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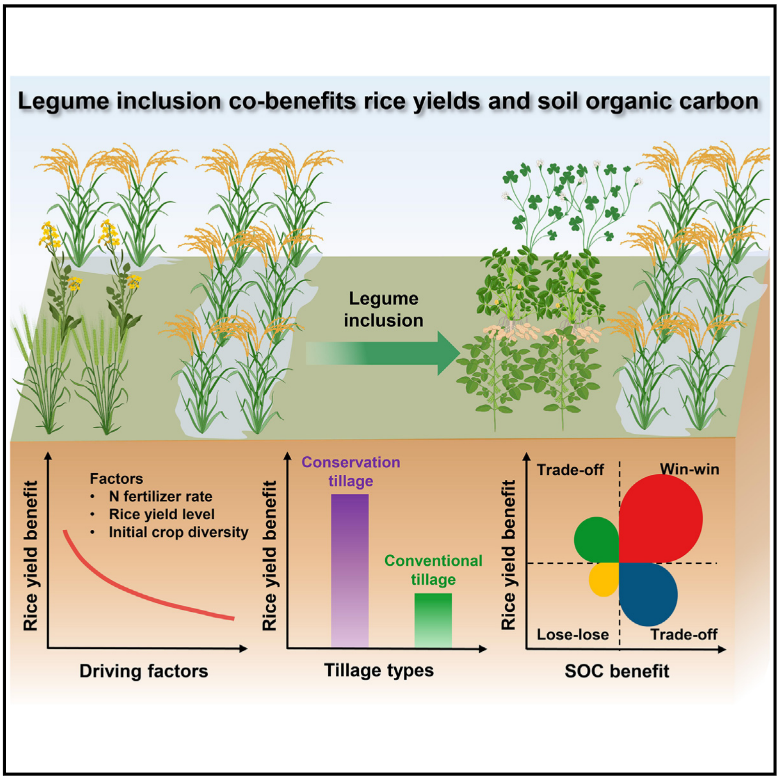
Legume-rice rotations increase rice yields and carbon sequestration potential globally

Graphical abstract



Highlights

- Legume inclusion increases subsequent rice yield by 15.7% at the global scale
- Greater legume pre-crop benefit under low N fertilizer input and conservation tillage
- High crop diversity and yield levels narrow the rice yield benefit after legumes
- Legume inclusion co-benefits subsequent rice yield and soil carbon sequestration

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In brief

Rice, a staple for billions, faces challenges from climate change and stagnant yield growth. Besides varietal improvement, diversified cropping, especially with legume inclusion, emerges as a promising strategy for enhancing productivity. Here, we show that legume pre-crops increased subsequent rice yields by an average of 15.7% globally. Legume inclusion also promotes a win-win situation of increased production and carbon sequestration, charting a path for sustainable rice production and the potential to mitigate climate change.

Yao et al., 2025, One Earth *8*, 101170
February 21, 2025
https://doi.org/10.1016/j.oneear.2024.12.006

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Legume-rice rotations increase rice yields and carbon sequestration potential globally

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https://doi.org/10.1016/j.oneear.2024.12.006

SCIENCE FOR SOCIETY Rice, sustaining over half of the global population, has been cultivated in diversified systems for millennia. As international policies increasingly embrace agroecology to ensure food security while mitigating environmental impacts, insights have emerged regarding the pivotal role of legumes in diversified cropping systems (e.g., rotations, intercropping, cover cropping, etc.). Legumes improve subsequent crop yields by enriching soil fertility and promoting beneficial interspecific interactions in upland systems. However, differences in water management, soil conditions, and nutrient cycling dynamics between paddy and upland pose challenges in directly extending the advantages of legume rotation benefits from upland systems to paddy systems. Furthermore, achieving multifunctional landscapes requires balancing production with climate resilience. The potential synergies between rice yields and soil carbon sequestration in legume rotations remain ambiguous. Our study demonstrates that legume rotations increased global rice yields by 15.7%, promoting both food production and carbon sequestration. As we transition toward sustainable development practices, optimizing these crop rotations may be key to balancing production and environmental health.

SUMMARY

Rice feeds half of the world's population but faces the pressures of yield demand under increasing environmental and climate pressures. Diversified cropping systems such as legume-based rotations may be a viable solution, but rice yield responses and environmental implications have not been synthesized globally. Here, based on 1,483 data pairs covering 17 major rice production countries worldwide, we revealed that legume inclusion increased subsequent rice yields by an average of 15.7% globally. Yield gains were more pronounced under conservation tillage (+58.4%) than conventional tillage (+13.9%). These benefits decline with nitrogen fertilizer inputs, initial crop diversity, and current rice yield levels. When considering trade-offs, integrating legumes in rice rotations results in win-win benefits for rice yields and an increased soil organic carbon content in 65.8% of all cases. These findings highlight the potential of legume inclusion to not only enhance rice yields but also foster soil carbon sequestration, thereby paving the way for sustainable rice production with the added potential to mitigate climate change.

