The Influence of nutrient management on soil organic carbon storage, crop production, and yield stability varies under different climates

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Abstract

Our understanding on how soil organic carbon (SOC) storage, crop yield, and yield stability are influenced by climate is limited. To critically examine this, the impact of long-term (≥10 years) application of nutrient management practices on SOC storage, crop productivity, and yield stability were evaluated under different climatic conditions in China using a meta-analysis approach. The cropping area of China was divided into four distinct groups based on local climatic conditions (warm dry, DW; warm moist, WM; cool dry, CD; cool moist, CM). Results indicated that the impact of nutrient management practices on SOC storage, crop yield, and yield stability varies under different climatic zone in China. The use of unbalanced mineral fertilizer

(UMF), and balanced mineral fertilizer (BMF) led to a loss in SOC storage by 6%, and 11% under CM climatic zone and gains in DW, WM, and CD climates. Organic fertilizers (OF), combined unbalanced mineral and organic fertilizers (UMOF), and combined balanced mineral and organic fertilizers (BMOF) were able to sustain and enhance SOC storage under all climatic conditions. However, the largest increase in SOC storage across all climates was seen for BMOF. Further, corresponding values of crop productivity and yield stability were also highest for BMOF among all the nutrient management treatments. A linear-plateau model indicated that maximal yield responsive SOC stock (C_{opt}) levels ranged from 33.43 to 45.51 Mg C ha^{-1} for rice (*Oryza sativa*), maize (*Zea mays*), and wheat (*Triticum aestivum*) production. To enhance and sustain SOC storage, and crop productivity of croplands under different climates, BMOF appears to be the most appropriate nutrient management strategy. Our findings demonstrate that it is essential to optimize nutrient management strategies according to the local climate to protect soil from SOC losses, and for achieving sustainable crop production.

Keywords

Crop yields, Nutrient management, Soil organic carbon, Yield stability, Climate change, Critical level

Introduction

Global agro-ecosystems occupy just 36% of the land surface to deliver food for over seven billion people. Ever-increasing pressure to enhance crop productivity is encouraging intensive farming practices across agro-eco systems (Zalles et al., 2019). Unfortunately, intensive farming practices are degrading soil quality. Improved soil quality is essential to attaining high crop productivity, and soil quality, which in turn is strongly dependent upon soil organic carbon (SOC) concentration and composition. The concentration of SOC maintains soil quality and contributes to high and stable soil productivity (Pan et al., 2019).

Global soils are the largest terrestrial reservoirs of SOC which encompasses about 1505 Pg carbon (C) in the top one meter layer (Lal, 2018). Presently, soils contribute significantly (37%)

to agricultural GHG emissions (mainly through nitrous oxide), and agricultural emissions are increasing at ~1% annually (Tubiello et al., 2015). However, agricultural soils can also be a sink for carbon to reduce the atmospheric CO_2 concentration (Hu et al., 2019). Carbon storage in soils is more than the total sum of carbon stored in living-vegetation and the atmosphere. Therefore, slight changes in SOC storage can cause a significant impact on atmospheric CO_2 concentration (Smith et al., 2019). Thus, an increase in SOC storage is a major concern for high crop yields, soil conservation, and environmental quality.

Changes in crop production practices and land use may affect SOC negatively or positively (Waqas et al., 2020), for instance, inappropriate farming practices has depleted 25–75% of SOC across the globe (Lal, 2013). Rational fertilizer applications can increase SOC storage due to higher biomass production, which provides more available organic matter (litter, plants residue, decaying roots) for input to soils (Šimanský et al., 2019). With the adoption of conservation agriculture (CA) and improved management practices, the SOC sequestration rate in croplands can be 0.25–1 Mg C ha^{-1} year^{-1} (Lal, 2018), which can build the foundation of sustainable agriculture productivity with less environmental cost (Alam et al., 2019; Lal et al., 2019).

However, impacts of crop production practices on SOC storage can be different in different climates (Ogle et al., 2019). China is an important agricultural country with a large cropping area (166.6 million hectares) and many distinct climatic zones (National Statistical Bureau, 2018). In China, organic inputs into the soils have decreased because of the separation of livestock and crop production systems. Therefore, limited availability of organic amendments have increased the use of mineral fertilizers (Sheldrick et al., 2003). China is now the world's largest user of mineral fertilizer by using 36% of total global fertilizer production (Farrell et al., 2014). Chinese farmers use more synthetic fertilizers (especially N) than recommended (Wu et al., 2018; Zhang et al., 2018). Because of fears of producing low yields, they are often reluctant to decrease application rates even when problems such as soil acidification occur. Decades of excessive use of mineral fertilizers has degraded soils, polluted water, and exacerbated environmental problems. Currently, in Chinese soils, the total SOC stock is 58.98 Pg in the upper 100 cm soil layer (Song et al., 2020). Because soils are depleted in carbon, there is a vast potential to improve SOC stocks, and the improved crop productivity to feed China's burgeoning population without, threatening the environment.

