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META-ANALYSIS

Crop residue return achieves environmental mitigation and enhances grain yield: a global meta-analysis

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Abstract

Inorganic fertilizers are widely used to provide crops with significant amounts of nitrogen (N) and phosphorus (P), but can exacerbate soil carbon (C) limitation and acidification. Crop residues with distinct ecological stoichiometry from inorganic fertilizers can help balance soil ecological stoichiometry and thus increase soil organic matter accumulation. The combined use of inorganic fertilizers and crop residues is expected to alleviate the metabolic limitations of organisms and enhance soil C, N, and P sequestration, hence increasing grain yields. However, the effects of this practice on soil C, N, and P stocks and grain yield remain unclear. In this study, we conducted a meta-analysis of 806 paired data to investigate the impact of crop residue return combined with inorganic fertilizer on soil and grain yield across different land uses (paddy, upland, paddy-upland rotation) and soil profiles (0–60 cm). Our findings indicate that crop residue return significantly enhances soil C (8–13%) stocks across all soil layers, particularly in the topsoil (0–20 cm). Soil N (9%) and P (5%) stocks also increase significantly in the topsoil. In uplands, crop residue return can mitigate soil acidification and increase grain yield (by 7%). Moreover, the soil C and N stocks increase depending on the initial soil pH, C and N levels, and C:N ratio. In contrast, the soil P stock increase depends on rainfall, while the grain yield increase is closely linked to the soil texture and fertilizer rate. Our study highlights that crop residue return can increase topsoil C, N, and P stocks, which can benefit crop growth and environmental mitigation efforts. Furthermore, this practice can increase C stocks in deeper soil horizons (below 20 cm), providing a long-term solution to mitigate climate change.

Keywords Organic fertilizer · Nutrient balance · Soil profile · Food security · Climate change · Land use · Crop residue return

1 Introduction

Soil is the largest available reservoir of carbon (C), nitrogen (N), and phosphorus (P) on land, not only providing fertility for crop growth but also mitigating environmental disturbances (Peñuelas et al. 2013). In the face of climate change and increasing soil nutrient losses, it is essential to sequester more C, N and P in soils (Liu et al. 2020a; Alewell et al. 2020; Zhang et al. 2017). Soil C, N, and P sequestration in natural ecosystems has become relatively stable and even saturated in some areas, but agroecosystems still have great potential to stock more C, N, and P through sustainable agronomic management (Yu et al. 2018; Liu et al. 2023). Whereas the topsoil C, N, and P stocks are relatively high and closely related to climate change and agronomic management, the deeper soil C, N, and P stocks and driving mechanisms are poorly understood (Balesdent et al. 2018; Liu et al. 2021; Chen et al. 2022). Furthermore, while topsoil C, N, and P stocks are generally in the form of organic matter with a close linkage of a simultaneous increase or decrease, there is little understanding of whether the C, N, and P in deeper soil are also closely linked, and the underlying mechanisms are less understood.

Inorganic fertilizer (chemical fertilizer) is an almost irreplaceable agronomic management practice to supply crops with nutrients, having contributed to a 30–50% increase in grain yield in the last half century (Yu et al. 2019). However, the limited efficiency of crops in utilizing inorganic fertilizer has increased the residual N and P in the soil, resulting in an imbalance in soil ecological stoichiometry (Abbruzzini et al. 2019; Liu et al. 2021, 2023). This leads to microbes being in C-limited environments, exacerbating soil organic matter

Extended author information available on the last page of the article mineralization to maintain their ecological stoichiometric homeostasis (Liu et al. 2023; Zechmeister-Boltenstern et al. 2015). Furthermore, these inorganic forms of N and P are typically not retained in the topsoil for a long time and are eventually lost in biogeochemical processes (Liu et al. 2020a; Martínez-Mena et al. 2020). Consequently, several environmental problems can arise, such as increased greenhouse gas emissions and water eutrophication (Shen et al. 2014; Fischer et al. 2017; Liu et al. 2022). Thus, the application of inorganic fertilizer alone depletes soil organic matter, threatening the eco-environment with respect to greenhouse gas emissions at a global and water quality degradation at a local scale.

Crop residue has a distinct ecological stoichiometry compared to inorganic fertilizer and is characterized by a high C:N(P) ratio (Liu et al. 2021, 2023; Tempesta et al. 2022). Because crop residues contain low N (1.7%) and P (0.4%) concentrations and are characterized by lignocellulosic biomass that is difficult to decompose, they are often burned in conventional agriculture, emitting large amounts of carbon-dioxide into the atmosphere and contributing to global warming (Liu et al. 2021; Deligios et al. 2021; Kaur et al. 2022). Given the high C concentrations of crop residue, it can alleviate soil C limitation caused by inorganic fertilizer application, thus slowing organic matter mineralization and increasing grain yield (Zechmeister-Boltenstern et al. 2015; Liu et al. 2021). Moreover, unlike the rapid leaching of inorganic N and P (especially nitrate-N), crop residue tends to increase stable soil organic matter (humic compounds), which can increase the soil exchangeable capacity, contributing to the better retention and slow release of nutrients, thus increasing its potential use efficiency (Liu et al. 2020b; Huddell et al. 2020). Crop residue return is expected to balance the soil ecological stoichiometry imbalance caused by inorganic fertilizer alone, thereby increasing soil organic matter accumulation. With the increase in soil organic matter accumulation, soil C, N, and P can be increased to mitigate the environmental problems caused by conventional agriculture, thus achieving a win-win situation for both environmental mitigation and food security.

Despite the growing interest in promoting crop residue return, uncertainties still exist regarding the sequestration of soil C, N, and P and the resulting increase in grain yield, especially in different soil layers and agroecosystems. Previous research has focused mainly on the effects of crop residue return on topsoil (0–20 cm), which is critical for providing nutrients for crop growth. However, the impact on deeper soil horizons (below 20 cm) requires further investigation (Chen et al. 2022; Liu et al. 2021). Deep soil horizons not only have more stable C storage, but there is also increasing evidence that soil N and P enrichment/legacy at deep soil horizons is the primary driver of water quality pollution in agricultural catchments (Balesdent et al. 2018; Gao et al. 2021; Liu et al. 2022). Moreover, paddy fields (flooded by long-term artificial irrigation) and uplands (water recharge mainly by rainfall) have distinct field water management practices, and differences in soil moisture affect not only the formation and decomposition of organic matter in the topsoil but also the potential for the downward leaching of C, N, and P under water saturation (Chen et al. 2021; Zheng et al. 2021). Thus, understanding the extent and mechanisms of soil C, N, and P stock responses across land uses and soil layers is crucial for promoting crop residue return strategies.

