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Research Article

Agronomic Efficiency and Yield Responses to Rainfall and Temperature Variability under Integrated Nutrient Management Practices for Rice-Wheat Cropping

Ajay Kumar Bhardwaj*, Kapil Malik, Bhumija Kaphaliya, Manu Rani and Rajender Kumar Yadav

ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana, India

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****Corresponding author:***

E-mail: ajaykbhardwaj@gmail.com, ak.bhardwaj@icar.gov.in

Abstract

Sustainable rice-wheat production requires nutrient-management strategies that maintain soil fertility and crop productivity while reducing dependence on mineral fertilizers and improving crop responses to climatic variability. A long-term field experiment evaluated the effects of biomass supplementation with an opportunity legume (*Vigna radiata*; LE), green manure (*Sesbania aculeata*; GM), farmyard manure (FYM), wheat straw (WS) and rice straw (RS) under reduced mineral fertilizer inputs in a rice-wheat cropping system. Ten years of weather data were classified into rainfall-deficit and rainfall-excess years and above- and below-average temperature years for rice and wheat separately. Relationships between C return to soil and crop yield and fertilizer-N-use efficiency were evaluated under contrasting climatic conditions. Biomass supplementation substantially increased soil C accumulation and C return. Green manuring recorded the highest soil C stock (3450 ± 270 g m^{-2}), C assimilation (20.6 ± 1.3 t ha^{-1}) and C return (69.9 ± 0.4 t ha^{-1}). Plant-available N was also substantially enhanced by biomass-based management; in rice it reached 231 ± 5 µg cm^{-2} under RS, while in wheat the highest value was 827 µg cm^{-2} under full mineral fertilization. During rainfall-deficit years, several biomass treatments maintained relatively stable grain yield despite increased C return, particularly LE in rice and LE, GM and WS in wheat, indicating greater nutrient sufficiency. Under rainfall-excess conditions, biomass C was more closely associated with crop yield, particularly in wheat. Below-average temperature conditions also favored wheat grain production, whereas above-average temperatures reduced productivity. Long-term biomass supplementation enhanced soil C and nutrient availability and enabled rice-wheat crops to maintain productivity under variable rainfall and temperature conditions with reduced mineral fertilizer inputs, suggesting a strong potential of biomass-based nutrient management to improve nutrient security, fertilizer-N-use efficiency and climate adaptability of intensive rice-wheat systems.

Keywords: Biomass supplementation, climate variability, integrated nutrient management, nitrogen-use efficiency, rice-wheat cropping system

1. Introduction

The sustainability of intensive cereal production increasingly depends on developing nutrient-secure agroecosystems that can maintain crop productivity with lower dependence on mineral fertilizers. Nutrient-secure systems maintain an adequate and readily available nutrient pool through efficient nutrient cycling, biological nutrient inputs and improved soil organic matter, thereby enhancing synchronization between nutrient supply and crop demand. Such systems can reduce external fertilizer requirements, improve nutrient-use efficiency and minimize losses of reactive nitrogen, while potentially increasing the adaptation of agroecosystems to climatic variability. This is particularly important for intensive rice-wheat (R-W) systems, where high and repeated nutrient inputs are required to sustain productivity. Mineral fertilizers have played a central role in increasing agricultural production and food security in India. Asia accounts for the largest share of global fertilizer consumption, with nitrogen constituting a major component of fertilizer use in the region (FAO, 2012). India is among the world's largest fertilizer-consuming countries, although fertilizer use varies considerably among regions (Sharma and Thaker, 2011). Increasing dependence on mineral nitrogen has contributed substantially to crop productivity; however, low nitrogen-use efficiency and losses of reactive nitrogen through volatilization, leaching and gaseous pathways create environmental concerns. Crop-management practices that increase recovery of fertilizer N in crop biomass can substantially reduce the quantity of reactive N escaping from cereal agroecosystems (Cassman *et al.*, 2002). Moreover, increasing N fertilizer application has frequently been associated with enhanced N O emissions from croplands (MacKenzie *et al.*, 1998; McSwiney and Robertson, 2005; Mosier *et al.*, 2006; Halvorson *et al.*, 2008). Thus, the challenge is not simply to increase nutrient inputs, but to maintain crop productivity with greater nutrient-use efficiency and lower dependence on mineral fertilizers.

The R-W cropping system is one of the most important cereal-based production systems of the Indo-Gangetic Plains. Continuous intensive cultivation, however, can deplete soil nutrient pools and organic matter and contribute to declining soil health and resource-use efficiency. These concerns have stimulated interest in integrated nutrient management (INM), in which mineral fertilizers are complemented by organic manures, legumes, green manures and crop residues. Such biomass inputs can provide nutrients while simultaneously increasing carbon inputs and improving soil biological and physical processes. Long-term studies have demonstrated that integrated application of fertilizers and organic sources can enhance soil N and organic carbon stocks, improve N uptake and increase N-use efficiency in rice-wheat systems (Bakht *et al.*, 2009). The contribution of different N sources to cropland nutrient supply also highlights the importance of biological N fixation, animal manures and crop residues in complementing mineral fertilizer inputs (Smil, 1999).