INTRODUCTION

Rice serves as a staple food for over half the global population.[1,2] However, over the past decade, rice yield levels have plateaued,[3] facing enormous pressures from high requirements of water and fertilizers, along with escalating environmental costs.[4–6] Ensuring sustainable rice production while minimizing environmental costs is crucial for global food security and advancing environmentally friendly agriculture.[7]

Diversified cropping, especially with legume inclusion, supports agricultural sustainability by enhancing food production with lower external input and less environmental impacts.[8–10] Globally, crop and pasture legumes contribute 21.5 Mt (million tonnes) of biological nitrogen (N) fixation for agriculture annually,[11,12] enhancing subsequent crop yields by 20% in rotation systems.[13] Although the yield effects of legume-based rotations have been widely studied in crops like maize, wheat, and canola,[14,15] there is a notable gap in understanding these impacts on rice. Given the heterogeneity of paddy and upland production systems,[16] such positive effects may not necessarily translate to rice. Moreover, building multifunctional agricultural landscapes requires the joint consideration of multiple objectives, including agricultural production and climate change mitigation. Although evidence of the synergies between soil organic carbon (SOC) and crop yields is accumulating,[17,18] broad trade-offs between rice yield and SOC outcomes from legume pre-crops are poorly understood and largely unquantified. Thus, understanding the yield and SOC relationship in paddies is critical to maximizing win-win outcomes for agriculture and climate.

The yield and SOC benefit in legume-rice rotation is driven by various factors, including regional conditions (i.e., climate and soil properties) and agronomic practices (by farmers). For instance, mean annual precipitation (MAP) and initial SOC content are crucial in enhancing N uptake and turnover.[19–22] Tillage disrupts soil aggregates and accelerates the microbial decomposition of exposed residues, potentially resulting in rapid N mineralization and release.[14] Meanwhile, excessive N fertilization may mask the yield and SOC benefits provided by the N legacy of legume pre-crops.[23] In addition, the purpose of legume cultivation (i.e., grain, forage, and green manure) and their residue management (i.e., return or remove) determine the quality and quantity of crop residues,[13,24] further affecting the potential benefits for rice yields and soil C sequestration. Thus, gaining a comprehensive understanding of these factors is essential for optimizing legume-rice rotations and developing site-specific sustainable strategies that enhance productivity and environmental resilience.

We conducted a meta-analysis of the effects of legume pre-crops on (1) rice yield and its main drivers at a global scale and (2) the trade-offs between yield and SOC benefits. Our database contains 1,483 pairwise comparisons from 96 publications across 17 countries (Figure S1).

RESULTS AND DISCUSSION

Our systematic review revealed that legume inclusion had predominantly positive effects on rice yields (80.1% of the data showed positive effects, 0.9% neutral, and 19.0% negative), with half of the datasets showing a yield benefit greater than 9% (Figure 1A). On average, legumes enhanced rice yields by 15.7% (median effect, 8.8%; 95% confidence interval [CI], 10.3%–21.3%; Figure 1A). Additionally, we found that the N fertilizer rate, tillage types, and crop diversity in initial cropping systems were the most dominant factors moderating the yield effects of legume pre-crops on rice (Figure 1B).

Greater legume pre-crop benefit under low N fertilizer input and conservation tillage

The benefit of legume inclusion is closely associated with biological N fixation and the quality of residue from legumes.[13,25] Within this study, the N input of rice was the primary predictor of the legume pre-crop effects (Figure 2A), indicating that optimal N fertilization is essential to maximize the benefits observed in crop rotations. A negative correlation was observed between the legume pre-crop effect and N fertilizer input, with yield effects ranging from +25.7% (95% CI: 19.2%–33.4%) at 0 kg N ha^{-1} to a negative impact when N input exceeded 241 kg N ha^{-1} (Figure 2A). Within the standard global N application range of 60–150 kg ha^{-1},[26] legume pre-crops boost rice yields significantly, with an average increase of 9.9% (95% CI: 2.9%–17.4%; Figure S3). Likewise, previous studies found a negative correlation between the yield increase of rice following a cover crop and the amount of N fertilizer applied.[10,27] We offer two possible explanations to account for our findings. First, external N input provides most of the crop's N demand, reducing the dependence on plant-available soil N. This weakens the N supply effect of the legume pre-crops[28] and narrows the gap in subsequent rice yields between legumes and non-legumes. This was confirmed by the significant enhancement of rice yields with N fertilizer inputs in the initial cropping system (Figure S2A). Second, sustained N application results in the accumulation of mineral N in the soil, leading to suppressed biological N fixation and, hence, reduced benefits provided by legume pre-crops and decreased residual effects from excessive mineral N.[25,29] Collectively, our findings indicate that the yield benefits of legume pre-crops on rice are mainly due to N benefits, and a reasonable N application strategy should account for the pre-crop N effect.