Currently, there is limited knowledge on the effects of crop residue return on soil C, N, and P stocks and grain yield under different land uses (paddy, upland, paddy-upland rotation) and in different soil horizons (topsoil: 0–20 cm; subsoil: 20–40 cm; deep soil: 40–60 cm). This knowledge gap leads to uncertainty in evaluating crop residue effects at large scales. To address these issues, we conducted a meta-analysis of 806 paired data from 261 publications (Fig. 1). Our study aimed to (1) quantify the effects of combined crop residue return and inorganic fertilization (CR) versus inorganic fertilizer application (IF) treatments on soil C, N, and P stocks; (2) explore the linkages between these effects and environmental variables; and (3) elucidate the effects of altered soil C, N, and P stocks on grain yield.

2 Methods

2.1 Data collection

Peer-reviewed articles published until August 2022 were searched from Web of Science (https://www.webofscience.com/), Google Scholar (https://scholar.google.com/), and China National Knowledge Infrastructure (https://oversea.cnki.net/index/) for related field studies on soil C, N, and P concentrations and ratios and grain yields following IF and CR treatments (Fig. S1) (References of the meta-analysis). All studies included in the final dataset had to meet the following criteria: (1) This study used 100% or > 80% of the crop residual return treatments (in some studies, there were no 100% return treatments) as CR; (2) the experimental period covered at least one complete crop cycle; (3) land use type and crop species were described or could be searched from related articles; (4) the IF and CR treatments should be spatially neighboring to ensure that there are no significant differences in microclimate and soil properties; (5) total N and P inputs for the IF and CR treatments were same or similar (since crop residues introduce some N and P, and few studies have been able to subtract the corresponding additional N and P brought in by crop residues from the chemical fertilizer inputs at the same time, it would result in the total amount of N and P inputs from CR treatments are slightly higher than that from IF treatments. In this study, to reduce uncertainty,

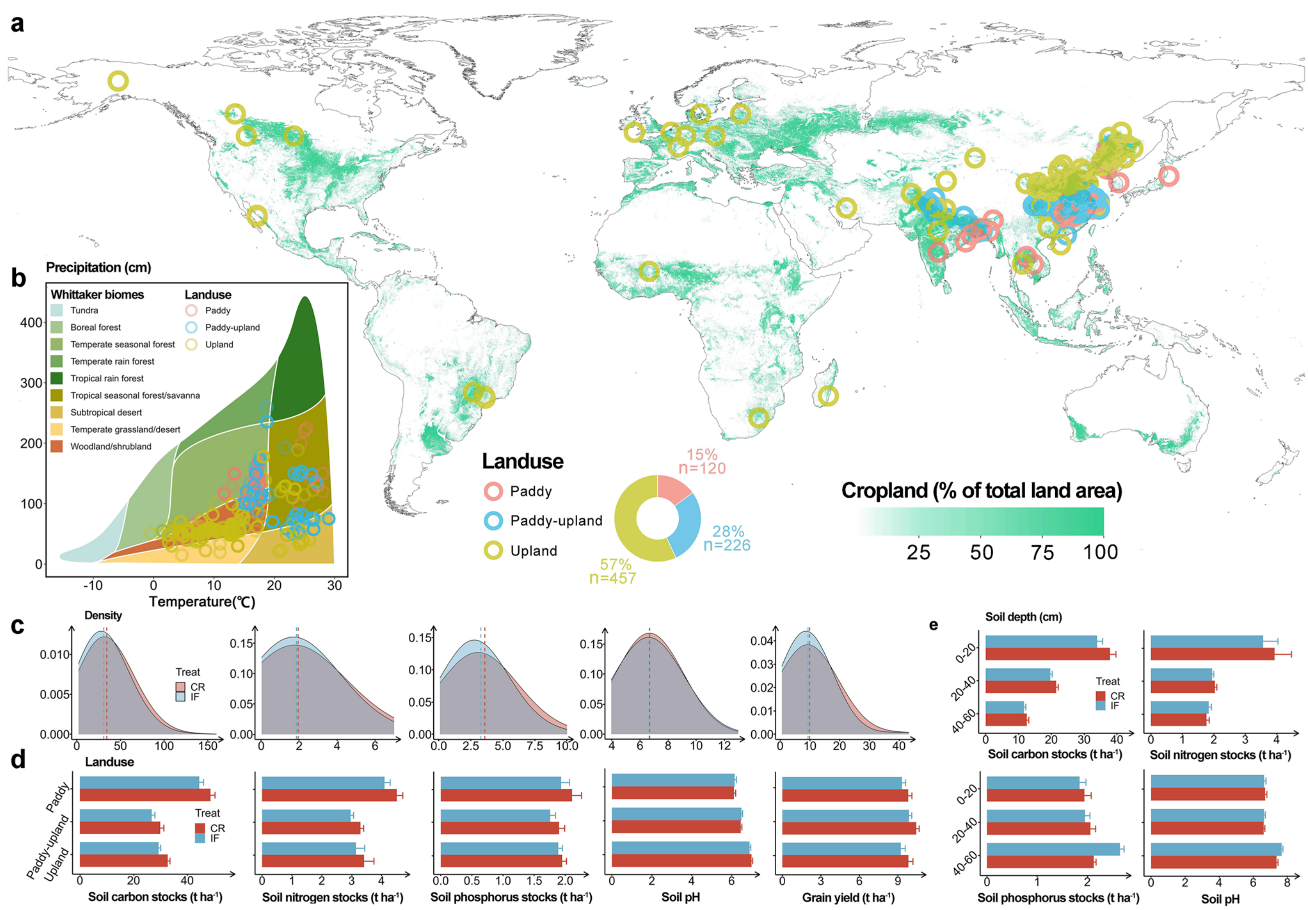

Fig. 1 Sampling location (**a**) and soil carbon, nitrogen, and phosphorus stocks, pH, and grain yield density (**b**), at different land uses (**c**), and at different soil depths (**d**). IF, inorganic fertilizer; CR, combined crop residue return and inorganic fertilization.

we selected only studies that had a surplus of N and P of no more than 10% for CR treatments compared to IF treatments for inclusion in the statistics), where the IF treatment was treated as the control; (6) postharvest soil properties were recorded for use in statistical analysis. As a result, we found 806 independent paired observations from 236 peer-reviewed studies globally (Fig. 1). The selected observations covered the most of climate zones except for tundra and tropical rainforests (Fig. 1).

