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Meta-analysis on the effects of types and levels of N, P, and K fertilization on organic carbon in cropland soils

Yuhuai Liu [a,b,c], Chuan Li [c], Guan Cai [a,d], Leopold Sauheitl [a], Mouliang Xiao [b,e,*], Olga Shibistova [a], Tida Ge [b], Georg Guggenberger [a]

[a] *Institute of Soil Science, Leibniz Universität Hannover, Hannover 30419, Germany*
[b] *State Key Laboratory for Managing Biotic and Chemical Threats to the Quality and Safety of Agro-products, Key Laboratory of Biotechnology in Plant Protection of MARA and Zhejiang Province, Institute of Plant Virology, Ningbo University, Ningbo 315211, China*
[c] *School of Resources and Environment, Xichang University, Xichang 615000, China*
[d] *The Second Surveying and Mapping Institute of Hunan Province, 410114 Changsha, China*
[e] *State Key Laboratory of Subtropical Silviculture, Zhejiang A & F University, Hangzhou, 311300, China*

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ABSTRACT

Most agroecosystems receive inputs of anthropogenically derived nutrients, which impact soil organic carbon (SOC). However, the impact of the combination of different fertilizer types, as well as of various amounts of nitrogen (N), phosphorus (P), and potassium (K) fertilization, on SOC remains to be determined. Here, we reviewed 212 published studies to identify the consequences of different types and levels of N, P, and K fertilization on SOC across northern hemisphere cropland soils. The average effect size of fertilization on SOC was 0.2707 ± 0.0086 (95% confidence interval: 0.2539–0.2875, $p < 0.0001$). Categorical variable analysis revealed that the fertilization type significantly influenced the effect size in mineral plus organic fertilization > pure organic fertilization > pure mineral fertilization. The increased available nutrients led to the retention of organic C from farmyard manure or crop straw and limited nutrient loss, increasing C sequestration. Intermediate N (100–300 kg ha^{-1} year^{-1}) and K (50–150 kg ha^{-1} year^{-1}) application with high P (>60 kg ha^{-1} year^{-1}) fertilization produced the most significant effect on the SOC stocks. Heterogeneity analysis revealed that the annual average precipitation, annual average temperature, water conditions, and tillage type significantly affected the average effect size. Overall, the meta-analysis revealed that multi-nutrient fertilization, with intermediate N and K levels and a high P level, decreased the dependency of the organisms released from SOM decomposition and had strong positive effects on increasing SOC in agroecosystems.

1. Introduction

Agricultural land occupies 37% of the Earth's land surface (Smith et al., 2008), providing sustenance for over seven billion people globally (Dai et al., 2018). Soil organic carbon (SOC) stocks in croplands (111–170 Pg C) account for approximately 10% of total soil C up to a depth of 1 m (1500 Pg C) globally (Eswaran et al., 1993; Paustian et al., 1997; Feng et al., 2014). The average SOC stocks of the arable layer ($\leq$35 cm) in upland soils (aerated soils or not water-affected soils in the long term) are 31 Mg C/ha (Wei et al., 2021). As nutrients are exported during harvest, fertilization is necessary to ensure plant production and increase crop yield (Khan et al., 2019). However, mineral fertilizers alone can have negative consequences on ecosystems, such as soil degradation, groundwater pollution, surface water eutrophication, and greenhouse gas emissions (Conley et al., 2009; Divito et al., 2011; Honeycutt et al., 2020; Toljander et al., 2008; Wang et al., 2020). Hence, the type and amount of fertilizer must be adjusted to prevent detrimental effects (Chen et al., 2016). Fertilization can also reportedly help maintain SOC levels (Ashraf et al., 2020; Templer et al., 2012), a key parameter for sustaining soil fertility and productivity (Demyan et al., 2012; Khan et al., 2019; Wang et al., 2020). Han et al. (2018) reported that in a typical agricultural region of subtropical China, increasing SOC by 0.35 Mg C/ha year^{-1} is related to an increase in wheat grain yield by 13.4%. According to Feng et al. (2014), Mi et al. (2018) and Mwangi & Box (2010), fertilization type (i.e. mineral, organic, combined mineral plus organic fertilization) and fertilization level are important factors for

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* Corresponding author.
E-mail address: xmlacy@126.com (M. Xiao).

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maintaining the SOC balance or increasing the SOC stocks.

The primary plant nutrients include nitrogen (N), phosphorus (P), and potassium (K) in organic and mineral forms and their various combinations (i.e., NP, NK, PK, and NPK). Körschens et al. (2013) reported from 20 long-term European experiments that mineral fertilizer (NPK) increased SOC by approximately 10%, compared with no fertilization, due to the increased plant productivity and crop residue input to soil. These results match the meta-analysis of Geisseler and Scow (2014), in which SOC content increased by 8.5% on average upon adding mineral N fertilizer. Kätterer et al. (2012) also reported an annual increase in SOC by 1–2 kg ha^{-1} for each kg of mineral N fertilizer applied in Swedish long-term cropland fertilization experiments.

Organic fertilizers, as farmyard manure or crop residues, are an important source of soil organic matter (SOM) and an adequate substitute for mineral fertilizer inputs (Chen et al., 2016; Ding et al., 2017). They can supply nutrients to crops and benefit soil quality, providing prolonged nutrient effects after application (Feng et al., 2014). The combined application of mineral and organic fertilizers increases crop yield and SOC content compared with only mineral fertilizer application (Hua et al., 2020; Morra et al., 2010). Chivenge et al. (2011) reported in a meta-analysis that organic resources, in addition to mineral N fertilizers, increase SOC contents by 12% in sub-Saharan Africa.

Despite these findings over a wide range of climates, soil types, and farming practices, the effect of fertilization on SOC has been controversially discussed because of the application of different amounts of fertilizer. Different fertilization levels in agricultural soils can increase (Obour et al., 2017) or decrease (Hao et al., 2017) the SOC content or cause no change at all (Liang et al., 2014). Chen et al. (2016) reported an increase of approximately 8% in SOC after mineral N (300 kg ha^{-1}) fertilization in a rice–wheat cropping system. In contrast, in a long-term fertilization experiment in croplands with wheat-corn rotation, Zhong et al. (2015) found that mineral N decreased SOC stocks by approximately 35% when the fertilizer is applied in the amount required for the maximum crop yield (i.e., 360 kg mineral N/ha decreased SOC by approximately 35%).

