Liu, Ji; Fang, Linchuan; Qiu, Tianyi; [et al.]. «Crop residue return achieves environmental mitigation and enhances grain yield : a global meta-analysis». Agronomy for Sustainable Development, Vol. 43, issue 6 (Dec. 2023), art. 78. DOI 10.1007/s13593-023-00928-2

Crop residue return achieves environmental mitigation and enhances grain yield

Ji Liu[1, 2], Linchuan Fang[3*], Tianyi Qiu[4], Ji Chen[5*], Hai Wang[1], Muxing Liu[1], Jun Yi[1], Hailin Zhang[1], Cong Wang[1], Jordi Sardans[6, 7], Li Chen[4], Josep Penuelas[6, 7]

[1] Hubei Province Key Laboratory for Geographical Process Analysis and Simulation, Central China Normal University, Wuhan, 430079, China

[2] Department of Ecohydrology, Leibniz Institute of Freshwater Ecology and Inland Fisheries, Berlin, 12587, Germany

[3] College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, China

[4] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling, 712100, Shaanxi, China

[5] Department of Agroecology, Aarhus University, Blichers Allé 20, 8830 Tjele, Denmark

[6] CSIC, Global Ecology Unit CREAF-CSIC-UAB, 08193 Bellaterra, Catalonia, Spain.

[7] CREAF, 08193 Cerdanyola del Vallès, Catalonia, Spain

List of Author’s ORCID iDs:

Ji Liu (Orcid ID: 0000-0003-2496-9521)
Linchuan Fang (Orcid ID: 0000-0003-1923-7908)
Ji Chen (0000-0001-7026-6312)
Sardans Jordi (Orcid ID: 0000-0003-2478-0219)
Josep Peñuelas (Orcid ID: 0000-0002-7215-0150)

E-mail address(es):

Ji Liu: liuji17@mails.ucas.ac.cn
Linchuan Fang: flinc629@hotmail.com
Tianyi Qiu: qiutianyi@nwafu.edu.cn
Ji Chen: ji.chen@agro.au.dk
Hai Wang: wanghai@mails.ccnu.edu.cn
Muxing Liu: liumuxing@mail.ccnu.edu.cn
Jun Yi: yijun@ccnu.edu.cn
Hailin Zhang: hailzhang@ccnu.edu.cn
Cong Wang: wangcong@ccnu.edu.cn
Jordi Sardans: j.sardans@creaf.uab.cat
Li Chen: chenlixkd@163.com
Josep Peñuelas: josep.penuelas@uab.cat

***Corresponding author**

Dr. Linchuan Fang
Telephone: +86 1524920446
College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, China
Email: flinc629@hotmail.com

Dr. Ji Chen
Department of Agroecology, Aarhus University, Blichers Allé 20, 8830 Tjele, Denmark
Email: ji.chen@agro.au.dk

Abstract

Inorganic fertilizers are widely used to provide crops with significant amounts of nitrogen (N) and phosphorus (P). However, they can also exacerbate soil carbon (C) limitation and acidification. Recent studies suggest that the combined use of inorganic fertilizer and crop residues can help alleviate metabolic limitations of organisms and enhance soil C, N, and P sequestration. However, the effects of this practice on grain yield and soil C, N, and P stocks across different land uses and soil profiles 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 crop yields. Our findings indicate that crop residue returns significantly enhance soil C stocks (8-13%) 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 upland areas, crop residue return can mitigate soil acidification and increase grain yield (by 7%). Moreover, soil C and N stocks increase depending on the initial soil pH, C and N levels, and C:N ratio. In contrast, soil P stock increase depends on precipitation, while grain yield increase is closely linked to 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 also increase C stocks in deep soil, providing a long-term solution to climate change mitigation.

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 (Penuelas 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 (Alewell et al., 2020; Liu et al., 2020a; Zhang et al., 2018). Soil C, N and P sequestrated in natural ecosystems have become relatively stable and even saturated in some areas as sources of emissions, but agroecosystems still have a great potential to stock more C, N and P through sustainable agronomic management (Liu et al., 2023; Yu et al., 2018). 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; Chen et al., 2022; Liu et al., 2021). Furthermore, while topsoil C, N and P stocks are generally in the form of organic matter with a close linkage of simultaneous increase or decrease, there is little understanding of whether 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 to supply crops with nutrients, contributing to a 30-50% increase in food yield in the last half century (Gowariker et al., 2008). However, the crop's limited efficiency 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; Liu et al., 2023). This leads to microbes being in C-limited exacerbated soil organic matter 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 difficult to remain 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 (Fischer et al., 2017; Liu et al., 2022; Shen et al., 2014). Thus, inorganic fertilizer alone depletes the soil organic matter, threatening the global-scale eco-environment for greenhouse gas emissions and regionalized water quality degradation.

Crop residue has distinct ecological stoichiometry compared to inorganic fertilizer and is characterized by a high C: N(P) ratio (Liu et al., 2021; Liu et al., 2023). Given the high C concentrations of crop residue, it can alleviate soil C limitation caused by inorganic fertilizer application, thus hopefully slowing down organic matter mineralization and increasing grain yield (Liu et al., 2021; Zechmeister-Boltenstern et al., 2015). Moreover, unlike the rapid leaching of inorganic N and P (especially nitrate-N), crop residue tends to increase stable soil organic matter (humic), which can increase the capacity of soil exchangeable capacity contributing to better retention and slow release of nutrients, thus increasing its potential use efficiency (Huddell et al., 2020; Liu et al., 2020b). Therefore, crop residue returns promises to be a win-win agricultural mode regarding 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 mainly focused on the effects of crop residue return on topsoil (0-20 cm), which is critical for providing nutrients to crop growth. However, the impact on deeper soils (> 20 cm) requires further investigation (Chen et al., 2022; Liu et al., 2021). Deep soils not only have more stable C storage, but there is also increasing evidence that deep soil N and P enrichment/legacy 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 and uplands have distinct field water management, and differences in soil moisture affect not only the formation and decomposition of organic matter in the topsoil but also the potential for downward leaching of C, N, and P with water saturation (Chen et al., 2021; Zheng et al., 2021). Thus, understanding the extent and mechanisms of soil C, N, and P stocks response 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 for different land uses (paddy, upland, paddy-upland rotation) and 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. Our study aimed to: 1) quantify the effects of inorganic fertilizer application (IF) versus combined crop residue return and inorganic fertilization (CR) treatments on soil C, N, and P stocks in different soil layers; 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. Method

2.1. Data collection

Peer-reviewed articles 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 by August 2022 (Fig. S1). All studies included in the final dataset must 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 can be searched from related articles; 4) microclimate and edaphic properties were similar between IF and CR treatments; 5) N and P inputs for the IF and CR treatments were similar, where the IF treatment was treated as the control; and 6) post-harvest soil properties were recorded for use in statistical analysis. As a result, we found 806 independent paired observations from 236 peer-reviewed studies across the globe (Fig. S2). The selected observations covered the majority of climatic zones except for the tundra and tropical rainforest (Fig. S3).

