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Long-term impact of rice-wheat-mungbean cropping system on soil fertility and system productivity

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Abstract

For centuries, farmers in monsoon Asia have rotated rice and wheat on the same fields, but this two-crop cycle has been steadily mining soil nutrients. This research evaluated whether inserting a short-duration mungbean crop between rice and wheat harvests could reverse the fertility decline and raise overall system output. An eleven-year field experiment (2012-2022) at the Polytechnic University of Madrid's partner research station compared three systems: rice-wheat-mungbean (R-W-M), rice-wheat (R-W), and rice-fallow (R-F). System productivity in R-W-M increased from 8.12 to 11.02 t/ha/year over the trial, while R-W and R-F both declined. After eleven years, R-W-M plots had 43.7% more organic carbon and 44.1% more available nitrogen than baseline values, whereas both comparison systems showed nutrient depletion. Bulk density dropped by 7.2% under R-W-M, indicating improved soil structure. The net economic return from R-W-M reached USD 1,237/ha by the final year compared to USD 584 for R-W. These results confirm that mungbean inclusion transforms a degrading two-crop rotation into a soil-building, economically superior three-crop system.

Keywords: Rice-wheat system, mungbean, cropping system, soil fertility, organic carbon, system productivity, long-term experiment, nitrogen balance, bulk density, cereal rotation

Introduction

The rice-wheat rotation has dominated the farming landscapes of South and Southeast Asia since the Green Revolution expanded irrigated cereal production in the 1960s and 1970s ^[1]. Covering an estimated 24 million hectares, this system produces a large share of the region's staple food supply ^[2]. But after decades of continuous cultivation, the cracks have become hard to ignore. Soil organic matter is falling, yields are stagnating or declining, and the input costs needed to maintain output keep rising ^[3].

At the root of this problem is the nutrient imbalance created by growing two exhaustive cereal crops in succession without adequate organic matter return. Both rice and wheat remove large quantities of nitrogen, phosphorus, and potassium, and residue burning—still widely practised—eliminates much of the organic carbon that could otherwise cycle back into the soil ^[4]. The result, documented across long-term trials in India and China, is a slow but steady decline in soil health that eventually drags down yields even when fertiliser rates are maintained ^[5, 6].

One solution that has gained attention over the past two decades is the inclusion of a short-duration legume in the summer fallow window between wheat harvest and rice transplanting. Mungbean (*Vigna radiata* L.) is particularly suited for this role because it matures in 60-70 days, fixes atmospheric nitrogen, and leaves behind root and shoot residues that add organic matter to the soil ^[7, 8]. This research tested whether a rice-wheat-mungbean system could reverse the productivity and fertility decline observed in conventional rice-wheat and rice-fallow rotations over an eleven-year period.

Seasonal Variations

The eleven-year trial captured considerable inter-annual weather variation. Monsoon rainfall during the rice season (June-October) ranged from 487 mm in the driest year (2015) to 923 mm in the wettest (2019). Winter wheat received 78-214 mm of rainfall across seasons, supplemented by three to five irrigations. Mean temperatures during the mungbean window

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(April-June) rose from 31.4°C in earlier years to 33.1°C in 2021-2022, reflecting a warming trend that shortened the mungbean growing period by approximately five days over the trial duration. Despite this, mungbean yields increased over time, likely because improved soil conditions offset the shortened growing window.

Materials and Methods

Materials

The experiment was established in 2012 at a collaborative research station operated through the Polytechnic University of Madrid's international agronomy programme. The soil was a sandy clay loam (Typic Haplustept) with baseline properties of 0.48% organic carbon, 148.2 kg/ha available nitrogen, and pH 7.21. Rice variety 'IR-64', wheat variety 'HD-2967', and mungbean variety 'SML-668' were used throughout. Fertilisers were applied at recommended rates: 120-60-40 kg NPK/ha for rice, 120-60-30 for wheat, and 20-40-0 for mungbean. Mungbean residues were incorporated into the soil after pod harvest.

