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Legume-based rotation enhances subsequent wheat yield and maintains soil carbon storage

Chunyan Liu¹ · Ximei Feng¹ · Yi Xu¹ · Amit Kumar² · Zhengjun Yan¹ · Jie Zhou¹ · Yadong Yang¹ · Leanne Peixoto³ · Zhaohai Zeng^{1,4,5} · Huadong Zang^{1,4,5}

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Abstract

Legume inclusion into cropping systems has been proposed to maintain high crop yields while offering multiple environmental benefits. However, the effect of legumes as pre-crop on subsequent wheat yield and soil has not been well explored. Thus, a 7-year field experiment was used to determine the interactive effects of mineral fertilization and legumes (peanut, mung bean, soybean, adzuki bean) inclusion on wheat productivity and soil quality. Our results showed that legume inclusion led to a higher wheat yield advantage (52% on average) than maize–wheat rotation under no fertilization but the advantage decreased to 26% with fertilization. All legume–wheat rotation systems supported stable wheat production, where a stronger effect was observed after peanut than after maize. Meanwhile, the wheat yield under legume–wheat systems was more resistant (i.e., less variability in the yield after ceasing fertilization) and more resilient (i.e., recovering more quickly after fertilizer re-application) relative to maize-wheat. Furthermore, soil ecosystem multifunctionality increased by 0.8 times in the topsoil while maintaining soil organic carbon stocks, even with low C and N inputs under legume–wheat. Interestingly, we also observed a positive correlation between wheat yield and soil ecosystem multifunctionality. In conclusion, legume inclusion as a sustainable practice can optimize crop yields by enhancing soil multifunctionality while maintaining soil organic carbon stocks, particularly for integration into low-yielding agroecosystems.

Keywords Cropping system · Fertilization · Crop productivity · Yield stability · Soil ecosystem multifunctionality

1 Introduction

Enhancing the biodiversity of cropping systems is imperative for promoting ecosystem services, thereby maintaining or increasing crop yields while reducing dependency on external inputs (German et al. 2017; Zhao et al. 2022).

Diversification via the inclusion of legumes is a key strategy for sustainable agriculture (Leoni et al. 2022; Notz et al. 2023). This results from their capacity to provide extensive ecosystem services which are pivotal for food production, soil fertility, greenhouse gas mitigation, and weed and pest control (Schwenke et al. 2015; Rebolledo-Leiva et al. 2022). A global meta-analysis has shown that the inclusion of legumes increased the main crop yield by 20% as compared to non-legume cropping systems (Zhao et al. 2022). However, the effects of the identity of legume species as a pre-crop on soil quality and the productivity and stability of subsequent crops are not conclusive, especially under field conditions.

The legacy effect of legumes in rotation strongly depends on the specific legume species, soil fertility, and management (Luce et al. 2015; Li et al. 2015). The legume species specifically affects the biological nitrogen (N) fixation and crop residue input, which further influence the subsequent crop growth (Smith & Chalk 2020; Zhang et al. 2022; Zhao et al. 2022). In a legume–wheat

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cropping experiment, the inclusion of peas indicated far superior rhizobial nitrogen fixation than that of lentils and chickpeas. In the Northern Great Plains of North America, wheat yield benefits caused by preceding legumes varied widely, up to 35% (Gan et al. 2015). In contrast, Kumar et al. (2021) found no effects of legume-based monocultures and intercropping on the subsequent barley productivity. These discrepancies in results may also be due to various reasons including climatic conditions and soil fertility (Preissel et al. 2015; Uzoh et al. 2019). However, the interactive effect of legume species and N fertilization on subsequent cereal yield was rarely evaluated.

Enhancing the stability of crop yield under climate change has emerged as a vital issue for agricultural sustainability (Knapp and van der Heijden 2018; Liu et al. 2019). Recently, several indices have been proposed to assess the sustainability of ecosystems, especially under changing environmental conditions, such as stability, resistance, and resilience (Lin 2011; Urruty et al. 2016). The relationship between coefficient of variation and average yield is often used to assess the static stability of crop yield (Raseduzzaman and Jensen 2017; Urruty et al. 2016). Yield stability is the crop's capacity to perform consistently well across changing environmental conditions and management practices at the same site (Chen et al. 2022). Resilience, on the other hand, is defined as the propensity of system to retain its productivity after a perturbation, and it is related to the self-regulation ability (Holling 1973). A resilient agroecosystem will continue to provide vital services such as stabilizing crop productivity under environmental pressures (Lin 2011). The stability of an ecosystem is a concept that has been defined and discussed as an important characteristic in state and transition models, and greater ecosystem stability is related to greater resistance and resilience to a disturbance factor (Liu et al. 2022). However, our understanding of yield stability and resilience under legume-based cropping remains incomplete.

Soil organic carbon (SOC) and nutrient cycling potential as key components of soil quality are closely linked with soil functioning (Bünemann et al. 2018; Garland et al. 2021). SOC is recognized as vital for the delivery of multiple ecosystem functions, which influences multiple soil-based ecosystem services, and as such recognized as one of the most common metrics for assessing soil quality (Krause et al. 2022). Growing legumes not only enhances soil nitrogen (N) via biological N fixation and crop residue return but also benefits soil C stocks due to high-quality residue input (Lal 2017). For example, legume-based rotation system increased SOC and N in soil aggregates by 9% and 12% after 6 years, respectively (Zhang et al. 2019). Moreover, soil ecosystem multifunctionality is increasingly applied in agroecosystems to quantitatively assess the nutrient cycling potential (Allan et al. 2015). Soil enzyme

activities as sensitive indicators of ecosystem-level functional potential directly mediate soil biochemical processes and strongly influence soil quality (Sinsabaugh et al. 2008; Zhou et al. 2021). Fundamental to the soil ecosystem multifunctionality approach is knowledge of the enzymes that catalyze the reactions in soil nutrient cycling (Ma et al. 2022; Nannipieri et al. 2012). Further, fertilization could strongly alter the diversity and community composition of soil microorganisms and in turn influence soil enzyme activity (Kumar et al. 2018; Kumar and Pausch 2022). Although legume-based rotation systems have been shown to improve soil fertility and environmental benefit (Yan et al. 2022), relatively less is known regarding the extent to which legume-based cropping affects SOC and soil ecosystem multifunctionality and the relationship between crop productivity and soil quality.