Additionally, a greater increase in rice yields caused by legume pre-crops was found under conservation tillage applied to rice (+58.4%; 95% CI: 35.5%–85.3%) compared with conventional tillage (+13.9%; 95% CI: 9.2%–18.8%) (Figure 2B). This substantial difference may be due to the initially lower yields associated with conservation tillage (Figure S4A). Meanwhile, we found that the legume pre-crop benefits were relatively high under conservation tillage compared to conventional tillage at low-yield levels (Figure S4B). A linear mixed-effects model confirmed that tillage type is the primary factor affecting the benefits of legume pre-crops (Figure S4C), suggesting that conservation tillage, especially in low-yield scenarios, could optimize rice production in legume-rice rotations. The probable reason for this is that conservation tillage promotes greater soil aggregate formation,[30] which enhances the soil's physical protection of the residual N from the legume pre-crops. Moreover, soil disturbance is lower with conservation tillage, which impacts N turnover and thus gaseous and leaching N losses, potentially strengthening the N benefit from legumes.[31–33] This results in slower decomposition of legume residues,[34] which increases the efficiency of the N utilization from legume pre-crops by rice under conservation

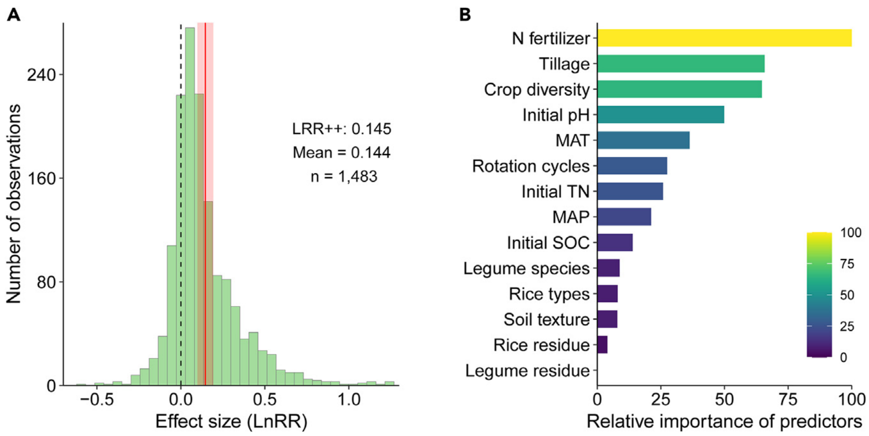

Figure 1. Overall effect and variable importance for the effects of legume pre-crops on rice yields

(A) Frequency distribution of natural log response ratio (lnRRs).

(B) Importance of the factors on rice yield response to legume pre-crops.

The dashed line in (A) was drawn at lnRR = 0. The red vertical line and shading area indicate the mean lnRR and 95% confidence intervals, respectively. The relative importance in (B) is quantified based on a meta-forest model. MAT, mean annual temperature; MAP, mean annual precipitation; SOC, soil organic carbon; STN, total nitrogen content in topsoil, respectively.

tillage.[35] The key factor is that this system enhances N supply to rice, matching legume residue mineralization with the crop's developmental N needs for a consistent N supply.[36] Given the above, adopting conservation tillage practices in paddies provides an effective way to strengthen the legume pre-crop benefits on rice yields, especially in low-yield paddy fields.

Notably, a significant interaction was observed between tillage types and N fertilizer rate (Figure S5D). The contribution of legumes to rice yields was strong (+81.3%; 95% CI: 23.3%–161.7%) without N (0 kg N ha^{-1}) and decreased sharply with increased fertilization (–10.3% for each 30 kg N ha^{-1}) under conservation tillage (Figure 2C). Contrarily, the average benefit of legumes was lower without N input (+21.9%; 95% CI: 16.3%–27.9%), and the decline in this effect was less pronounced with increased fertilization (–2.8% for each 30 kg N ha^{-1}) under conventional tillage. This suggests that the rice yield benefits derived from legume pre-crops under conservation tillage are more responsive to N fertilizer application. However, wide CIs indicate that high uncertainty may occur for conservation tillage. In other words, conservation tillage retains more N from legume pre-crops than conventional tillage, thereby reducing the amount of external N input required for the optimal growth of the subsequent rice.[37] The effect of legume inclusion was no longer positive when N fertilization exceeded 240 kg N ha^{-1} (Figure 2C), regardless of tillage type. Taken together, these findings indicate that legumes play a greater role under conservation tillage with reduced fertilization.