Besides the types and levels of fertilization, SOC stocks in agroecosystems are also closely related to the climate (precipitation and temperature), water conditions (alternate wetting and drying), tillage types, crop rotation, etc. (Khan et al., 2019; Trumbore et al.,1996; Wei et al., 2021; Six et al., 1999). Gupta Choudhury et al. (2018), Tian et al. (2013) and Witt et al. (2000) reported that SOC in upland soils was highest under dry conditions in temperate climates. In addition, soils experiencing intervals of aerobic and anoxic conditions (paddy-wheat/corn rotation) had relatively higher SOC stocks than adjacent upland (Keiluweit et al., 2018; Wei et al., 2021). Furthermore, when compared with conventional tillage (CT), no-tillage (NT) causes the least amount of soil disturbance, stimulates biological activity, and enhances aggregate formation (Nicoloso et al., 2016; Šimanský et al., 2017). The tillage also affects SOC stocks. So Luo et al. (2010), in a meta-analysis based on global data from 69 paired experiments found an increase in SOC stocks of the surface layer (0–10 cm) by 3.15 ± 2.42 t ha^{-1} but declined by 3.30 ± 1.61 t ha^{-1} in the 20–40 cm soil layer.

To elucidate the relationship between the SOC of croplands and the level of fertilization along with management and environmental factors, we conducted a meta-analysis, which is a powerful tool to compute site-specific, temporally variable results and to draw general conclusions at a global scale (Geisseler & Scow, 2014; Jian et al., 2016; Luo et al., 2010; Ren et al., 2017). Thus, quantifying the influence of the types and levels of fertilization can resolve uncertainties regarding the spatial and temporal variations in SOC related to fertilization. Previous meta-analyses have mainly analysed the impact of mineral and organic fertilization on SOC from a microbial and C emission perspective (Geisseler & Scow, 2014; Ren et al., 2017; Wei et al., 2021). However, there are a few studies aimed to evaluate the effect of type (inorganic *versus* organic and mixed fertilization), the combination of different nutrients, and the amount of fertilizer applied on SOC sequestration in cropland soils. The objective of the current study was to analyse the impact of fertilization, particularly with respect to fertilizer types and levels of nutrient application, on SOC in agricultural upland soils. We hypothesized that (1) fertilization significantly increases the SOC in agricultural upland soils; (2) the combination of organic and mineral nutrient application has the largest effect due to OC input by organic fertilizer and increasing crop residue input with fertilization; and (3) precipitation, temperature, and water conditions as well as tillage types under fertilization affect SOC sequestration in agricultural upland soils.

2. Materials and methods

2.1. Selection criteria and data collection

To quantify the effect of fertilization on SOC, we analysed the results from peer- reviewed articles indexed by the Web of Science (https://apps.webofknowledge.com/) database from 1945 to 2020 in a meta-analysis using the following search terms: “fertilization” AND (“SOM” OR “soil organic matter” OR “SOC” OR “soil organic carbon”), NOT “forest”, NOT “grassland”, NOT “paddy”.

Only primary studies that satisfied the following criteria were included: (i) all studies reported must include an unfertilized control and a treatment with fertilization; (ii) fertilization must not include biochar, Cu, Zn, and Mo; (iii) the experimental duration was clearly recorded, and measurements of the variables in the experimental and control groups were performed at the same spatial and temporal scales; (iv) at least two replicates for each treatment were conducted; and (v) the means, sample sizes, and standard deviations (SDs) or standard errors (SEs) of the chosen variables (SOC) were directly provided. When the studies reported data from several soil layers, data only on topsoil were included in the present study. Considering the predominant concentration of sites in the Northern Hemisphere and the credibility of the results, five sites in the Southern Hemisphere (two studies in Africa, two studies in Latin America, and one study in Australia) were not included in the meta-analysis. Finally, 1102 data points from 212 articles in the northern hemisphere met our criteria and were included in the synthesis analysis (Fig. 1 and S1). In most studies used for the meta-analysis, no taxonomic unit soil types are given, and where it is given, quite often national classification systems have been used. However, in the few articles that used the World Reference Base for Soil Resources (WRB) system and presented also the respective soil types, it is obvious that most soils were Fluvisol, Vertisol and Cambisol. Missing latitude and longitude data were estimated using Google Maps (https://maps.google.com/). Climatic data included mean annual precipitation (MAP) and mean annual temperature (MAT), and if climatic data were not provided in the manuscripts, they were obtained from https://en.climatedata.org/. In addition to climatic data, water conditions (alternate wetting (W) and drying (D)), tillage type (CT: conventional tillage (20–30 cm); DT: deep tillage (30–45 cm); RT: reduced tillage (10–20 cm); MT: minimum tillage ($\leq$10 cm); and NT: no tillage), and crop rotation were considered as moderators, i.e. supporting variables that help to explain the effect of fertilization on the SOC content or stock. Because these dates both can be gotten in each study. Some data were extracted from published figures using the Getdata software (Version 2.20).