The North China Plain is one of the major cereal-producing areas in China, which produces more than 30% and 60% of the national maize and wheat, respectively (Luo et al. 2018). Summer maize–winter wheat double cropping is the predominant cropping system in this region (Wang et al. 2020; Zhang et al. 2022). However, soil degradation constrains crop yields due to intensive crop production and overuse of mineral fertilizer (Nie et al. 2022; Yin et al. 2021). Therefore, we set up a 7-year field experiment to assess the impact of including legumes on the subsequent wheat yield and stability, as well as on soil quality. In this study, we hypothesized that not only wheat yield and SOC stock are improved, but also the yield stability and soil ecosystem multifunctionality are higher in crop rotation that includes legumes. We aimed to (1) estimate the interactions between the legume pre-crop and fertilization on wheat productivity and stability; (2) assess the effects of fertilizer application on moderating the benefit of legumes on wheat productivity; and (3) determine the effect of legume-wheat cropping on soil quality in the topsoil and subsoil.

2 Materials and methods

2.1 Study sites

The study was conducted at the Wuqiao Experimental Station of China Agricultural University (37° 41' N, 116° 36' E), Hebei Province, China, with a mean annual temperature of 14.3 °C and precipitation of 552 mm. At the start of the experiment in 2016, the soil texture within the top 20 cm was a loamy mollisol developed on an alluvial plain with pH (H₂O, 1:2.5) of 8.0, SOC of 9.3 g kg⁻¹, total nitrogen of 1.0 g kg⁻¹, available phosphorus of 20.3 mg kg⁻¹, and available potassium of 87.5 mg kg⁻¹ (Wang et al. 2021).

2.2 Experimental design and crop management

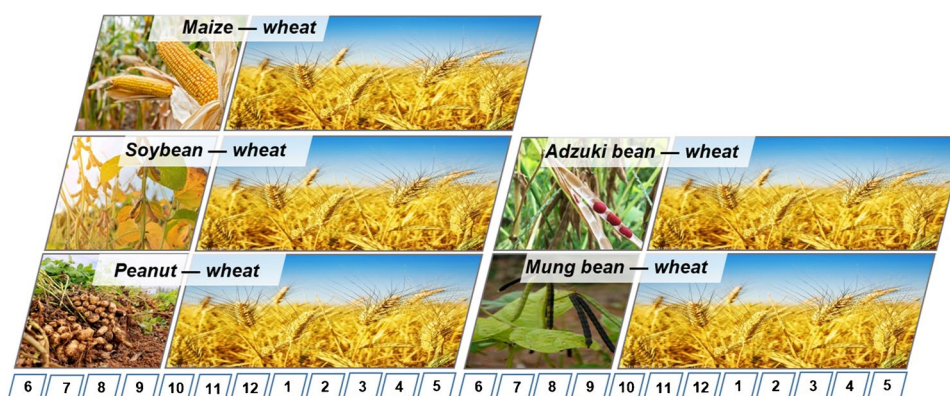
Long-term maize (*Zea mays* L.; Zhengdan 958)—wheat (*Triticum aestivum* L.; Jimai 22)—a double-cropping field—was established for this study. Peanut (*Arachis hypogaea* L.; Yuhua 9719), mung bean (*Vigna radiata* L.; Bailv 8), soybean (*Glycine max* L.; Zhonghuang 35), and adzuki bean (*Vigna angularis* L.; Baihong 7) were included to examine the pre-crop benefit of rotation system in this region. Therefore, the field experiment (since 2016) was initiated with five rotation systems: (1) the control with maize–wheat (maize-W; MW); (2) peanut–wheat (peanut-W; PW); (3) mung bean–wheat (mung bean-W; BW); (4) soybean–winter wheat (soybean-W; SW); and (5) adzuki bean–wheat (adzuki bean-W; AW). The crop rotation sequence can be found in Fig. 1. The field experiment used a split-plot design with three replicates (plot size of 8 m × 6.5 m). Fertilizer was only applied since 2019 to avoid confounding effects of previously applied fertilizers. The main plots consisted of two fertilization treatments: with (+ F) and without fertilizer (– F) application, while the subplot represented the five-rotation system. For the fertilized plots, 158.4 kg N ha⁻¹ year⁻¹, 138 kg P₂O₅ ha⁻¹ year⁻¹, and 112.5 kg K₂O ha⁻¹ year⁻¹ were applied to wheat. 179.7 kg N ha⁻¹ year⁻¹, 103.5 kg P₂O₅ ha⁻¹ year⁻¹, and 112.5 kg K₂O ha⁻¹ year⁻¹ were applied to maize. Only 60 kg N ha⁻¹ year⁻¹ were applied to the four legumes, and the amount of P₂O₅ and K₂O applied was consistent with maize. The full rate of fertilizer used was a basal application before planting.

Wheat was sown 15 cm rows apart in mid-October. Maize was sown in mid-June with 22-cm plant distance in each row and 60-cm row spacing. Four legumes were sown in mid-June with 15-cm plant distance in each row and 40-cm row space. For all crops, only the grains were harvested, and the remaining residues were retained on the field. Specifically, rotary tillage was implemented for the legume–wheat rotation, in which residues were crushed and returned to the field. Additionally, no-till was implemented for the maize–wheat rotation, in which residues were crushed and applied to the soil surface. Irrigation, pest control, and other agronomic practices were applied based on normal local practice.

2.3 Plant and soil sampling and analysis

Yield, aboveground biomass, and harvest index of wheat and maize were collected from an area of 2 m² (2 sites × 1 m width × 1 m length) in each plot, respectively. Five 1-m rows of four legume crops were selected for yield reporting. The aboveground parts of all crops were cut and then air-dried to reach a constant weight. The harvest index was calculated as the ratio of wheat yield (WY) to aboveground biomass (AGB). For wheat, the ear number per square meter was counted from two 1-m² sites in each plot, and the grain number per ear was determined from 40 random plants in each plot. The 1000-grain weight was measured by taking 1000 kernels with six replicates from each yield-measured sample and weighing them.

Fig. 1 The picture showed the cropping sequence of five rotation systems in the North China Plain: peanut–wheat, soybean–wheat, adzuki bean–wheat, mung bean–wheat, and conventional maize–wheat. Numbers represent the growing months.