High crop diversity and yield levels narrow legume pre-crop effects

A greater legume pre-crop effect on rice yields was observed at low initial crop diversity (defined as the total number of crop species × the total number of crop functional groups × the average number of crop species per year).[13] Specifically, increasing crop diversity in the initial cropping system boosts rice yields (Figure S2B), while the yield benefits from legume pre-crops narrowed with increasing crop diversity and became negative with crop diversity higher than 15 (Figure 2D). Each 1-unit increase in crop diversity resulted in a 1.1% reduction in the yield benefit from legume pre-crops for rice (Figure 2D). This indicates that the rice yield benefits of diversified cropping systems via the inherent capacity of the break-crop (non-N) effect might mask the N fixation benefits with legume inclusion.[38] The break-crop effect, also known as niche complementarity, strengthens the resilience of cropping systems to biotic and abiotic stressors by improving soil physicochemical and biological properties.[39] This indicates that crop diversification through the inclusion of other crops instead of legumes benefits rice yields when legumes are agronomically or economically unfeasible.[7,40]

Notably, a stronger effect of legume pre-crops was observed in low-yield rice systems (Figure 3A). Similarly, this positive effect was insignificant when SOC content exceeded 20 g kg^{-1} (Figure S3). The potential reason is that high-fertility soils sustained rice yields via an adequate nutrient supply, thus partially narrowing the yield gap when utilizing legume pre-crops. Interestingly, the yield advantage of integrating legumes decreased significantly as the initial rice yields increased. The higher marginal benefit of legume pre-crops in scenarios of low rice yields could be partly linked to alleviating stress conditions (e.g., N deficiency).[41] The yield benefit derived from legume pre-crops is very limited when the rice yield is above 7.0 t ha^{-1} (Figure 3A), which is near the global mean yield (6.8 t ha^{-1})[42] and lower than the highest average farmer yield recorded (7.5 t ha^{-1}, according to FAO data) in Asia,[3] where 90% of global rice production occurs. Moreover, our results revealed that 98% of the observed yield increments >20% were found in cases where the initial rice yields were lower than the global mean yield of 6.8 t ha^{-1}. Similarly, the yield benefit of legume pre-crops in Benin (West Africa) significantly exceeds that of major rice-producing countries in Southeast Asia, which was mainly attributed to lower N fertilization and crop productivity levels (Figure S6). Overall, our study suggests that including legumes in rice-based rotations notably boosts rice yields, especially in rice systems characterized by low yields and poor soil fertility.

Synergies and trade-offs between rice yields and SOC with legume inclusion

SOC sequestration offers a range of environmental and health advantages, emerging as a highly eco-friendly approach to climate change adaptation and mitigation.[43] Beyond the rice yield benefit of legume pre-crops, we evaluated the trade-offs and synergies between yields and SOC sequestration (an important indicator of soil fertility) to assess the sustainability of legume inclusion in paddies. We examined concurrent rice yield and SOC responses to legume inclusion based on 177 pairs of