2.2. Data analysis

When data on the SOM content or stock were reported, they were divided by 1.724 to calculate the SOC content or stocks (Alison, 1965). When different amounts of N, P, and K fertilizers were applied for different years, their average value was calculated as the rate (kg ha^{-1} year^{-1}). Two categorical variables, fertilization type and level, were introduced. The fertilisation types were differentiated into mineral (N, P, and K), organic (manure, slurry, compost, and straw) (Liang et al., 2014), and mineral plus organic. With respect to the effects of the amount of fertilization, low (<100, 20, and 50 kg ha^{-1} year^{-1}),

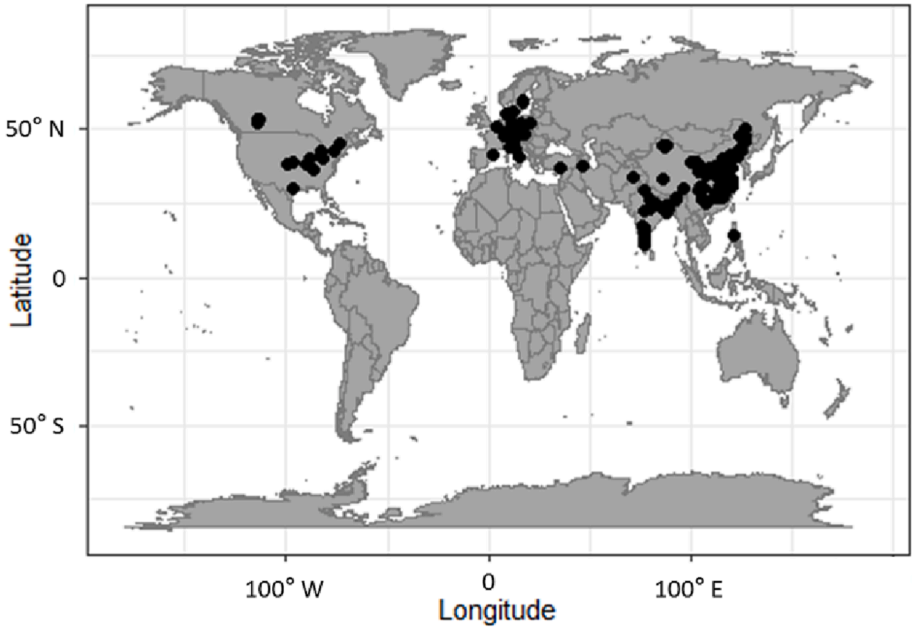

Fig. 1. Geographical location of the 212 studies included in the meta-analysis. Locations are indicated by black dots, which may represent multiple effect sizes from multiple individual studies.

intermediate (100–300, 20–60, and 50–150 kg ha^{-1} $year^{-1}$), and high (>300, 60, and 150 kg ha^{-1} $year^{-1}$) levels for N, P, and K, respectively, were differentiated for mineral fertilization (M), organic fertilization (O), and mineral plus organic fertilization (MO) to explain the intensity of the effect size. The means, standard deviations (SD), and sample sizes (n) of the selected variables were extracted from the articles for each case study. If only the standard errors (SE) were given in a paper, the SD was calculated according to the following formula:

$$SD = SE\sqrt{\mathrm{n}}$$

where n represents the number of replicates (sample size).

The natural log of the response ratio (effect size) was used as the effect size according to the following equation (Hedges et al., 1999):

$$Effectln\left(\frac{X_t}{X_c}\right) = ln(X_t) - ln(X_c)$$

where X_t and X_c represent the means of SOC in the fertilised and control treatments, respectively.

The variance (υ) was estimated according to Chen et al. (2016), as follows:

$$\upsilon = \frac{S_t^2}{n_t x_t^2} + \frac{S_c^2}{n_c x_c^2}$$

where n_t and n_c represent the sample sizes for the fertilization treatments and control, respectively. S_t and S_c represent the SD for fertilization treatments and control, respectively.

Average effect sizes and 95% confidence intervals (CI) were calculated using randomeffect models (Geisseler & Scow, 2014), including the following analyses:

Weight of individual (w_i) study conclusions:

$$w_i = 1/\left(v_i + \tau^2\right)$$

Average effect size:

$$\overset{\hat{A}}{y} = \frac{\sum_{i=1}^{k} w_{i=1}^{k} y_i}{\sum_{i=1}^{k} w_i}$$

Overall standard error:

$$SE = \sqrt{\frac{1}{\sum_{i=1}^{k} w_i}}$$

95% confidence interval of average effect value:

$$CI = \overset{\hat{A}}{y} \pm 1.96 \times SE$$

where v_i is the intrastudy variance, τ^2 the interstudy variance, and y_i is the single study effect value.

Heterogeneity test of effect size (Q_t):

$$Q_t = \sum_{i=1}^{k} w_i (yi - \overset{\hat{A}}{y})^2$$

Test of the influence of explanatory variables on effect size (Q_m):

$$Q_m = \sum_{j=1}^{p} \sum_{i=1}^{ni} w_i \left(y_{ij} - \overset{\hat{A}}{y}\right)^2$$

The ratio of total (residual) heterogeneity to total (unaccounted) variability (I^2):

$$I^2 = \frac{\tau^2}{\tau^2 + S^2}$$

where S^2 is the residual variance:

$$S^2 = \frac{(k-1)\sum w_i}{\left(\sum w_i\right)^2 - \sum W_i^2}$$

Effect size variation (R^2):

$$R^2 = \frac{\tau_{\Re}^2 - \tau_{ME}^2}{\tau_{\Re}^2}$$

where $\tau_{\Re}$ is the inter study variance in the random effects model without the explanatory variables, and τ_{ME} is the inter study variance in the mixed effects model with all explanatory variables added.

All analysis and figures were made using R software with the “metafor” package (BenítezLópez et al., 2017; Viechtbauer, 2010). The variance–covariance matrix was computed due to non-independence of the effect sizes (Midolo et al., 2019). The estimated effect size and standard error were analysed using the random effect model, in which SOC was used a random factor (independent factor). Fertilization types and levels were used categorical variables. The residual heterogeneity with different moderators was explained using a mixed effects model, in which MAP, MAT, water conditions, tillage types, and crop rotation were used as moderators. The explained moderator heterogeneity statistic (Qm) was calculated to test for significance in single covariate meta regressions (Du et al., 2021). Two by two comparison in fertilization types and levels, MAP, MAT, water condition, tillage types and crop rotation on SOC used *holm* method.

