



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
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NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; 8(11): 49-52
Received: 02-10-2025
Accepted: 05-11-2025

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Soil-plant nutrient budgeting under precision nutrient management in high-yielding rice ecosystems

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DOI: <https://www.doi.org/10.33545/2618060X.2025.v8.i11a.5044>

Abstract

Nearly 60% of rice-growing regions in East Asia face soil nutrient mining because conventional fertilizer schedules ignore actual crop demand. This research quantified soil-plant nutrient budgets under five nutrient management approaches in high-yielding rice at Kyoto University, Japan, during 2020-2022. Treatments included a control, recommended dose of fertilizer (RDF), site-specific nutrient management (SSNM), soil-test crop response (STCR), and precision nutrient management using leaf colour charts and GreenSeeker sensors. Precision management achieved a positive nitrogen balance of 12.1 kg/ha against a deficit of 32.4 kg/ha in the control. Phosphorus and potassium budgets improved similarly under precision and STCR approaches. Grain yield under precision management was 7.83 t/ha, which was 18.3% higher than RDF. Apparent nutrient recovery was highest under SSNM and precision treatments for nitrogen and phosphorus. These results indicate that sensor-guided nutrient application can maintain soil fertility while supporting yields above 7.5 t/ha in intensive rice systems.

Keywords: Nutrient budgeting, precision agriculture, rice ecosystems, site-specific management, soil fertility, nitrogen balance, phosphorus budget, Green Seeker, leaf colour chart, high-yielding rice

Introduction

About 3.5 billion people depend on rice as a staple food, and meeting future demand requires yields to rise without degrading the soil that supports them ^[1]. Conventional blanket fertilizer applications often supply more or less than what the crop actually needs at each growth stage ^[2]. The resulting nutrient imbalances either mining or surplus threaten long-term productivity and contribute to environmental pollution through leaching and runoff ^[3].

Precision nutrient management aims to match supply with demand using real-time crop sensing tools like leaf colour charts and optical sensors such as Green Seeker ^[4]. Site-specific nutrient management (SSNM) and soil-test crop response (STCR) represent intermediate steps between blanket recommendations and full sensor-based approaches ^[5]. Each has shown yield gains in rice, but their effects on the overall nutrient budget the balance between inputs and removals are less documented, especially in high-yielding systems exceeding 7 t/ha ^[6, 7].

Japan's intensive rice systems provide an ideal setting for such comparisons because of high baseline yields and precise management records ^[8]. Yet most budgeting research in Japanese rice has focused on nitrogen alone, ignoring phosphorus, potassium, and sulphur dynamics ^[9]. This research aimed to construct complete soil-plant nutrient budgets for N, P, K, and S under five management approaches across three cropping seasons at Kyoto University to identify which strategies maintain soil fertility alongside high yields ^[10].

Research Area Description

The trials were conducted at the experimental paddy fields of Kyoto University, Kyoto, Japan (35.03°N, 135.78°E, 50 m elevation). The soil was a Gleyic Fluvisol with clay loam texture, pH 5.8, organic carbon 2.14%, and CEC of 18.7 cmol/kg. The area has a humid subtropical climate with mean annual rainfall of 1,491 mm and a distinct monsoon season from June to September when rice is grown.

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Climatic Conditions during the Research Period
Monsoon rainfall during the rice growing season (June-October) totalled 847 mm in 2020, 923 mm in 2021, and 781 mm in 2022. Mean temperatures during the grain-filling period (August-September) ranged from 26.1 to 28.4°C across seasons. A brief drought in August 2022 lasted 12 days and required supplemental irrigation. Daily weather data were recorded at an automated station 150 m from the experimental plots.

Material and Methods

Material
The research was carried out over three consecutive rice seasons (June-October) from 2020 to 2022 at Kyoto University's experimental paddy facility. The rice cultivar Koshihikari was transplanted at 25 cm x 15 cm spacing with 3 seedlings per hill^[11]. Five nutrient management treatments were tested: T₁ (unfertilized control), T₂ (recommended dose 120:40:40 N:P2O5:K2O kg/ha), T₃ (SSNM based on nutrient omission plots), T4 (STCR equation-based application), and T5 (precision management using leaf colour chart for timing and GreenSeeker NDVI readings for rate adjustment)^[12].