Data extracted from the studies comprised (1) land use type, categorized as paddy (long-term flooded cropland used for the cultivation of aquatic crops, such as rice), upland (rainfed cropland, with no irrigation facilities), and paddy-upland rotations; (2) crop type (species); (3) experimental duration; (4) latitude and longitude; (5) climatic variables (mean annual rainfall/precipitation (MAP); mean annual air temperature (MAT); aridity index, (AI)); (6) initial soil physical properties (sand, silt, clay concentrations; bulk density (BD)); (7) initial soil chemical properties (total organic C (TOC), soil total N (TSN), and soil total P (TSP) concentrations; soil pH); (8) rate of inorganic fertilizer N, P, and potassium (K) inputs; (9) number of experimental replicates and soil sample depth; 10) crop postharvest soil C, N, and P concentrations (g kg^{-1}) and stoichiometric ratio (molar ratio; if only absolute masses or mass ratios were reported, we converted the data to molar ratios) as well as errors for the IF and CR treatments; and (11) grain yields and soil pH as well as errors for the IF and CR treatments. We extracted data from tables and text directly, while data reported in figures were extracted using GetData Graph Digitize software (version 2.25.0.32). If the MAT and MAP were not reported, they were obtained from the 1970–2000 mean climate data from the World Climate Database (https://worldclim.org) using ArcGIS 10.2 software. Missing soil BD was extracted from the Harmonized World Soil Database v 1.2 (https://iiasa.ac.at/models-tools-data/hwsd). Soil C, N, and P stocks were calculated based on soil C, N, and P concentrations and BD:

$$\mathrm{TOC(TSN;TSP)stock} = \mathrm{TOC(TSN;TSP)} \times \mathrm{BD} \times \frac{20}{10} \quad (1)$$

where TOC/TSN/TSP is the soil C/N/P concentration (g kg^{-1}) and BD is the treatment-specific soil BD (g cm^{-3}).

The numbers 20 and 10 are the soil depth (cm) and area conversion factor, respectively.

The missing AI was derived from the Global Aridity Index and Potential Evapotranspiration Climate Database v2 (Zomer et al. 2022) and was calculated as follows:

$$\mathrm{AI} = \frac{\sum_{i-1}^{30}\left(\frac{R_i}{PET_i}\right)}{30} \tag{2}$$

where i denotes the ith year of study and R_i and PET_i are the rainfall and potential evapotranspiration in year i, respectively.

2.2 Data analysis

The classical meta-analysis of response ratios (RR) (Hedges et al. 1999) was used to evaluate the effects of CR vs. IF treatments on soil C, N, and P stocks and grain yields. Soil pH is critical to soil organic matter formation and nutrient availability and is an essential variable for statistical analysis. The natural logarithm of RR, which was used to represent the effect sizes of the soil C, N, and P properties, soil pH, and grain yields, was calculated as follows:

$$RR = \ln\left(\frac{\overline{x}_T}{\overline{x}_C}\right) \tag{3}$$

where $\overline{x}_C$ and $\overline{x}_T$ are the respective means of the IF and CR treatments (standardized by year). Variance was calculated as follows:

$$var(RR) = \frac{SD_T^2}{N_T\overline{x}_T^2} + \frac{SD_C^2}{N_C\overline{x}_C^2} \tag{4}$$

where SD_C^2 and SD_T^2 are the standard deviations and N_C and N_T are the sample sizes for the control and crop residue treatments, respectively. When the standard error (SE) was given instead of SD in the selected studies, we converted the SE to SD using the following formula:

$$SD = \sqrt{n} \times SE \tag{5}$$

The weighting factor (W_{ij}) for each RR was calculated using the following equation:

$$W_{ij} = \frac{1}{var(RR)} \tag{6}$$

The weighted response ratio (RR_{++}) and standard error of RR_{++} (S) were calculated from the RR values of the same subgroup by weighting as follows:

$$RR_{++} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{k} W_{ij}RR_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{k} W_{ij}} \tag{7}$$

$$S(RR_{++}) = \sqrt{\frac{1}{\sum_{i=1}^{m}\sum_{j=1}^{k} W_{ij}}} \tag{8}$$

where m is the number of studies in the subgroup and k is the number of experimental replicates in the study.

The interpretation of RR_{++} was facilitated by transforming the mean values and the confidence intervals (CIs) to percentages:

$$\left(e^{RR_{++}} - 1\right) \times 100\% \tag{9}$$

This study used the standard error (SE) to represent the indicator errors. The weighted effect sizes for the CR compared to the IF treatments were calculated using a random effects model, along with 95% CIs using the "Metafor" package in R. Values > 0 and < 0 indicated positive and negative effects, respectively, and CIs that overlapped with 0 indicated a nonsignificant effect. Subgroup categories were based on land use patterns and soil layers. Pearson correlation analysis was used to test for associations between environmental variables and soil C, N, and P stocks and soil pH and grain yield using the "GGally" package in R. The Köppen climate classification was used to group the data for climate zone analysis (A, tropical; B, arid; C, temperate; D, cold). No samples were located in polar zones (Beck et al. 2018). The Wilcoxon test was used to test for significant differences between climate zones. The random forest model was performed using the "randomForest" package in R (Breiman 2001) to quantify the relative contribution of environmental variables associated with crop residue impacts, and variables that did not contribute significantly to the random forest model were removed. Furthermore, a partial least squares pathway model was used to establish pathway relationships between RR-Yield/RR-TOC and environmental variables (all variables with loadings less than 0.7 were removed) (Russolillo 2012). In addition, the stepwise multivariate fit model (two-way) was conducted using the "MASS" package in R (Venables and Ripley 2002) to identify the most parsimonious predictor variables for the random forest model. The above statistical analyses were performed using R 4.0.3 (R Development Core Team 2020).

3 Results

3.1 The responses of soil C, N, and P stocks, pH, and grain yield to crop residue return

Crop residue return increased the soil C, N, and P stocks along the soil profile, but the increases in the N and P stocks in subsoil and deep soil horizons were insignificant (Fig. 2). Overall, the average crop residue return increased the C stock by 11.8% (CI: 30.9±0.7–34.4±0.7 t ha^{-1}), which increased significantly among soil layers (Fig. 1). Taking all data together, we observed that the soil C stock increased by 12.7% in the topsoil, 8.2% in the subsoil horizon, and 9.5% in the deep soil horizon. Moreover, crop residue return contributed differently to soil C stocks under various land use types, with the highest increase in soil C stocks in the paddy-upland rotation (12.1%), followed by upland (11.9%) and paddy (11.1%) fields. The average increase in soil N (8.8%; 3.28±0.23–3.59±0.26 t ha^{-1}) and P (5.2%; 1.86±0.11–1.95±0.11 t ha^{-1}) stocks were due to crop residue return. The increased soil N and P stocks were observed mainly in the topsoil, where the values increased by 10.2% and 5.9%, respectively. While the soil N stock (11.7%) increased the most in paddy fields, the soil P stock (9.4%) increased the most in paddy-upland rotations and did not differ significantly among land use types.