3. Results

3.1. Effect size of fertilization on SOC

In the individual studies chosen for this meta-analysis, fertilization effects on SOC in agricultural upland soils were mainly positive. Over all studies, the calculated value of the effect size ranged from −0.30 ± 0.003 to 2.19 ± 0.039, with an average effect size of 0.2707 ± 0.0086 (95% confidence interval (CI): 0.2539–0.2875) (Fig. 2), thus illustrating significant ($P < 0.0001$) overall positive response of SOC to fertilization. In addition, there was substantial residual heterogeneity in the random effects meta-analysis for the SOC dataset (I^2 = 99.55%, Qt = 218376.5488, $P < 0.0001$; Table 1), which we attempted to explain using different moderators via categorical variable analysis.

3.2. Effect size of different fertilizer types and amounts on SOC

The test of moderators (I^2 = 99.41%, Qm = 1574.7836, $p < 0.0001$; Table 1) revealed a significant difference in effect size among fertilization types based on a mixed effects model (Fig. 3). The average effect size was significantly affected by the three fertilization types in the order of MO (0.40 ± 0.01) > O (0.38 ± 0.02) > M (0.13 ± 0.01). The order of the effect of different components in M on the effect size was NP > NPK > NK > K > PK > P > N, which has no significant difference; the order of the effect of different components in M plus farmyard manure (F) fertilization on the effect size was PKF > NPKF > F > NPF > NF > PF, in which PKF was significantly higher than NPKF, F, NPF, NF, and PF; the order of the effect of different components in M plus straw (S) fertilization on the effect size was NPKS > NPS > NS > S, in which S was significantly lower than NPKS, NPS, and NS (Fig. 4). Overall, S fertilization always needs mineral fertilizer as well in order to have a positive response on SOC stocks. In contrast, F is having a direct positive impact on SOC stocks. Interestingly, only if K is added as mineral fertilizer coincidently with farmyard manure the effect level is more significant as for farmyard manure alone.

Different levels of N, P, and K fertilizer from the three different fertilization types had significantly different effect sizes on the OC in agricultural soils ($p < 0.05$); however, the effect size was not significantly affected among three different levels of N, P, and K fertilizer from the three different fertilization types. In terms of effect size alone, for N,

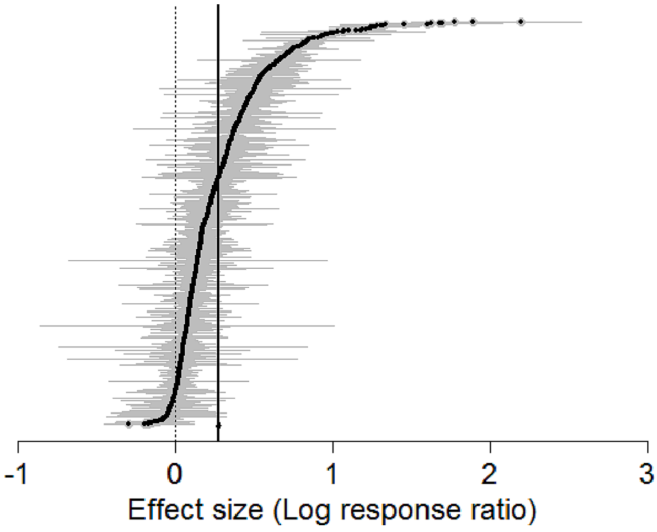

Fig. 2. Forest plot of effect of fertilization on SOC in agricultural upland soil. Effect size, response ratios and black dots with 95% confidence intervals (CI). Black dotted line and black dashed line represent effect size = 0 and averaged effect size.

Table 1
Test of heterogeneity for the effect sizes of fertilization and categorical variable analysis of the different types on fertilization effect size among global agricultural upland soil.

Upland	Test for heterogeneity (Qt)	df	*p*	τ^2	I^2
	218376.5488	1101	<0.0001	0.0762	99.55%
Fertilization types	Test for moderators (Qm)	df	*p*	τ^2	I^2
	1574.7836	3	<0.0001	0.0584	99.41%
	Test for residual heterogeneity (Qe)	df	*p*		
	143748.1815	1099	<0.0001		

τ^2, interstudy variance; I^2, ratio of total (residual) heterogeneity to total (unaccounted) variability.

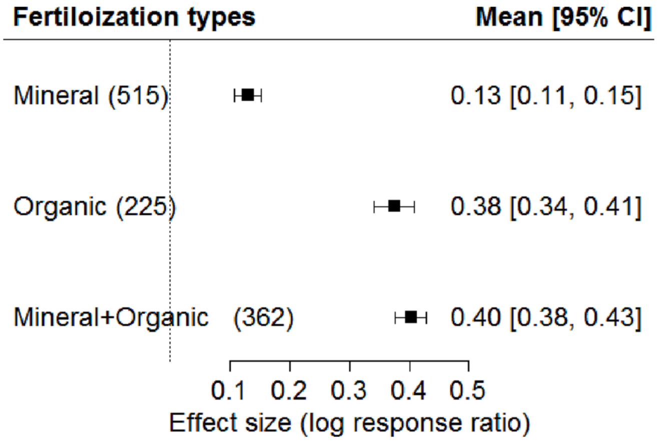

Fig. 3. Forest plot of the effect of three different fertilization types (mineral, organic, mineral plus organic fertilization) on SOC in agriculture upland soil. Effect size, response ratios and black dots are presented with 95% confidence intervals (CI).

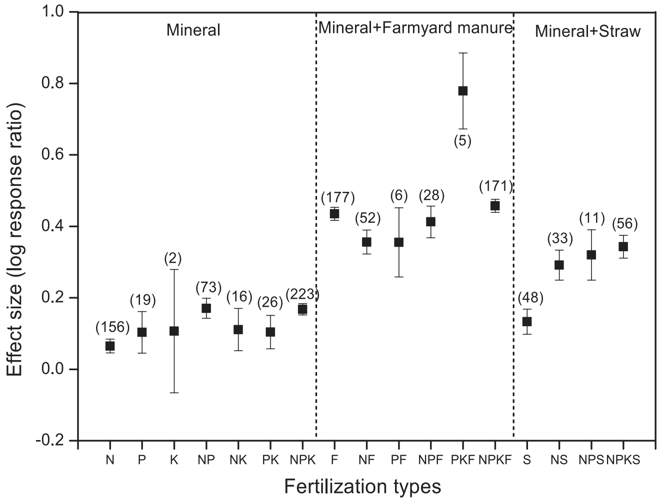

Fig. 4. Forest plot of effect of different combinations of N, P, and K fertilization in mineral, farmyard (F) and mineral, and straw (S) and mineral fertilization on SOC in agriculture upland soil. The numbers above and bottom the single points mean sample size.

