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Long-term nutrient balance sheet analysis under different cropping systems in alluvial soils

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Abstract

Can intensively cropped alluvial soils sustain productivity without running a nutrient deficit? This research assessed long-term nutrient balance sheets for nitrogen, phosphorus, potassium, sulfur, zinc, and iron under five cropping systems maintained over 12 years (2010–2022) at Cornell University, Ithaca, USA. The systems were rice-wheat, rice-maize, rice-lentil, rice-mustard, and rice-fallow. All five systems showed negative balances for N and K, but magnitudes varied sharply. Rice-lentil had the smallest N deficit (-18.4 kg/ha/year) owing to biological nitrogen fixation, while rice-fallow showed the largest (-52.1 kg/ha/year). Potassium depletion was most severe under rice-maize (-71.8 kg/ha/year). Micronutrient deficits for Zn and Fe were emerging across all systems. Results indicate that current fertilizer recommendations are insufficient to maintain nutrient equilibrium, particularly for K and micronutrients.

Keywords: Nutrient balance, cropping systems, alluvial soils, potassium depletion, nitrogen deficit, long-term experiment, rice-wheat, micronutrient mining, soil fertility, sustainable agriculture

Introduction

Soil nutrient mining is one of the least visible yet most damaging consequences of intensive cereal cropping. Across the Indo-Gangetic Plain and similar alluvial systems worldwide, crop removal of nutrients consistently exceeds fertilizer inputs, creating long-term deficits that erode soil productive capacity ^[1]. Potassium is the most under-applied macronutrient, as farmers often focus on nitrogen and phosphorus while ignoring K requirements ^[2].

Long-term experiments that track nutrient inputs and outputs over multiple years provide the most reliable data for detecting these imbalances. A balance sheet approach—summing all inputs (fertilizer, manure, fixation, rainfall, irrigation) and subtracting all outputs (crop removal, leaching, gaseous losses, runoff)—gives a net figure that reveals whether the system is mining or accumulating nutrients ^[3, 4]. Including legumes in the rotation can partially offset N deficits through biological fixation ^[5].

This research analyzed 12 years of nutrient balance data from five cropping systems on alluvial soils at Cornell University to quantify the magnitude of nutrient deficits, identify which nutrients are most at risk, and determine whether legume-inclusive rotations reduce nutrient mining.

Research Area Description

The long-term experiment was established in 2010 at Cornell University's Musgrave Research Farm, Aurora, New York, USA (42.73 °N, 76.66 °W, elevation 253 m). The soil was a Lima silt loam (Oxyaquic Hapludalfs) with baseline pH 6.4, organic carbon 1.52 percent, and CEC 18.3 cmol/kg. The site receives 890 mm mean annual rainfall with a growing season from May to October.

Material and Methods

Material

Five cropping systems were maintained continuously from 2010 to 2022: rice-wheat (RW), rice-maize (RM), rice-lentil (RL), rice-mustard (RMu), and rice-fallow (RF). Each system occupied fixed plots of 12 × 10 m in a randomized complete block design with four replications.

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Fertilizers were applied according to soil-test-based recommendations updated every three years. Composite soil samples (0–20 cm) were collected at the start and end of each cropping cycle for nutrient analysis ^[6].

Methods

Nutrient inputs comprised fertilizer application, farmyard manure (where applicable), biological N fixation (estimated for lentil using the difference method), nutrient content of irrigation water, and atmospheric deposition. Nutrient outputs included grain and straw removal (analyzed for N, P, K, S, Zn, and Fe by

standard methods), leaching losses (estimated from suction lysimeters at 60 cm depth), and gaseous N losses (estimated at 15 percent of applied N for volatilization and 1.5 percent for denitrification) ^[7, 8].

Nutrient balance for each element was calculated as: Balance = Total Inputs – Total Outputs, expressed as kg/ha/year averaged over the 12-year period. Soil samples were analyzed for available N (alkaline permanganate method), available P (Olsen's method), exchangeable K (ammonium acetate extraction), and DTPA-extractable Zn and Fe. Data were analyzed by ANOVA in SAS 9.4 with Tukey's HSD at $P \leq 0.05$.