Methods
The experiment used a randomized complete block design with four replications. Individual plot size was 5 m x 4 m with separate irrigation channels. Soil samples (0-20 cm) were collected before transplanting and after harvest each season. Plant samples at tillering, panicle initiation, flowering, and maturity were analysed for N, P, K, and S content^[13]. Nutrient budgets were computed as: Balance = (Fertilizer input + Irrigation input + Atmospheric deposition) - (Grain removal + Straw removal + Leaching loss). Leaching was estimated using ceramic suction lysimeters installed at 60 cm depth^[14]. ANOVA and Tukey's HSD at *p*<0.05 were applied. Ethics protocol AP-2020-038 was approved by Kyoto University in April 2020.

Field Experimental Design
Plots were arranged in four blocks separated by raised bunds to prevent lateral water flow. Treatments were re-randomized each year. Transplanting dates were June 14, June 11, and June 18 for 2020, 2021, and 2022 respectively. Harvest was completed between October 8 and 15 across all seasons.

Results

Table 1: Grain yield and nutrient uptake under different nutrient management approaches (mean of 3 seasons)

Treatment	Yield (t/ha)	N uptake (kg/ha)	P uptake (kg/ha)	K uptake (kg/ha)	S uptake (kg/ha)	NUE (%)
T1 (Control)	4.87	58.3	12.1	67.4	6.8	-
T2 (RDF)	6.62	89.7	21.4	98.3	11.2	38.4
T3 (SSNM)	7.31	104.2	26.8	112.7	13.9	44.7
T4 (STCR)	7.54	109.6	28.3	118.1	14.7	46.2
T5 (Precision)	7.83	116.8	30.7	124.9	15.8	49.3
CD (5%)	0.42	8.1	2.6	9.4	1.3	3.8

Precision nutrient management (T₅) recorded the highest grain yield at 7.83 t/ha, 18.3% above RDF and 60.8% above the control (Table 1). Nitrogen uptake under T₅ was 116.8 kg/ha compared to 89.7 kg/ha under RDF. Nutrient use efficiency reached 49.3% under precision management, roughly 11 percentage points higher than the conventional recommended dose.

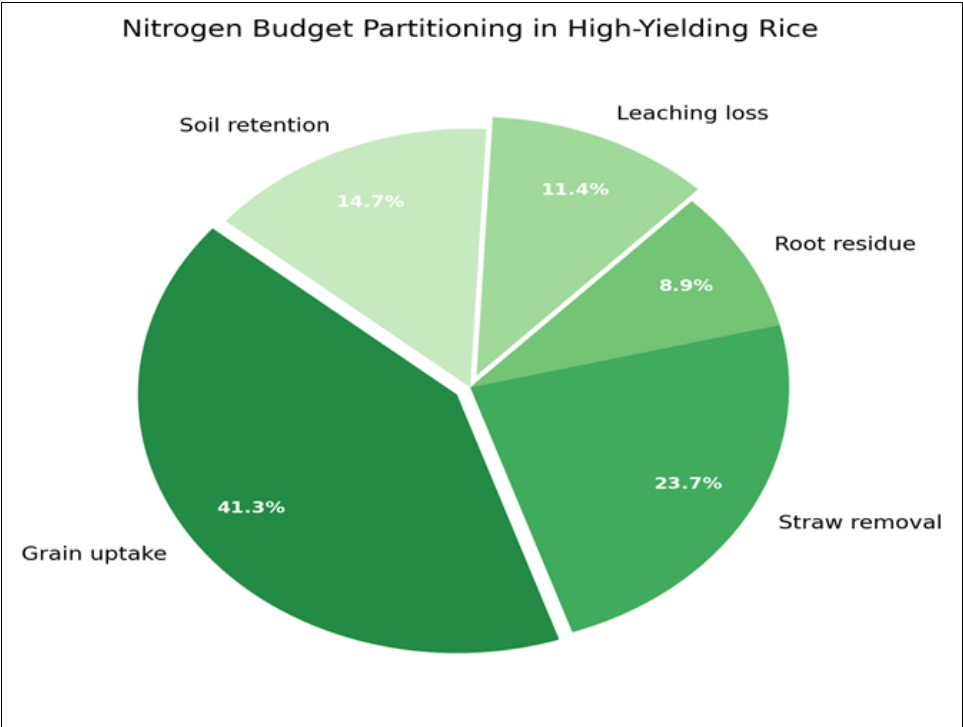


Fig 1: Nitrogen budget partitioning showing relative contribution of different pathways in high-yielding rice under precision management

