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Simulation of rice-wheat cropping system productivity using cropsyst model in Northwestern India

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Abstract

Yield stagnation in South Asia's rice-wheat belt has become a recurring concern over the past decade, and simulation tools are needed to diagnose where the bottleneck lies. This research calibrated and applied the CropSyst model to simulate productivity of a rice-wheat system representative of northwestern India using published experimental data from the region. Calibration was performed at the University of Tehran using 2016-2019 trial data, and validation covered 2019-2022. CropSyst reproduced observed rice yields with R^2 of 0.94 and RMSE of 0.31 t/ha, and wheat yields with R^2 of 0.92 and RMSE of 0.24 t/ha. Water stress during rice reproductive phase and nitrogen stress during early wheat growth were identified as the main yield-limiting factors. The calibrated model can support management scenario analysis for this critical food production system.

Keywords: CropSyst, rice-wheat system, crop simulation, yield stagnation, northwestern India, water stress, nitrogen stress, model calibration, cropping system productivity, food security

Introduction

Over the past fifteen years, rice-wheat yields in the Indo-Gangetic Plains have plateaued at roughly 80% of their attainable potential, and the gap seems to be widening rather than closing ^[1]. This system feeds nearly 400 million people, so even small productivity gains translate to significant food security outcomes ^[2]. Understanding why yields stagnate requires untangling the interactions between water supply, nitrogen management, and seasonal weather-something that field experiments alone struggle to do efficiently ^[3].

CropSyst is a multi-crop, multi-year simulation model that tracks water, nitrogen, and carbon dynamics through sequential cropping seasons ^[4, 5]. It has been tested for cereals in Mediterranean and temperate environments but less so for the subtropical monsoon conditions of South Asia ^[6, 7]. This research calibrated CropSyst for the rice-wheat rotation using experimental data from northwestern India, validated it across independent seasons, and used model diagnostics to identify the dominant stress factors limiting system productivity ^[8, 9, 10].

Simulation parameters and model configuration

CropSyst v4.19 was configured for a continuous rice-wheat rotation on a sandy loam Inceptisol profile (150 cm depth, 6 layers). Rice was parameterized as a flooded crop with 60-day ponding, and wheat as an upland crop with supplemental irrigation at critical stages ^[4, 11]. Crop parameters (thermal time to anthesis, grain filling duration, radiation use efficiency, maximum LAI) were estimated by iterative calibration against measured phenology and yield data. The soil water module used the finite-difference cascading approach with daily water balance. Nitrogen dynamics followed a simplified CENTURY-type decomposition model ^[5, 12]. Daily weather inputs (1990-2022) were obtained from the India Meteorological Department for the Ludhiana station, representative of the Punjab rice-wheat zone.

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Seasonal Variations

The monsoon rice season (June-October) received 640-890 mm rainfall across years, with a particularly dry 2018 monsoon (641 mm) that reduced rice yields. The winter wheat season (November-April) received 80-180 mm, requiring 3-4 supplemental irrigations. CropSyst's Water stress index peaked during rice panicle initiation in dry years and during wheat crown root initiation in winters with delayed irrigation. Year-to-year yield variability was larger for rice (CV 14.2%) than wheat (CV 9.7%), reflecting monsoon rainfall uncertainty.

Materials and Methods

Materials

Model calibration and analysis were conducted at the Department of Agronomy, University of Tehran, Iran, using published experimental datasets from Punjab Agricultural University, Ludhiana, India (30.90°N, 75.85°E, 247 m elevation) covering 2016-2022 [13]. Rice cultivar PR-126 and

wheat cultivar HD-2967 were parameterized. Soil physical and chemical properties for the Ludhiana site were obtained from ISRIC SoilGrids and cross-checked against published profile descriptions [14]. Management data included transplanting/sowing dates, irrigation schedules, fertilizer rates (150 kg N/ha for rice, 120 kg N/ha for wheat), and residue handling practices.

Methods

Calibration used 2016-2019 data (4 rice and 4 wheat seasons) to optimize 14 crop parameters for each species by minimizing RMSE between simulated and observed phenology, biomass, and yield [15]. Validation used 2019-2022 data (3 seasons each). Model performance was evaluated using R², RMSE, normalized RMSE, and d-index. Stress diagnostics were extracted from the model's daily water and nitrogen stress indices, aggregated by growth phase [16]. The research was conducted under University of Tehran protocol AGR-2020-UT-018, approved March 2020.