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 (rain-fed 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 precipitation (MAP); mean annual air temperature (MAT);

aridity index, (AI)) ; 6) initial soil physical properties (sand, silt, clay content; 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) the rate of inorganic fertilizer N, P, and potassium (K) inputs; 9) number of experimental replicates and soil sample depth; 10) crop post-harvest soil C, N, and P concentrations (g kg^{-1}) and stoichiometric ratio (molar ratio; if only absolute masses or mass ratios are reported, we converted 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 collected from the 1970–2000 mean climate data from the World Climate Database (https://worldclim.org) using ArcGIS 10.2 software. For missing soil BD, it was extracted from 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 concentration and BD:

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

where, TOC/TSN/TSP was the soil C/N/P concentration (g kg^{-1}), and BD was the average soil BD (g cm^{-3}) for a specific treatment. The numbers 20 and 10 represent the soil depth (cm) and area conversion coefficient, respectively.

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

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

where i denotes the ith year of study; P_i and PET_i were precipitation and potential evapotranspiration in the 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 soil C, N and P properties, soil pH, and grain yields, was calculated as follows:

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

where $\bar{x}_C$ and $\bar{x}_T$ were the means of the IF and CR treatments (standardized by year), respectively. Variance was calculated as:

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

where SD_C^2 and SD_T^2 were the standard deviation and N_C and N_T were the sample size 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:

$$SD = \sqrt{n} \times SE \quad (5)$$

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

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

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

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

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

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

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

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

This study used 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 indicate positive and negative effects, respectively, and CIs that overlap with 0 indicate non-significant effect. Subgroup categories are based on land use patterns and varied soil layers. Pearson correlation analysis was used to test for associations between environmental variables with soil C, N and P stocks and soil pH and grain yield value, 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 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. Further, 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. Above statistical analyses were constructed in 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 soil C, N and P stocks along soil profile, but the increased N and P stocks in sub- and deep-soils were insignificant (Fig. 1 and 2). Overall, crop residue returns average increased C stock by 11.8% (CI: 30.9±0.7 - 34.4±0.7 t ha^{-1}), which increased significantly differed among soil layers (Fig. S4). Taking all data together, we observed that soil C concentration increased by 12.7% in the topsoil, 8.2% in the subsoil, and 9.5% in the deep soil. 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 field (11.1%). The average increased 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 by crop residue return was detected. And the increased soil N and P stocks were mainly observed in the topsoil, which was increased by 10.2% and 5.9%, respectively. While soil N stock (11.7%) increased the most in paddy fields, 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 soil ecological stoichiometry due to different rates of C, N, and P increased. Soil C: N, C:P, and N:P ratios increased by 2.9%, 8.3%, and 3.0%, respectively, in overall data. The increased in C: N (4.3%) and C:P (10.3%) ratios were more evident in the upland, while the N:P ratio (5.9%) was in paddy fields. Although overall crop residue return did not significantly affect soil pH, it was markedly enhanced in upland (1.7%; 5.86 to 6.07) and topsoil (1.0%; 6.64 to 6.69).

Returning crop residue to the field average increased grain yields by 6.9% (CI=5.6-8.1%), with the greatest improvement in upland (7.5%), followed by paddy-upland rotations (5.8%) and paddy field (5.6%).

3.2. Environmental drivers of crop residue return

The improvement of soil C, N and P stocks as well as pH and grain yield by crop residue return, depends mainly on the initial soil properties and precipitation conditions (R^2 = 0.27-0.62; $P < 0.05$) (Fig. 2 and 3). The potential of soil C and N stocks was mainly influenced by initial soil pH, C and N concentrations, while precipitation conditions especially drove that of soil P stocks. And soil texture contributed even more to grain yield improvement than fertilizer rate, climatic conditions, and soil chemical properties. Particularly, a significant positive correlation was found for the increased soil C, N and P stocks, which implies that crop residues returned increased the soil organic matter accumulation.

The partial least squares pathway model suggested that increased soil C stock by crop residue return can further enhance grain yield (Goodness of Fit = 0.48; n = 99) (Fig. 4, S8 and S9). Although increased soil C stock (total effect = 0.14) was significant for enhanced grain yield, the initial soil textures (total effect = 0.15) were more critical for the grain yield potential. Further, whereas crop residue returns lead to increased C stock across all soil layers, only an increased in the topsoil significantly enhanced grain yield (Fig. S10).

Crop residue return had significant spatial-temporal heterogeneity for soil C, N and P sequestration and grain yield improvement (Fig. S11, S12 and S13). Soil C and N stocks reached saturation around 20 years after the return of successive crop residues ($P < 0.01$), whereas P stock shows no significant trend on the time scale. In contrast, soil pH continued to trend upward over more than 30 years of observed data scales ($P < 0.01$). Spatially, crop residue return was most effective for C sequestration in the tropics (21.8%) ($P < 0.05$). Though crop residue returns in the tropics (17.8%) sequestered more N than in the cold regions ($P < 0.05$), there was no significant difference compared to other climatic zones.