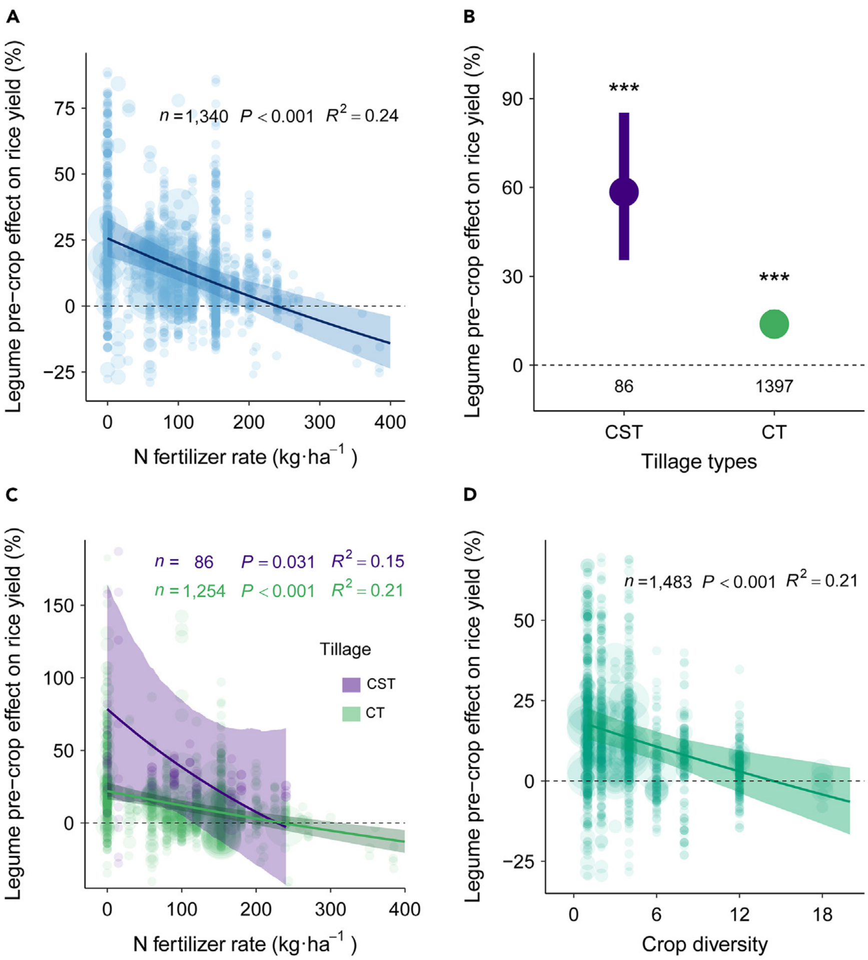

Figure 2. Moderators of legume pre-crop effect on rice yield benefit

(A) Nitrogen (N) fertilizer rate (kg ha^{-1}) for rice.
(B) Conventional tillage (CT) and conservation tillage (CST).
(C) The interaction between rice tillage types and N fertilizer rate.
(D) Crop diversity in initial cropping systems.
Colored lines in (A), (C), and (D) represent the average N fertilizer rate and crop diversity specific responses, respectively, with their 95% confidence intervals (CIs) indicated by shading. The size of each dot represents the relative weights of corresponding observations. Values are mean effect sizes and error bars show the 95% CIs in (B). The numbers of observations for each category are shown along the x axis. Asterisks denote significant effects: ***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$.

effect sizes (Figure 3B). The results indicated that legume pre-crops mainly promoted a win-win scenario sustaining rice yields and enhancing SOC content (65.8% probability), thus benefitting both farmers and climate impact mitigation. Trade-offs, in which either the rice yield or SOC increased while the other decreased, accounted for 28.7% of the cases. In 5.5% of cases, legume inclusion reduced the rice yield and SOC. Notably, green manure cultivation (probability: 76%) and residue incorporation (probability: 69%) in legume-rice rotation promoted a higher win-win scenario for the rice yield and SOC (Figure S7). Likewise, the introduction of legumes into farmland with low crop diversity and low initial SOC demonstrated a greater contribution to the win-win scenario. Furthermore, legumes exhibited notable efficacy in enhancing soil organic matter (SOM) pools, particularly mineral-associated SOM, that benefit soil C sequestration and rice yields with an N supply.[44–46] As demonstrated, soil C sequestration is consistently improved by legume inclusion,[23,47] which ensures the long-term sustainability of the rice yield increase. Maintaining and enhancing SOC stocks is critical for ensuring soil health, fertility, and agricultural production and reducing net greenhouse gas (GHG) emissions. Overall, introducing legumes into rice rotation has the potential for soil C sequestration to mitigate climate change, although potential impacts on nitrous oxide (N_2O) and methane (CH_4) emissions from the legume residues should also be considered.[48] Future research should focus on optimizing the introduction and management strategies of legumes, aiming to maximize both the productive and ecological dual benefits within rice systems.

Toward sustainable rice production with legume inclusion

Our study focused on one of the world's major staple foods and provides an evidence-based synthesis of legume inclusion as a general strategy to increase sustainable rice production globally. The yield increase (+15.7%) and benefits for yields and soil C sequestration (65.8% of all cases) in paddies with legume pre-crops indicate a transformative shift toward integrating legume-rice rotations. First, there is potential for a global reconfiguration of cropping system, where legume inclusion becomes widespread in paddies. This would enhance yields, improve soil health, and mitigate climate change, aligning with sustainable agricultural goals.[7,23,49,50] The observed benefits under conservation tillage and low fertilization conditions suggest that regions with resource constraints will have larger potential in this transformative shift for sustainable rice production. Second, optimization strategies must be tailored for different regions, considering local climatic, soil, and ecosystem variables[51] (Figure S3). For instance, areas with lower initial SOC or rice yield potentials might prioritize legume rotations differently from regions with higher initial levels. Furthermore, the integration of legume rotations in paddies should be accompanied by research and development efforts focusing on crop diversity and appropriate legume species selection (Figure S8). Therefore, globally, adopting legume pre-crops in paddies is promising to increase rice yields and contribute toward more sustainable and resilient agricultural systems.