Crop residue return also changed the soil ecological stoichiometry due to different rates of C, N, and P increases. The soil C:N, C:P, and N:P ratios increased by 2.9%, 8.3%, and 3.0%, respectively, in the overall data. The increases in the C:N (4.3%) and C:P (10.3%) ratios were more evident in the upland areas, while the N:P ratio (5.9%) was more evident in paddy fields. Although overall crop residue return did not significantly affect soil pH, there was increase in the uplands (1.7%; 5.86 to 6.07) and topsoil (1.0%; 6.64 to 6.69) (Fig. 2g).

The return of crop residue to the field increased the average grain yield by 6.9% (CI=5.6–8.1%), with the greatest improvement in uplands (7.5%), followed by paddy-upland rotations (5.8%) and paddy fields (5.6%).

3.2 Environmental drivers of crop residue return

The improvement in the soil C, N and P stocks as well as the pH and grain yield by crop residue return depended mainly

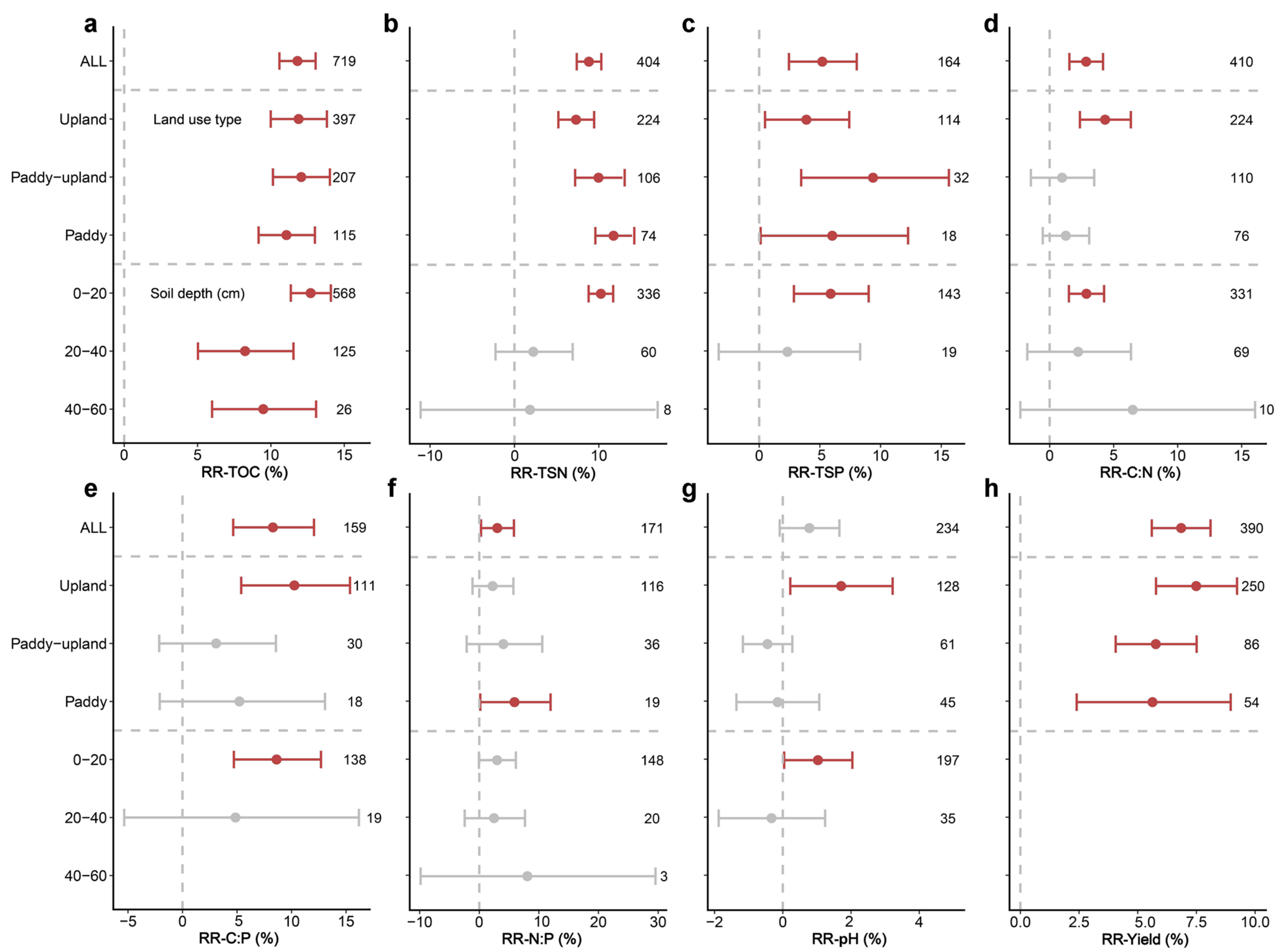

Fig. 2 Weighted effect values (RR) of soil carbon (TOC), nitrogen (TSN), and phosphorus (TSP) stocks (**a**–**c**) and ratios (**d**–**f**), pH (**g**), yield (**h**) under different land uses and in different soil layers. The value on the right (left) side of the error bar is the sample size.

on the initial soil properties and rainfall conditions (R^2 = 0.27–0.62; $p < 0.05$) (Figs. 3 and 4). The potential soil C and N stocks were influenced mainly by the initial soil pH and C and N concentrations, while rainfall conditions mainly drove the soil P stocks. In addition, soil texture contributed more to grain yield improvement than did the fertilizer rate, climatic conditions, and soil chemical properties. In particular, a significant positive correlation was found for the increased soil C, N, and P stocks, which implied that crop residue return increased the soil organic matter accumulation.

The partial least squares pathway model suggested that the increased soil C stock from crop residue return could further enhance grain yield (goodness of fit = 0.48; n = 99) (Figs. 5, S8, and S9). Although the increased soil C stock (total effect = 0.14) had a significant increasing effect on grain yield, the initial soil texture (total effect = 0.15) was more critical for the grain yield potential. Furthermore, whereas crop residue return led to increased C stocks across all soil layers, only an increase in the topsoil significantly enhanced the grain yield (Fig. S10).

Crop residue return had significant spatial-temporal heterogeneity with respect to soil C, N, and P sequestration and grain yield improvement (Fig. S11, S12 and S13). The soil C and N stocks reached saturation approximately 20 years after the successive return of crop residues ($p < 0.01$), whereas the P stocks showed no significant temporal trend. In contrast, soil pH continued to trend upward for more than 30 years ($p < 0.01$). Spatially, crop residue return was most effective for C sequestration in the tropics (21.8%) ($p < 0.05$). Although crop residue return in the tropics (17.8%) resulted in higher N sequestration than that in the cold regions ($p < 0.05$), there was no significant difference compared to other climatic zones.