Legumes and green manures are particularly attractive components of nutrient-secure cropping systems because they contribute biologically fixed N and organic matter. Sharma and Behera (2009) reported substantial fertilizer-N savings through *Sesbania aculeata*, cowpea and greengram, including residual N economy in wheat following summer legumes. Similarly, incorporation of legumes in R-W rotations can maintain soil N status (Bakht *et al.*, 2009), while green manure and legume incorporation have been reported to increase rice grain and straw yield and N uptake (Shah *et al.*, 2011). Lauringson *et al.* (2012) further demonstrated the substantial contribution of legume biomass to the return of N, P and K to soil, with effects persisting beyond the year of incorporation. Crop residues and farmyard manure can likewise contribute to nutrient recycling and soil organic matter accumulation. Appropriate accounting of nutrients supplied through organic amendments can therefore permit reductions in mineral fertilizer application without compromising crop yield (Rosa *et al.*, 2016). Residue retention has also been identified as an important component of conservation-oriented nutrient management for reducing fertilizer-N losses and improving resource-use efficiency (Murphy *et al.*, 2016).

However, the performance of a nutrient-management strategy cannot be evaluated independently of the climatic environment in which crops grow. Rainfall and temperature variability are major determinants of crop growth and yield, particularly in R-W systems (Kang *et al.*, 2009). Increasing temperature can accelerate crop development within an optimum range, but temperatures exceeding crop-specific thresholds can impair reproductive development and grain formation. Many regions of Asia are already approaching critical heat-stress limits for rice, making temperature variability an increasingly important determinant of future productivity (IPCC, 2014). Similarly, variability in rainfall affects soil water availability, nutrient mobility and crop water requirements. Changes in precipitation patterns may increase irrigation requirements in water-deficit regions and consequently influence crop water productivity (Kijne *et al.*, 2003). An important but relatively less explored question is whether long-term biomass supplementation can buffer crop productivity against interannual rainfall and temperature variability while permitting a reduction in mineral fertilizer inputs. Biomass incorporation increases carbon return to soil and may improve nutrient availability and soil moisture conditions, potentially creating a more buffered soil environment during periods of climatic stress. However, different biomass sources differ considerably in their quantity and quality of carbon and nutrients returned to soil, and their effects on crop productivity and fertilizer-N efficiency may therefore vary with climatic conditions.

The present long-term experiment provides a unique opportunity to address this issue by comparing 100% mineral fertilization with a 45% reduction in mineral fertilizer inputs supplemented with biomass from an opportunity legume (*Vigna radiata*), green manure (*Sesbania aculeata*), farmyard manure, wheat straw and rice straw. The treatments have generated contrasting carbon stocks, carbon returns, plant-available N and fertilizer-N-use efficiency, providing a basis for evaluating nutrient security under variable weather conditions. The experimental dataset further permits classification of growing seasons into rainfall-deficit and rainfall-excess years and into above- and below-average temperature years, thereby allowing climate sensitivity of crop productivity to be examined under contrasting nutrient-management strategies. Therefore, this study aimed to (i) evaluate the effects of reduced mineral fertilizer inputs supplemented with different biomass sources on rice and wheat productivity and agronomic efficiency; (ii) quantify the relationships between seasonal rainfall and temperature variability and crop yield under contrasting nutrient-management practices; and (iii) determine whether long-term biomass supplementation enhances the resilience of rice-wheat productivity to climatic variability. We hypothesized that partial substitution of mineral fertilizer with biomass-derived nutrients and carbon would maintain or improve agronomic efficiency and crop productivity while reducing the sensitivity of the rice-wheat system to rainfall and temperature variability.

2. Material and Methods

2.1 Experimental design and nutrient-management treatment

A long-term field experiment was conducted to evaluate the effects of reduced mineral fertilizer inputs supplemented with different biomass sources on productivity, nutrient-use efficiency and crop responses to rainfall and temperature variability in a rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) cropping system. The experiment comprised seven nutrient-management treatments arranged in a randomized block design with four replications. Individual plots measured 5 m × 4 m. The treatments represented a gradient from complete absence of external nutrient inputs to full mineral fertilization and partial substitution of mineral fertilizer with different organic and crop-residue sources. The treatments were: (i) no external nutrient input (O); (ii) 100% recommended mineral fertilizer (F); and five biomass-supplemented treatments receiving 55% of the mineral fertilizer used in F, namely (iii) opportunity legume (*Vigna radiata*) biomass (LE), (iv) green manure (*Sesbania aculeata*) (GM), (v) farmyard manure (FYM), (vi) wheat straw (WS), and (vii) rice straw (RS). Thus, the biomass-supplemented treatments represented a 45% reduction in mineral fertilizer inputs relative to the full-fertilizer treatment. The detailed fertilizer rates and biomass sources are presented in Table 1.

The treatment-wise management practices were as follows:.

1. (control): Rice-wheat was grown without inorganic fertilizer or organic nutrient inputs.
2. F (100% mineral fertilizer): Rice followed by wheat received the full recommended rate of inorganic fertilizer. The fertilizer schedule comprised 180, 26, 42 and 7 kg ha^{-1} of N, P, K and Zn, respectively. No organic or crop-residue input was added.
3. LE (opportunity legume): *Vigna radiata* was grown as an opportunity crop during the summer fallow period between wheat harvest and rice establishment. The crop was sown in early April and harvested for pods in early July. The remaining above-ground biomass was

incorporated into the soil before rice transplanting. The rice–wheat system subsequently received 55% of the mineral fertilizer rate used in F, equivalent to 100 kg N, 16 kg P and 28 kg K ha^{-1}.