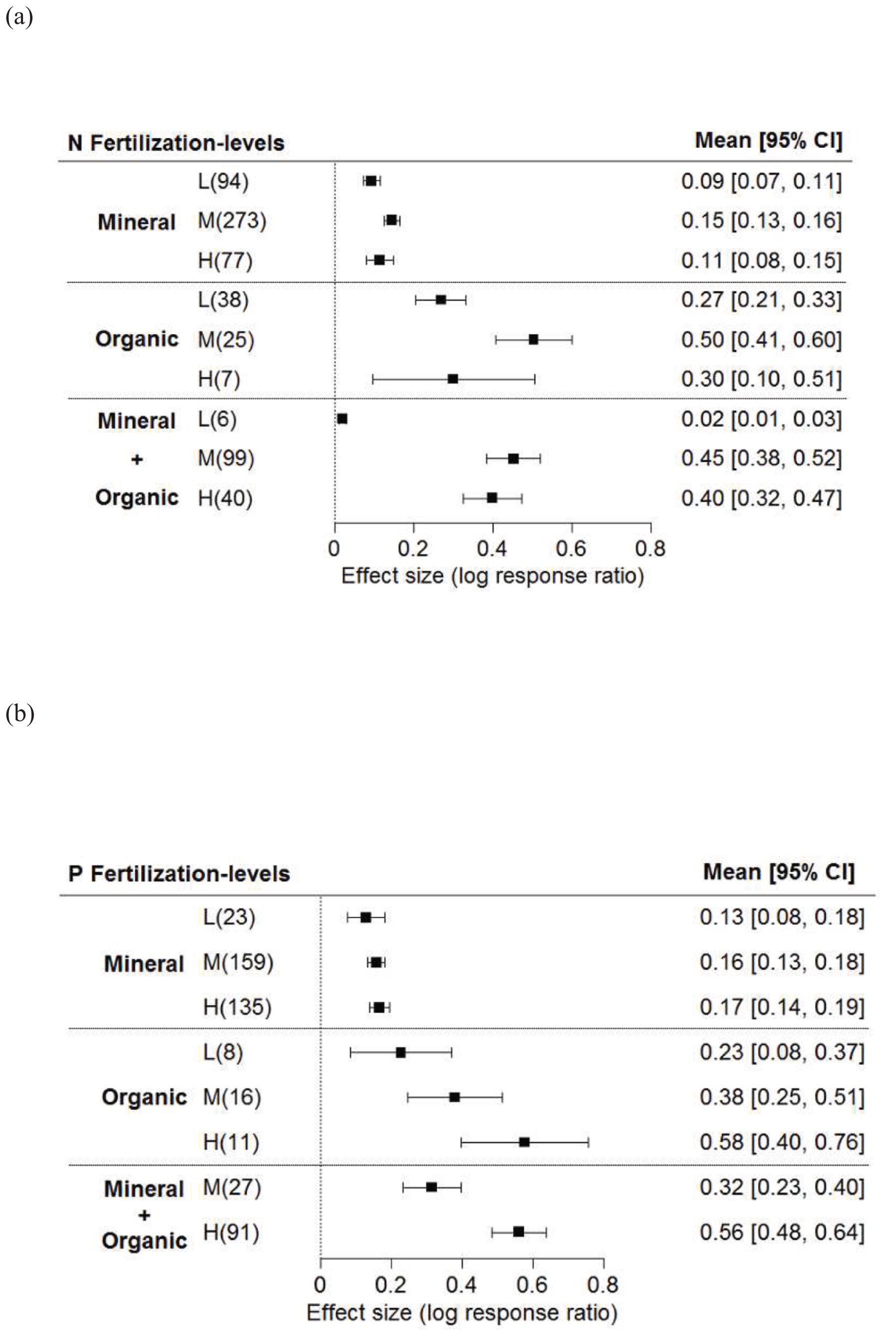

Fig. 5. Forest plot of effect of N (a), P (b), and K (c) fertilization level (low, intermediate, and high levels) from mineral, organic, and mineral plus organic fertilization on SOC in agriculture upland soil. L, low levels; M, intermediate levels; H, high levels.

the order of effect size was: intermediate N level > high N level > low N level for M, O, and MO (Fig. 5a). For P, the order of effect size was: high P level > intermediate P level > low P level for M and O, and high P level > intermediate P level for MO (Fig. 5b). For K, the order of effect size was: intermediate K level > high K level > low K level for M, high K level > intermediate K level > low K level for O, and high K level > low K level > intermediate K level for MO (Fig. 5c). The test for residual heterogeneity (Qe = 143748.1815, $p < 0.0001$; Table 1) showed that the residuals were still heterogeneous, and that other moderators should be included.

3.3. *Response of average effect sizes on environmental and management factors*

As explanatory variables for the heterogeneity in fertilization effects on the SOC content or stocks in agricultural upland soils, MAP, MAT, water conditions, tillage type, and crop rotation were introduced. The heterogeneity analysis revealed that the explanatory variables MAP, MAT, water condition, and tillage type had a significant impact ($p < 0.0001$) on the average effect size and that they could explain approximately 0.68%, 0.95%, 0.48%, and 3.67% of effect size variations,