4. Discussions

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

Our study demonstrates that returning crop residues to the soil can increase soil C, N, and P stocks across the soil profile, while the increase in N and P stocks is limited to the topsoil (Fig. 1). Our quantitative analysis shows that returning crop residues can increase topsoil C stock by 11.8%, which supports previous evaluations based on increased soil C content (10.5-14.9%) (Liu et al., 2023; Xia et al., 2018). Crop residues are high-C organic matter, and their application to the soil can alleviate soil C limitation caused by inorganic fertilizer applications alone (Liu et al., 2023; Zechmeister-Boltenstern et al., 2015). This is achieved by slowing down microbial mineralization of organic matter while also acting as an additional input of C itself, compared to inorganic fertilizer applications alone. Moreover, we found that returning crop residues can increase C stock in deeper soils, which is generally more stable and essential for coping with climate mitigation. Although most of the C in the soil exists in the form of organic matter, especially in agroecosystems nearing 100%, microbial mineralization processes can decompose organic matter into inorganic C (Liu et al., 2021). 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). As crop residue return mitigates C limitation in the topsoil, the evidence is derived from 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 deep soil.

Despite the limited N content concentration (0.4-0.9%) of crop residues themselves (Christensen, 1986; Liu et al., 2021), their return still increases soil N stock by 10.2%, a percentage similar to the increase in topsoil C stock (12.7%). 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 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). Our long-term field trials support this finding, based on consecutive six-year experiments with crop residue return, with an average increase in crop N use of 0.07 t ha-1 yr-1, which is higher than the crop residue N input of 0.04 t ha-1 yr-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 increase in soil P stock was relatively lower in the topsoil. This is because most of the soil P exists in the form of inorganic matter, and the contribution of organic matter 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 found that crop residue return has a limited impact on deeper soil N and P stocks. Although crop residue returns increase topsoil N and P, most of those N and P are in the form of organic matter, which also reduces the potential for 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 topsoil in the form of organic matter, this will not increase the risk of leaching of N and P into groundwater while also providing long-term nutrients for crop growth.

4.2. Variability in soil C, N, and P stocks across land use Crop residue return has a higher increase in soil C stock in upland and paddy-upland rotation than in paddy fields, while soil N stock increases more than in paddy fields (Fig. 1). Generally, C and N constitute the largest content 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 the anaerobic environment caused by flooding (Fig. 1a and 1b). 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 slower 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 co-precipitation 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 adjacent uplands (Chen et al., 2021). Given that the initial C stock is higher in paddy fields than in uplands, the percentage increase in organic C by crop residue return is more significant in uplands.

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, further reducing the N loss in denitrification in paddy fields. Moreover, paddy fields are generally N-limited and have a lower C:N ratio than uplands (12.1 vs. 16.4), resulting in a higher N use efficiency, thus reducing the loss of inorganic N during metabolism (Liu et al., 2023). Therefore, the increase in N stock by crop residue is more significant in paddy fields compared to uplands.

While soil carbon (C) and nitrogen (N) stocks exhibit distinct differences across land use types, soil phosphorus (P) stocks have a larger margin of error due to the limited effect of irrigation management on P cycling. This is because P has poor mobility and combines with soil minerals, resulting in a lack of gaseous loss pattern (Liu et al., 2020a). Our findings suggest that crop residue return across all land uses can enhance soil fertility and environmental mitigation by increasing soil C, N, and P stocks. However, the potential for mitigating global warming through C sequestration is more pronounced in uplands, while the possibility of mitigating regionalized water quality through N sequestration is more pronounced in paddy fields.

4.3. Environmental driving mechanisms for soil C, N, and P stocks

, The impact of crop residue return on P stocks is primarily affected by precipitation conditions, while the effect on soil C and N stocks is mainly influenced by initial soil properties. 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). Soil N stock is mainly influenced by soil C and N contents and their ratio. Soils with low soil C and N contents have a higher potential for organic matter accumulation, while low C:N ratios tend to be N-limited, where microbes can use N more efficiently to form organic matter and maintain their homeostasis (Liu et al., 2023; Zechmeister-Boltenstern et al., 2015). Therefore, crop residue return is more favorable for soil C sequestration in areas with low soil pH, while it is more favorable for soil N sequestration in areas with low soil C and N contents concentrations and C:N ratios.

In high precipitation areas, promoting crop residue return can effectively avoid the direct washing of rainwater on the soil surface to carry away P, while the organic P put in by crop residue is more difficult to move with hydrology than inorganic P (Liu et al., 2020a). Thus, promoting crop residue return in areas with higher precipitation has more potential for soil P sequestration. It is worth noting that 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 processes.

4.4. Enhanced soil properties further improve grain yields

Crop residue return not only sequesters more soil C, N, and P but also reduces soil acidification, especially in upland areas (Fig. 1, 2, 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 content 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 reveals that the mitigation of soil acidification by crop residue return decreases with increasing soil P, which may be due to two mechanisms. First, crop residue releases organic acids during decomposition that activate P in soil pores and reduce soil pH (Kpomblekou-A and Tabatabai, 2003; Roy et al., 2016); second, organic C input to soils with high P content promotes heterotrophic microbial nitrification, leading to soil acidification (O'Neill et al., 2021). Crop residue return alleviates upland soil acidification, improving soil nutrient supply, as evidenced by higher grain yield increases relative to paddy and paddy-upland rotations.

Soil physical properties **are crucial in driving crop residue return's effects on grain yield and are** subject to climatic conditions, field management, and fertilizer input **(Fig.** 4). Although our **results have** shown that crop residue return generally increases grain yield, there is a 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 rooting of the next season's crop **(Chen et al., 2021).** Our research shows that crop residue return effectively **avoids** the adverse effects mentioned above in areas with clay soil due to high soil porosity. Furthermore, we point out that crop residue return in regions with high inorganic fertilizer input has a limited impact on grain yield increases. This is due to the surplus supply of soil nutrients caused by excessive fertilizer application **(Liu et al., 2020a; Xu et al., 2019),** while the nutrients supplied by organic matter accumulation are 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 carbon, nitrogen, and phosphorus stocks, particularly in the topsoil (Fig. 5). Although the increase in carbon stock in sub- and deep-soils is less compared to topsoil, it is still higher than the 0.4% increase required to achieve climate mitigation 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 shows that the majority of sequestered carbon, nitrogen, and phosphorus are stored as organic matter in the topsoil, which can mitigate soil acidification and improve soil fertility for crops. Therefore, returning crop residues 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 for the increase in soil carbon and nitrogen stocks by crop residue return with time (Fig. S11). Soil carbon and nitrogen sequestration tends to saturate around 20 years after crop residue returns, while the mitigating effect of soil acidification continues. Furthermore, the increasing trends of soil carbon, nitrogen, and phosphorus stocks across soil profiles are mostly not statistically significant on the time scale