4. GM (green manure): *Sesbania aculeata* was grown after wheat harvest as a green-manure crop and incorporated into the soil approximately 35-40 days after sowing, before rice establishment. The rice–wheat system received 55% of the mineral fertilizer rate.
5. FYM: Farmyard manure was applied at 10 t ha^{-1} and incorporated into the soil before puddling and rice transplanting. The rice–wheat system received 55% of the mineral fertilizer rate.
6. WS (wheat straw): Approximately 30 cm of standing wheat stubble, corresponding to about one-third of the total wheat straw biomass, was retained in situ after wheat harvest and incorporated into the soil before rice transplanting. The rice–wheat system received 55% of the mineral fertilizer rate.
7. RS (rice straw): Approximately 30 cm of standing rice stubble, corresponding to about one-third of the total rice straw biomass, was retained in situ after rice harvest and incorporated into the soil during wheat establishment in November. The rice–wheat system received 55% of the mineral fertilizer rate.

In brief, FYM was applied at 10 t ha^{-1}; approximately 30 cm of standing wheat and rice stubble, corresponding to about one-third of the respective straw biomass, was retained and incorporated; Vigna radiata above-ground biomass was incorporated before rice transplanting; and Sesbania aculeata was incorporated approximately 35-40 days after sowing, at the time of rice puddling. The biomass-based treatments therefore differed not only in the quantity of carbon returned to soil but also in the nature and timing of nutrient and carbon release. Long-term application of these treatments resulted in substantial differences in soil carbon stock, carbon assimilation and carbon return to the soil.

Table 1: Inorganic and organic input details for treatments.

Treatment	Inorganic Fertilizer (N: P: K: Zn), kg ha^{-1}	Organic Source
O	0	-
F	180: 26: 42: 7	-
LE	100: 16: 28: 0	Moong (*Vigna radiata*)
GM	100: 16: 28: 0	Green Manure (*Sesbaniaesculeata*)
FYM	100: 16: 28: 0	Farmyard manure (FYM)
WS	100: 16: 28: 0	Wheat Straw
RS	100: 16: 28: 0	Paddy Straw

2.2 Crop establishment and management

The annual cropping sequence consisted of rice during the summer season from July to October, followed by wheat during the winter season from November to April. Dry ploughing was performed during the last week of June, followed by puddling under flooded conditions for rice establishment. Thirty-day-old nursery-raised seedlings of rice cv. Pusa 44 were transplanted during the first week of July. A minimum water depth of approximately 10 cm was maintained during the first month after transplanting. Rice was harvested during the last week of October. For wheat establishment, the soil was dry-tilled using a power tiller, and wheat cv. HD 2967 was sown during the second week of November. Three to four surface irrigations were applied at approximately one-month intervals depending on crop requirement. During the second and third months of wheat growth, irrigation was managed to maintain soil saturation without standing water. Irrigation was discontinued approximately two weeks before wheat harvest. Wheat was harvested during the last week of March. In both rice and wheat, nitrogen was supplied through urea in three equal splits at 0, 21 and 42 days after transplanting in rice and after sowing in wheat. Phosphorus and potassium were supplied through diammonium phosphate (DAP) and muriate of potash (MOP), respectively, and were applied at crop establishment. Zinc sulphate ($ZnSO_4$) was applied only in the F treatment. The treatment-wise fertilizer application rates are presented in Table 1.

2.3 Characterisation of rainfall and temperature variability

Historical weather data covering the experimental period were used to characterise interannual variability in rainfall and temperature separately for the rice and wheat growing seasons. Years were classified according to seasonal rainfall as rainfall-deficit or rainfall-excess years and according to temperature as below- or above-average temperature years. For rice, rainfall and temperature during July, August and September were considered because these months represented the principal growing period. For wheat, rainfall and temperature during December, January, February and March were considered. Seasonal values for each year were compared with the corresponding long-term seasonal average to classify years according to rainfall and temperature conditions. The resulting segregation of years into contrasting rainfall and temperature categories is presented in Fig. 1. This classification enabled assessment of whether crop productivity and nutrient-use efficiency under the different nutrient-management treatments responded differently under contrasting climatic environments.

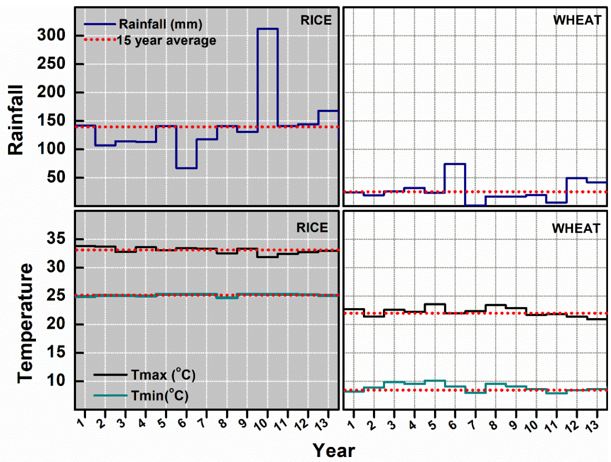

Fig. 1. Details of rainfall (mm) and temperature during the study period (yearly)and their segregation based on the last 15-year average.

2.4 Soil bulk density and carbon stock

Soil bulk density was determined using a metallic core of known volume. Soil samples were collected from 0-15, 15-30 and 30-60 cm depths. The samples were oven-dried at 105 °C for 24 h, and bulk density was calculated as the ratio of oven-dry soil mass to core volume following Blake and Hartge (1986):

BD= frac{W}/{V} (i)

where BD is soil bulk density (g cm^{-3}), W is the oven-dry mass of soil (g), and V is the volume of the sampling core (cm^3).

Soil carbon stock was calculated following the approach of Batjes (1996), using soil organic carbon concentration, bulk density and soil-layer thickness. Carbon stock for each soil layer was calculated as:

C stock in soil = C content x Bulk density x Depth (ii)

where C content is expressed as g C g^{-1} soil, bulk density as Mg m^{-3} and soil depth as m. Carbon stocks were summed across the 0-60 cm soil profile to obtain total soil C stock.