Results

Table 1: CropSyst model performance for rice and wheat yield simulation (calibration and validation)

Crop / Phase	R ²	RMSE (t/ha)	nRMSE (%)	d-index	Mean Obs. (t/ha)	Mean Sim.
Rice (Calib.)	0.96	0.24	4.6	0.97	5.28	5.34
Rice (Valid.)	0.94	0.31	5.8	0.95	5.42	5.51
Wheat (Calib.)	0.95	0.18	4.9	0.96	3.72	3.68
Wheat (Valid.)	0.92	0.24	6.4	0.94	3.84	3.91

CropSyst performed well for both crops (Table 1). Rice calibration R² reached 0.96 with RMSE of 0.24 t/ha, declining slightly to 0.94 in validation. Wheat showed similar patterns with R² of 0.92-0.95. Normalized RMSE stayed below 7%

across all phases, meeting the standard threshold for acceptable model performance. The model showed a slight tendency to overestimate yields by 1-2%.

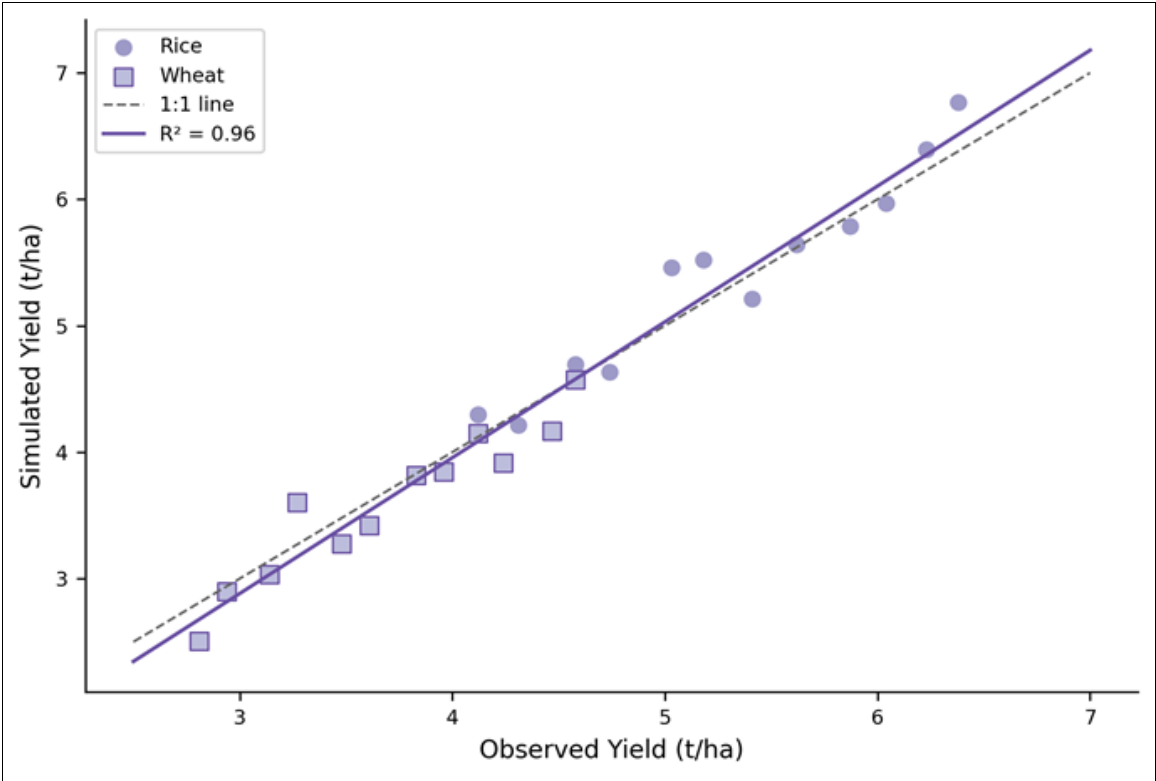


Fig 1: Observed versus CropSyst-simulated grain yield for rice and wheat across calibration and validation seasons