However, short-term financial gains are the key driving factor for farmers when adopting new practices. This study shows

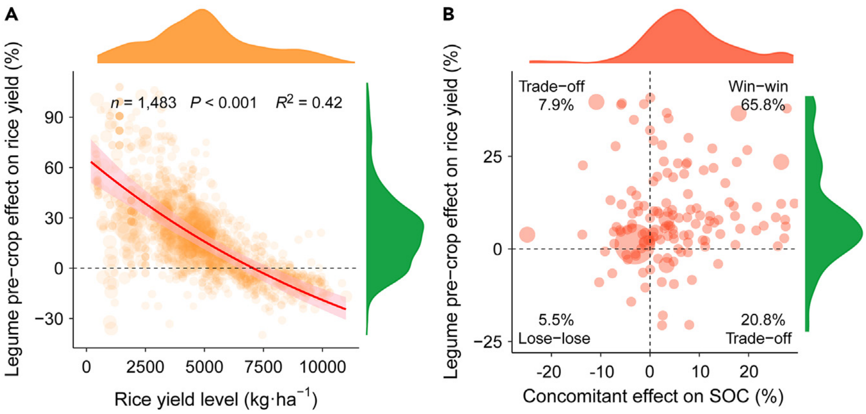

Figure 3. The benefits of legume pre-crops on rice yields decreased with increasing initial yield levels and promoted a win-win scenario for rice yields and SOC

(A) Legume pre-crop effect on yield benefit decreased with increasing rice yield level.

(B) Legume pre-crops promoted a win-win scenario for both rice yield and soil organic carbon (SOC).

The red line in (A) represents the rice-yield-level-specific responses, with its 95% confidence intervals shaded. Scattered dots in (A) represent the yield benefit of rice from each observation, with dot size proportional to the relative weight of each observation in the meta-regressions. Data in (B) containing rice yield and SOC responses to legume-rice rotation were used for visualization (177 pairs of effect sizes). The position of the circles in (B) displays the effect on rice yields and SOC for each observation, with the dot size proportional to the relative weight of each observation. The probability of each scenario is calculated based on the number of points and their weights.

that legume-rice rotations can boost net economic benefits by 51.0% (95% CI: 15.2%–98.1%; Figure S9), with 78.7% of the data showing positive effects and 21.3% negative. However, in high-yield systems, these rotations may not be as profitable. While long-term benefits like soil fertility improvement are clear, the transition to legume-rice systems can be challenging due to the learning curve and risks of short-term economic losses.[52] Future research should assess the economic viability of these rotations under different conditions and explore market opportunities for legumes to encourage their adoption. Supportive policies, including subsidies and training, are crucial for successful implementation. Collaboration among researchers, policymakers, and farmers is key to scaling out these practices for sustainable agriculture. In conclusion, our study offers insights for further exploration into the strategic design and implementation of diversification practices in paddies, but this needs to be explored and implemented locally.

METHODS

Study selection

We searched English and Chinese literature sources through the Web of Science core database (http://apps.webofknowledge.com/) and the China National Knowledge Infrastructure (CNKI; http://www.cnki.net/) until December 2023. These search strings (Table S1) yielded 1,856 studies published between 1980 and 2023.

Studies from the retrieved publications were screened and meet the following selection criteria: (1) the study was based on field experiments, and treatments were randomized with replications; (2) the preceding crop in the treatment group must be a legume and in the control group must be a non-legume; (3) the mean rice yields must be reported directly as numerical or graphical data or can be calculated from the reported data; and (4) the site location of the field experiment was reported. Additionally, we regarded them as distinct observations, typically conducted in different locations, as distinct studies in cases where multiple experiments were reported within a single publication. However, if multiple publications were derived from the same experiment, particularly a long-term experiment, then we classified them as the same study. If a publication documented different "rotation cycles" of a crop rotation, then we treated each cycle as an independent inclusion. Our final dataset encompassed 17 countries and comprised data from 88 unique experiments collected from 96 sources (92 peer-reviewed journal articles, 1 doctoral thesis, and 4 master's theses). A list of data sources used in this study is provided in the supplemental information.