4 Discussion

4.1 Soil C stocks increase across the soil profile, but N and P stocks increase only in the topsoil

Our study demonstrates that the return of crop residues to the soil can increase the soil C stocks across the soil profile, while the increase in the N and P stocks is limited to the topsoil (Fig. 2). Our quantitative analysis shows that crop residue return increases the topsoil C stock by 11.8%, which supports previous evaluations based on increased soil C concentrations (10.5–14.9%) (Liu et al. 2023; Xia et al. 2018). Crop residues have high amounts of C organic matter that can mitigate soil C limitation caused by inorganic fertilizer application (Liu et al. 2023; Zechmeister-Boltenstern et al. 2015). Then, crop residue return both slows microbial mineralization of organic matter and acts as an additional C input compared to inorganic fertilizer treatments. Moreover, we found that crop residue return increased the C stock in subsoil and deep soil horizons, and this increase was generally stable and essential for climate mitigation. Although

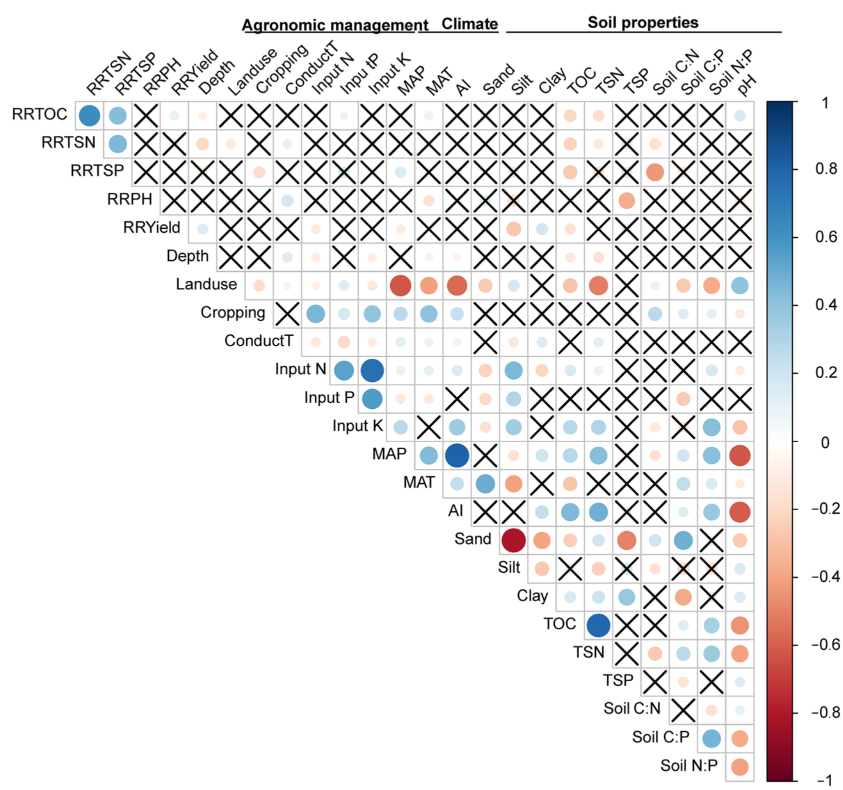

Fig. 3 Correlation analysis between weighted effect values (RR) of soil carbon (TOC), nitrogen (TSN) and phosphorus (TSP) stocks, pH, and grain yields (Yield) and agronomic management, climate, and soil properties. Duration, experimental duration; MAP, mean annual rainfall/precipitation; MAT, mean annual temperature; AI, aridity index.