A quantitative assessment of the effects of nutrient management practices on SOC storage identifies appropriate strategies for enhancing SOC concentration in soils and mitigating the increasing problem of low soil productivity. Past studies investigating changes in SOC storage and crop productivity in China have mostly focused one a region, single fertilizer management practice (Han et al., 2018; Ji et al., 2016; Ren et al., 2018), or a specific crop (Tian et al., 2015). Thus, data from these studies are insufficient to describe changes in SOC storage and crop yields under different fertilizer applications across diverse climatic conditions. Although the response of SOC to management practices is rather a slow process that can only be credibly assessed with data from long-term field experiments (Johnston and Poulton, 2018), previous meta-analyses were based primarily on the data from experiments of short (3-10 years) duration (Han et al., 2018; Lu, 2015; Zhu et al., 2015).

In this study, a dataset of long-term field fertilizer experiments (≥10 years) was used to evaluate SOC storage and crop yield changes under different climatic conditions**.** We hypothesized that the influence of nutrient management practices on SOC storage, crop production, and yield stability varies under different climates. We posit that after reaching to a certain increase in SOC stocks with fertilization practices, further increases in corresponding crop yield values would be lower. Although determining such upper SOC stocks are important to address climate change and food security challenges, only few studies have reported maximal yield as a response to SOC stock (C_{opt}). The objectives of the present study were to: (1) quantify changes in SOC storage and crop yield under different climatic conditions in response to various fertilizer management; (2) test the yield stability under different climatic conditions over the long term; (3) identify the critical values of SOC storage required for maximum crop production.

Materials and methods

We used online internet databases at the Chinese Academy of Agricultural Sciences (http://apps.webofknowledge.com, http://www.sciencedirect.com, http://link.springer.com, http://onlinelibrary.wiley.com, http://www.cnki.net, and http://g.wanfangdata.com.cn, https://www.scopus.com), with search strings related to SOC or crop yield change in croplands caused by nutrient management. Data were collated from different long-term fertilization experiments across different climatic zones of China using the above-mentioned literature survey according to the guidelines from PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; Supplementary Fig. S1) (Moher, Liberati, Tetzlaff, & Altman, 2009). All field experiments considered had a common focus on the impact of fertilization on SOC and yields. Strict selection criteria were followed to maintain a high standard of data quality such as, (1) the experiment must have at least one of the following management treatments: mineral fertilizers only, only organic fertilizers including animal manure, compost or green manure, straw return, or integrated fertilizer management (combination of both mineral and organic fertilizers) and must have a control treatment (no fertilizer); (2) the experimental duration must be longer than 10 years, (3) initial and final SOC content or stock must have been provided in the publications; and (4) must contain information on both SOC and agronomic yield. Observations on annual crop yields and SOC from 58 long term field experiments were collected (Fig. 1). The dataset included distinct locations, climates, crop spp., fertilizer practices, annual crop yields, initial and final year SOC concentrations, etc. Based on management practices categorized into six treatments:(1) no fertilization (CK); (2) unbalanced application of one or two mineral fertilizers, i.e., nitrogen, phosphorous, and potassium (UMF); (3) balanced mineral fertilizer with NPK (BMF); (4) only organic fertilizer with manure or straw application (OF); (5) unbalanced mineral + organic fertilizer (UMOF); (6) balanced mineral + organic fertilizer (BMOF). These treatments represent a majority of the fertilization practices across China. Following the IPCC 2014 (Intergovernmental Panel on Climate Change) climatic classification, all experimental locations were divided into four distinct climates. All experimental locations were considered to be in the temperate climate zone with mean annual temperature (MAT) lower than 18°C. Temperate locations were further divided into warm (MAT 10-18°C) and cool regions (< 10°C) (Fischer et al., 2002).. Dry/moist region classification was defined according to the ratio of potential evapotranspiration to precipitation, as described by (Zhang et al., 2019). From these indices, warm-moist (WM), warm-dry (WD), cool-moist (CM) and cool-dry (CD) zones were defined.

