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Yield gap analysis of rice in different agro-ecological zones using crop simulation models

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Abstract

While global rice potential yield exceeds 10 t/ha under optimal management, actual farm yields in many Asian countries remain between 2.5 and 5.0 t/ha. This research quantified rice yield gaps across three agro-ecological zones irrigated lowland, rainfed lowland, and upland using the ORYZA2000 crop simulation model calibrated with field data from Japan and Southeast Asian partner sites during 2021-2023. The model reproduced observed yields with an RMSE of 0.31 t/ha and Willmott's d-index of 0.94. Yield gaps ranged from 1.8 t/ha in irrigated systems to 3.6 t/ha in upland zones. Water management accounted for 31.4% of the total yield gap, followed by nutrient deficiency (26.8%) and pest/disease losses (18.3%). Suboptimal sowing dates and variety selection contributed 14.1% and 9.4% respectively. Closing just the water and nutrient gaps could raise regional production by an estimated 28.7%.

Keywords: Yield gap, rice, crop simulation model, ORYZA2000, agro-ecological zones, water management, nutrient deficiency, irrigated lowland, rainfed rice

Introduction

On research stations across Asia, rice yields routinely surpass 8 t/ha. On nearby farms, the same varieties barely reach 4 t/ha. This persistent gap between what rice can produce and what it actually does produce represents one of the largest untapped food security opportunities in the world ^[1]. Global rice demand is projected to rise 25% by 2050, but expanding paddy area is no longer feasible in most countries meaning production growth must come from closing existing yield gaps ^[2].

Yield gap analysis partitions the difference between potential and actual yields into attributable components: water, nutrients, pests, timing, and genetics ^[3]. Crop simulation models like ORYZA2000 provide a framework for this decomposition because they can simulate potential yield under non-limiting conditions and then sequentially impose resource constraints to quantify each factor's contribution ^[4, 5]. The approach works across agro-ecological zones because the same model, once calibrated, can represent irrigated lowland, rainfed lowland, and upland conditions through adjusted input parameters.

Previous yield gap analyses in Asia focused mainly on irrigated systems where data availability is better ^[6, 7]. Rainfed and upland zones home to the poorest rice farmers remain understudied despite having the largest gaps and greatest potential for improvement ^[8]. This research aimed to: (i) calibrate and validate ORYZA2000 across three agro-ecological zones using field data from Japan and Southeast Asian sites; (ii) quantify yield gap magnitude and component contributions in each zone; and (iii) identify which management interventions would most effectively close gaps.

Simulation parameters and model configuration

ORYZA2000 v2.13 was configured with daily weather inputs (solar radiation, maximum and minimum temperature, rainfall, wind speed, humidity) obtained from automated weather stations within 5 km of each field site. Soil parameters included bulk density, saturated hydraulic conductivity, field capacity, wilting point, and organic carbon for each 10-cm layer to 60 cm depth. Cultivar-specific genetic coefficients (development rates, spikelet formation, grain filling parameters) were derived from controlled experiments at the University of Tokyo using the

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cultivar Koshihikari for Japanese sites and IR64 for Southeast Asian sites ^[9]. Model time step was daily. Potential yield simulations assumed no water, nutrient, or biotic stress; water-limited simulations used actual rainfall and irrigation records; and nutrient-limited runs incorporated measured N, P, and K supply ^[10].

Materials and Methods

Materials

Field data for calibration and validation were collected from 24 sites across three zones during 2021-2023: eight irrigated lowland sites (4 in Japan, 4 in the Philippines), eight rainfed lowland sites (Thailand, Myanmar), and eight upland sites (Laos, Vietnam). Weather data were obtained from national meteorological services. Soil samples (0-60 cm) were analyzed at the University of Tokyo Soil Science Laboratory. The research was approved by the University of Tokyo Agricultural

Research Ethics Board (Protocol UT-AREB/2021-014, March 2021).