Bulk soil samples were taken from three depth intervals (i.e., 0–20, 20–40, and 40–60 cm) using a soil auger (3-cm diameter) in 2021. From each of the three replicates, three subsamples were collected to form a composite soil sample and then sieved (< 2 mm) to remove visible plant and organic debris. One part of the soil sample was stored at 4 °C refrigerator for the analysis of soil enzymatic activity, and the other part was air-dried and sieved (< 0.15 mm) for the determination of SOC and total nitrogen (TN). In addition, the bulk density of each depth interval was determined by the volumetric ring method (Li et al. 2014).

2.4 Calculation and statistical analyses

2.4.1 Wheat productivity stability

The wheat yield was used to evaluate the legacy effect of pre-crops. The wheat yield static stability (S_i) across various cropping systems was determined based on the coefficient of variation (Knapp and van der Heijden 2018; Chen et al. 2022). The yield sustainability was calculated based on the sustainable yield index (SYI) (Singh et al. 1996) as follows:

$$S_i = \frac{SD_i}{\text{Mean}_i} \quad (1)$$

$$\text{SYI} = \frac{\text{Mean}_i - SD_i}{Y_{\max}} \quad (2)$$

where Mean_i , Y_{\max} , and SD_i indicate the average wheat yield during the experimental years, the observed maximum wheat yield, and the standard deviation of wheat yield, respectively. A cropping system with a lower coefficient of variation represents a high yield stability. A high sustainable yield index indicates a high yield potential.

2.4.2 Wheat productivity resistance and resilience under fertilization application

Resistance refers to the proximity of wheat yield to normal levels during a fertilizer removal event where we define fertilizer removal and re-application as environmental events. Resilience indicates the rate of return toward normal wheat yield levels after a fertilizer re-application. The resistance (Ω) and resilience (Δ) of cropping systems were calculated as follows (Isbell et al. 2015):

$$\Omega \equiv \frac{WY_n}{|WY_e - WY_n|} \quad (3)$$

$$\Delta \equiv \left| \frac{WY_e - WY_n}{WY_{e+1} - WY_n} \right| \quad (4)$$

where WY_n , WY_e , and WY_{e+1} indicate the expected wheat yield productivity during a normal year (the 1st year), during a fertilizer removal event (the 2nd and 3rd years), and during the year after a fertilizer removal event (the 4th year), respectively. If the fertilizer removal lowers wheat yield, then a greater wheat yield growth rate during recovery will indicate greater resilience in the subsequent year to regain full recovery to normal levels of yield. Thus, a high resistance and resilience value represents the stability of the cropping system.

2.4.3 Soil organic carbon and nitrogen stock

The SOC and TN were determined by dichromate oxidation and Kjeldahl method, respectively (Bao 2000; Bremner 1960).

The different soil layers of SOC and N stocks were calculated as follows:

$$\text{SOC}_{\text{Stock}} = \text{SOC}_{\text{content}} \times \text{BD}_{\text{soillayer}} \times H \quad (5)$$

$$\text{N}_{\text{Stock}} = \text{TN}_{\text{content}} \times \text{BD}_{\text{soillayer}} \times H \quad (6)$$

where $\text{SOC}_{\text{Stock}}$ and N_{Stock} are the SOC and N stocks (Mg ha^{-1}) in the corresponding soil layer, respectively. BD is the bulk density in each soil layer (g cm^{-3}). H means the thickness of each soil layer (m).

2.4.4 Enzyme activities and soil ecosystem multifunctionality

The activity of the C-related enzymes (β -1, 4-glucosidase, β -xylosidase, β -cellobiohydrolase), N-related enzymes (β -1,4-N-acetylglucosaminidase, L-leucine aminopeptidase), and P-related enzyme (alkaline phosphomonoesterase) was measured using two substrates including 7-amino-4-methylcoumarin (AMC) and 4-methylumbelliferone (MUF) (Marx et al. 2001). The assay methods are described in detail in Appendix S1.

The six soil enzyme activities were used to represent the soil ecosystem multifunctionality (EMF). The standardization of individual functions uses the Z-score transformation described in Eq. 7, which is then averaged to calculate a multifunctionality index (Delgado-Baquerizo et al. 2016; Wagg et al. 2014).

$$Z - \text{score} = \frac{X - \text{mean}_i}{SD_i} \quad (7)$$

$$\text{EMF} = \sum (Z - \text{score})_i / 6 \quad (8)$$

where X , mean_i , and SD_i indicate the enzyme activity, the average of enzyme i , and the standard deviation of enzyme i , respectively.

2.4.5 Statistical analyses

A three-way ANOVA and a subsequent Waller-Duncan's test at a 5% level of significance were used to explore the effects of year, fertilizer treatment, and cropping system on winter wheat yield and yield components. A two-way ANOVA was used to determine the effects of fertilizer treatment and cropping system on yield stability and sustainability, resistance and resilience, SOC and N stocks, crop residue C and N input, and soil ecosystem multifunctionality. The normality and homogeneity of variance were measured with Shapiro-Wilk and Leneve's tests, respectively. No variables required transformation in this study. Pearson correlations between winter wheat yield, aboveground biomass, yield component, and harvest index were calculated using the R package "corrplot." Additional correlations were also conducted

between average winter wheat yield and soil ecosystem multifunctionality. All graphics were plotted using OriginPro 2021 (OriginLab Corporation, Northampton, MA, USA).