The SOC concentration was analyzed for 0-20 cm soil depth. The SOC content or stock and crop yields were either obtained directly from tables and/or text of the published papers or extracted from the figures using graph digitizing software; GetData Graph Digitizer 2.26 (getdata-graph-digitizer.com). If a study provided a measurement of soil organic matter concentration, it was converted into an SOC concentration using a coefficient of 0.58 (Yang et al., 2007). The SOC stock was determined using the Eq.1 (Yang et al., 2007):

$$C_{SOC} = SOC \times \gamma \times H \times 10^{-1} \quad (1)$$

Where C_{SOC} is the SOC stock (Mg C ha^{-1}), SOC represents SOC concentration (g C kg^{-1}), γ is the soil bulk density (SBD; g cm^{-3}), H is the measured soil depth (cm), and 10^{-1} is a constant to align the units. Although SBD is one of the critical parameters in determining cropland SOC storage, some studies did not provide its value. We employed the empirical functions stated in equations 2 (for paddy soils) and 3 (for upland soil) to obtain SBD when it was not reported (Xie et al., 2007).

$$SBD = -0.22 \times \ln(SOC) + 1.2627\ (Paddy\ soil) \quad (2)$$

$$SBD = -0.1019 \times \mathrm{SOC} + 1.406\ (Upland\ soil) \quad (3)$$

Data Analysis

Responses of crop yield to different modes of fertilization

The effect size is a quantitative measure that represents the impact of a treatment effect (fertilization) in comparison with a reference treatment (no fertilization) (Borenstein et al., 2011). For crop yield, the effect size of each observation (taken to be the comparison between fertilization and control in our study) was calculated as the natural log of the response ratio (lnR; (Rosenberg et al., 2000)), as in Eq. (4):

$$\ln R = ln \frac{X_t}{X_c} \quad (4)$$

Where, X_t represents the mean crop yield of the fertilizer treatments and X_c is the mean yield of the no fertilizer treatment (control). Relative yield change with fertilization was calculated as (R-1) × 100 % (Chivenge et al., 2011). Positive values of yield improvement rate indicated an increase in crop production with fertilizer treatment and *vice versa*.

Responses of SOC storage to different types of fertilization

The effect size of SOC storage was quantified using Eq.5 (Li et al., 2018):

$$\ln R = ln\frac{SOC_f}{SOC_i} \quad (5)$$

Where, SOC_f and SOC_i are SOC stocks for the final year of fertilizers addition and initial year of fertilizers addition. A positive value of this response ratio (SOC storage) indicates gains in SOC stock due to fertilization and a negative value indicates losses in SOC stock.

Yield sustainability

Effect size of yield sustainability was calculated using empirical equation 6 as explained by (Manna et al., 2005).

$$YSI = (\overline{y} - \sigma)/Y_{max} \times 100 \quad (6)$$

Where, YSI is the yield sustainability index, $\overline{y}$ is the mean crop yield, σ is the standard deviation of yield across the whole duration (years) and Y_{max} is the maximum observed yield.

Meta-analysis

A meta-analysis using a random effects model was conducted using MetaWin 2.1 software (Rosenberg et al., 2000). As standard deviations were rarely available in the selected literature, an unweighted analysis was adopted to include as many studies as possible (Rosenberg et al., 2000). The weighting factor for each effect size was calculated using empirical Eq.7.

$$w_i = \frac{(n_{ck} \times n_{tr})}{(n_{ck} + n_{tr})} \quad (7)$$

Where w_i indicates the weight of *i*th effect size and n_{ck} and n_{tr} represent field replicates of control and treatment groups, respectively.

We used bootstrapping (4999 iterations) to generate the mean effect size and bias-corrected 95% confidence interval (95% CI) for each categorical variable. Mean effect sizes were significantly different if their 95% CIs did not overlap, and also were significantly different from the control if their 95% Cl did not overlap with zero (Chivenge et al., 2011). Likewise, the effects of the categories were deemed to be significantly different if the probability (p) values of betweengroup heterogeneity (Q_b) were less than the 0.05 ($p < 0.05$). Publication bias indicates biases in the publication of articles displaying positive results over others. It is suspected that academic journals are more likely to publish significant results, and researchers may discard or decide not to publish non-significant results. Publication bias can therefore result in an overestimation of effect sizes. To avoid publication bias, we evaluated the potential publication bias using the graphical method (normal quantile plot), rank correlation test, and Rosenthal's (Alpha value = 0.05) and Orwin's (negligible effect = 0.20) methods (Rosenberg et al., 2000), (see supplementary material). Further, we used bias-corrected bootstrap confidence intervals as explained above (Rosenberg et al., 2000).