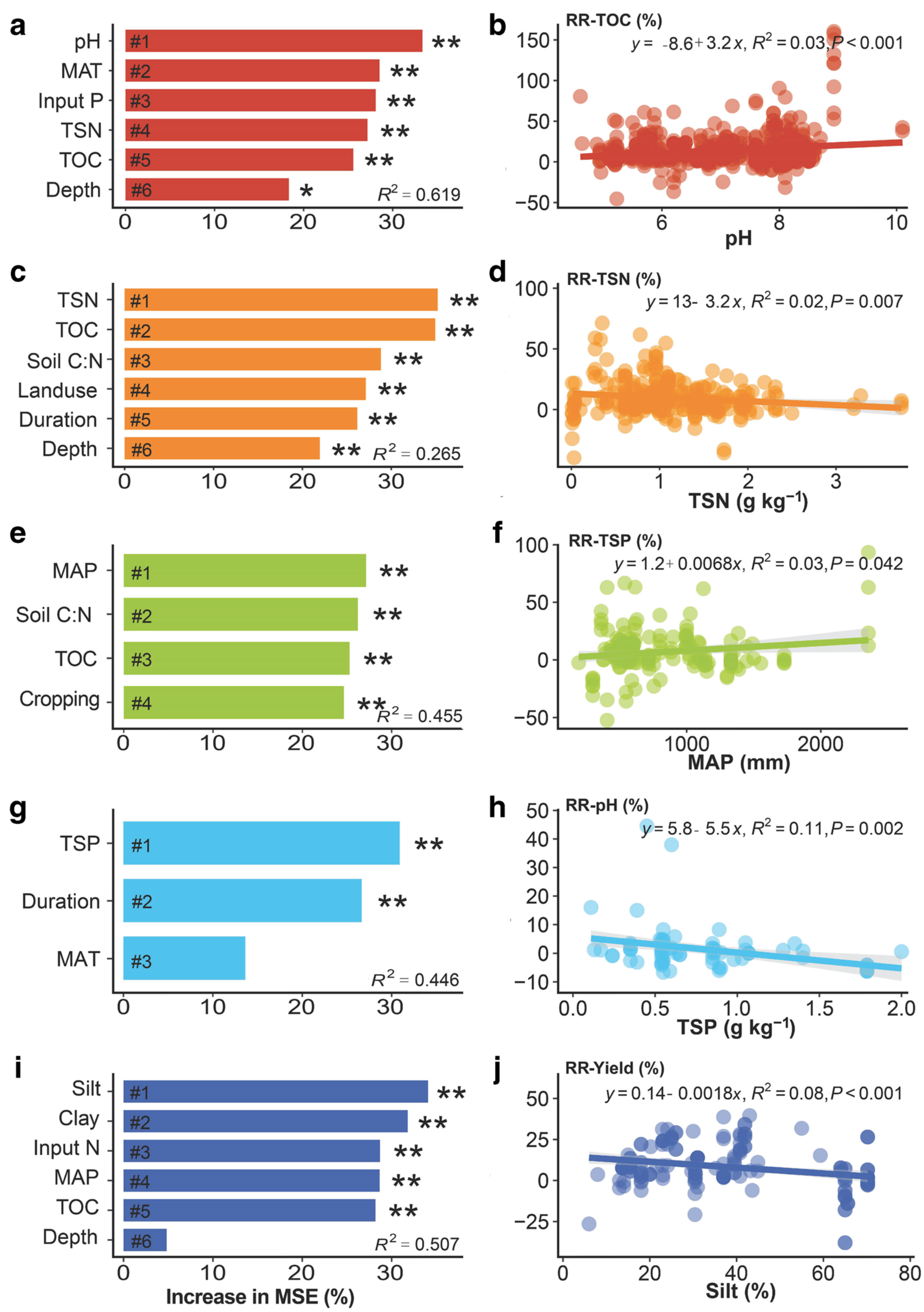

Fig. 4 Contribution of environmental factors to the weighted effect values (RR) of soil carbon (TOC), nitrogen (TSN), and phosphorus (TSP) stocks, pH, and yield. Duration, experimental duration; MAP, mean annual rainfall/precipitation; MAT, mean annual temperature; AI, aridity index.

most of the C in the soil exists in the form of organic matter, especially in agroecosystems and acidic soils, microbial mineralization processes can decompose organic matter into inorganic C (Liu et al. 2021; Lal 2004). The microbial C use efficiency is only 30–50%, which means that a large proportion of inorganic C will be released into the atmosphere or leached into the deeper soil layers (Chen et al. 2020). Crop residue return mitigates C limitation in the topsoil, as shown by the increased soil C:P and C:N ratios. This can further reduce soil biological C use efficiency, increasing inorganic C infiltration and C stocks in the subsoil and deep soil horizons.

Despite the low N concentration (0.4–0.9%) of the crop residues themselves (Christensen 1986; Liu et al. 2021), their return was still able to increase the soil N stock by 10.2%, a percentage similar to the increase in the topsoil C stock (12.7%) (Fig. 2a and b). This suggests that crop residue return not only immobilizes the organic N input but also sequesters inorganic N to form additional organic matter and decreases N loss. As a result of the additional

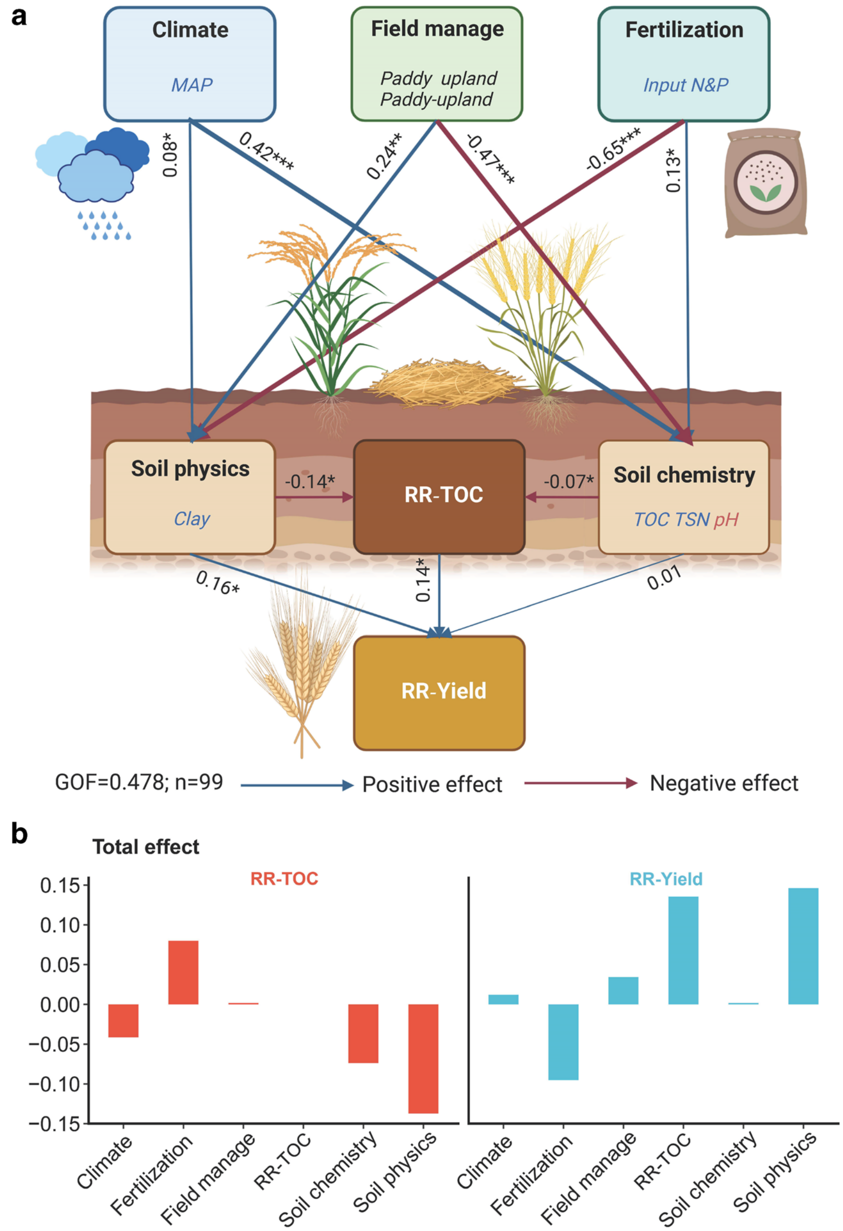

Fig. 5 The partial least squares pathway model (PLS-PM) disentangles the main pathways of the influence of the key climate, field management, fertilization, soil physics and chemistry on the weighted effect values (RR) of soil carbon (TOC) and grain yield (Yield) (**a**) and the total effects of these variables (**b**). * Denotes $p < 0.05$, ** denotes $p < 0.01$, *** denotes $p < 0.001$. MAP, mean annual rainfall/precipitation; TSN, soil nitrogen.

