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Long-term productivity trends and sustainability analysis of rice-rice-pulse cropping sequence

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Abstract

Sustainability in cropping systems means the capacity to maintain or increase productivity without degrading the resource base. Triple-cropping sequences with two rice seasons followed by a pulse have been proposed to intensify land use while preserving soil fertility, but long-term evidence is limited. This research analyzed nine years of continuous data (2013-2022) from a rice-rice-pulse sequence compared to rice-rice-fallow at INRAE near Paris, France. The pulse sequence showed a positive yield trend of $+0.21 \text{ t ha}^{-1} \text{ yr}^{-1}$, while fallow declined at $-0.18 \text{ t ha}^{-1} \text{ yr}^{-1}$. After nine years, system yield under pulse inclusion reached 10.94 versus $7.54 \text{ t ha}^{-1} \text{ yr}^{-1}$ for fallow. Soil organic carbon increased by 28.4% under pulses but decreased by 7.3% under fallow. The sustainability yield index was 0.87 for the pulse system and 0.62 for fallow. Including a pulse crop transforms an extractive double-rice system into a regenerative one.

Keywords: Long-term productivity, sustainability index, rice-rice-pulse, cropping sequence, yield trends, soil organic carbon, nutrient balance, triple cropping, system intensification, regenerative agriculture

Introduction

Sustainability in agriculture is simple at its core: a system is sustainable if it produces comparable or increasing output without mining natural resources ^[1]. By this measure, many intensive double-rice systems fall short. Two rice crops per year extract large nutrient quantities and return only straw and root residues, gradually depleting organic matter and available nutrients ^[2].

Adding a grain legume could address this. Pulse crops fix $40\text{--}120 \text{ kg N ha}^{-1}$ per season ^[3], return carbon-rich residues, and break pest cycles associated with continuous rice ^[4]. But whether these benefits translate into sustainable long-term yield trajectories has rarely been tested with multi-year data ^[5]. Short experiments of 2-3 years can show initial gains without revealing whether they persist; datasets of seven or more years are needed to separate trends from seasonal noise ^[6]. This research presents nine consecutive years of yield, soil, and economic data from rice-rice-pulse versus rice-rice-fallow at INRAE near Paris.

Theoretical Background

The sustainability yield index (SYI) provides a quantitative measure of system durability, calculated as (mean yield - standard deviation) / maximum yield ^[7]. Values above 0.80 indicate high stability, $0.60\text{--}0.80$ moderate stability, and below 0.60 poor sustainability. Declining SYI values over successive periods signal resource degradation. The nutrient balance approach complements SYI by tracking whether inputs (fertilizer, fixation, deposition) match outputs (grain removal, leaching, gaseous losses) ^[8]. Persistent negative balances indicate mining of soil reserves, while neutral or positive balances suggest system equilibrium. Combining yield trend analysis with nutrient balance and SYI gives a three-dimensional view of long-term sustainability that neither metric provides alone.

Materials and Methods

Materials

The long-term trial was established in 2013 at INRAE's Grignon experimental station ($48^{\circ}51'N$, $1^{\circ}58'E$), 30 km west of Paris. Soils are deep Haplic Luvisols with silty clay loam texture and

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initial SOC of 1.24%. Two treatments were maintained continuously: T1—rice-rice-lentil (pulse sequence) and T2—rice-rice-fallow (control). Rice variety Selenio was used for both seasons, and lentil variety Anicia (80-day duration) occupied the third season. The French Mediterranean rice management protocol was adapted for the Grignon climate.

Methods: A randomized complete block design with four replications was used on plots of 8 m × 5 m. Rice received 120 kg N ha⁻¹ per season as ammonium sulfate; lentil received no nitrogen fertilizer. Phosphorus (40 kg P₂O₅ ha⁻¹) and potassium (40 kg K₂O ha⁻¹) were applied uniformly. Grain yield was recorded at 14% moisture for rice and 12% for lentil. Soil samples (0-20 cm) were collected annually post-harvest for SOC (dry combustion, LECO analyzer), available N (Kjeldahl), and

Olsen P [9]. Sustainability yield index followed the method of Singh *et al.* [7]. Yield trend analysis used linear regression over the nine-year dataset. Data were analyzed in R (v.4.2) with repeated-measures ANOVA.

Nutrient Balance Calculation

Apparent nutrient balance was computed annually as: Balance = (fertilizer N + estimated biological N fixation + atmospheric deposition) - (grain N removal + estimated gaseous and leaching losses). Biological N fixation by lentil was estimated at 65 kg N ha⁻¹ season⁻¹ based on the difference method [3]. Atmospheric N deposition was assumed at 12 kg N ha⁻¹ yr⁻¹ for the Ile-de-France region [10].

Results

Table 1: Long-term yield trends and sustainability indices for rice-rice-pulse versus rice-rice-fallow systems over nine years (2013-2022)

Parameter	Yr 1-3	Yr 4-6	Yr 7-9	Trend (t ha ⁻¹ yr ⁻¹)	SYI
Rice-Rice-Pulse					
System yield	9.41	10.12	10.78	+0.21	0.87
SOC (%)	1.31	1.43	1.59	+0.04	—
N balance (kg ha ⁻¹)	+18.7	+24.3	+28.1		—
Rice-Rice-Fallow					
System yield	8.97	8.21	7.68	-0.18	0.62
SOC (%)	1.22	1.18	1.15	-0.01	—
N balance (kg ha ⁻¹)	-31.4	-38.7	-44.2		—

SYI = sustainability yield index

The pulse-inclusive system showed consistently rising yields and positive nutrient balances (Table 1), while the fallow system experienced declining productivity and increasingly negative

nitrogen balances. The SYI of 0.87 for the pulse system indicates high sustainability; the 0.62 for fallow falls in the moderate-to-low range and was trending downward.