Data extraction

For a given study, treatment (legume pre-crop) values were matched to control (non-legume pre-crop) values only if the two groups did not differ in anything other than legume introductions (e.g., same tillage system, same N fertilizer application, etc.) and the treatments were sampled at the same time. We aimed to be able to manage confounding effects that might obscure direct comparisons of raw data across studies on environmental conditions, agronomic practices, or soil factors. For each observation, we extracted the values, the number of replications, and the standard deviation of the effect sizes (i.e., rice yield, SOC content after crop rotation, and net economic benefit of system). Data presented in the figures were extracted using the GetData Graph Digitizer software (http://getdata-graph-digitizer.com/). We also extracted location, climate, soil characteristics, and agronomic practices, which we used to explain the variation in natural log response ratio (lnRR) (Table S2).

For each site, latitude and longitude were extracted or estimated based on the location of the nearest city or experimental station where the study took place. Mean annual temperature (MAT) and precipitation (MAP) were extracted from study reports or obtained from the WorldClim database[53] using geographic location (i.e., latitude and longitude). The soil's initial pH, SOC, and total N (STN) content were collected from the materials and methods section of studies or extracted from the HWSD database[54] using latitude and longitude coordinates. Soil texture was further categorized into fine, medium, and coarse in terms of the USDA soil classification.[55] In terms of agronomic practices, we documented residue management (returned/removed), tillage types for rice (conservation/conventional tillage), irrigation practices (yes/no), control types (fallow/continuous monoculture/rotation), rice types (single rice/early rice of double rice/late rice of double rice), legume pre-crop purposes (grain/green manure/forage), and legume species as binary variables. N fertilizer rate, rotation cycles, and initial crop diversity were recorded as continuous variables. We first tested the difference between fallow and no-fallow control and found that no differences were observed (Figure S10). Consequently, we considered all these differences in control as a crop diversity index. Crop diversity within the control (initial) cropping systems was determined using the formula[13] crop diversity = $N_{species} \times N_{group} \times N_{year}$. This calculation integrates the total number of cultivated crop species ($N_{species}$) and functional groups (N_{group}), along with the average annual crop species count (N_{year}). The concept of crop functional groups helps recognize species diversity with similar environmental responses and comparable effects on ecosystem functioning.[56] For example, rice and canola belong to different functional groups, while rice and wheat belong to the same functional group. The count of crop species annually is a differentiating factor for cropping intensity (e.g., two harvests per year versus one).

Data analysis

We used the lnRR to calculate the effect of legume pre-crops on rice yield compared to non-legume pre-crops.[57] The lnRR was calculated as follows:

$$\mathrm{lnRR} = \ln(x_t/x_c) = \ln(x_t) - \ln(x_c), \quad \text{(Equation 1)}$$

where x_t and x_c are the observed values of the rice yields with (treatment) and without (control) legume pre-crops, respectively. In our database, standard deviations were missing in most studies, but the sample sizes were available. Weights for lnRR were therefore calculated using the number of replications by the following formula[58]:

$$w_i = (n_t \times n_c)/(n_t + n_c), \quad \text{(Equation 2)}$$

where w_i is the weight associated with each lnRR observation and n_t and n_c are the numbers of replications of the treatment and control groups, respectively.

We calculated weighted overall effects in a mixed-effects model using the rma.mv function in the R package metafor[59] in R 4.3.2.[60] Then, we analyzed the rice yield lnRR for different factors (F) through the following mixed-effects model:

$$\mathrm{lnRR} = \beta_0 + \beta_1 * F + \pi_{study} + \varepsilon, \quad \text{(Equation 3)}$$

where β, π_{study}, and ϵ are the coefficients of fixed effects, the random-effect factor of "study," and sampling error, respectively. The potential non-independence of studies was included in "study" as a random factor due to most studies contributing to more than one lnRR. The "study" was directly numbered according to latitude and longitude (field-experiment locations). For consistency, we analyzed all binary variables with Equation 3.

Weighted vote counting was used to show whether there was a win-win, trade-off, or lose-lose effect of legume inclusion on rice yields and SOC. The formula is as follows:

$$P_i = \sum w_j \Big/ \sum w_{ij}, \quad \text{(Equation 4)}$$

where p_i, w_{ij}, and w_j represent the probability of the i-th scenario among the four scenarios, the weight assigned to each observation across all scenarios, and the weight assigned to each observation specifically in the i-th scenario, respectively. When the yield and SOC weights of each pair of observed values are inconsistent, we choose the smaller weight to obtain a more conservative result.