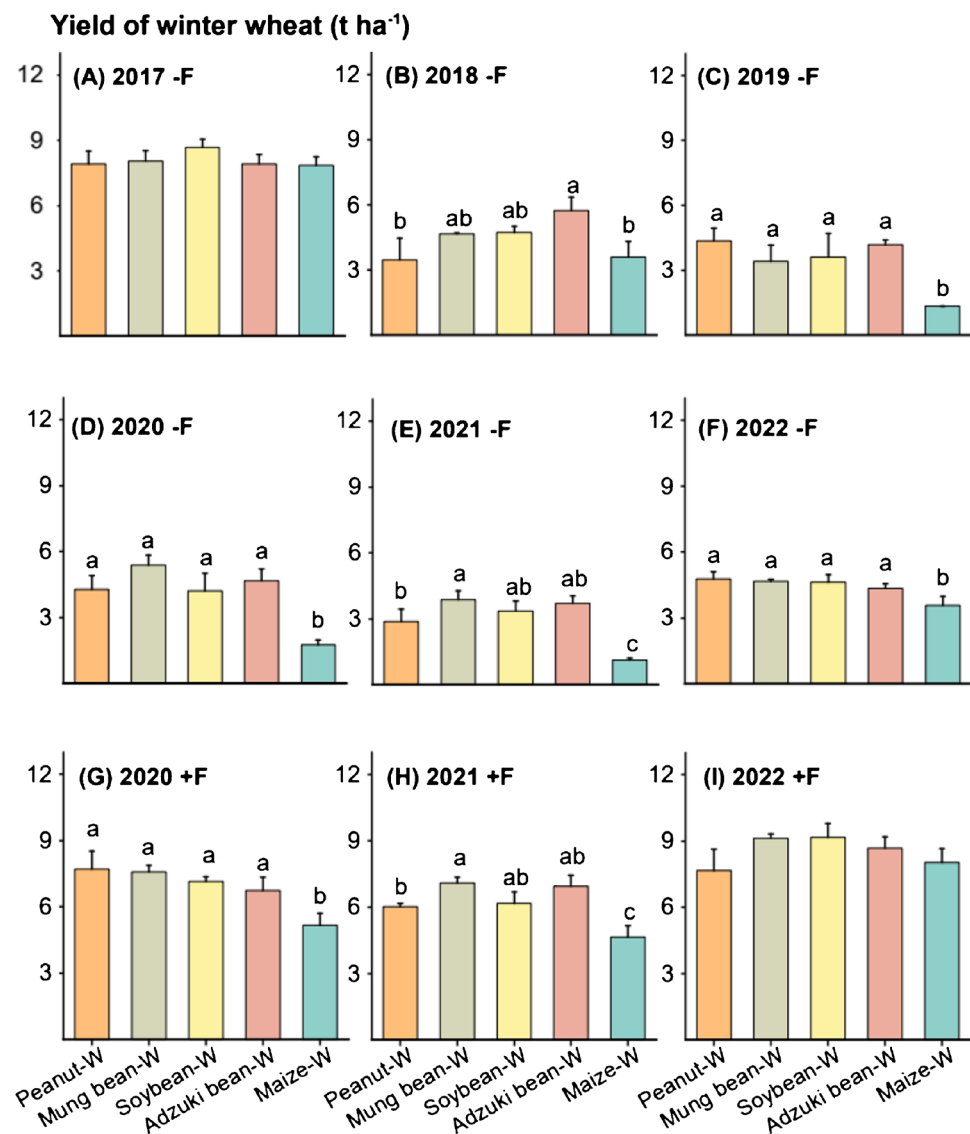
3 Results and discussion

3.1 Results

3.1.1 Legume inclusion on wheat yield and stability

Winter wheat yield was affected by year, fertilization, cropping system, and their interactions ($p < 0.001$; Fig. 2). The average wheat yield was $4.6 \text{ t ha}^{-1} \text{ year}^{-1}$ and $7.2 \text{ t ha}^{-1} \text{ year}^{-1}$ without and with fertilization, respectively. Growing four legumes as pre-crops resulted

Fig. 2 The wheat yield depends on crop rotation and fertilization from 2017 to 2022. Five rotation systems were maize-wheat (maize-W), peanut-wheat (peanut-W), mung bean-wheat (mung bean-W), soybean-wheat (soybean-W), and adzuki bean-wheat (adzuki bean-W). Two fertilization regimes were with (+ F) and without (- F) NPK application. Values are means \pm standard errors ($n = 3$). Different lowercase letters indicate significant differences ($p < 0.05$) among five rotation systems within the same fertilization treatment in the same year.



in a higher average wheat yield without fertilization (+ 52.3%), but a lower yield advantage with fertilization (− 26.0%) compared to the maize pre-crop. However, the annual yield advantage via legume inclusion gradually declined with a longer period of fertilization, and there was no significant difference among cropping systems after 3 years (Fig. 2I). Further, the legume pre-crop increased subsequent wheat yield stability and sustainability by 60.6 and 113.6% without fertilization (Fig. 3). Specifically, the adzuki bean–wheat cropping and mung bean–wheat had the smallest variation (CV, 16.7%) and the highest yield potential (SYI, 69.7%). Overall, legume inclusion increased subsequent wheat yield and benefited both yield stability and sustainability, especially without fertilization.

3.1.2 Legume inclusion on wheat yield resistance and resilience

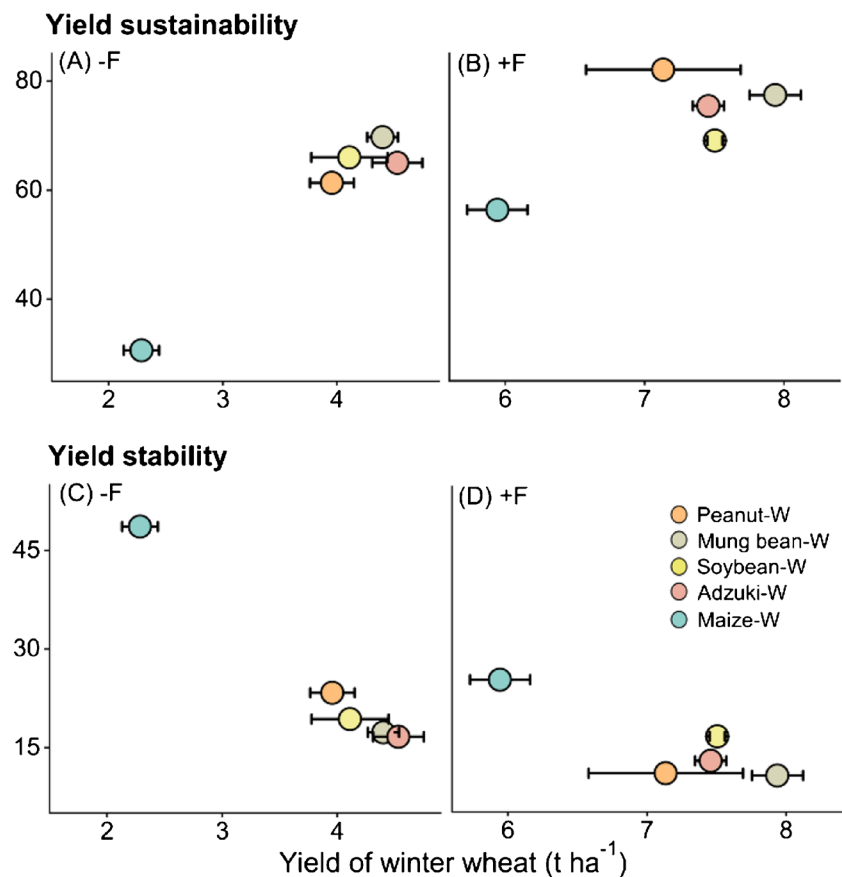
Legume inclusion increased both the wheat yield resistance and resilience ($p < 0.001$). After fertilizer removal, the wheat yield following maize decreased by 69%, while by 37–52% following legumes in 2018 (Fig. 2B). This was also shown by the higher resistance index of wheat yield after legumes (Fig. 4A). The wheat