2.5 Agronomic efficiency and fertilizer nitrogen-use efficiency

Fertilizer nitrogen-use efficiency was evaluated using agronomic efficiency (AE), following Fageria *et al.* (2012). Agronomic efficiency represents the additional crop production obtained per unit of nutrient applied and was calculated as:

$$AE=(G_f-G_u)/N_a \quad \text{(iii)}$$

where G_f is the grain yield of the fertilized/managed plot (t ha^{-1}), G_u is the grain yield of the unfertilized plot (O in t ha^{-1}), and N_a is the quantity of nutrient applied (t ha^{-1}).

2.6 Grain yield, biomass production, carbon assimilation and carbon return

Grain yield was determined from harvested crop biomass and expressed on a dry-weight basis. At harvest, crop plants were sampled from multiple 1 m^2 areas within each treatment plot. The samples were separated into grain and straw fractions, oven-dried at 60 °C for at least 48 h, and weighed. Annual crop biological yield was determined from the harvested plot biomass using a field combine, and grain yield was expressed in t ha ^{1} on a dry-weight basis. Plant carbon assimilation was estimated from above- and below-ground biomass produced by the rice–wheat system. Biomass sampling and processing followed the procedure described above. Carbon return to soil was estimated annually from the carbon contained in crop residues and other biomass returned to the soil through the respective management practices, including opportunity legume biomass, green manure, FYM, wheat stubble and rice stubble. The long-term treatments resulted in distinct amounts of carbon returned to the soil, which were subsequently related to crop yield and fertilizer-N-use efficiency under contrasting weather conditions.

2.7 Measurement of plant-available nitrogen

Plant-available nitrogen during the crop-growing season was assessed using ion-exchange resin (IER) membranes as an indicator of soil N availability and net mineralization. Commercially available cation- and anion-exchange resin sheets (General Electric, Watertown, MA, USA) were cut into strips measuring 2.5 × 10 cm. The resin strips were conditioned by immersion and stirring in 0.5 mol L^{-1} HCl for 1.2 h, followed by immersion and stirring in 0.5 mol L^{-1} $NaHCO_3$ for 5 h. The strips were subsequently rinsed with deionized water. Vertical slots were made in the soil, and conditioned resin strips were inserted so that they maintained direct contact with the soil. Cation- and anion-exchange strips were positioned approximately 5 cm apart and left in the soil for 15 days. After each 15-day period, the resin strips were removed and replaced with freshly conditioned strips. This procedure was repeated throughout the crop-growing season. After removal, the resin strips were thoroughly rinsed with deionized water to remove adhering soil particles and transferred to vials for laboratory extraction. Ammonium-N and nitrate-N adsorbed by the resin were extracted using 70 mL of 2 mol L^{-1} KCl. The vials were agitated for 1 h, after which the extract was decanted into scintillation vials. NH_4^+-N and NO_3^--N concentrations were determined using a Kjeltec 2200 analyzer (Foss, Hillerød, Denmark). The treatment effects on plant-available N are presented in Fig. 6.

2.8 Soil temperature and volumetric water content

Soil temperature was measured using a digital soil-temperature probe inserted vertically into the soil at a predetermined depth. Measurements were taken at the same time of day on each sampling date to minimize the influence of diurnal temperature variation, and values were expressed in °C. Soil volumetric water content (VWC) was determined using a TDR probe and meter (Acclima, SDI-12).

3. Results

3.1 Rainfall and temperature variability

Marked interannual variability in rainfall and temperature was observed during both rice and wheat seasons (Fig. 1). The mean seasonal rainfall was 139.7 mm day^{-1} for rice and 28.2 mm day^{-1} for wheat. During the 2005-2014 period, six rice years were classified as rainfall-excess and four as rainfall-deficit years, whereas wheat experienced four rainfall-excess and six rainfall-deficit years. The mean maximum temperature during the wheat season was 22.1 °C and mean minimum temperature was 8.9 °C. Rice maximum temperature averaged 33.1 °C, with four years classified as above-average and five as below-average maximum-temperature years. These contrasting climatic years provided a basis for evaluating treatment responses to rainfall and temperature variability.

3.2 Soil carbon stock and carbon return

Long-term biomass supplementation substantially increased soil carbon accumulation and carbon return compared with the control and mineral fertilizer alone (Table 2). Soil C stock in the 0-60 cm profile increased from 2764 g m^{-2} in the control to 3101 g m^{-2} under full mineral fertilization and reached a maximum of 3450 g m^{-2} under green manuring (GM). Carbon return showed an even greater treatment effect, increasing from only 6.9 t ha^{-1} in the control and 18 t ha^{-1} under F to 69.9 and 41.6 t ha^{-1} under GM and LE, respectively.

Carbon assimilation was also considerably greater under biomass-based management, with the highest value under GM (20.6 t ha^{-1}) compared with 15.5 t ha^{-1} under F and 6.1 t ha^{-1} under the control. Mean bulk density was lowest under LE (1.6 g cm^{-3}) and highest under the control (1.71 g cm^{-3}).

3.3 Carbon return and grain yield under rainfall variability

The relationship between C return and grain yield varied with rainfall conditions and nutrient-management treatment (Fig. 2). During rainfall-deficit years, rice grain yield was strongly and positively associated with C return under FYM, WS and RS, with Pearson's r values of 0.92, 0.91 and 0.82, respectively, whereas LE showed virtually no relationship. In wheat, FYM and F showed strong positive relationships during rainfall-deficit years ($r = 0.86$ and 0.84), while responses under LE, WS and RS were negative.