(Fig. S12). However, both soil carbon and nitrogen stocks have a positive slope over time, and the slope is greater for sub- and deep-soils than the topsoil. Therefore, different soil layers should have different time thresholds for soil carbon and nitrogen saturation. In the long term, we can expect greater potential for sequestering carbon in sub- and deep-soils, which are more stable and essential for long-term climate change mitigation. Spatially, our study highlights that crop residue return in the tropics has higher benefits for soil carbon and nitrogen stocks (Fig. S13). Given that the tropics have more frequent cropping ecosystems due to favorable hydrothermal conditions for supplying crops, crop residue return in the tropics has a higher priority for soil fertility and ecological-environment improvement.

In the past, crop residue return experiments have primarily focused 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 deeper soils. Thus, environmental variables of topsoil were more fully reported than those of deeper soils. However, recent studies have shown that deep soils have distinct environmental conditions (Chen et al., 2022; Chen et al., 2023), which may lead to different accumulation mechanisms of soil carbon, nitrogen, and phosphorus in different soil layers. Further research on the mechanisms of deep soil carbon, nitrogen, and phosphorus stocks could help to understand elemental cycling and reduce their upward release as greenhouse gases and downward leaching into groundwater, thereby reducing environmental pollution.

References (These references are inserted by endnote and I will manually check them before the official submission)

Abbruzzini, T.F., Davies, C.A., Toledo, F.H., Cerri, C.E.P. (2019) Dynamic biochar effects on nitrogen use efficiency, crop yield and soil nitrous oxide emissions during a tropical wheat-growing season. J Environ Manage 252, 109638.

Alewell, C., Ringeval, B., Ballabio, C., Robinson, D.A., Panagos, P., Borrelli, P. (2020) Global phosphorus shortage will be aggravated by soil erosion. Nat Commun 11, 4546.

Álvaro-Fuentes, J., Morell, F.J., Madejón, E., Lampurlanés, J., Arrúe, J.L., Cantero-Martínez, C. (2013) Soil biochemical properties in a semiarid Mediterranean agroecosystem as affected by long-term tillage and N fertilization. Soil and Tillage Research 129, 69-74.

Balesdent, J., Basile-Doelsch, I., Chadoeuf, J., Cornu, S., Derrien, D., Fekiacova, Z., Hatte, C. (2018) Atmosphere-soil carbon transfer as a function of soil depth. Nature 559, 599-602.

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., Wood, E.F. (2018) Present and future Koppen-Geiger climate classification maps at 1-km resolution. Sci Data 5, 180214.

Breiman, L. (2001) Random forests, machine learning 45. Journal of Clinical Microbiology 2, 199-228.

Chen, J., Luo, Y., Katterer, T., Olesen, J.E. (2022) Depth-dependent responses of soil organic carbon stock under annual and perennial cropping systems. Proc Natl Acad Sci U S A 119, e2203486119.

Chen, J., Luo, Y., Sinsabaugh, R.L. (2023) Subsoil carbon loss. Nature Geoscience.

Chen, X., Hu, Y., Xia, Y., Zheng, S., Ma, C., Rui, Y., He, H., Huang, D., Zhang, Z., Ge, T., Wu, J., Guggenberger, G., Kuzyakov, Y., Su, Y. (2021) Contrasting pathways of carbon sequestration in paddy and upland soils. Glob Chang Biol 27, 2478-2490.

Chen, X., Xia, Y., Rui, Y., Ning, Z., Hu, Y., Tang, H., He, H., Li, H., Kuzyakov, Y., Ge, T., Wu, J., Su, Y. (2020) Microbial carbon use efficiency, biomass turnover, and necromass accumulation in paddy soil depending on fertilization. Agriculture, Ecosystems & Environment 292, 106816.

Christensen, B.T. (1986) Barley straw decomposition under field conditions: effect of placement and initial nitrogen content on weight loss and nitrogen dynamics. Soil Biology and Biochemistry 18, 523-529.

Cleveland, C.C., Liptzin, D. (2007) C:N:P stoichiometry in soil: is there a “Redfield ratio” for the microbial biomass? Biogeochemistry 85, 235-252.

Fischer, P., Pothig, R., Venohr, M. (2017) The degree of phosphorus saturation of agricultural soils in Germany: Current and future risk of diffuse P loss and implications for soil P management in Europe. Sci Total Environ 599-600, 1130-1139.

Freeman, C., Ostle, N., Kang, H. (2001) An enzymic 'latch' on a global carbon store. Nature 409, 149.

Gao, J., Wang, S., Li, Z., Wang, L., Chen, Z., Zhou, J. (2021) High Nitrate Accumulation in the Vadose Zone after Land-Use Change from Croplands to

Orchards. Environ Sci Technol 55, 5782-5790.

Gowariker, V., Krishnamurthy, V., Gowariker, S., Dhanorkar, M., Paranjape, K. (2008) The Fertilizer Encyclopedia.

Goyne, K.W., Jun, H.J., Anderson, S.H., Motavalli, P.P. (2008) Phosphorus and nitrogen sorption to soils in the presence of poultry litter-derived dissolved organic matter. J Environ Qual 37, 154-163.

Guo, X., Li, H., Yu, H., Li, W., Ye, Y., Biswas, A. (2018) Drivers of spatio-temporal changes in paddy soil pH in Jiangxi Province, China from 1980 to 2010. Scientific Reports 8.

Hedges, L., Gurevitch, J., Curtis, P. (1999) The Meta-Analysis of Response Ratios in Experimental Ecology. Ecology 80, 1150-1156.

Huddell, A.M., Galford, G.L., Tully, K.L., Crowley, C., Palm, C.A., Neill, C., Hickman, J.E., Menge, D.N.L. (2020) Meta-analysis on the potential for increasing nitrogen losses from intensifying tropical agriculture. Glob Chang Biol 26, 1668-1680.