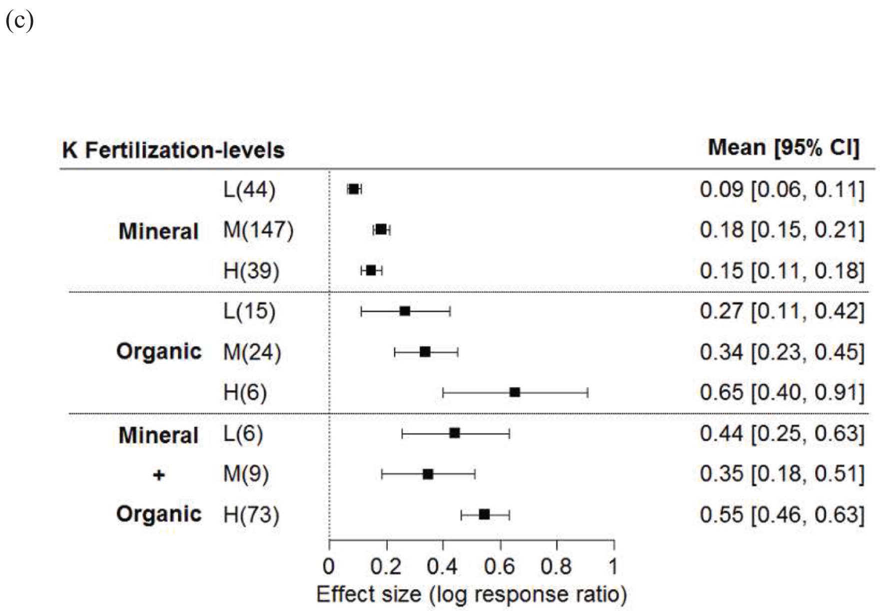

Fig. 5. (*continued*).

respectively (Table 2).

3.4. *Symmetry test of the effect size of fertilization on OC in agricultural upland soils*

A meta-analysis involves the quantitative evaluation of the average effect size of variables. The data are obtained from published papers, which may be affected by selection bias. Therefore, funnel plots with Egger's test (Du et al., 2021), and failsafe numbers (Viechtbauer, 2010) were used herein to test for potential publication bias. The funnel plots were not asymmetric ($z = 4.2111$, $p < 0.0001$) (Fig. S2), however, the failsafe analysis indicated that 34846732 additional studies with null results would be needed in the dataset to reduce the significance level to $p = 0.05$. As such, publication bias was not considered as an issue for the interpretation of the results.

4. Discussion

4.1. *General effects of fertilization on SOC*

The results of this meta-analysis demonstrated that fertilization significantly increased the SOC content or stocks of agricultural upland soils, with an average effect size of 0.2707 ± 0.0086. When examining the three main types of fertilization, the effect size of the mineral fertilization was 0.13 ± 0.01. These results are consistent with a previous meta-analysis that reported an effect size of 0.12 for long-term mineral fertilization on SOC in global agricultural upland soils (Geisseler & Scow, 2014). Although the authors reported a decrease in SOC over time, this decrease was less pronounced in plots that received mineral N than the unfertilized control (Ladha et al., 2011). There are multiple processes by which mineral fertilization influences SOC stocks in agricultural soils. Mineral fertilization (i.e., N, P, and K) increases photosynthetic C uptake by plants and thus increases crop residue input to soil (Saffigna et al., 1989; Liang et al., 2014). Concurrently, mineral fertilization directly improves nutrient availability in the soil, leading to higher crop root exudation due to crop growth (Willig et al., 2020; Zhu et al., 2016). This promotes microbial metabolism, thus increasing the microbial biomass C and microbially derived SOM in the soil (Liu et al., 2020). Finally, mineral fertilization reduces SOM decomposition through increased microbial turnover, decreasing the dependency of the organisms on the original nutrients from SOM decomposition (Ding et al., 2017; Liu et al., 2018). It can have a positive influence on C sequestration. Together, these processes lead to a smaller C loss by microbial mineralization as the input of crop residues, leading to an overall increase in SOC.

4.2. *Role of individual nutrients for SOC*

When investigating the effects of the primary nutrients N, P, and K, our results indicate the increase of available N, P and K is beneficial to SOC sequestration. Li et al. (2020) reported that single P and K fertilization and their co-application did not significantly change crop yield and SOC, but solo N significantly increased the yield without changing SOC. This illustrates that N is the main limiting factor for the growth of crops in agricultural upland soils. However, to translate the increased plant productivity into raising SOC values, following SOC stabilisation must be assured by combining multiple nutrients. The impact of multi-nutrient combined fertilization (NP, NK, PK, NPK) on SOC is higher than that of single-nutrient fertilization (N, P, K) (Fig. 4) because multi-nutrient fertilization provides more balanced nutrition for both microbial populations and plants, resulting in higher SOC accumulation in soils (Dai et al., 2018). Hence, our study is in line with Li et al. (2020), who reported that NP and NPK fertilization resulted in 19 – 47% higher SOC stocks than single N, P, and K fertilization. Combined multi-nutrient fertilization thus has the potential to improve not only soil fertility but also SOC stocks.

4.3. *Impacts of farmyard manure and crop residues on SOC*

The effect sizes of organic fertilization and organic plus mineral fertilization on the SOC were 0.38 ± 0.02 and 0.41 ± 0.01, respectively, which were clearly higher than mineral fertilization (0.13 ± 0.01). This illustrates that organic manure and residue management is essential for improving SOC (Ladd et al., 1994; Mi et al., 2018). When addressing

Table 2
Analysis of the effects of environmental and management factors on the effect size.