Critical SOC levels for crop productivity

As the current dataset represents long-term experiments conducted in different regions/climates of China, SOC and crop productivity levels cannot be directly compared. To eliminate the impacts of climatic variability, influence of variety replacement during long-term experiments, and seasonal variations among sites and years, relative grain yields were calculated as explained by (Bai et al., 2013) for rice, maize, and wheat crops.

$$\text{RGY} = Yt/\,Ymax \qquad (8)$$

RGY indicates relative grain yield. Yt is a particular treatment yield, and $Ymax$ is the maximum attained yield at a particular experimental site. A linear-plateau model was used to calculate optimum SOC stock (C_{opt}) for maximum crop yield response of rice, maize, and wheat (Zhang et al., 2016).

$$\text{Ypr} = a + bx \quad if\ C_{SOC} < C_{opt} \qquad (9)$$

$$\text{Ypr} = Ypl \qquad if\ C_{SOC} \geq C_{opt} \qquad (10)$$

Where Ypr indicates predicted grain yield. a and b indicates intercept, and slope, while x is SOC stock and Ypl is the predicted plateau-grain yield fitted with the model. Linear-plateau model was performed by using R software package "easyreg" (Arnhold, 2019).

Results

Estimation of SOC storage under different climatic zones

An analysis of all experimental sites together shows a response ratio *(ln* (SOC_f / SOC_i)*)* of -0.1396 for the control treatment (no fertilizer) under CM climate, with a significant loss of 14.0% in SOC storage. However, the control treatment showed a slight increase of 8.8%, 0.8%, and 1.7% in SOC storage under WD, WM, and CD climatic regions. Unbalanced application of mineral fertilizers (UMF) also resulted in a significant loss (-11%) in SOC storage under CM climate region compared with other climatic conditions ($p < 0.05$). However, UMF application slightly increased the SOC storage by 16%, 3%, and 10% in WD, WM, and CD regions. Even balanced application of mineral fertilizers (BMF) did not positively influence the SOC storage (-6%) in the CM climate zone of China. But in other climatic regions [(i.e. WD (24%), WM (14%), and CD (1.7%)] BMF enhanced SOC storage. Organic fertilizer application (OF) increased SOC storage across all climatic conditions. For OF inputs, the largest SOC increases were observed in WD (36%) followed by WM (30%), CD (28%), and CM (18%) climate zones. The positive impact on SOC was enhanced when organic fertilizers were integrated with unbalanced fertilizers (UMOF). For instance, UMOF application increased the SOC storage by 31%, 34.81, 35.2% and 19% in WD, WM, CD, and CM climatic zones, respectively. There was no significant difference among different climate regions for SOC storage with OF or UMOF treatments. Integration of balanced chemical fertilizers with organic inputs increased SOC storage the most (36%) across all climatic conditions. BMOF increased the SOC storage by 33%, 38, 36%, and 26% in the WD, WM, CD, and CM climatic zones, respectively (Fig. 2). This trend shows the importance of organic amendments to sustain and enhance SOC in croplands for an extended period of time under diverse pedoclimatic conditions.

Response of crop yield to fertilization practices in different climatic zones

In general, fertilization increased the grain yield relative to no-fertilization controls (Fig. 3). While the agronomic yield responded to diverse types of fertilization practices, the magnitude of response differed under different climatic zones. In all climatic zones, UMF treatment did not strongly influence crop yield, compared to other fertilization treatments (Fig. 3). There was a significant difference for yield increment (%) under different climatic zones with the use of UMF. For UMF treatment, increment in crop yield (7%) was significantly lower in the CM climate, compared with other climatic regions i.e. WD (125%), WM (79%), and CD (96%). The influence of unbalanced fertilization on crop yield across the climates zones increased when practiced in conjunction with organic fertilizers (UMOF). Thus, the increase in crop yield with UMOF was 290%, 93%, 144%, 71% in WD, WM, CD, and CM climatic zones, respectively in comparison with that of the control. In the WD and CD climate zones, crop productivity for the UMOF treatment was significantly higher compared with that of the WM and CM climate regions ($p < 0.05$). Likewise, balanced mineral fertilization (BMF) significantly enhanced average crop yield compared to that of the UMF fertilization (182% vs 82%) across climates. Crop yield benefits with BMF were significantly lower in the CM climate region (74%) compared with crop yield in the WD climate zone (263%). Moreover, compared to BMF (inorganic), OF fertilization (organic) was less effective in increasing the crop yield (182% vs 149%) across all climate zones. For the OF treatment, crop yield improvement was significantly lower in the cool climate zone (CM, CD) compared with that of warm moist climate zone ($p < 0.05$). Like other fertilization treatments, use of organic inputs also exhibited the largest increase (205%) in crop yield relative to the control in the WD climate zone of China. However, the maximum increase in crop production among all treatments under all the climatic conditions was observed for the combined application of balanced mineral and organic fertilizers (Fig. 3). For BMOF treatment, crop yield improvement was significantly lower in the CM climate (75%) compared with that of the WD (270%), WM (268%), and CD (190%) climatic zones ($p < 0.05$).