Kemmitt, S., Wright, D., Goulding, K., Jones, D. (2006) pH Regulation of Carbon and Nitrogen Dynamics in Two Agricultural Soils. Soil Biology and Biochemistry 38, 898-911.

Kpomblekou-A, K., Tabatabai, M. (2003) Effect of low-molecular weight organic acids on phosphorus release and phytoavailabilty of phosphorus in phosphate rocks added to soils. Agriculture, Ecosystems & Environment 100, 275-284.

Li, Y., Wu, J., Liu, S., Shen, J., Huang, D., Su, Y., Wei, W., Syers, J.K. (2012) Is the C:N:P stoichiometry in soil and soil microbial biomass related to the landscape and land use in southern subtropical China? Global Biogeochemical Cycles 26, n/a-n/a.

Li, Z., Reichel, R., Xu, Z., Vereecken, H., Brüggemann, N. (2021) Return of crop residues to arable land stimulates N2O emission but mitigates NO3− leaching: a meta-analysis. Agronomy for Sustainable Development 41.

Liu, J., Jiang, B., Shen, J., Zhu, X., Yi, W., Li, Y., Wu, J. (2021) Contrasting effects of straw and straw-derived biochar applications on soil carbon accumulation and nitrogen use efficiency in double-rice cropping systems. Agriculture, Ecosystems & Environment 311.

Liu, J., Liu, X., Wang, Y., Li, Y., Li, Y., Yuan, H., Fang, L., Wu, J. (2022) Upstream 2000 ha is the boundary of the stream water nitrogen and phosphorus saturation concentration threshold in the subtropical agricultural catchment. CATENA 211.

Liu, J., Ouyang, X., Shen, J., Li, Y., Sun, W., Jiang, W., Wu, J. (2020a) Nitrogen and phosphorus runoff losses were influenced by chemical fertilization but not by pesticide application in a double rice-cropping system in the subtropical hilly region of China. Sci Total Environ 715, 136852.

Liu, J., Qiu, T., Penuelas, J., Sardans, J., Tan, W., Wei, X., Cui, Y., Cui, Q., Wu, C., Liu, L., Zhou, B., He, H., Fang, L. (2023) Crop residue return sustains global soil ecological stoichiometry balance. Glob Chang Biol 29, 2203-2226.

Liu, J., Wang, Y., Li, Y., Liu, X., Jiang, Y., Fu, Y., Jin, W., Wu, J. (2020b) Ecosystem N:P stoichiometric ratios determine the catchment surface water N:P ratio through subsurface hydrological processes. CATENA 194.

Martínez-Mena, M., Carrillo-López, E., Boix-Fayos, C., Almagro, M., García Franco, N., Díaz-Pereira, E., Montoya, I., de Vente, J. (2020) Long-term effectiveness of sustainable land management practices to control runoff, soil erosion, and nutrient loss and the role of rainfall intensity in Mediterranean rainfed agroecosystems. CATENA 187.

Minasny, B., Malone, B., McBratney, A., Angers, D., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B., Field, D., Gimona, A., Hedley, C.B., Hong, S.-Y., Mandal, B., Marchant, B., Martin, M., McConkey, B.G., Mulder, V.L., Winowiecki, L. (2017) Soil Carbon 4 per mille. Goderma 292, 59-86.

O'Neill, R.M., Krol, D.J., Wall, D., Lanigan, G.J., Renou-Wilson, F., Richards, K.G., Jansen-Willems, A.B., Müller, C. (2021) Assessing the impact of long-term soil phosphorus on N-transformation pathways using 15N tracing. Soil Biology and Biochemistry 152.

Penuelas, J., Fernández-Martínez, M., Ciais, P., Jou, D., Piao, S., Obersteiner, M., Vicca, S., Janssens, I., Sardans, J. (2019) The bioelements, the elementome, and the biogeochemical niche. Ecology 100.

Penuelas, J., Poulter, B., Sardans, J., Ciais, P., van der Velde, M., Bopp, L., Boucher, O., Godderis, Y., Hinsinger, P., Llusia, J., Nardin, E., Vicca, S., Obersteiner, M., Janssens, I.A. (2013) Human-induced nitrogen-phosphorus imbalances alter natural and managed ecosystems across the globe. Nat Commun 4, 2934.

Roy, T., Biswas, D., Datta, S., Sarkar, A. (2016) Phosphorus Release from Rock Phosphate as Influenced by Organic Acid Loaded Nanoclay Polymer Composites in an Alfisol. Proceedings of the National Academy of Sciences, India Section B: Biological Sciences 88.

Russolillo, G. (2012) Non-Metric Partial Least Squares. Electronic Journal of Statistics 6.

Shen, J., Tang, H., Liu, J., Wang, C., Li, Y., Ge, T., Jones, D.L., Wu, J. (2014) Contrasting effects of straw and straw-derived biochar amendments on greenhouse gas emissions within double rice cropping systems. Agriculture, Ecosystems & Environment 188, 264-274.

Tranckner, J., Wricke, B., Krebs, P. (2008) Estimating nitrifying biomass in drinking water filters for surface water treatment. Water Research 42, 2574-2584.

Venables, B., Ripley, B., (2002) Modern Applied Statistics With S.

Wei, L., Zhu, Z., Razavi, B., Xiao, M., Dorodnikov, M., Fan, L., Yuan, H., Yurtaev, A., Luo, Y., Cheng, W., Kuzyakov, Y., Wu, J. (2022) Visualization and quantification of carbon “rusty sink” by rice root iron plaque: mechanisms, functions, and global implications. Global Change Biology.

Xia, L., Lam, S., Wolf, B., Kiese, R., Chen, D., Butterbach-Bahl, K. (2018) Trade-offs between soil carbon sequestration and reactive nitrogen losses under straw return in global agroecosystems. Global Change Biology 24.

Xu, R., Tian, H., Pan, S., Prior, S.A., Feng, Y., Batchelor, W.D., Chen, J., Yang, J. (2019) Global ammonia emissions from synthetic nitrogen fertilizer applications in agricultural systems: Empirical and process-based estimates and uncertainty. Glob Chang Biol 25, 314-326.