During rainfall-excess years, grain yield generally increased with C return, particularly in wheat, where strong relationships were observed under F, WS and FYM ($r = 0.96$, 0.99 and 0.86, respectively).

Table 2: Effect of management practices on the carbon (C) stock (0-60 cm), C-assimilated, C-returned and soil bulk density.

Treatment	C Stock (g m^{-2})	C Assimilated (t ha^{-1})	C Return (t ha^{-1})	Soil bulk density (g cm^{-3})
O	2764±243	6.1±0.5	6.9±0.1	1.7±0.01
F	3101±279	15.5±1.2	18.0±0.2	1.7±0.04
LE	3253±321	17.8±1.5	41.6±0.3	1.6±0.08
GM	3450±270	20.6±1.3	69.9±0.4	1.6±0.09
FYM	3362±288	13.4±1.4	26.7±0.2	1.7±0.03
WS	3285±303	12.9±1.2	29.2±0.4	1.7±0.04
RS	3202±224	12.8±1.3	22.6±0.2	1.7±0.08

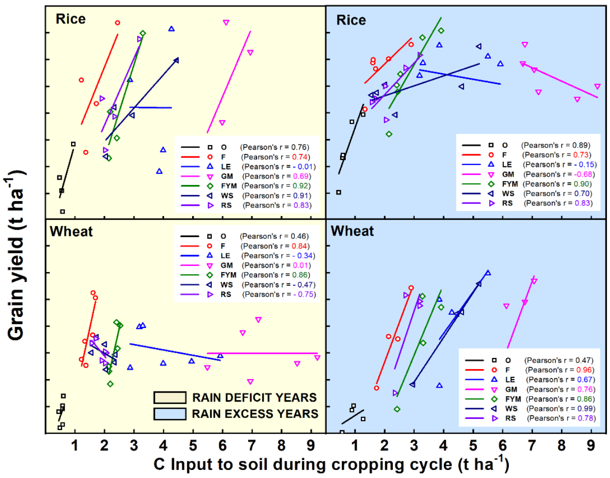

Fig. 2. Correlation between carbon input to soil and grain yield in rice and wheat during rainfall deficit and excess years.

3.4 Carbon return and straw yield

Straw yield also responded differently to C return under contrasting rainfall conditions (Fig. 3). Rice generally showed positive associations between C return and straw yield during rainfall-deficit years, whereas LE showed a negative response under rainfall-excess conditions (r = −0.73). In wheat, C return was generally positively associated with straw yield during rainfall-excess years, although LE and RS showed weak or negative responses.

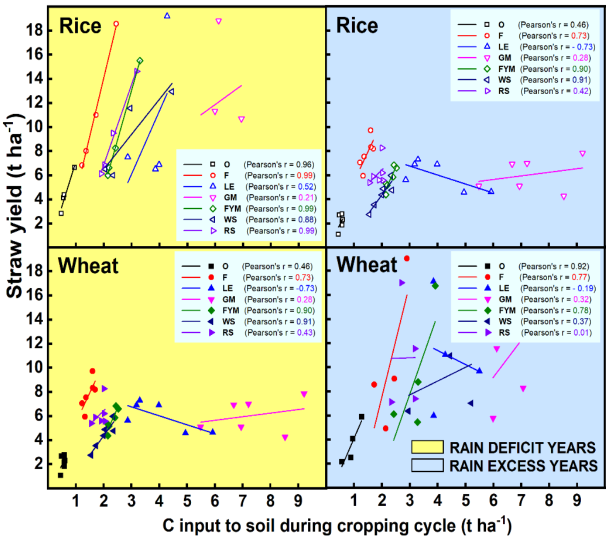

Fig. 3. Correlation between carbon input to soil and straw yield in rice and wheat during rainfall deficit and excess years.

3.5 Carbon return and yield under temperature variability

Temperature conditions modified the relationship between C return and grain yield (Figs. 4 and 5). In rice, most treatments showed positive relationships during both above- and below-average maximum-temperature years, with LE being the major exception. In wheat, all treatments except WS showed positive relationships during above-average maximum-temperature years, whereas all treatments showed positive relationships under below-average maximum temperature.

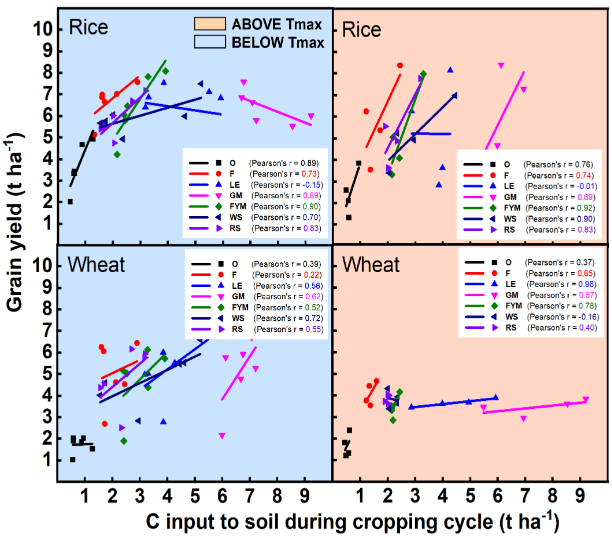

Fig. 4: Correlation between carbon input to soil and grain yield in rice and wheat,below and above average-maximum-temperature-years.