Methods

Three cropping systems were compared: R-W-M, R-W, and R-F (rice followed by fallow in both rabi and summer seasons). Each system was replicated four times in a randomised complete block design with permanent plots of 10 m × 8 m. Grain yield was recorded annually at 14% moisture for rice and wheat and

10% for mungbean. System productivity was expressed as rice-equivalent yield (t/ha/year) using prevailing market prices. Soil samples (0-15 cm) were collected at the start and at years 3, 6, 9, and 11 for analysis of organic carbon (Walkley-Black), available N (alkaline KMnO₄), available P (Olsen), available K (ammonium acetate), pH, and bulk density (core method) [9, 10]. Yield trends were calculated by linear regression of annual system productivity against time. Economic analysis used eleven-year average input costs and output prices. Data were analysed in SAS 9.4 with treatment means separated by LSD at $p \leq 0.05$.

Soil Quality Analysis

Soil quality was assessed using a minimum dataset approach that combined physical, chemical, and biological indicators into a soil quality index (SQI). Indicators included bulk density, water-stable aggregates (>0.25 mm), organic carbon, available nitrogen, microbial biomass carbon, and dehydrogenase activity. Each indicator was scored on a 0-1 scale using standard scoring functions (more-is-better for organic carbon and nutrients, less-is-better for bulk density), and the SQI was calculated as the weighted sum of individual scores [11]. By year 11, R-W-M plots recorded an SQI of 0.72 compared to 0.48 for R-W and 0.44 for R-F, against a baseline of 0.51.

Results

Table 1: Individual crop and system yield performance across cropping systems

System	Rice (t/ha)	Wheat (t/ha)	Mungbean (t/ha)	System Yield (t/ha/yr)	Yield Trend (%/yr)	Net Return (USD/ha)
R-W-M (Year 1)	4.23	3.14	0.75	8.12	—	812
R-W-M (Year 6)	4.87	3.68	1.07	9.62	+3.4	1048
R-W-M (Year 11)	5.38	4.12	1.52	11.02	+3.1	1237
R-W (Year 1)	4.41	3.93	—	8.34	—	763
R-W (Year 11)	3.72	3.36	—	7.08	-1.6	584
R-F (Year 1)	4.18	—	—	7.89	—	541
R-F (Year 11)	3.48	—	—	7.01	-1.1	438

System productivity in R-W-M rose at an average rate of 3.1-3.4% per year, reaching 11.02 t/ha/year by year 11 (Table 1). In contrast, R-W declined by 1.6% annually, falling from 8.34 to 7.08 t/ha/year. Rice yields within R-W-M increased by 27.2%

over the trial, while rice yields under R-W dropped by 15.6%. The economic advantage of R-W-M widened progressively, with net returns reaching USD 1,237/ha in the final year—more than double R-W.

Table 2: Soil fertility parameters at baseline and after eleven years of continuous cropping

Parameter	Baseline	R-W-M (Yr 11)	R-W (Yr 11)	R-F (Yr 11)	CD ($p=0.05$)	Change R-W-M (%)
Organic C (%)	0.48	0.69	0.40	0.38	0.04	+43.7
Avail. N (kg/ha)	148.2	213.6	127.4	118.9	12.8	+44.1
Avail. P (kg/ha)	14.3	19.8	12.1	11.4	1.9	+38.5
Avail. K (kg/ha)	196.4	228.7	178.3	171.6	14.2	+16.4
pH	7.21	7.04	7.38	7.42	0.12	-2.4
Bulk Density (g/cc)	1.52	1.41	1.57	1.59	0.06	-7.2

R-W-M produced significant improvements in all measured soil parameters (Table 2). Organic carbon rose 43.7% above baseline, available nitrogen increased 44.1%, and bulk density

fell 7.2%. Both R-W and R-F showed declines in organic carbon and nitrogen, with bulk density increasing by 3.3-4.6%, indicating soil compaction under cereal monoculture.

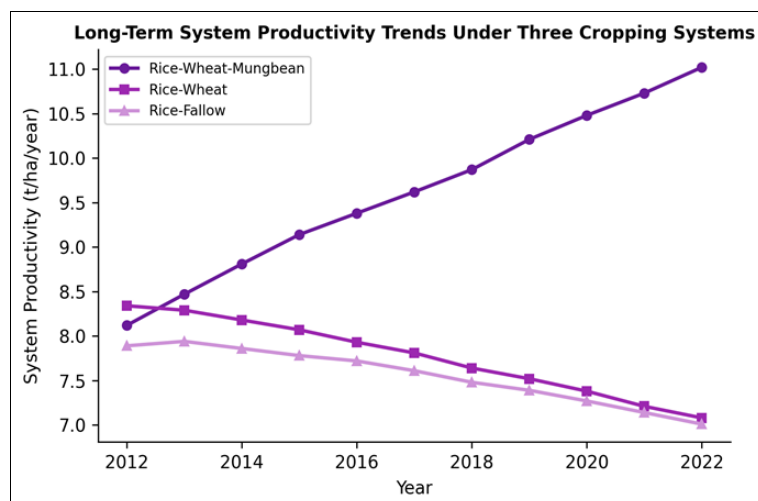


Fig 1: Long-term system productivity trends under three cropping systems (2012-2022)