Yu, Q., Duan, L., Yu, L., Chen, X., Si, G., Ke, P., Ye, Z., Mulder, J. (2018) Threshold and multiple indicators for nitrogen saturation in subtropical forests. Environ Pollut 241, 664-673.

Zechmeister-Boltenstern, S., Keiblinger, K.M., Mooshammer, M., Peñuelas, J., Richter, A., Sardans, J., Wanek, W. (2015) The application of ecological stoichiometry to plant–microbial–soil organic matter transformations. Ecological Monographs 85, 133-155.

Zhang, K., Song, C., Zhang, Y., Dang, H., Cheng, X., Zhang, Q. (2018) Global-scale patterns of nutrient density and partitioning in forests in relation to climate. Glob Chang Biol 24, 536-551.

Zheng, S., Xia, Y., Hu, Y., Chen, X., Rui, Y., Gunina, A., He, X., Ge, T., Wu, J., Su, Y., Kuzyakov, Y. (2021) Stoichiometry of carbon, nitrogen, and phosphorus in soil: Effects of agricultural land use and climate at a continental scale. Soil and Tillage Research 209.

Zomer, R.J., Xu, J., Trabucco, A. (2022) Version 3 of the Global Aridity Index and Potential Evapotranspiration Database. Scientific Data 9, 409.

Figure captions

Fig. 1. Weighted effect values (RR) of soil carbon (TOC), nitrogen (TSN), phosphorus (TSP) stocks (a-c) and ratios (d-f), pH (g), yield (h) at different land uses and soil layer. The value on the right (left) side of the error bar is the sample size.

Fig. 2. 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 precipitation; MAT, mean annual temperature; AI, aridity index.

Fig. 3. 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 precipitation; MAT, mean annual temperature; AI, aridity index.

Fig. 4. The partial least squares pathway model (PLS-PM) disentangles the main pathways of influence of key climate, field management, fertilization, soil physics and chemistry on 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 precipitation; TSN, soil nitrogen.

Fig. 5. Effect of crop residue return on soil carbon, nitrogen and phosphorus stocks in different soil layers and the enhanced grain yield.

No se puede mostrar la imagen en este momento.

Fig. 1. Weighted effect values (RR) of soil carbon (TOC), nitrogen (TSN), phosphorus (TSP) stocks (a-c) and ratios (d-f), pH (g), yield (h) at different land uses and soil layer. The value on the right (left) side of the error bar is the sample size.

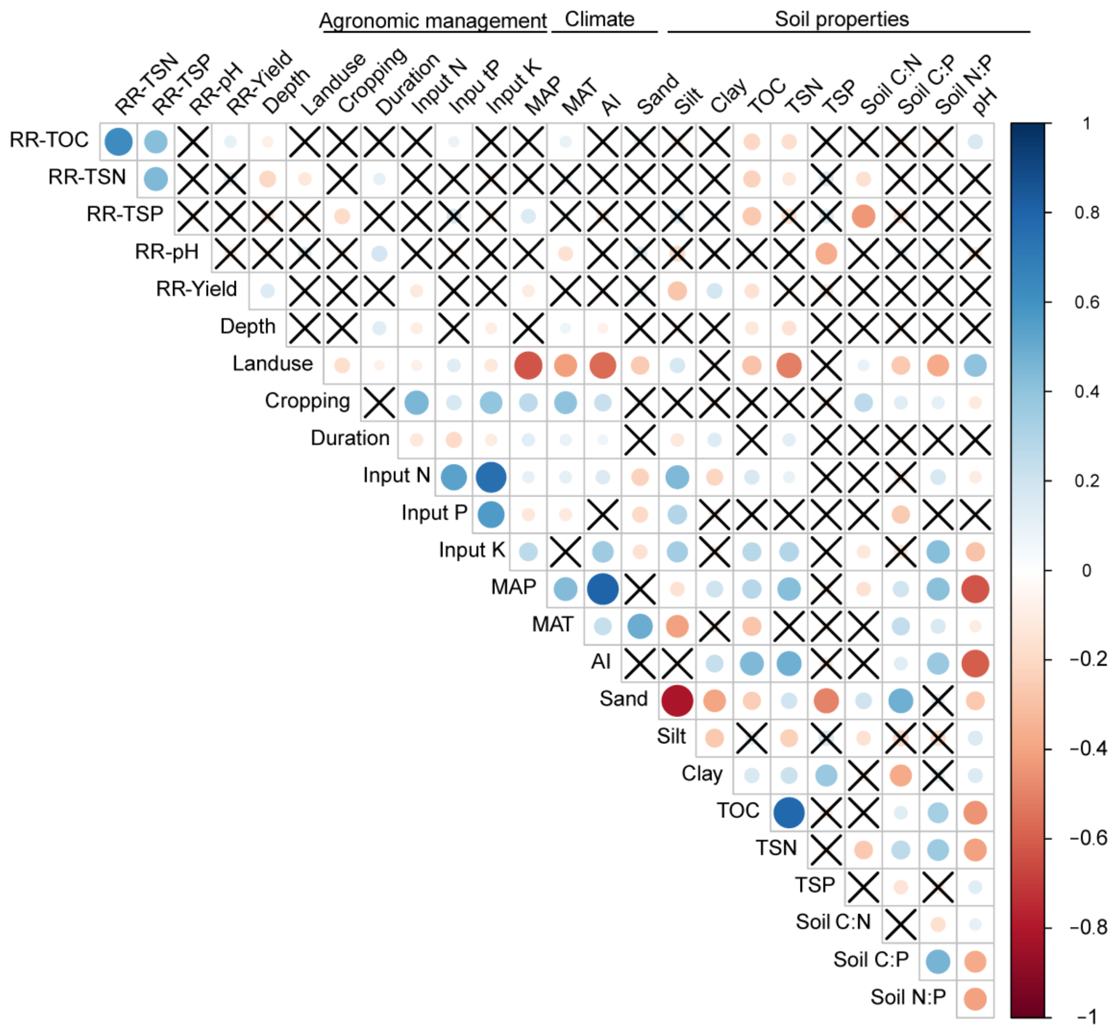

Fig. 2. Correlation analysis between weighted effect values (RR) of soil carbon (TOC), nitrogen (TSN) and phosphorus (TSP) stocks, pH and grain yields (Yield) and agronomic management, climate and soil properties. Duration, experimental duration; MAP, mean annual precipitation; MAT, mean annual temperature; AI, aridity index.