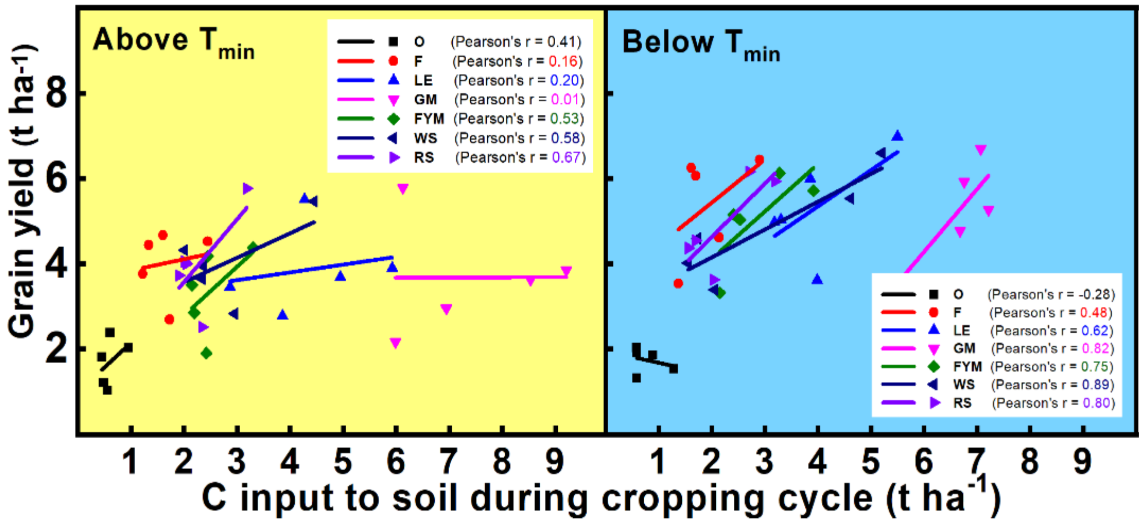

Fig. 5. Correlation between carbon input to soil and grain yield in wheat in above and below average-minimum-temperature years.

Minimum temperature had a particularly clear effect on wheat productivity. Grain yield was consistently higher during below-average minimum-temperature years than during above-average minimum-temperature years across the nutrient-management treatments.

3.6 Plant-available nitrogen

Long-term nutrient management substantially increased plant-available N relative to the unfertilized control (Fig. 6). In rice, available N increased from 112.92 µg cm^{-2} under the control to approximately 217-231 µg cm^{-2} across the biomass and fertilizer treatments. In wheat, the control recorded 433.44 µg cm^{-2} compared with 827.05 µg cm^{-2} under F; the biomass-supplemented treatments ranged from 512.43 µg cm^{-2} under WS to 719.17 µg cm^{-2} under GM. Thus, the treatments receiving reduced mineral fertilizer maintained substantially greater plant-available N than the unfertilized control, despite receiving only 100 kg N ha^{-1} compared with 180 kg N ha^{-1} under F.

3.7 Carbon return and fertilizer-N-use efficiency

Fertilizer-N-use efficiency showed treatment-specific relationships with C return (Fig. 7). In wheat, particularly strong positive relationships were observed under WS ($r = 0.89$) and FYM ($r = 0.72$), while F and RS showed weaker positive relationships. In rice, positive responses were observed under FYM and RS, whereas LE showed a weak negative relationship and F and GM showed little association. These results indicate that the effect of biomass-derived C on fertilizer-N-use efficiency depended on both crop and biomass source rather than increasing uniformly with C input.

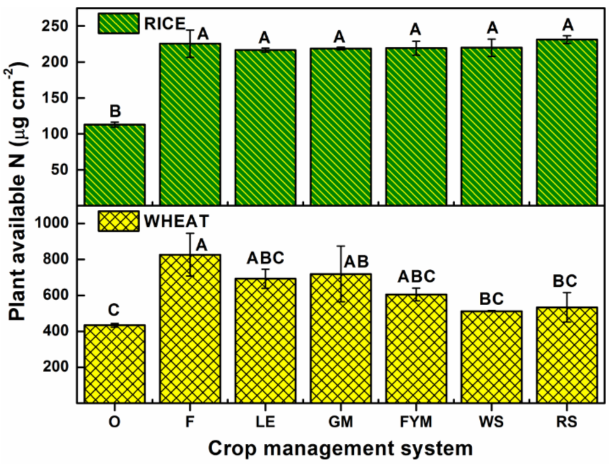

Fig. 6: Effect of crop management systems on plant-available N.

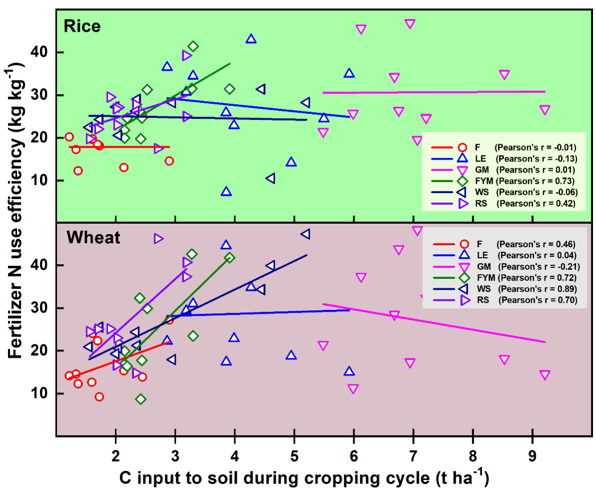

Fig. 7. Effect of C input to soil on fertilizer nitrogen use efficiency in rice and wheat during a one-decade experimental period.