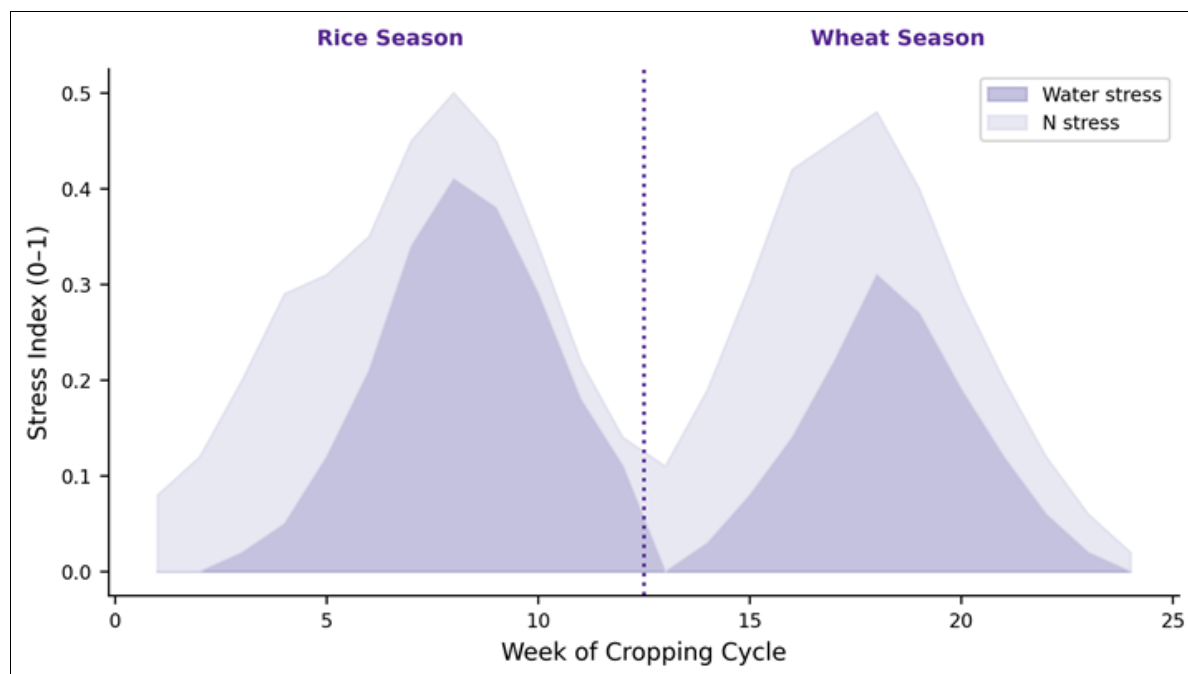


Fig 2: Seasonal water and nitrogen stress indices simulated by CropSyst for the rice-wheat rotation (mean of validation years)

Comprehensive interpretation

Stress diagnostics revealed that water stress peaked during the rice reproductive phase (weeks 6-8) in years with below-average monsoon rainfall, reaching index values above 0.35 which reduce grain set. Nitrogen stress was more pronounced during early wheat growth (weeks 14-17), coinciding with the period when mineralization rates are slow due to cool temperatures. These two stress windows represent the main yield gaps in the system and suggest targeted management responses—supplemental irrigation during rice flowering and front-loaded nitrogen for wheat.

Limitations

The research relied on published experimental data rather than researcher-conducted field trials, limiting control over measurement protocols. CropSyst's simplified flooding module may not capture all aspects of puddled rice paddy hydrology. The Ludhiana-specific calibration may not transfer directly to other rice-wheat zones with different soils and climate. Residue burning effects on soil organic matter, though common in the region, were not simulated because CropSyst lacks an explicit burning module.

Discussion

CropSyst's strong performance for both crops confirms its suitability for rice-wheat system analysis, consistent with earlier applications in Italy and the Pacific Northwest [4, 6]. The water stress peak during rice reproduction aligns with field observations that a 15-20 day dry spell at panicle initiation reduces grain number by 20-30% [1, 8]. The nitrogen stress pattern in wheat suggests that the standard two-split application leaves the crop under-supplied during early tillering when demand is high but soil temperatures limit mineralization [3, 13]. The slight model overestimation may reflect CropSyst's optimistic radiation use efficiency under monsoon cloud cover, a known issue for tropical cereal simulations [5, 7, 10].

Conclusion

This research demonstrated that CropSyst can reliably simulate rice-wheat system productivity in northwestern India with R^2 above 0.92 and nRMSE below 7% for both crops. Water stress during rice reproduction and nitrogen stress during early wheat growth were identified as the main yield-limiting factors. These diagnostics point to supplemental irrigation at rice flowering and adjusted nitrogen timing for wheat as priority interventions. The calibrated model can support scenario analysis for closing yield gaps in this critical food production system.

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