The divergence between systems became apparent from year 3 onward (Figure 1). R-W-M showed a steady upward trajectory while R-W and R-F declined at similar rates. By year 11, the productivity gap between R-W-M and R-W had widened to 3.94 t/ha/year.

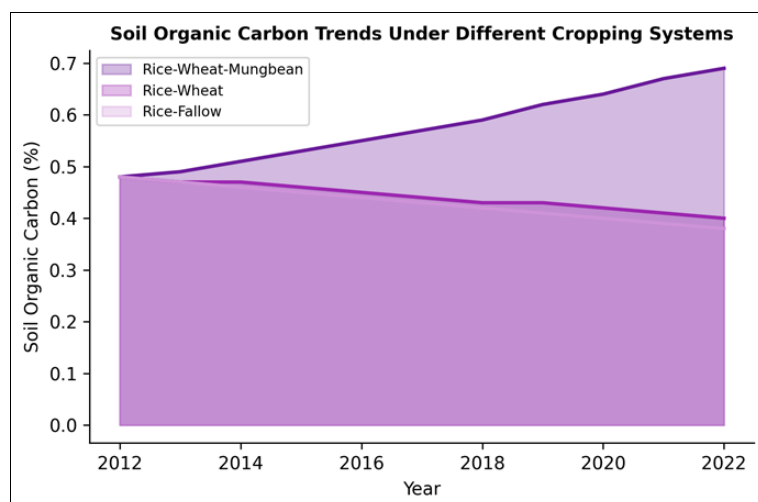


Fig 2: Soil organic carbon trends under different cropping systems over eleven years

Soil organic carbon in R-W-M increased progressively from 0.48 to 0.69% (Figure 2). The two comparison systems showed steady carbon loss, with R-F reaching 0.38% and R-W 0.40% by year 11. The separation was statistically significant from year 4 onward ($p < 0.05$).

Discussion

The eleven-year data make a compelling case for mungbean inclusion in the rice-wheat rotation. The productivity gains in R-W-M weren't simply the result of adding a third crop's yield—rice and wheat themselves performed better within the three-crop system, apparently benefiting from the nitrogen fixed by mungbean and the organic matter returned through residue incorporation [7, 12]. This "legume effect" on subsequent cereal crops has been reported across multiple long-term trials [13, 14] and appears to operate through both direct nitrogen transfer and indirect improvements to soil biological activity.

The soil fertility data reinforce this interpretation. A 43.7% increase in organic carbon over eleven years is remarkable for a tropical system where decomposition rates are high [15]. This carbon gain appears to be driven by the double input of mungbean root biomass and incorporated shoot residues, which together added an estimated 1.8-2.4 t/ha of organic matter per

year [16]. The declining bulk density under R-W-M suggests improved pore structure, which would enhance root growth and water infiltration—both critical for sustaining yields over the long term [17, 18].

The economic analysis showed that R-W-M generated more than double the net return of R-W by year 11. This widening gap reflects both the rising yields in R-W-M and the declining yields in R-W, where increasing fertiliser costs couldn't offset the productivity loss driven by soil degradation [19, 20].

Conclusion

Eleven years of continuous data confirm that inserting mungbean into the rice-wheat rotation transforms a degrading system into a productive and soil-improving one. System productivity rose by 35.7% in R-W-M while declining 15.1% under R-W. Soil organic carbon increased 43.7%, available nitrogen rose 44.1%, and bulk density improved 7.2% under the three-crop system. The economic advantage of R-W-M reached USD 1,237/ha, more than double that of R-W. These results provide strong evidence that legume inclusion in cereal-dominated rotations is not merely a soil conservation measure but a pathway to sustained and increasing productivity. Wider adoption of R-W-M systems could help reverse the fertility

decline affecting millions of hectares under rice-wheat cultivation.

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