yield of the legume–wheat cropping rapidly recovered to its initial level in the first year of re-fertilization in 2020 (Fig. 2G), which showed higher resilience than maize–wheat (Fig. 4B). However, the annual wheat yield of maize–wheat cropping also gradually recovered to its initial level only after 3 years of fertilization (Fig. 2I). Additionally, after re-fertilization, ear number was positively correlated with wheat yield ($p < 0.001$; Fig. S2), regardless of year and cropping system, indicating that ear number was the main yield component of wheat yield (Table 1). Overall, legume inclusion provides greater resistance and stability for wheat productivity under potential nutrient limitations.

3.1.3 Legume inclusion on soil ecosystem multifunctionality

The C-, N-, and P- related enzyme activities in the topsoil (0–20 cm) increased with fertilization and legume inclusion. Specifically, NAG and LAP increased by 87.0–196.5% and 82.1–156.3% with the legume–wheat cropping system than the corresponding maize–wheat with fertilization (Fig. 5). With fertilization, the soil ecosystem multifunctionality in the topsoil and subsoil

Fig. 3 The sustainability (A, B) and yield stability (C, D) of wheat depend on crop rotation and fertilization from 2017 to 2022. Five rotation systems were maize–wheat (maize-W), peanut–wheat (peanut-W), mung bean–wheat (mung bean-W), soybean–wheat (soybean-W), and adzuki bean–wheat (adzuki bean-W). Two fertilization regimes were with (+ F) and without (− F) NPK application. Values are means \pm standard errors ($n = 3$).



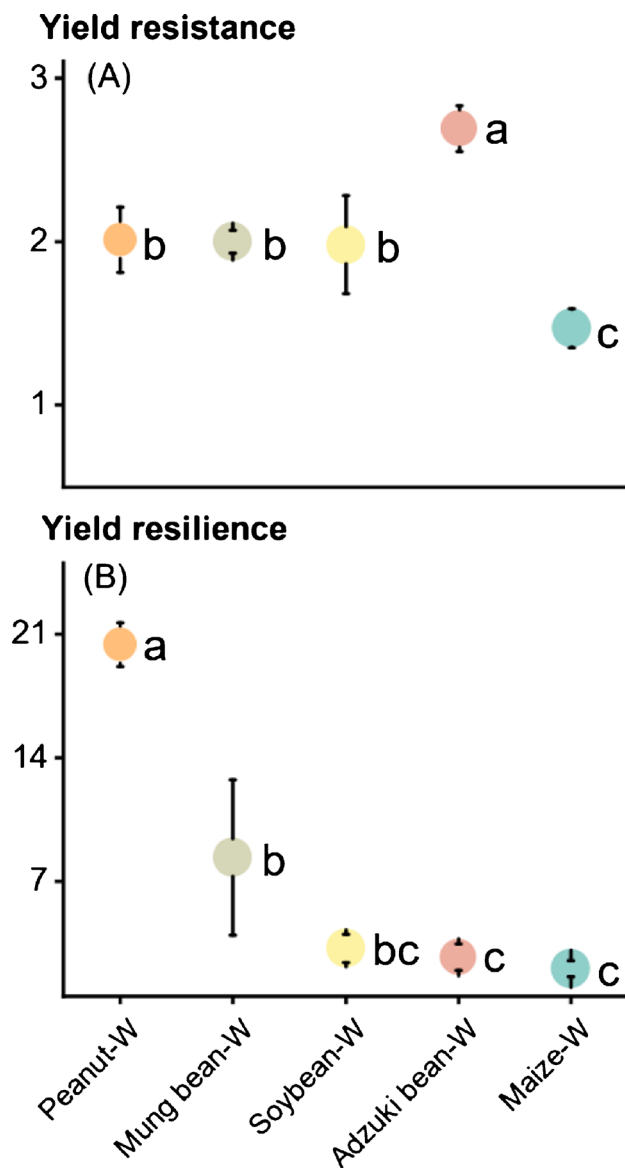


Fig. 4 The resistance and resilience of wheat productivity in response to fertilizer removal event. Five rotation systems were maize–wheat (maize-W), peanut–wheat (peanut-W), mung bean–wheat (mung bean-W), soybean–wheat (soybean-W), and adzuki bean–wheat (adzuki bean-W). Values are means \pm standard errors ($n = 3$). Different lowercase letters indicate significant differences ($p < 0.05$) among the five rotation systems. Note: some error bars appear inside the circle due to the small error.

(40–60 cm) was 118.7% and 30.5% higher than without fertilization. The inclusion of legumes enhanced the soil ecosystem multifunctionality in the topsoil by 41.5–119.6% compared to the maize pre-crop ($p < 0.05$), whereas no difference was observed without fertilization ($p > 0.05$). Further, the Pearson correlation analysis revealed a strong positive link between average wheat

Table 1 Yield components of wheat depend on crop rotation after fertilizer re-application in 2020–2022. Five cropping systems were maize–wheat (maize-W), peanut–wheat (peanut-W), mung bean–wheat (mung bean-W), soybean–wheat (soybean-W), and adzuki bean–wheat (adzuki bean-W). Values are means \pm standard errors ($n = 3$). *Significant differences ($p < 0.05$) among five cropping systems in the same year. Different lowercase letters indicate significant differences ($p < 0.05$) among five rotation systems in the same year.