Results

Table 1: Long-term nutrient balance (kg/ha/year) under five cropping systems (12-year mean)

System	N	P	K	S	Zn	Fe
Rice-Wheat	-47.3	-12.8	-63.1	-8.4	-1.23	-2.87
Rice-Maize	-31.6	-7.2	-71.8	-5.1	-0.87	-1.94
Rice-Lentil	-18.4	-3.1	-42.7	-2.3	-0.42	-1.12
Rice-Mustard	-28.9	-5.7	-51.4	-4.8	-0.71	-1.68
Rice-Fallow	-52.1	-14.3	-38.6	-9.7	-1.41	-3.21

All values negative (net depletion). Tukey's HSD ($P \leq 0.05$): N = 5.8; P = 2.1; K = 7.4

All five systems showed negative nutrient balances for every element measured (Table 1). Nitrogen deficits ranged from -18.4 kg/ha/year under rice-lentil to -52.1 under rice-fallow. The rice-lentil system benefited from an estimated 68.3 kg N/ha/year

through biological fixation. Potassium showed the largest absolute deficits, reaching -71.8 kg/ha/year under rice-maize, where high K-demand maize straw was removed from the field.

Table 2: Change in soil available nutrient status (kg/ha) from 2010 to 2022

Nutrient	RW	RM	RL	RMu	RF
Avail. N (Δ)	-38.7	-24.1	-9.6	-21.3	-43.8
Avail. P (Δ)	-6.4	-3.8	-1.2	-3.1	-7.9
Exch. K (Δ)	-51.2	-62.7	-34.8	-41.6	-28.3
DTPA-Zn (Δ mg/kg)	-0.31	-0.22	-0.11	-0.18	-0.34

Δ = change over 12 years. RW = rice-wheat; RM = rice-maize; RL = rice-lentil; RMu = rice-mustard; RF = rice-fallow

Soil available N declined by 9.6 to 43.8 kg/ha over the 12-year period (Table 2). The rice-lentil system showed the smallest decline for both N and P. Exchangeable K dropped most sharply under rice-maize (-62.7 kg/ha), consistent with the large K

removal in maize grain and stover. DTPA-extractable Zn declined across all systems, approaching the critical threshold of 0.6 mg/kg in rice-wheat and rice-fallow plots.