Moderators	df	Test of moderator (Qm)	intrcpt	p	τ^2	I^2	R^2
MAP	1	9.6464	0.3176	0.0019	0.0757	99.55%	0.68%
MAT	1	10.5579	0.2166	0.0012	0.0755	99.54%	0.95%
Water condition	1	5.9378	0.2764	0.0140	0.0758	99.55%	0.48%
Tillage types	4	47.3521	0.2640	<0.0001	0.0734	99.54%	3.67%
Crop rotation	1	2.4696	0.2939	0.1161	0.0761	99.55%	0.14%
Total	8	91.2224	0.2565	<0.0001	0.0708	99.51%	7.11%

MAP, mean annual precipitation; MAT, mean annual temperature; τ^2, interstudy variance; I^2, ratio of total (residual) heterogeneity to total (unaccounted) variability; R^2, effect size variation.

organic matter application to soil, one needs to differentiate between organic manure and crop residues. Organic manure is an important source of SOM and an adequate substitute for mineral fertilizer inputs (Ding et al., 2017). For example, horse and pig manure (18600 and 22500 kg ha^{-1} year^{-1}, respectively) increased SOC by 13% over 35 years and 32% over 37 years, respectively (Ashraf et al., 2020; Ding et al., 2017). Under a high input of organic manure, crops have solid and extensive root systems (Zhang et al., 2020). As such, the application of manure helps maintain the soil nutrient balance, improves soil structure and water-holding capacity, and is beneficial for environmental protection compared with the application of mineral fertilizers alone (Mwangi & Box, 2010). However, this also leads to spatial heterogeneity in resource distribution, resulting in the microbial decomposition of organic materials, which can release organic and inorganic nutrients for plant uptake (Zhang et al., 2020). Finally, the input of crop residues in the form of roots and stubbles increases as a result of fertilization of organic manure, which in turn increases the SOC content more than mineral fertilization alone (Sherrod et al., 2005).

Also, straw input has been shown to be important for increasing SOC (Fig. 4). Straw, derived from wheat, maize, soybean, and corn, is the main form of crop residue in agricultural practice (Guo et al., 2014; Li & Han, 2016; Yang et al., 2015). These crop residues include easily decomposable and more stable substrates (Liu et al., 2020; Mi et al., 2018). The return of crop residues to soil stimulates microbial activity to accelerate the accumulation of microbial residues in SOM and enhance the contribution of microbial residues to SOM sequestration (Liu et al., 2019). However, the effect level was least when no nutrients were added with additional fertilization (Fig. 4). Residues of wheat and many other kinds of cereal are characterized by high C: nutrient (i.e., N, P, K, S, micronutrients) ratios. The high C: nutrients ratio mineralize more organic C to acquire more nutrients for microbes along with a higher investment of extracellular hydrolytic enzymes (Wei et al., 2019; Zhang et al., 2023), leading to a reduced microbial carbon use efficiency (CUE) (Wang et al., 2019) and increase nutrients use efficiency (Mooshammer et al., 2014).

Application of mineral fertilizer in addition to crop residue return leads to lower C: nutrient ratio, which modifies the decomposition pathways of crop residues (Soong et al., 2018). Added mineral nutrients (as available nutrients) can be preferentially utilized by microorganisms, leaving crop residue intact (Duan et al., 2021). Furthermore, crop residue retention can decrease mineral N, P, and K fertilizer losses by inducing N, P, and K immobilization in the short term, increasing C sequestration in the soil and enhancing soil quality (Plante et al., 2006; You et al., 2014; Zhao et al., 2014). Therefore, straw plus mineral fertilization leads to more SOC than straw return alone (Fig. 4). Interestingly, only if K is added as mineral fertilizer together with farmyard manure, the effect level is more significant than for farmyard manure alone. This means that low-quality residues (high C:N:P) ratio is simply burned by microorganisms, and additional nutrients are needed to increase the CUE of the residue. On the contrary, for high-quality organic substrates, obviously the C:N:P ratio is obviously optimum. Microbial CUE of the residues decreases after mineral fertilization. Thus, it infers that K likely inhibits oxidative enzymes involved in the degradation of aromatic compounds by K in combination with a reduced energy requirement for microbial K acquisition in the fertilized soils (Spohn et al., 2016). Overall, organic fertilization improves SOC stocks. Particularly for organic amendments with high C:nutrient ratios, additional nutrient dressings are decisive in shifting the decomposition from a catabolic to an anabolic pathway (Akhtar et al., 2019; Ashraf et al., 2020; You et al., 2014).

4.4. *Role of the amount of fertilizer application on SOC*

Adapted mineral N, P, and K fertilization contributes not only to the enhanced crop yield but also to the amount of plant residues returned to the soil (Geisseler & Scow, 2014). Concerning the rate of fertilization, our results show that N and K have the most decisive impact on effect size at intermediate levels (100–300 kg N ha^{-1} year^{-1}, Fig. 5a, and 50–150 kg K ha^{-1} year^{-1}, Fig. 5c) of fertilization, whereas, for P, a high fertilizer amount (>60 kg P/ha year^{-1}, Fig. 5b) resulted in the most remarkable effect size. Hence, for N and K, there appears to be a positive response to the rate of fertilization on SOC stocks, whereas, beyond a certain level, higher fertilization rates instead lead to a decline in the SOC level. Compared with intermediate N, excess N fertilization (>300 kg ha^{-1} year^{-1}) combined with a low N use efficiency led to N loss by leaching and deterioration in soil structural quality, causing a negative effect on C sequestration (BlancoCanqui & Schlegel, 2013; Brown et al., 2014; Follett et al., 2005; Zhu et al., 2016). At low N fertilization rates (<100 ha^{-1} year^{-1}), roots exudate less organic substances into the soil to gain nutrients through SOM decomposition for the growth of crops, thus causing a reduction in SOC content (Zhao et al., 2019). Similarly, intermediate K fertilization (50–150 kg ha^{-1} year^{-1}) alleviated soil K depletion. It increased soil K fertility (Zhao et al., 2014), however excess of K fertilizer (>150 kg ha^{-1} year^{-1}) couldn't stimulate the rate of OC transfer from the crop residues and roots to induce significant changes in SOC pool (Yuan et al., 2021). Differently, the efficient use of P fertilizer to improve SOC levels ultimately enhances crop production and simultaneously increases soil C sequestration, which highly depends on soil initial P fertility (poor or rich P) (BlancoCanqui & Schlegel, 2013; Bansal et al., 2020). In addition, P has a low plant availability due to sorption or occlusion within aluminium and iron in acidic soils or calcium and magnesium cations in alkaline soils. It leads to an increase in SOC with the amount of P fertilizer increasing.