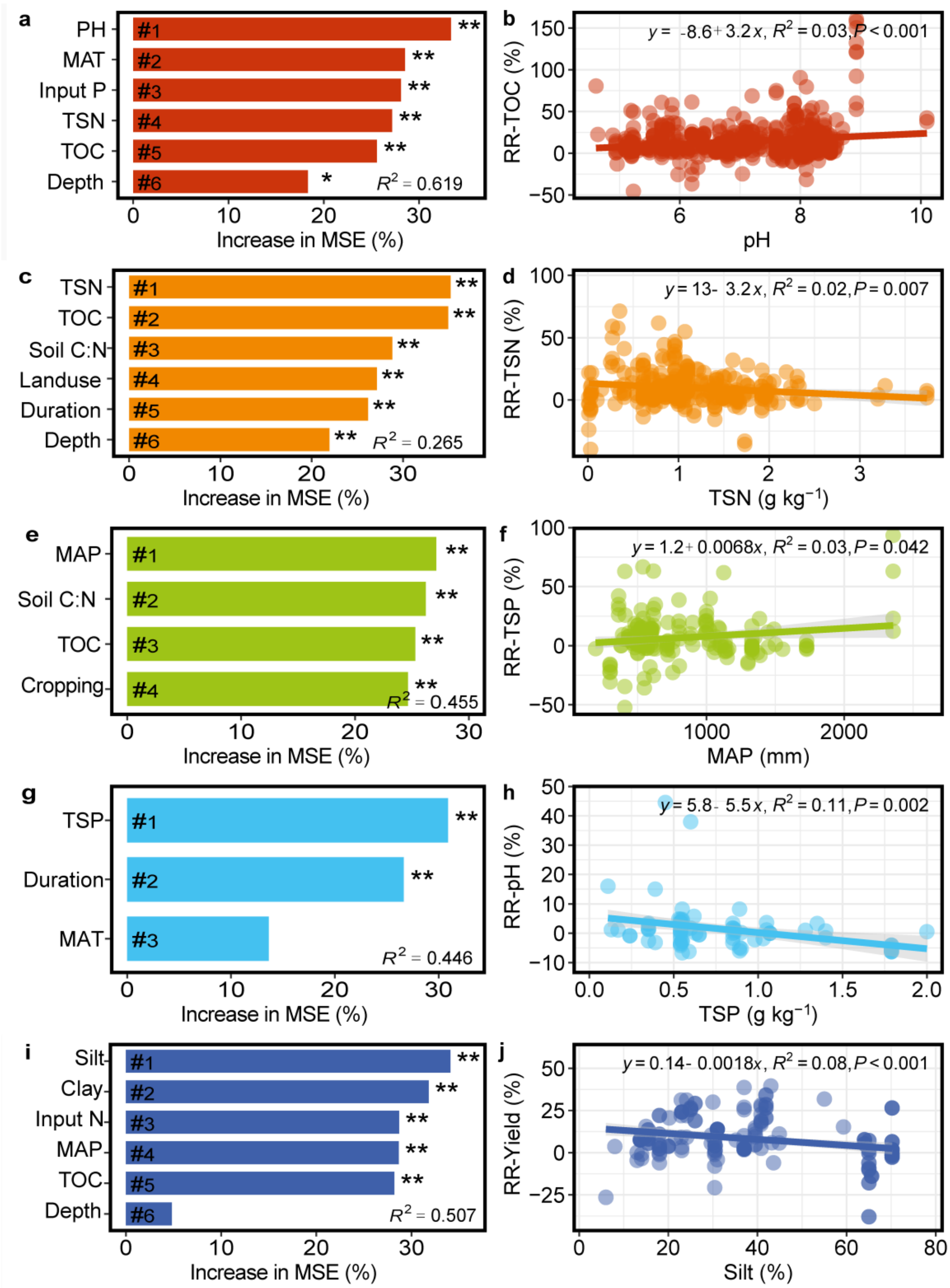

Fig. 3. Contribution of environmental factors to the weighted effect values (RR) of soil carbon (TOC), nitrogen (TSN) and phosphorus (TSP) stocks, pH and yield. Duration, experimental duration; MAP, mean annual precipitation; MAT, mean annual

temperature; AI, aridity index.