C input, the microbes sequester more inorganic N and P, forming organic matter and maintaining their homeostasis (Liu et al. 2023; Penuelas et al. 2019). This finding is supported by our long-term field trials based on consecutive 6-year experiments with crop residue return, with an average increase in crop N use of 0.07 t ha^{-1} year^{-1}, which is higher than the crop residue N input of 0.04 t ha^{-1} year^{-1}, and the topsoil N stock increased by 0.18 t ha^{-1} relative to the inorganic fertilizer treatment in paddy fields (Liu et al. 2021). Unlike the high percentage increase in soil C and N stocks, the increased in the soil P stock was relatively low in the topsoil (Fig. 2c). This is because most of the soil P exists in the form of inorganic P, and the contribution of organic matter that is increased by crop residue return is relatively weak to the soil P stock, which depends more on the initial soil inorganic P (mainly orthophosphate) background value (Goyne et al. 2008; Liu et al. 2023). Additionally, our study revealed that crop residue return had a limited impact on deeper soil N and P stocks. Although crop residue return increased the topsoil N and P, most of the N and P was in the form of organic matter, which also reduced the potential for the downward leaching of inorganic N and P, thus limiting the impact of crop residue return on the deeper soil N and P stocks. Given that the sequestered C, N and P are contained in the topsoil in the form of organic matter, this will not increase the risk of N and P leaching into groundwater while providing long-term nutrients for crop growth.

4.2 Variability in soil C, N, and P stocks across land uses

Crop residue return resulted in a higher increase in the soil C stock in uplands and paddy-upland rotations than in paddy fields, while the soil N stock increased more than in paddy fields (References of the meta-analysis) (Fig. 2). Generally, C and N constitute the largest concentration of soil organic matter excluding water, and they are tightly coupled with their accumulation and reduction in topsoil (Cleveland and Liptzin 2007; Li et al. 2012). However, our study shows that agronomic management should strongly mediate the topsoil C and N coupling relationship, particularly in anaerobic environments caused by flooding (Fig. 1a and b). Paddy fields are subjected to prolonged flooding, which limits the inhibition of aerobic microbial activity and the consequent production of critical enzymes such as phenol oxidase and hydrolase (Freeman et al. 2001). As a result, the mineralization rate of organic matter is lower in paddy fields than in uplands due to the thermodynamic limit of microbial decomposition (Chen et al. 2021). Simultaneously, the formed iron-organic associations contribute to soil C preservation through the adsorption of organic compounds or coprecipitation with iron oxides during frequent alternations of flooding and draining (Wei et al. 2022). These mechanisms result in 39-127% higher soil C in paddy fields than in adjacent uplands (Chen et al. 2021). Due to the soil C accumulation saturation mechanism, it is relatively difficult to further increase soil C in areas with a high soil C background (Liu et al. 2023; Craig et al. 2021). Therefore, the percentage increase in organic C due to crop residue return was more significant in uplands than in paddy fields.

On the other hand, an anaerobic environment can limit the activity of aerobic microbes, such as nitrifying bacteria (Tranckner et al. 2008), inhibiting the nitrification process, and further reduces N gas losses during denitrification in paddy fields (Fig. 2b). Moreover, the N:P ratio needed for crops to maintain their metabolism is approximately 16:1 (Liu et al. 2023), and soil N limitation (C:N < 16) is more severe in paddy fields (8) than in uplands (14), resulting in a higher crop N use efficiency and thus reducing the loss of inorganic N during metabolism. Therefore, the increase in the N stock by crop residue return is more significant in paddy fields than in to uplands.

The effect of crop residue return on P stocks was not significantly different across land use types and is subject to large errors (Fig. 2c). This was due to P cycle not existing in the form of gas emission, so flooding management does not affect the gas loss of P. Moreover, the organic P imported by crop residue is hydrolyzed by phosphatase enzymes to release soluble phosphate with poor mobility, which is easily adsorbed, complexed, and precipitated by soil particles, organic matter and minerals, as well as absorbed and immobilized by soil microbes, and so hardly leaches to the deeper soil layers (Liu et al. 2020a; Yan et al. 2018). As a result, most of the P imported from crop residues is immobilized in topsoil, and biogeochemical cycles induced by flooding management have a limited effect on P stocks.

Our findings suggest that crop residue return across all land uses can enhance soil fertility and environmental mitigation by increasing the soil C, N, and P stocks. However, the potential for mitigating global warming through C sequestration is most pronounced in uplands, while the possibility of mitigating regional water quality through N sequestration is most pronounced in paddy fields.

4.3 Environmental driving mechanisms of soil C, N, and P stocks

The impact of crop residue return on P stocks was affected primarily by rainfall, while the effect on soil C and N stocks was influenced mainly by the initial soil properties (Figs. 3 and 4). The soil C stock is mainly driven by soil pH due to the greater potential for accumulation with inhibited microbial decomposition of organic matter in alkaline soils (Kemmitt et al. 2006; Li et al. 2021). The soil N stock is mainly influenced by soil C and N concentrations and their ratio. Soils with low soil C and N concentrations have a higher potential for organic matter accumulation, while soils with low C:N ratios tend to be N-limited, where microbes can use N more efficiently to form organic matter and maintain their homeostasis (Zechmeister-Boltenstern et al. 2015; Liu et al. 2023). Thus, crop residue return is more favorable for soil C sequestration in areas with a low soil pH, while it is more favorable for soil N sequestration in areas with low soil C and N concentrations and C:N ratios.

In areas with high rainfall, crop residues return can effectively avoid soil erosion caused by rainfall directly washing over the soil surface, while the organic P input from crop residues is more difficult to move with hydrology than inorganic P (Liu et al. 2020a). Thus, promoting crop residue return in areas with higher rainfall has more potential for soil P sequestration. Notably, the effect of crop residue return on soil C and N stocks is mainly based on biochemical processes, while soil P stocks depend on physical and chemical processes.

4.4 Enhanced soil properties further improve grain yields

Crop residue return not only sequestered more soil C, N, and P but also reduced soil acidification, especially in upland areas (Fig. 2, 3, and Table S1). We found that 16.6% of upland soils are acidified, and crop residue return could increase soil pH in these areas. Upland soils have lower organic matter concentrations and cation exchange capacity than paddy soil, resulting in a lower acid-base buffering capacity (Guo et al. 2018). Thus, upland soils have a lower buffering effect on soil acidification than paddy and paddy-upland ecosystems, but crop residue return can mitigate this trend. Our study further revealed that the mitigation of soil acidification by crop residue return decreased with increasing soil P, which may be due to two mechanisms. First, crop residues release organic acids during decomposition, which cause P mobilization in the soil phosphate minerals and lower the soil pH (Roy et al. 2018; Kpomblekou-A and Tabatabai 2003); second, organic C input in soils with high P concentrations promotes heterotrophic microbial nitrification, leading to soil acidification (O'Neill et al. 2021). Crop residue return alleviates upland soil acidification, improving the soil nutrient supply, as evidenced by higher grain yield increases relative to those in paddy and paddy-upland rotations.