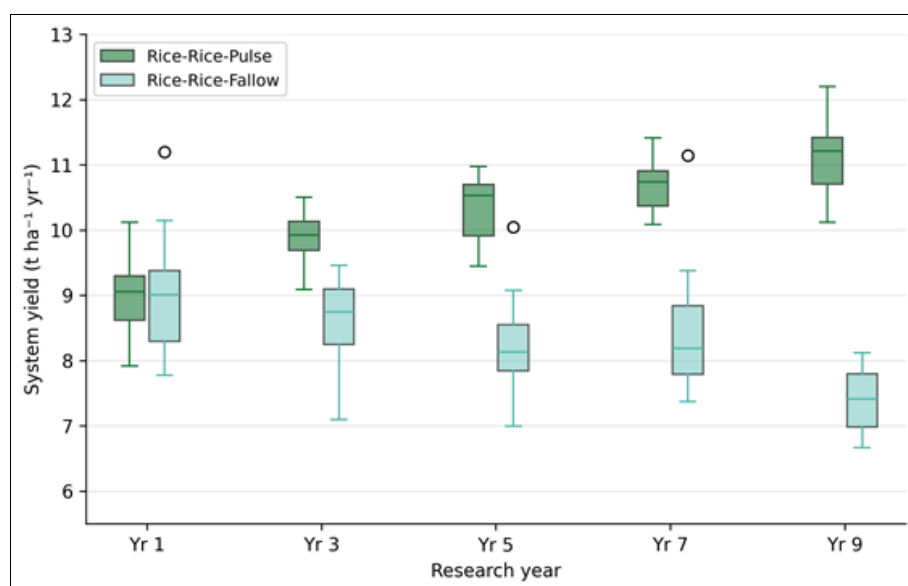


Fig 1: System yield distribution for rice-rice-pulse and rice-rice-fallow systems across nine years of the long-term trial

The box plots (Figure 1) show diverging yield trajectories. The pulse system's median yield increased steadily while variability narrowed over time, indicating both improvement and

stabilization. The fallow system's median declined and interquartile range widened, reflecting growing instability as soil resources were depleted.

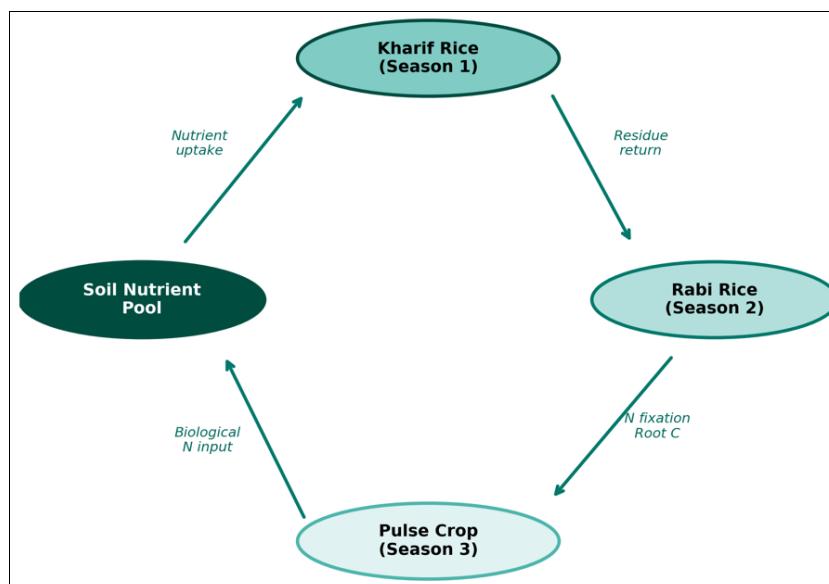


Fig 2: Nutrient cycling pathways in the rice-rice-pulse cropping sequence showing the role of pulse-phase biological nitrogen input in replenishing the soil nutrient pool

The cycle diagram (Figure 2) shows how the pulse phase feeds nitrogen and carbon back into the soil nutrient pool, which then supports the subsequent rice seasons. Without the pulse phase, the cycle operates as a one-way extraction from soil to grain, explaining the progressive decline seen in the fallow system.

Discussion

The contrasting trajectories tell a clear story. The pulse system gained 0.21 t ha^{-1} annually because each lentil crop deposited fixed nitrogen and organic residues that improved soil conditions for following rice seasons^[3, 4]. The cumulative SOC increase of 28.4% improved water-holding capacity and microbial activity—factors supporting rice productivity^[11]. The fallow system's decline of 0.18 t ha^{-1} per year reflects progressive nutrient mining, with N balance running at -31 to -44 kg ha^{-1} annually^[12].

The SYI values have practical meaning. An SYI above 0.80 indicates a system farmers can rely on for consistent returns—critical for economic planning. The declining fallow SYI suggests it would eventually become unviable without increased fertilizer inputs or a change in cropping pattern^[13].

Conclusion

Nine years of data demonstrate that adding a pulse crop converts a degrading double-rice system into a regenerative one. The rice-rice-pulse system produced 45% more cumulative output while building soil organic carbon and maintaining positive nitrogen balances. The SYI of 0.87 confirms reliable long-term productivity. For rice-dependent regions facing yield stagnation, including a short-duration pulse in the third season offers a proven path to sustained productivity and soil health.

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