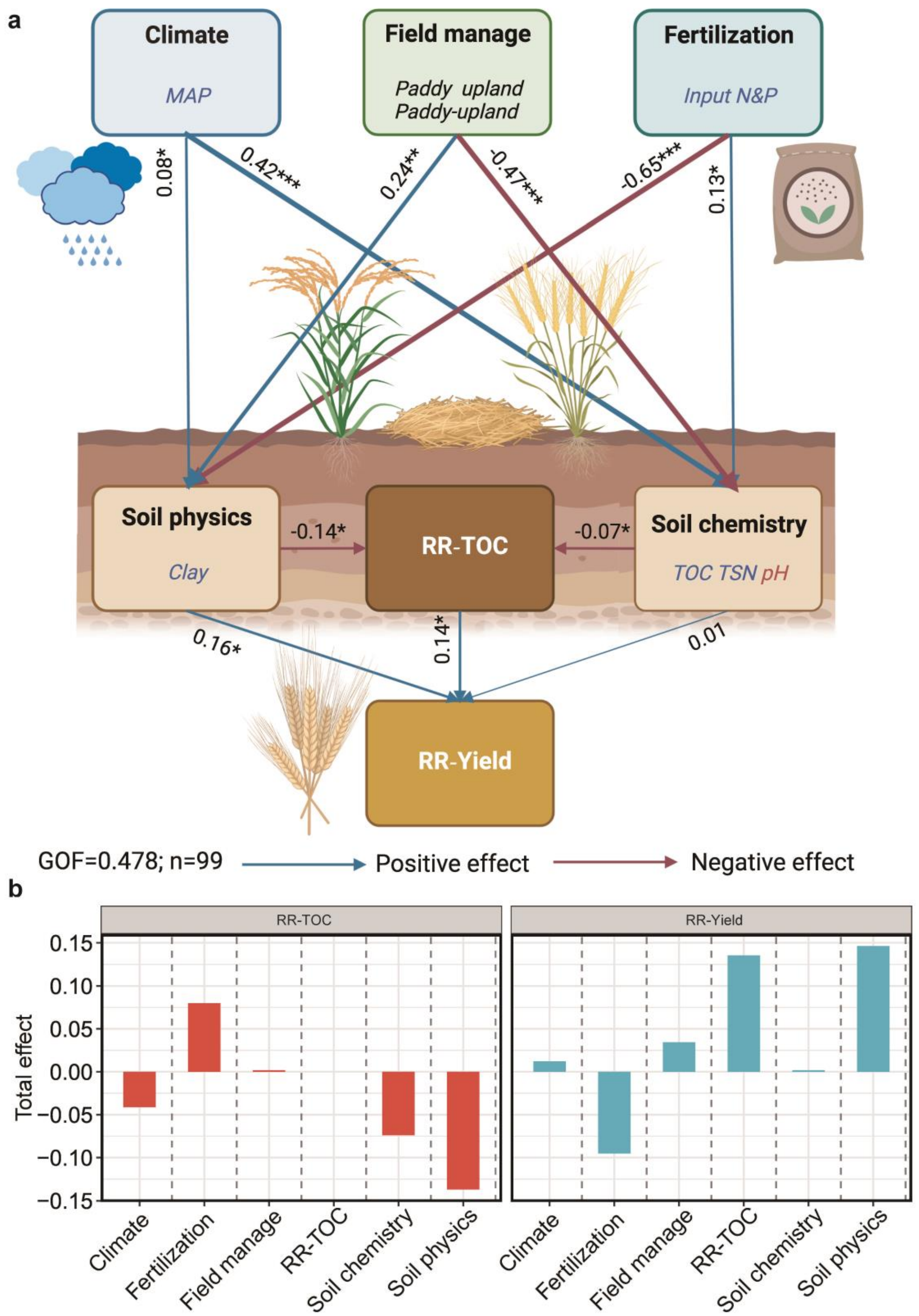

Fig. 4. The partial least squares pathway model (PLS-PM) disentangles the main pathways of influence of key climate, field management, fertilization, soil physics and chemistry on weighted effect values (RR) of soil carbon (TOC) and grain yield (Yield)

(a), and the total effects of these variables (b). * Denotes $p<0.05$, ** denotes $p<0.01$, *** denotes $p<0.001$. MAP, mean annual precipitation; TSN, soil nitrogen.

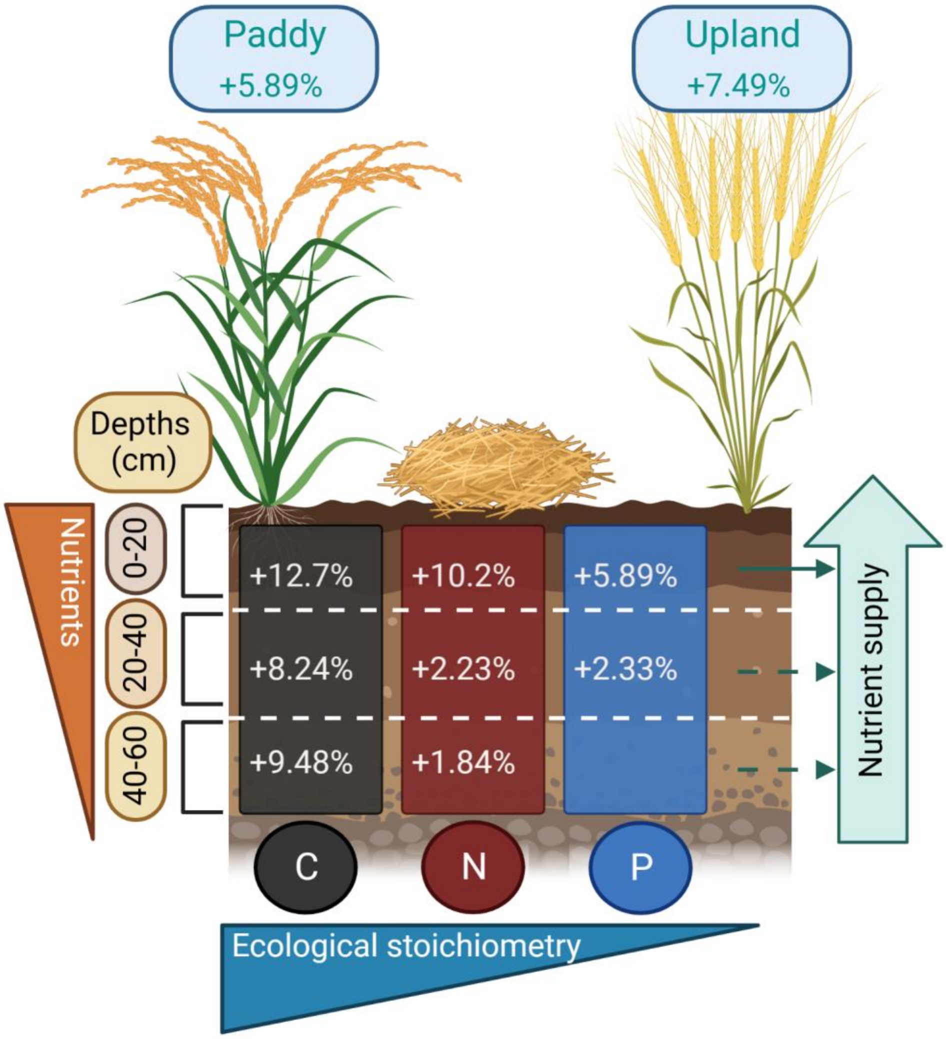

Fig. 5. Effect of crop residue return on soil carbon (C), nitrogen (N) and phosphorus (P) stocks in different soil layers and the enhanced grain yield.