Soil physical properties are crucial in driving the effects of crop residue return on grain yield and are subject to climatic conditions, field management, and fertilizer input (Fig. 5). Although our results have showed that crop residue return generally increased grain yield, there is critical uncertainty. This is because the slow decomposition of crop residue can affect the rooting of the current season's crop, resulting in stiff seedlings and decaying roots (Álvaro-Fuentes et al. 2013; Liu et al. 2021). In addition, the lignin in crop residue is difficult to decompose and remains in the soil for a long time, hindering soil aeration and the rooting of the next season's crop (Chen et al. 2021). Our research showed that crop residue return effectively avoided the adverse effects mentioned above in areas with clay soil due to high soil porosity. Furthermore, we noted that crop residue return in regions with high inorganic fertilizer input had a limited impact on grain yield increases. This was due to the surplus supply of soil nutrients caused by excessive fertilizer application (Liu et al. 2020a), while the nutrients supplied by organic matter accumulation were less significant. Accordingly, we recommend crop residue return in clay soil areas to reduce the uncertainty of grain yield increases. Additionally, crop residue return can be an appropriate substitute for inorganic fertilizer input.

4.5 Implications and uncertainties

Our study found that returning crop residues to soil can increase the C, N, and P stocks, particularly in the topsoil (Fig. 6). Although the increase in the C stock in subsoil or deep soil horizons was less than that in topsoil, it was still higher than the 0.4% increase required to achieve climate mitigation effects and food security goals (Minasny et al. 2017). Considering the global cropland area (1.56 billion ha, https://www.fao.org/), returning crop residues to soil could sequester approximately 6.24 billion t C, 0.48 billion t N, and 0.14 billion t P, thereby mitigating climate warming and water eutrophication. Our study further showed that most of the sequestered C, N, and P was stored as organic matter in the topsoil, which can mitigate soil acidification and improve soil fertility for crops. Therefore, crop residue return can have a dual benefit of environmental mitigation and food security.

However, given the global heterogeneity of spatial and temporal environmental variables, it is essential to target and scale up crop residue return strategies. Our results suggest that there is a nonlinear saturation mechanism affecting the increase in soil C and N stocks by crop residue return with time (Fig. S11). Soil C and N sequestration tended to saturate approximately 20 years after crop residue returns, while the mitigating effect on soil acidification continued. Furthermore, the increasing trends of the soil C, N, and P stocks across soil profiles were mostly not statistically significant on the temporal scale (Fig. S12). However, both soil C and N stocks had a positive slope over time, and the slope was greater for subsoil and deep soil horizons than for topsoil. Therefore, different soil layers should have different time thresholds for soil C and N saturation. In the long term, we can expect a greater potential for C sequestration in subsoil and deep soil horizons, which are more stable and essential for long-term climate change mitigation. Spatially, our study highlights that crop residue return in the tropics

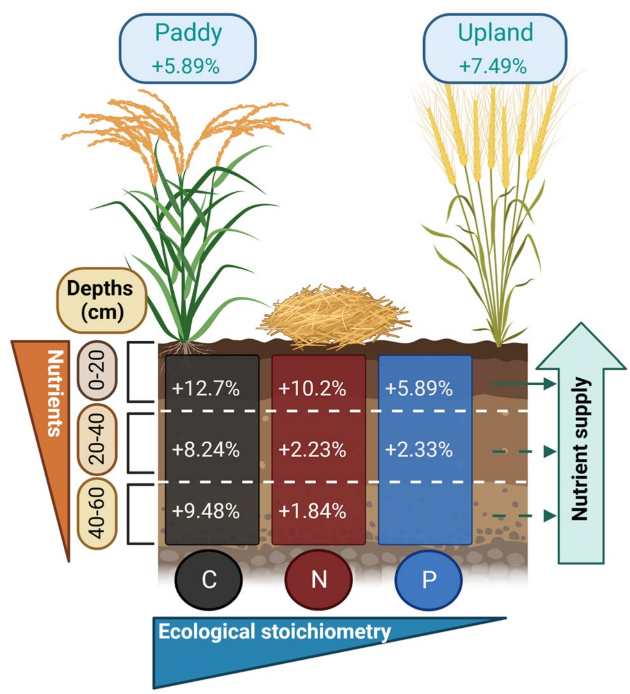

Fig. 6 Effect of crop residue return on soil carbon, nitrogen, and phosphorus stocks in different soil layers and the increased grain yield.

had higher benefits for soil C and N stocks (Fig. S13). Given that the tropics have more frequent cropping ecosystems due to favorable hydrothermal conditions for crops, crop residue return in the tropics should be prioritized to maintain soil fertility and improve the ecological-environment.

In the past, crop residue return experiments have focused primarily on field-scale grain production and nutrient cycling comparative experiments. It is widely accepted that topsoil contributes more to grain production and greenhouse gas emissions than subsoil or deep soil horizons. Thus, the environmental variables of the topsoil were more fully reported than those of subsoil or deep soil horizons. However, recent studies have shown that subsoil and deep soil horizons have distinct environmental conditions from topsoil (Chen et al. 2022, 2023), which may lead to different accumulation mechanisms of soil C, N, and P in different soil layers. Further research on the mechanisms of deep soil C, N, and P stocks could help in the understanding of elemental cycling and reduce their upward release as greenhouse gases and downward leaching into groundwater, thereby reducing environmental pollution.

5 Conclusion

In this study, by combining meta-analysis with machine learning models and path analysis models, we quantified, for the first time, the impacts of crop residue return combined with inorganic fertilizer versus inorganic fertilizer application on soil C, N, and P stocks in different land uses and soil profiles at the global scale, and we also identified the driving mechanisms. The study results showed that crop residue return increased C stocks across the soil profile, but increased P stocks only in the topsoil. Flooding management caused differential soil C and N accumulations in different land uses, while the percentage increase in C stocks was higher in uplands and paddy-upland rotations, whereas the percentage increase in N was higher in paddy fields. Moreover, crop residue return also mitigated soil acidification in upland soils, and combined with the increased soil C, N, and P, increased the grain yields in cropland. Furthermore, the soil C and N stocks increased depending on the initial soil pH, C and N levels, and C:N ratio. In contrast, the soil P stock increase depended on rainfall, while the grain yield increase was closely linked to the soil texture and fertilizer rate. Our study highlights that crop residue return can increase topsoil C, N, and P stocks, which can benefit crop growth and environmental mitigation efforts. Furthermore, this practice can increase C stocks in deeper soil horizons (below 20 cm), providing a long-term solution to mitigate climate change.

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Data availability All data used in this study are available at Figshare (https://doi.org/10.6084/m9.figshare.22707691).

Code availability Not relevant for this research.

Declarations

Ethics approval Not relevant for this research.

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