	Pre-crop	Ear number (m^{-2})	Grain number (ear^{-1})	1000-grain weight (g)
2020	Peanut	738.2 ^a	29.2 ^c	23.0
	Mung bean	693.5 ^{ab}	32.4 ^a	22.9
	Soybean	605.2 ^b	31.5 ^{ab}	24.3
	Adzuki bean	661.3 ^{ab}	30.1 ^{bc}	23.5
	Maize	613.5 ^b	28.3 ^c	22.0
ANOVA	<i>F</i> -value	4.3*	9.7*	1.7
2021	Peanut	522.8 ^{ab}	38.4	21.7 ^a
	Mung bean	600.8 ^a	43.8	20.6 ^{ab}
	Soybean	544 ^b	37.3	20.2 ^b
	Adzuki bean	501.5 ^b	40.1	20.7 ^{ab}
	Maize	444.8 ^b	40.7	21.8 ^a
ANOVA	<i>F</i> -value	3.7*	2.5	4.1*
2022	Peanut	769.0	36.5	20.5
	Mung bean	807.8	34.6	20.4
	Soybean	796.0	35.0	20.1
	Adzuki bean	799.5	36.6	20.2
	Maize	752.8	35.2	20.2
ANOVA	<i>F</i> -value	0.5	1.1	1.0

yield and soil ecosystem multifunctionality in the topsoil ($p < 0.001$, Fig. 6). In short, legume inclusion increased soil ecosystem multifunctionality but was dependent on fertilization.

3.1.4 Legume inclusion on nitrogen and soil organic carbon stock

Without fertilization, the mung bean–wheat cropping significantly increased the SOC stock by 3.6 Mg ha^{-1} compared to the maize–wheat cropping system in the topsoil ($p = 0.017$, Figs. 5 and 7). In the lower soil depths (20–40 cm), soybean–wheat significantly increased the N stock by 0.36 Mg N ha^{-1} compared to maize–wheat. Further, legume inclusion had no significant effect on SOC stocks and N stocks between 0 and 60 cm (Fig. S3).

Cumulative crop residue C and N input was affected significantly by fertilization, cropping system, and their interaction ($p < 0.001$, Fig. S4). Maize–wheat system produced the relatively highest amount of crop residue C and N. Moreover, no obvious relationship was observed between N and SOC stocks and crop N and C input (Fig. S5).

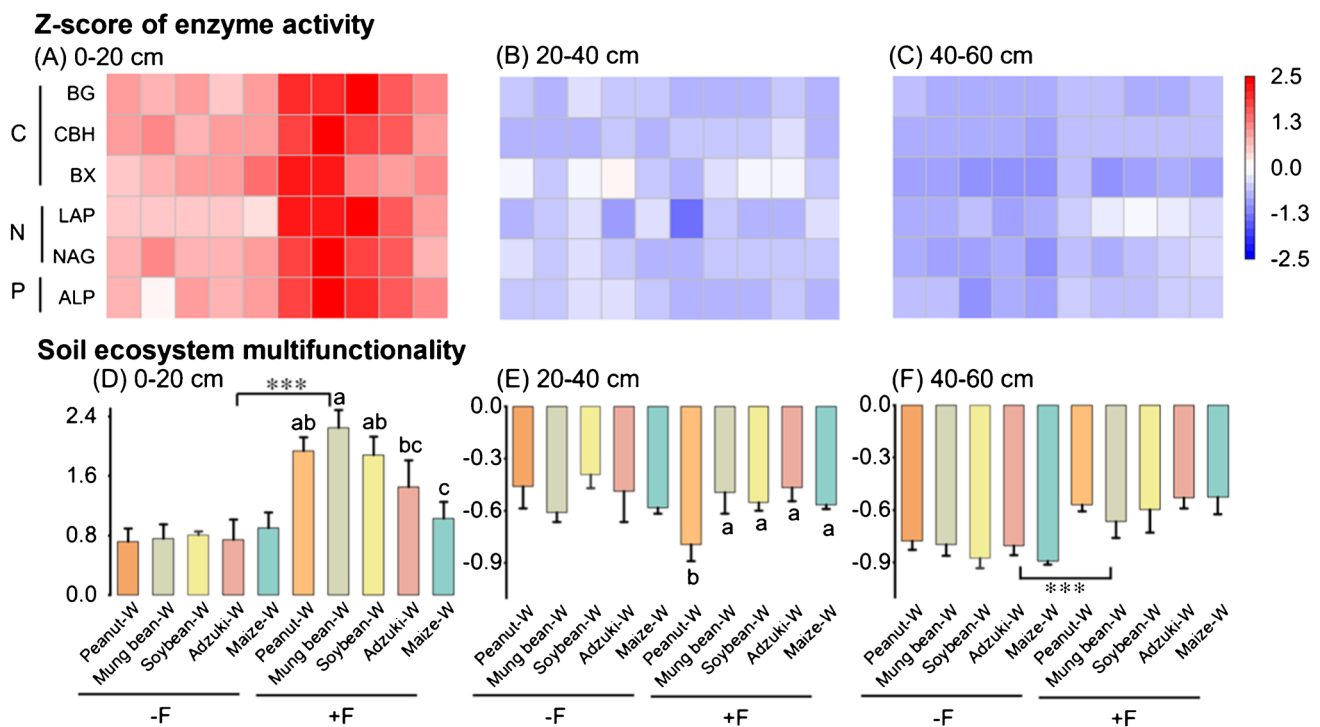


Fig. 5 Heat map showing the changes in multiple enzyme activities across the 0–20 cm, 20–40cm, and 40–60cm soil depth. The C-related enzymes include β -1, 4-glucosidase (BG), β -cellobiohydrolase (CBH), and β -xylosidase (BX); the N-related enzymes include β -1,4-Nacetylglucosaminidase (NAG) and L-leucine aminopeptidase (LAP), while P-related enzymes include alkaline phosphomonoesterase (ALP). The soil ecosystem multifunctionality was calculated based on the average standardized Z-score of six soil

enzyme activities. Five rotation systems were maize–wheat (maize-W), peanut–wheat (peanut-W), mung bean–wheat (mung bean-W), soybean–wheat (soybean-W), and adzuki bean–wheat (adzuki bean-W). Two fertilization regimes were with (+ F) and without NPK (– F) application. Values are means \pm standard errors ($n = 3$). Different lowercase letters indicate significant differences ($p < 0.05$) among five rotation systems with the same fertilization. ***Significant differences ($p < 0.001$) between the two fertilization treatments.