4. Discussion

4.1 Biomass supplementation strengthened nutrient security and soil carbon storage

The results demonstrate that long-term biomass supplementation substantially altered the soil C and nutrient environment of the rice–wheat system. Despite receiving only 100 kg N ha^{-1} compared with 180 kg N ha ^{1} under full mineral fertilization, the LE, GM, FYM, WS and RS treatments maintained considerably greater plant-available N than the unfertilized control. This indicates that the reduced mineral fertilizer inputs were effectively complemented by nutrient release from biomass and associated improvements in soil nutrient cycling. Integrated N management has been recognized as an important strategy for improving fertilizer-use efficiency while maintaining soil fertility (Fageria and Baligar, 2005).

The particularly high C return under GM and LE provides a strong explanation for their nutrient-secure behavior. Over the experimental period, GM returned approximately 70 t C ha^{-1} to the soil, compared with 41.7 t C ha^{-1} under LE and only 18.0 t C ha^{-1} under full mineral fertilization. Legumes are particularly valuable organic-matter sources because of their relatively high N concentration and biological N fixation capacity (Ashraf *et al.*, 2004). Previous studies have similarly demonstrated greater nutrient return and residual benefits from legume and green-manure incorporation in cereal systems (Sharma and Behera, 2009; Bakht *et al.*, 2009; Shah *et al.*, 2011; Lauringson *et al.*, 2012). Greater C input was also reflected in higher soil C stocks and lower bulk density. GM recorded the highest soil C stock, while LE recorded the lowest bulk density. Residue incorporation can increase soil organic C and improve aggregation, microbial activity and other soil physical properties (Roldán *et al.*, 2003). Similar reductions in bulk density following residue incorporation have been reported by Surekha *et al.* (2003). The improvement in soil C status therefore represents an important pathway through which biomass supplementation can enhance the long-term nutrient-buffering capacity of the rice-wheat system.

4.2 Biomass inputs buffered crop productivity under rainfall variability

The response of grain yield to C return varied considerably with rainfall conditions, indicating that the benefits of biomass inputs cannot be interpreted independently of soil moisture. In rice during rainfall-deficit years, strong positive relationships between C return and grain yield were observed particularly under FYM, WS and RS, whereas LE showed almost no relationship. The latter response, together with its relatively high C return and sustained yield, suggests that the LE system had reached a relatively nutrient-secure state in which additional C input did not proportionately increase grain production. A similar pattern was evident for GM under rainfall-excess conditions. Biomass incorporation can improve crop performance under water-limited conditions by increasing soil organic matter, improving soil structure and enhancing water and nutrient retention. Crop residues can also support arbuscular mycorrhizal associations, which contribute to nutrient acquisition and plant water relations (Garg and Chandel, 2010). Improvements in soil organic C following residue incorporation (Brar *et al.*, 2013) and the role of residue management in improving crop performance under variable moisture conditions (Sharma *et al.*, 2011; Singh and Sidhu, 2014) provide support for this mechanism.

The wheat response was more sensitive to rainfall conditions than rice. Under rainfall-deficit conditions, LE, WS and RS showed negative relationships between C return and grain yield, whereas FYM and full fertilization showed strong positive relationships. In contrast, during rainfall-excess years, grain yield increased with C return across all treatments, with particularly strong relationships under WS, F and FYM. This contrast is consistent with the role of water in decomposition and nutrient release from residues. Adequate moisture accelerates decomposition, mineralization and nutrient availability, whereas moisture limitation can restrict microbial activity and residue decomposition (Schomberg *et al.*, 1994; Yadvinder-Singh *et al.*, 2005). Thus, the effectiveness of residue-based nutrient management depends not only on the quantity of biomass returned but also on the climatic environment controlling its decomposition.

4.3 Temperature variability imposed an additional constraint on wheat productivity

Temperature variability produced a particularly clear response in wheat. Grain production was generally greater during below-average maximum-temperature years than during above-average maximum-temperature years. The wheat growing season in below-average Tmax years was within approximately 20.7-22.0 °C, close to the reported favorable temperature range for anthesis and grain filling, whereas above-average Tmax years exceeded 22 °C. Wheat is particularly sensitive to temperature during reproductive development, and temperatures above the optimum can accelerate phenological development and reduce grain filling (Farooq *et al.*, 2011; Mullarkey and Jones, 2000; Tewolde *et al.*, 2006). The adverse effect of above-average temperature was probably amplified by rainfall deficit because several above-Tmax years also coincided with rainfall-deficit years. Temperature and moisture jointly regulate decomposition and nutrient cycling; consequently, the combination of higher temperature and lower moisture can restrict the biological processes responsible for releasing nutrients from crop residues. Residue decomposition is controlled by temperature, moisture and residue quality (Yadvinder-Singh *et al.*, 2005), while inadequate soil moisture can markedly reduce microbial activity and C mineralization (Doel *et al.*, 1990; Sommers *et al.*, 1981).

Importantly, all biomass and mineral-fertilizer treatments maintained higher wheat yield than the unfertilized control even under adverse temperature conditions. This indicates that maintaining a biologically active and nutrient-rich soil through biomass supplementation can partially buffer the yield penalty associated with climatic stress. The response therefore supports the potential of integrated nutrient management as a component of climate-resilient cereal production. Minimum temperature also influenced wheat productivity. Grain production was consistently higher during below-average Tmin years than during above-average Tmin years. The mean minimum temperature of approximately 8.9 °C during the favorable years was close to the optimum range reported for wheat grain development (Porter and Gawith, 1999). Thus, relatively small departures from the favorable thermal range can influence wheat productivity, particularly when combined with water limitation.