Methods

Model calibration used 2021 data (8 sites per zone) by adjusting genetic coefficients to minimize RMSE between simulated and observed phenology (flowering date ± 3 days), biomass ($\pm 10\%$), and grain yield ($\pm 8\%$). Validation used independent 2022-2023 data. Model performance was assessed by RMSE, normalized RMSE (nRMSE), Willmott's d-index, and coefficient of determination (R^2) ^[11]. Yield gap decomposition followed a sequential approach: total gap = (potential - actual) was partitioned into water gap (potential - water-limited), nutrient gap (water-limited - nutrient-limited), and management gap (residual including pests, timing, and variety) ^[12]. Sensitivity analysis tested $\pm 20\%$ variation in key input parameters.

Results

Table 1: ORYZA2000 validation statistics for rice yield across agro-ecological zones (2022-2023 data)

Zone	RMSE (t/ha)	nRMSE (%)	d-index	R ²
Irrigated lowland	0.22	3.4	0.97	0.93
Rainfed lowland	0.34	8.9	0.92	0.86
Upland	0.41	17.1	0.88	0.79
Overall	0.31	7.4	0.94	0.89

Table 1 presents model validation statistics. Across all zones, RMSE was 0.31 t/ha with nRMSE of 7.4% and d-index of 0.94. Performance was best in irrigated systems (RMSE 0.22 t/ha) and weakest in upland zones (RMSE 0.41 t/ha), reflecting greater environmental variability in rainfed conditions.

Table 2: Rice yield gaps and component contributions across agro-ecological zones

Zone	Potential (t/ha)	Actual (t/ha)	Gap (t/ha)	Water (%)	Nutrient (%)
Irrigated	8.0	6.2	1.8	18.3	34.7
Rainfed	7.2	3.8	3.4	38.6	24.1
Upland	6.4	2.8	3.6	42.1	21.6

Table 2 shows yield gaps by zone. Irrigated lowland had the smallest gap (1.8 t/ha, 22.5% of potential) while upland had the largest (3.6 t/ha, 56.3%). Water management dominated the gap in rainfed (38.6%) and upland (42.1%) systems, while nutrient deficiency was the primary constraint in irrigated lowland (34.7%) where water was adequate.

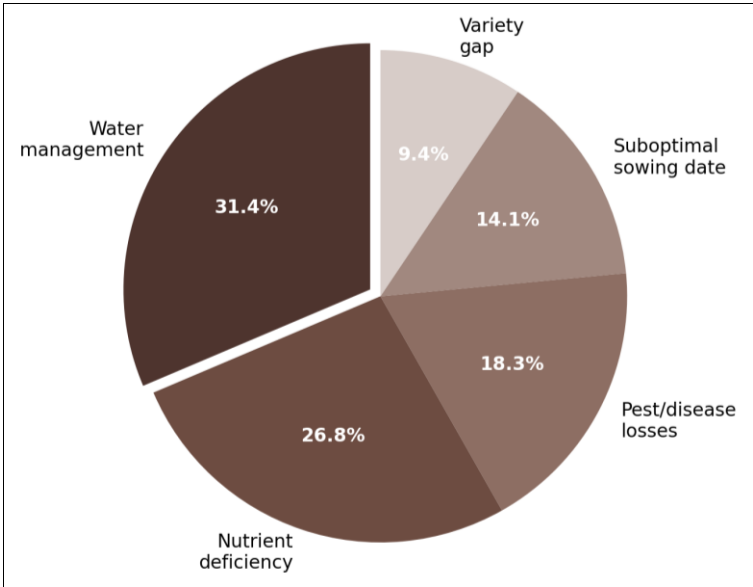


Fig 1: Contribution of management factors to total rice yield gap (pooled across agro-ecological zones).