In addition to the local climate or other management factors, intermediate N and K with high P fertilization may stimulate both the growth and development of plant shoots and roots (Razaq et al., 2017; Sustr et al., 2019), leading to more photosynthetic derived C being allocated to soil through crop residues and rhizodeposition (Zang et al., 2019). Therefore, comparable to the well-known concept of optimum fertilization with respect to crop yield, SOC gains seem to follow a nonlinear correlation with fertilizer amounts. To some extent, this might be a result of the input amounts following the optimum concept of crop yield. Still, our meta analysis also indicates that soil processes, like triggering anabolic and catabolic functions of microbes, are affected by the amount of fertilizers leading to a delicate balance between positive and negative fertilizer effects.

4.5. *Modulation of fertilizer effects on SOC by environmental variables*

SOC stocks in agricultural soils depend on climate conditions and soil physical, chemical, and microbiological properties that are affected by fertilization (Adams et al., 1995; Kirschbaum et al., 2001). Environmental variables also affected OC stocks in agricultural upland soils. Our results show that MAP, MAT, water conditions, and tillage types caused variations in effect value. Li et al. (1994) and Wei et al. (2021) reported that MAP is an essential variable for the impact of fertilization on SOC stocks. Our results align with Márton (2008) statement that precipitation negatively affects SOC stocks in the case of mineral fertilization. In the 20-year experimental term, for the site with the lower precipitation (204 mm), an increase of the SOC stocks from 1.28 $\mathrm{Mg \cdot ha^{-1}}$ to 1.79 $\mathrm{Mg \cdot ha^{-1}}$ was observed (Márton, 2008). Regarding the effects of MAT, our results indicate a decreasing impact of higher temperatures (i.e., >15℃ as compared to 5–15℃) on the effect size of fertilization on SOC. This is because the increase in temperature may lead to the enhanced decomposition of SOM in soils under long-term agricultural use (Wiesmeier et al., 2015). Trumbore et al. (1996) reported that decreasing temperature with altitude has been shown to limit SOC turnover, increasing SOC storage. Soil moisture is an essential factor for plants to utilize nutrients added to stimulate their growth (Kramer, 1944), as well as it is of utmost necessity for the development and activity of soil microbiota (Cui et al., 2020; Skopp et al., 1990). Therefore SOM mineralization rates are regulated by oxygen limitations through water conditions (alternating anaerobic wetting and aerobic drying) (Keiluweit et al., 2018; Liu et al., 2016). Even within seemingly well-drained upland soils, when oxygen consumption (microbial respiration) in soil microsites outpaces oxygen supply (through diffusion), oxygen limitations may arise in otherwise well-aerated soils (Keiluweit et al., 2018; Wei et al., 2021). Regular intervals of aerobic and anaerobic conditions lead to the accumulation of SOC stocks in fertilized arable systems (Ashraf et al., 2020) because of reduced decomposition of crop residues under anaerobic conditions (Qiu et al., 2018). Another *meta*-analysis demonstrated that aerobic conditions positively affect soil bacterial diversity, while anaerobic conditions negatively affect soil bacterial diversity with fertilization in agroecosystems worldwide (Dai et al., 2018).

Also, different tillage types modulate the effect of fertilization on SOC stocks (Table 2). De Sanctis et al. (2012) reported that over a 50-year simulation period, the SOC content in the top 40 cm of soil was consistently higher under NT than that under CT at a given level of N fertilizer application (90 and 180 kg $\mathrm{ha^{-1}}$ $\mathrm{year^{-1}}$). The simulated SOC under NT increased at a mean annual rate of 0.43, 0.31, and 0.03 t $\mathrm{ha^{-1}}$ in response to 180, 90, and 0 kg N $\mathrm{ha^{-1}}$ $\mathrm{year^{-1}}$, respectively. This can be explained by the higher crop residue return to the surface soil at NT with increasing fertilization. ÁlvaroFuentes et al. (2012) found that at NT, higher N addition resulted in greater C inputs and an increase in SOC, while at CT, N addition did not affect C inputs or SOC stocks at 0–30 cm soil depth. Also, Poirier et al. (2009) reported higher SOC stocks in the surface soil layer at NT at a given mineral fertilization level, reflecting more significant residue accumulation on the soil surface. Tillage incorporates crop residues to soil layers of 5–45 cm and induces changes SOC distribution compared to natural soils (Luo et al., 2010). Consequently, in a global meta-analysis, Luo et al. (2010) reported that SOC was 3.15 ± 2.42 t $\mathrm{ha^{-1}}$ larger under NT in the 0–20 cm soil layer but 3.30 ± 1.61 t $\mathrm{ha^{-1}}$ smaller in the 20–40 cm soil layer than under CT. Thus, NT has been considered an effective way to increase SOC stocks in surface soil (Luo et al., 2010; Šimanský et al., 2017). Thermal conditions and a disturbed soil microbiota community with CT as compared to NT (Coppens et al., 2007; Mazzoncini et al., 2011; Six et al., 1999) might have additional consequences the different impact of soil management on the effect level of fertilization on SOC stocks.

5. Conclusion

Using a heterogeneity test and categorical variable analysis on a global dataset, our study demonstrated a significant positive response of fertilization on SOC in agricultural upland soils. Combined organic plus mineral fertilization had the most significant on SOC stocks, followed by organic fertilization alone, while the effect of mineral fertilization alone was minor. Concerning organic fertilization, the C:nutrient ratio of the substrate is decisive. For low-quality substrates (i.e., high C: nutrient ratios), additional nutrient dressings are necessary to secure a high effect level. Intermediate N (100–300 kg $\mathrm{ha^{-1}}$ $\mathrm{year^{-1}}$) and K (50–150 kg $\mathrm{ha^{-1}}$ $\mathrm{year^{-1}}$) application with high P (>60 kg $\mathrm{ha^{-1}}$ $\mathrm{year^{-1}}$) fertilization demonstrated the most prominent effect on the SOC stocks, indicating moderate fertilization reduces SOM decomposition through decreasing microbial organic matter turnover, which might positively affect C sequestration. The fertilization effect on SOC stocks is modulated by environmental factors such as MAP, MAT, and soil management. The impact of soil properties (i.e., clay and pH) and different microbial taxa on the contribution of fertilization to SOC should be paid more attention to in the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2023.116580.

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