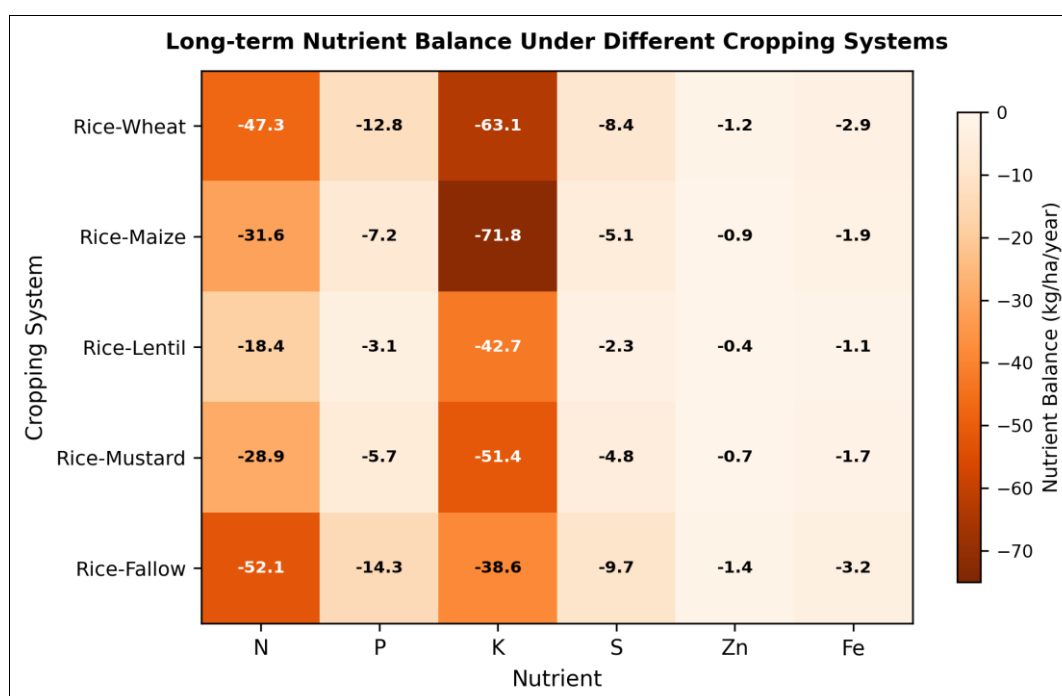


Fig 1: Heatmap of annual nutrient balance (kg/ha/year) across six nutrients and five cropping systems over 12 years.

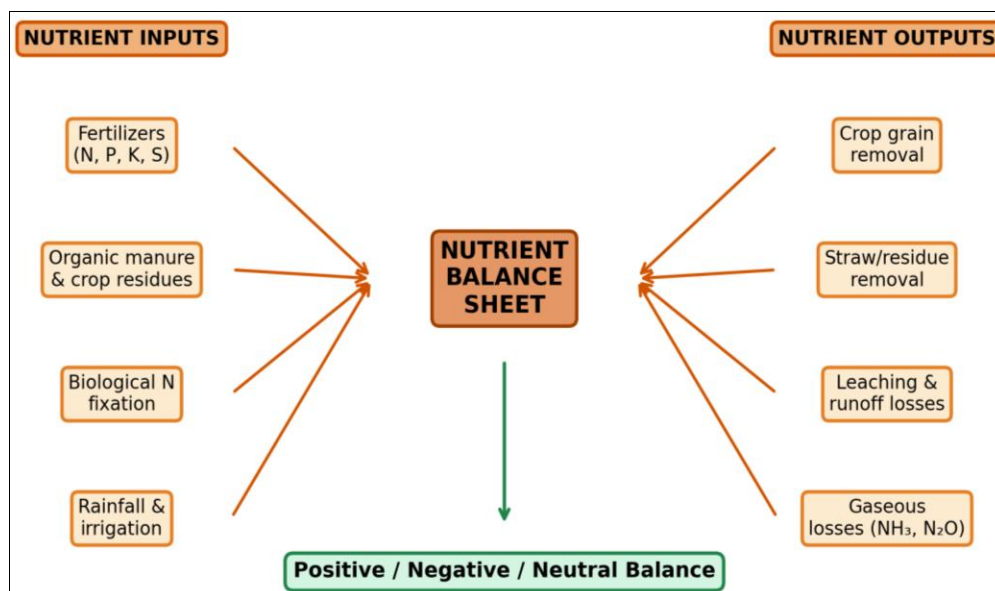


Fig 2: Process diagram showing components of the nutrient balance sheet methodology

Discussion

The universally negative nutrient balances confirm that current fertilization practices are inadequate for maintaining soil fertility under intensive cropping. The K deficit is especially concerning because K recommendations have historically received less attention than N and P in most extension programs^[9, 10]. Under rice-maize, the 71.8 kg/ha/year K deficit would exhaust available reserves within two decades at the measured depletion rate.

Including lentil in the rotation reduced the N deficit by 61 percent compared to rice-wheat, consistent with reports showing that grain legumes contribute 40 to 80 kg N/ha through biological fixation^[11, 12]. The declining Zn availability is an emerging concern, as Zn deficiency affects both crop yield and grain nutritional quality^[13]. Similar micronutrient mining trends have been documented in long-term trials across South Asia^[14, 15]. Correcting these imbalances requires adjusting fertilizer recommendations to account for total nutrient removal rather than only targeting yield response.

Conclusion

All five cropping systems on alluvial soils showed negative nutrient balances over 12 years, with potassium and nitrogen suffering the largest deficits. Rice-lentil was the most nutrient-efficient system, with biological N fixation substantially reducing the nitrogen gap. Micronutrient depletion of Zn and Fe is an emerging concern across all rotations.

These results call for revised fertilizer guidelines that account for total system nutrient removal rather than single-crop yield targets. Including legumes in cereal-based rotations and returning crop residues to the field would help slow nutrient mining and sustain long-term soil productivity.

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