3.2 Discussion

3.2.1 Wheat yield depends on legume inclusion and fertilization

Legume inclusion notably under low fertilizer input increased the wheat yield and yield stability. This was likely attributed to the biological nitrogen fixation and subsequent high-quality residues derived from legumes (Watson et al. 2017; Liu et al. 2019). As such, legumes display the potential to enhance soil N (often by 50 kg N ha^{-1}) as a response to the lower N uptake from soils coupled with a higher N release from residue mineralization. (Franke et al. 2018; Liu et al. 2020). Also, increased microbial activity and the overall rate of soil nutrient cycling as stimulated by legume residues facilitate more N uptake by wheat with subsequently higher yields (Garland et al. 2021; Nunes et al. 2018). A positive link between the activities of the various enzymes

involved in C, N, and P turnover and wheat yield supports this idea (Fig. 6).

Fertilization mediated the effect of legumes on wheat yield, yield stability, and yield resistance. Although fertilizer removal constrained wheat productivity, the yield losses were much lower for maize–wheat cropping than the legume–wheat (Fig. 2 and 4). Further, legume inclusion resulted in a quicker wheat yield recovery, suggesting higher resilience after nutrient limitation (Fig. 4). This was attributed to the greater legume pre-crop effect than the recovery from the environmental stress of wheat such as N deficiency (Anderson 2011; Mason-Jones et al. 2018). For example, legume residues can supply more available N to wheat by improving net N mineralization and reducing soil N immobilization, which contributes to the recovery of wheat under N deficiency (Anderson 2011; Dhakal et al. 2016; Li et al. 2020). Other explanations, such as non-N effects of legume pre-crop, are crucial for improving soil quality via

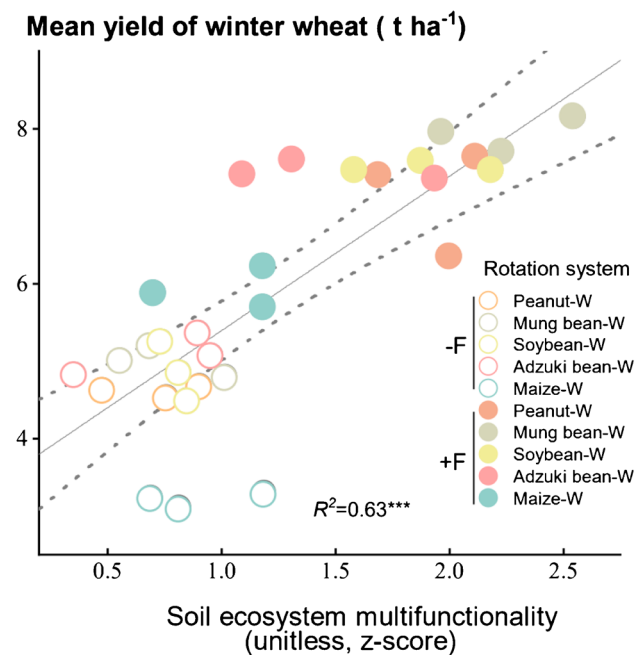


Fig. 6 Pearson correlation between the mean yield of winter wheat and soil ecosystem multifunctionality at 0–20 cm soil depth. The area within the dotted line represents the 95% confidence interval for the slope ($***p < 0.001$). Five rotation systems were maize–wheat (maize-W), peanut–wheat (peanut-W), mung bean–wheat (mung bean-W), soybean–wheat (soybean-W), and adzuki bean–wheat (adzuki bean-W). Two fertilization regimes were with (+ F) and without NPK (– F) application.

enhancing soil water conservation and pest control (Miller et al. 2002) and consequently result in better yield recovery of wheat (Franke et al. 2018). However, benefits derived from legumes can be replaced in part by increased fertilization, which is based on the idea that N effects from legumes depend on the amount of fertilizer applied and in general are more pronounced in N-deficient than in N-rich environments (Franke et al. 2018). To a greater extent, a higher N fertilizer rate will maintain soil available N to meet the crop demand and suppress the legume BNF and carryover effect of “spared” mineral N (Anderson 2011; Salvagiotti et al. 2008). Consequently, legume inclusion as a critical pathway for increasing crop yield may be more applicable, in agricultural systems reliant on ecosystem services, where access to chemical fertilizers is limited.

3.2.2 Soil quality depends on legume inclusion and fertilization

Legumes had no significant effect on the SOC stock between 0 and 60 cm depth and received fewer fertilizers relative to the maize season. On the one hand, compared with maize–wheat, the legume–wheat rotation system reduced plant-derived C and N inputs due to its relatively low

residual biomass (Fig. S4) and consequently limiting SOC and N sequestration (Adkins et al. 2019). However, the lack of relationship between SOC and N stocks and crop C and N input suggests a great potential for the inclusion of legumes for SOC sequestration even with lower plant-derived C input (Fig. S5). On the other hand, legume inclusion could likely contribute to increased C sequestration by increasing microbial activity and subsequent C turnover due to the input of low C to N residues (Virk et al. 2022). It was reported that the C to N ratio of maize residues can exceed 60, while a ratio of 15–20 for legumes (Sprunger et al. 2019). Moreover, legume root/residue decomposition and root exudates also provide more food and energy for microorganisms relative to maize, which in turn facilitates aggregate formation and SOC stability (Kirkegaard and Ryan 2014). In general, these two opposing effects might in part counteract each other, which may be the reason for similar SOC stock between legume–wheat and maize–wheat cropping.

