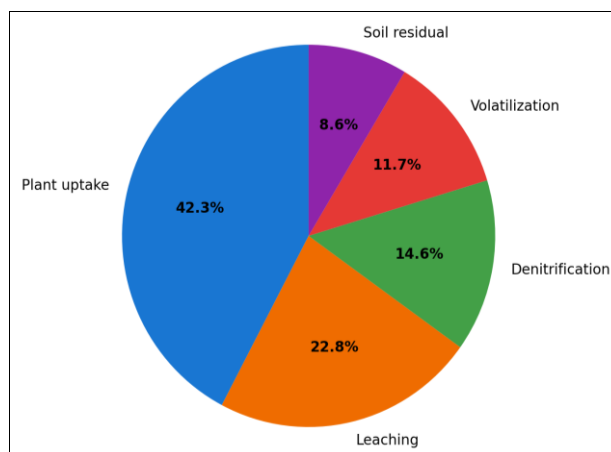


Fig 2: Nitrogen fate partitioning under current management (S1) in the rice-wheat rotation.

Figure 1 shows the non-linear relationship between N application rate and N leaching for both rice and wheat seasons leaching accelerates sharply above 160 kg N/ha. Figure 2 presents the N fate partitioning pie chart under current management, illustrating that over half of applied N is lost.

Discussion

The 42.3% N recovery rate confirms that current rice-wheat N management wastes over half of applied fertilizer. This aligns with Ladha *et al.*'s [2] field-measured recovery of 30-45% across South Asian sites. The non-linear leaching response (Figure 1) shows that each additional kilogram of N above 160 kg/ha produces diminishing yield returns but accelerating environmental loss a classic case of diminishing marginal productivity meeting increasing marginal pollution [3, 6].

The nitrification inhibitor DCD reduced leaching by 38.4% by slowing the conversion of NH_4^+ to mobile NO_3^- , keeping N in the ammonium form longer where it is less prone to leaching and denitrification [8]. Combined with a 20% rate reduction (S4), this achieved 93.8% of baseline yield a 6.2% penalty that may be economically acceptable given reduced fertilizer costs and environmental benefits [5, 7].

Limitations

Lysimeter conditions may not fully represent field-scale hydrology where lateral flow and deep percolation patterns differ. DNDC's denitrification estimates showed higher uncertainty (nRMSE 18.6%) than other outputs, reflecting the model's difficulty capturing episodic anaerobic events. Two years of validation data limit assessment of interannual variability.

Conclusion

Current N management in intensive rice-wheat systems recovers only 42.3% of applied nitrogen, with 22.8% lost through leaching. DNDC modelling showed that combining a 20% N rate reduction with nitrification inhibitor (DCD) can cut leaching by 38.4% while sacrificing only 6.2% of yield. The non-linear relationship between N application and leaching provides a clear target: keeping rates below 160 kg N/ha per season dramatically reduces environmental losses. These findings support transitioning from blanket high-N recommendations to precision N management in rice-wheat systems.

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