The lnRR was transformed back to the percentage change as $(e^{\mathrm{lnRR}} - 1) \times 100\%$ for ease of interpretation. The legume pre-crop effects on rice yields were considered significant if the 95% CIs of lnRR did not include zero.

Varying importance and publication bias

We coded 16 potential moderators (Figure S5A) to identify the potentially relevant factors in predicting the rice yield benefits of legume pre-crops using the R package metaforest.[61] The approach is based on the machine-learning "random forest" algorithm, which is robust to overfitting non-linear correlations between moderators and the response variables. In this study, our algorithm commenced with a preselection phase involving 10,000 iterations and a replicated 100-fold feature selection process. Moderators exhibiting consistent negative effects on variable significance were eliminated using the preselect_vars function. Those contributing positively to the model's predictive capacity were advanced for further refinement. Finally, we optimized the parameters of the meta-forest model using the train function from the caret package[62] based on 10-fold cross-validation. This method effectively handles multiple predictors and their interactions, recognizing non-linear relationships. In addition, we fitted different numbers of moderators using a meta-forest model to screen for major factors that were both important and stable (Figure S5). Subsequently, we used the metafor[59] and glmulti[63] packages to automatically fit all possible models containing the three most important predictors and their interactions (at level 2).[64] Model selection was based on the Akaike information criterion corrected for small samples (AICc). The relative importance value for the corresponding factors is equal to the sum of the Akaike weights for the models that contain the influential predictor. Therefore, predictors included in models with substantial Akaike weights will be assigned higher importance values. These values can be interpreted as overall solid evidence supporting the relevance of each variable in all models. Generally, if its threshold value is greater than 0.8, then this indicates that this factor is relatively essential.

Publication bias was tested by funnel plots and Egger's test (Figure S11). Although we initially observed an outlier in the funnel plot, its removal did not significantly impact our results. Thus, we decided to retain it in our analysis. Egger's test[65] quantifies the extent of funnel plot asymmetry by evaluating the intercept obtained from regressing standard normal deviates against precision ($Z = -1.10$, $p = 0.27$). Rosenberg's fail-safe number[66] was 36,859 ($n = 1{,}483$, $p < 0.0001$). Collectively, publication bias was unlikely to have affected our results. Crucially, we employed the trim-and-fill method[67] to estimate the average impact of missing studies. All revisions involved a systematic increase in the effect size. Given that the 95% CIs from the main analysis and trim-and-fill analysis still overlapped (i.e., 95% CIs: 0.10–0.19 and 0.11–0.31), we have chosen to report the more conservative results of the main analysis. All analyses were conducted in R

4.3.2. The R packages ggplot2[68] and ggsankeyfier[69] were used for data visualization. The map was generated using QGIS v.3.32 (Open Source Geospatial Foundation Project, http://qgis.osgeo.org).

RESOURCE AVAILABILITY

Lead contact

Further information and resource requests should be directed to the lead contact, Huadong Zang (zanghuadong@cau.edu.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

The data used in this study are publicly available on the Web of Science (www.webofscience.com) and the CNKI database (https://www.cnki.net). As some studies did not include information on climate or soil properties, we obtained the missing data from the World Climate Database (https://www.worldclim.org) and the Harmonized World Soil Database (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/) according to the geographic locations. The datasets and R scripts used in the current study have been deposited in Figshare under https://doi.org/10.6084/m9.figshare.26164030.

ACKNOWLEDGMENTS

This study was financially supported by the National Natural Science Foundation of China (32101850 and 32172125), the Joint Funds of the National Natural Science Foundation of China (U21A20218), the National Key Research and Development Program of China (2022YFD1901100), the Hainan Provincial Natural Science Foundation of China (320LH041), the Sanya Yazhou Bay Science and Technology City (SYND-2021-02), and the Graduate Student Innovation Research Fund Project of China Agricultural University (2024TC184).

AUTHOR CONTRIBUTIONS

Conceptualization, W.Y., Z.Z., and H.Z.; methodology, W.Y., Y.Y., D.B., J.Z. (author 4), J.Z. (author 6), T.C.W., and H.Z.; investigation, W.Y., Y.Y., and J.Z. (author 4); visualization, W.Y.; writing – original draft, W.Y.; writing review & editing, D.B., J.Z. (author 4), J.E.O., J.Z. (author 6), P.S., H.L., M.C.R., T.C.W., and H.Z.; funding acquisition, Z.Z. and H.Z.; supervision, Z.Z. and H.Z.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2024.12.006.

Received: July 27, 2024
Revised: October 10, 2024
Accepted: December 10, 2024
Published: January 2, 2025

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