4.4 Carbon input enhanced fertilizer-N-use efficiency, but the response depended on biomass source

The relationship between C return and fertilizer-N-use efficiency provides an important explanation for why reduced mineral fertilizer inputs could be sustained in the biomass treatments. In wheat, strong positive relationships between C return and fertilizer-N-use efficiency were observed under WS and FYM, whereas LE and GM showed weak or negligible relationships. The latter response is consistent with their relatively high nutrient supply and C return: once the crop system becomes sufficiently nutrient secure, additional C input may no longer translate proportionately into greater fertilizer-N-use efficiency. The positive response under FYM, WS and RS suggests that C inputs from these sources were associated with improved efficiency of the mineral N applied to the system. Improved synchronization between nutrient release and crop demand is a central principle of integrated nutrient management (Fageria and Baligar, 2005). In the present experiment, the biomass treatments received approximately 45% less mineral N than F while maintaining substantially higher available N than the control. This indicates that mineral fertilizer reduction was compensated, at least partly, by biological nutrient cycling and nutrient release from organic resources.

The treatment-specific response is important because it demonstrates that increasing C input alone does not guarantee a proportional increase in N-use efficiency. The quality, decomposability and nutrient composition of the biomass source, together with crop and weather conditions, determine the extent to which additional C contributes to nutrient availability and crop production. Improved N-use efficiency has implications beyond productivity. Greater recovery of applied N can reduce the amount of reactive N susceptible to loss from agricultural systems and thereby contribute to lower environmental N loading and potentially lower N O emissions (Cassman *et al.*, 2002; Kanter *et al.*, 2016). Thus, replacing part of the mineral fertilizer requirement with biologically derived nutrient and C inputs may provide simultaneous agronomic and environmental benefits.

4.5 Implications for climate-resilient rice–wheat production

The combined responses of soil C, available N, crop yield and fertilizer-N-use efficiency indicate that biomass supplementation created a more buffered nutrient environment than either the unfertilized control or mineral fertilizer alone. The particularly high C return under GM and LE, together with their relatively stable yield responses across contrasting environments, suggests that legume-based nutrient management can move the rice–wheat system toward greater nutrient security.

Previous long-term studies have likewise demonstrated the benefits of legumes, green manures and crop residues for maintaining soil fertility and productivity in cereal-based systems (Bakht *et al.*, 2009; Sharma and Behera, 2009; Shah *et al.*, 2011). However, the results also demonstrate that climate resilience is not synonymous with consistently higher C return or higher mean yield. The response depended on the interaction among C input, biomass quality, rainfall and temperature. Under rainfall-excess conditions, increased moisture generally strengthened the relationship between C return and crop production, probably by facilitating residue decomposition and nutrient release. Under rainfall-deficit and above-temperature conditions, some biomass sources maintained crop yield despite weaker relationships between C return and yield, indicating that the system had sufficient internal nutrient reserves.

Therefore, the principal contribution of long-term biomass supplementation was not simply an increase in soil C or crop yield, but the development of a nutrient-buffered production system capable of maintaining productivity with substantially lower mineral fertilizer inputs. This is particularly relevant for intensive rice–wheat systems, where improving N-use efficiency while reducing reactive N losses is essential for sustainable intensification. Overall, the findings support the use of opportunity legumes, green manures, FYM and crop-residue retention as complementary components of reduced-fertilizer nutrient management. Among these, GM and LE were particularly effective in building soil C and returning biomass-derived C to the system, whereas FYM, WS and RS showed strong associations between C return and fertilizer-N-use efficiency under specific environmental conditions. The results therefore suggest that strategic biomass supplementation can enable substantial mineral fertilizer reduction while maintaining nutrient availability and improving the capacity of rice–wheat systems to cope with rainfall and temperature variability.

5. Conclusion

Long-term biomass supplementation demonstrated strong potential to support a 45% reduction in mineral N input in the rice-wheat system while maintaining crop productivity and nutrient availability relative to 100% mineral fertilization. The biomass-based treatments differed in their capacity to supply C and nutrients, with green manure (*Sesbania aculeata*) and the opportunity legume (*Vigna radiata*) contributing particularly high C inputs and soil C accumulation. The response of crop yield and fertilizer-N-use efficiency to C input varied with biomass source and climatic conditions. Under rainfall deficit and temperature stress, several biomass-based treatments maintained stable crop performance, whereas under favorable moisture conditions, greater C return was more closely associated with yield and N-use efficiency. These responses indicate that the effectiveness of reduced-fertilizer strategies depends on both the quality of the biomass resource and the prevailing climatic environment. Long-term integration of organic resources and crop residues with reduced mineral fertilizer inputs can improve nutrient security, enhance fertilizer-N-use efficiency and strengthen the adaptability of rice-wheat production to rainfall and temperature variability. Among the evaluated options, legume and green-manure-based systems showed particular promise for building soil C and sustaining productivity with lower dependence on mineral fertilizer.

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Conflict of interest statement

The authors declare no competing financial or academic interests. The funding agency had no involvement in the study design, data collection and analysis, or the preparation of the manuscript.

Author contributions

Conceptualization of the experiments was carried out by AKB. Data collection, data analysis, visualization preparation, and drafting of the original manuscript were performed by BK, KP, and MR. RKY provided support in conceptualization, manuscript review and editing. All authors contributed to the writing of the manuscript, critically reviewed the draft, and approved the final version.

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