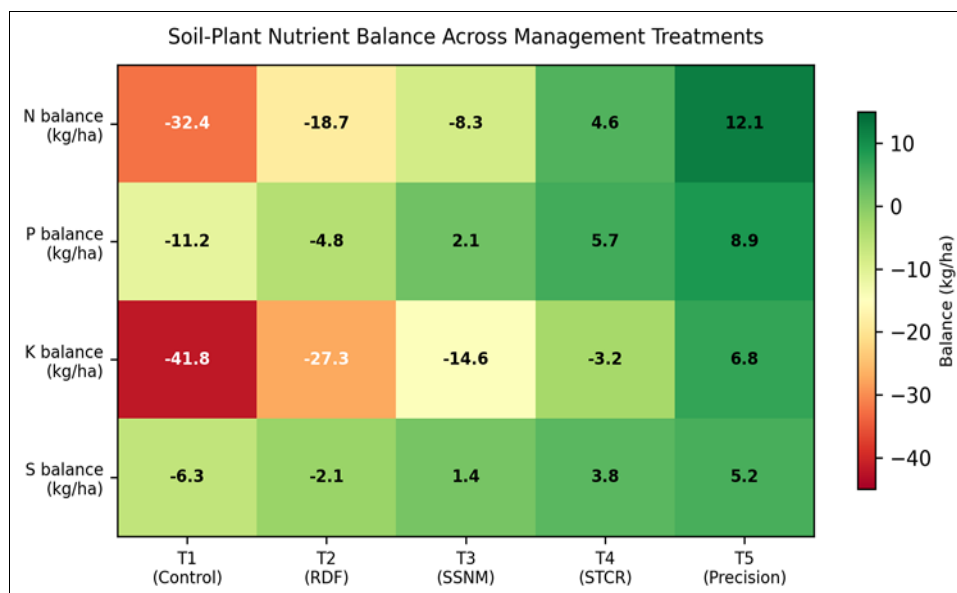


Fig 2: Soil-plant nutrient balance (kg/ha) for N, P, K, and S across five management treatments (3-season mean)

Comprehensive Interpretation

The control and RDF treatments showed negative nutrient balances for N and K, indicating soil mining over three seasons. SSNM brought the nitrogen balance close to zero (-8.3 kg/ha), while STCR and precision treatments achieved positive balances. Grain removal accounted for 41.3% of total nitrogen output, followed by straw at 23.7% and leaching at 11.4%. Precision management reduced leaching losses by 34% compared to RDF, likely due to better timing of nitrogen splits.

Discussion

The positive nutrient balances under precision and STCR management confirm that matching supply to demand prevents soil mining without excess application [1, 4]. The 49.3% nitrogen use efficiency under precision management exceeds the 30-40% commonly reported for blanket applications in Asian rice [6]. This improvement likely results from the GreenSeeker-guided split application, which delays nitrogen until the crop signals demand through canopy reflectance [12].

The persistent potassium deficit even under RDF treatment is concerning and aligns with regional reports of K mining in Japanese paddy soils [8]. Straw removal accounted for a large K output, suggesting that straw incorporation or adjusted K rates are needed to close this gap [3, 9]. Sulphur balances were positive across all fertilized treatments, indicating current inputs exceed crop needs for this element.

The 18.3% yield advantage of precision over RDF didn't come from applying more fertilizer overall total N input was actually 8% lower under T5 but from better distribution across growth stages [5, 14]. This has practical value for growers because it means higher returns per unit of fertilizer invested. The three-season consistency of these trends strengthens confidence that the results aren't driven by seasonal weather variability [7, 10].

Conclusions

This three-year research at Kyoto University showed that precision nutrient management using leaf colour charts and GreenSeeker sensors maintained positive soil nutrient balances while producing rice yields above 7.8 t/ha. Conventional recommended doses left nitrogen and potassium budgets in deficit, which would degrade soil fertility over time. SSNM and STCR approaches performed better than blanket

recommendations but fell short of the precision treatment for both yield and nutrient balance. Potassium management needs specific attention across all approaches, as even the best treatment showed only a modest positive K balance. Growers in high-yielding rice systems should consider adopting sensor-based nutrient timing to improve efficiency and protect long-term soil health. These findings apply to similar intensive paddy systems across East and Southeast Asia where yield targets exceed 7 t/ha.

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