Fertilization increased C-, N-, and P-related enzyme activities in both top and subsoils (Fig. 5), which was ascribed to the increased nutrient availability (Han et al. 2021; Kumar and Pausch 2022). Further, soluble inorganic compounds decomposed from fertilizer can be leached into the deep soil, thus stimulating microbial nutrient cycling (Yan et al. 2018). Compared with the maize–wheat cropping system, the adoption of legume–wheat cropping under fertilization can significantly enhance soil enzyme activities in the topsoil. This results from the faster decomposition of SOM due to leguminous residue input than maize–wheat (Jensen et al. 2012; McDaniel et al. 2014; Virk et al. 2022). Available N generally increased under legume-based rotation resulting in lower microbial N limitations (Scalise et al. 2015; Salvagiotti et al. 2008), which indicates better nutritional conditions for microbial growth and consequently drivers of soil ecosystem multifunctionality (Curtright and Tiemann 2021; Jia et al. 2022; Ma et al. 2022). Given that nodules are mainly concentrated in the root system of legumes between 0 and 20 cm, this facilitates an enhanced N fixation in topsoil (Liu et al. 2017). Therefore, the soil ecosystem multifunctionality was not different among cropping systems due to similar microbial N limitations. Overall, legume inclusion combined with fertilization exerted a much stronger effect on soil ecosystem multifunctionality and was pivotal in maintaining soil services in agroecosystems.

4 Conclusion

Legume–wheat cropping improved wheat productivity even under a 35% reduction in fertilizer application relative to the maize–wheat. The yield advantages declined with fertilizer legacy, which was more pronounced in low-input and low-yielding environments. Legume inclusion enhanced

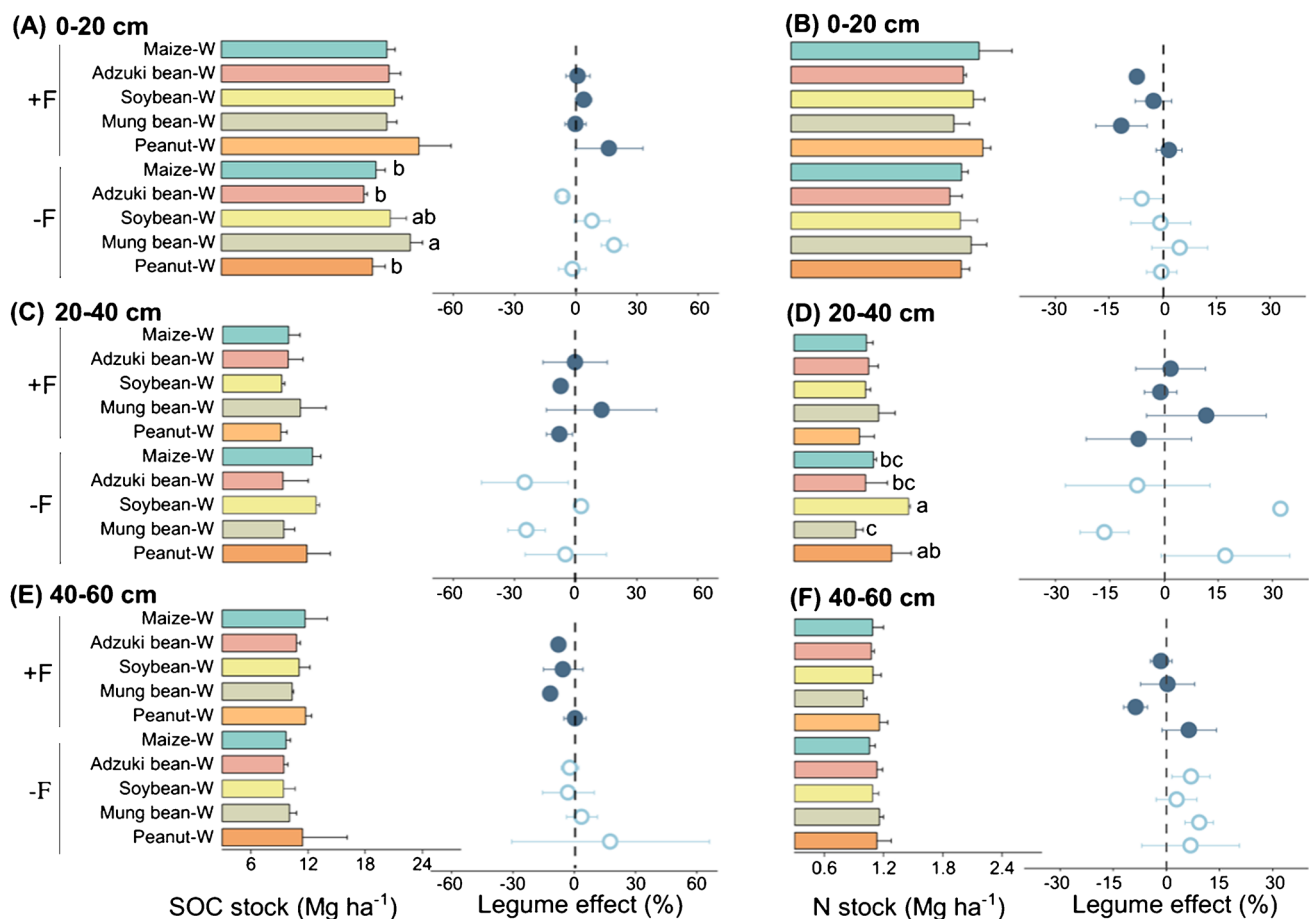


Fig. 7 Soil organic carbon (SOC) stock and nitrogen (N) stock of 0–20 cm (A, B), 20–40 cm (C, D), and 40–60 cm (E, F) depend on crop rotation and fertilization. Five rotation systems were maize–wheat (maize-W), peanut–wheat (peanut-W), mung bean–wheat (mung bean-W), soybean–wheat (soybean-W), and adzuki bean–wheat (adzuki bean-W). Two fertilization regimes were with (+ F)

and without NPK (– F) application. The effect of legume on SOC stock and N stock was estimated as the relative changes to the control maize-W. Values are means \pm standard errors ($n = 3$). Different lowercase letters indicate significant differences ($p < 0.05$) among five rotation systems with the same fertilization.

subsequent wheat yield resistance and resulted in lower yield losses relative to maize–wheat after fertilizer removal and a faster recovery after re-fertilization. Moreover, legume-wheat maintained SOC and N stocks despite a lower plant-derived C input. Legume inclusion could gain traction in improving the soil ecosystem multifunctionality but was highly dependent on fertilization, especially between 0 and 20 cm. In conclusion, legume inclusion into cropping is likely to enhance subsequent wheat yield by enhancing soil ecosystem multifunctionality and maintaining SOC stock. Future research regarding legume pre-crop benefits should focus on the mechanisms of the above- and below-ground interactions, which is crucial for future management and sustainability of cropping systems.

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Data availability For privacy reasons, qualitative raw data will not be shared.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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