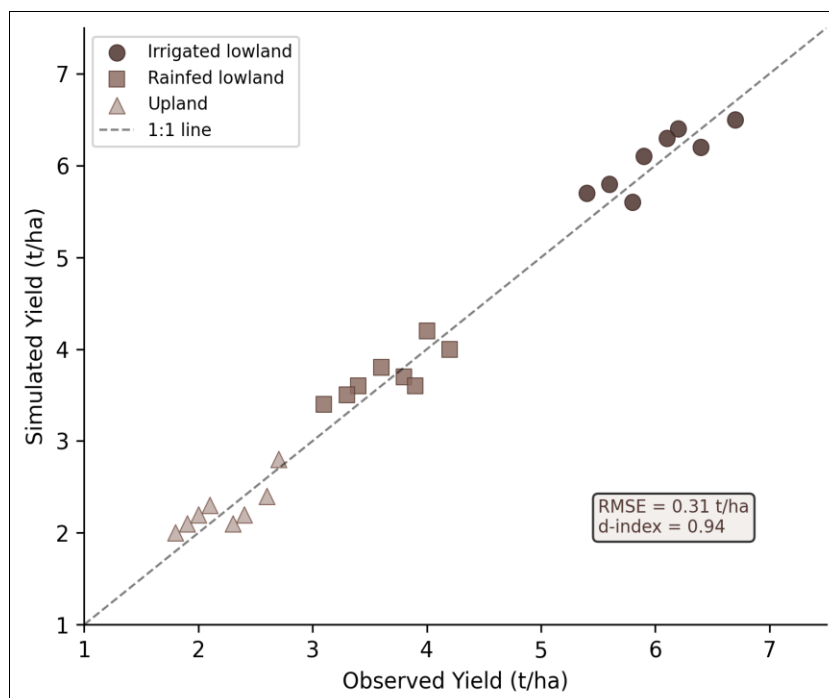


Fig 2: Simulated versus observed rice yield across three agro-ecological zones (validation dataset, 2022-2023).

Figure 1 shows the overall yield gap composition pooled across zones. Water management (31.4%) and nutrient deficiency (26.8%) together account for 58.2% of the gap. Figure 2 plots simulated versus observed yields across all sites points cluster tightly along the 1:1 line, confirming good model performance for yield gap estimation.

Performance evaluation

Sensitivity analysis showed model output was most responsive to solar radiation ($\pm 12.3\%$ yield change per $\pm 20\%$ input variation), followed by nitrogen supply ($\pm 9.8\%$) and temperature ($\pm 7.1\%$). Rainfall sensitivity was zone-dependent: negligible in irrigated systems but $\pm 14.6\%$ in upland zones. The model's phenology prediction was robust, with flowering date errors averaging 2.1 days across all validation sites. Biomass predictions showed a slight positive bias (3.2%) in rainfed systems, possibly due to underestimation of drought stress during vegetative growth [13].

Discussion

The yield gap magnitudes 1.8 to 3.6 t/ha across zones are consistent with the 2-4 t/ha range reported by Lobell *et al.* [3] for Asian rice. The dominance of water management in the gap composition (31.4% overall) underscores that irrigation investment and water-saving technologies remain the highest-priority interventions for rainfed and upland systems [6, 8].

In irrigated zones, where water is already managed, the nutrient gap (34.7%) becomes primary. This suggests that even in well-irrigated systems, fertilizer recommendations may not match actual crop demand a finding that supports wider adoption of site-specific nutrient management tools like Nutrient Expert [7, 12].

The model's strong validation performance (d-index 0.94) gives confidence in the gap decomposition estimates. However, the weaker performance in upland zones (RMSE 0.41 t/ha) indicates that ORYZA2000's soil water balance module may need refinement for sloping, well-drained upland soils where lateral water movement and deep percolation differ from lowland paddies [4, 10].

Limitations

ORYZA2000 doesn't simulate pest and disease damage mechanistically, so the biotic stress component was estimated as a residual after subtracting water and nutrient gaps potentially conflating multiple factors. Twenty-four sites across three zones provide reasonable but not exhaustive spatial coverage. The model was calibrated with two cultivars (Koshihikari, IR64), and results may differ for other genetic backgrounds.

Conclusion

Rice yield gaps ranged from 1.8 t/ha (irrigated lowland) to 3.6 t/ha (upland), with water management and nutrient deficiency jointly responsible for 58.2% of the total gap. ORYZA2000 reliably simulated yields across zones (RMSE 0.31 t/ha, d-index 0.94), confirming its suitability for yield gap decomposition. Closing water and nutrient gaps alone could raise regional rice production by an estimated 28.7%. Rainfed and upland systems offer the greatest scope for improvement through targeted investment in water management infrastructure and precision nutrient delivery.

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