Response of grain yield sustainability to fertilization practices in different climatic zones

There was no significant difference in mean grain yield sustainability index (YSI) between the control and unbalanced mineral fertilization under different climates. For both (CK and UMF) treatments, the highest YSI was seen in the CM climatic zone. Furthermore, YSI did not increase substantially over the experimental durations, even when organic sources were combined with unbalanced mineral fertilizers (UMOF) (Fig. 4). For the UMOF treatment, YSI was significantly greater in the WM (64%) climatic zone compared with the WD (41%), CD (50%), and CM (53%) climatic zones ($p < 0.05$). Moreover, compared to BMF (inorganic), OF fertilization (organic) was less effective in enhancing crop yield stability under different climates. For BMF there was no significant difference in YSI across climatic zones. Balanced mineral (BMF) and combined balanced mineral with organic fertilizers (BMOF) delivered the best YSI compared to other fertilization practices across the climatic zones of China. For BMOF, the highest YSI was observed in the CM climate (64%), followed by WM (63%), CD (58%) and WD (56.75%) climatic zones.

Optimum SOC levels for crop productivity

Data from different experimental sites, and climatic zones across the China were combined to observe the relationship between SOC stocks and relative grain yield (RGY) of rice, wheat, and maize. The linear-plateau model indicated plausible the highest yield-responsive SOC stock (C_{opt}). There may be no more benefit to RGY with SOC stock above Copt. There was a significant positive relationship between SOC stocks and RGY of rice, wheat, and maize. The linear-plateau model indicated that changes in SOC stock explained 12%, 22%, and 18% of the RGY variations in rice ($R^2 = 0.12$), maize ($R^2 = 0.22$), and wheat ($R^2 = 0.18$), respectively. The predicted plateau-yield (Y_{pl}) was 0.91, 0.88 0.86 for rice, wheat, and maize, respectively. Corresponding values of C_{opt} (Mg C ha^{-1}) were 45.51, 36.40, and 33.43 for rice, wheat, and maize, respectively (Fig. 5, 6 & 7).

Discussion

Data analysis suggest that various fertilization practices being used across China vary significantly in their influence on SOC stocks, grain yield, and YSI under different climates. It is, therefore, crucial to choose the right kind of nutrition management while adapting to climate change and advancing food security. The data from experiments conducted across China suggest that the use of only chemical fertilizers is not enough to enhance SOC storage across all climatic conditions, and it may result in SOC loss, and soil degradation. Integration of balanced mineral fertilizers with organic inputs is necessary for maximal SOC storage and agriculture productivity under different climatic zones. However, SOC stocks in soils have a limit (C_{opt}) above which there may be no more benefits to crop yield. For grain production (rice, maize, and wheat) C_{opt} ranged from 33.43 to 45.51 Mg C ha^{-1}. This conclusion is based on the data from a wide range of climatic conditions. Thus, it is appropriate to suggest that judicious soil fertility management practices may be used elsewhere in developing countries to enhance and sustain productivity by improving soil quality and adapting to, and mitigating, climate change.

SOC storage in the soils of different climates receiving different fertilization practices

Data suggest that intial SOC stock is one of the pricipal soil charactristics which controls the change in SOC storage under different climates. For every fertilizer treatment, SOC storage was greater in dry climate zones compared with moist climate zones (Fig. 2) as intial SOC stocks (Mg C ha^{-1}) were higher in the moist climatic zone (30.68, SD = 11.28) compared with the warm climate zone (19.90, SD = 8.07). Mean highest intial SOC stocks (37 Mg C ha^{-1}, SD = 9.61) in CM climate also explained the lowest SOC storage in the CM climate zone for every fertilizer management practice. An ANOVA indicated that initial SOC levels significanlty influences SOC storage levels (Table S1). The long-term balance between C input and decomposition (which is influenced by management practices, e.g., fertilization) governs the magnitude of SOC in soils (Gonçalves et al., 2019; Wang et al., 2016). Because fertilization practices differed in the amount of C input into the soil because of their diverse sources (organic, inorganic, and integrated), the SOC storage also differed significantly among them (Fig. 2) under different climates. For example, the CK, UMF, and BMF treatments had little impact on SOC across different climatic conditions. These results are in accord with other studies conducted in China

(Han et al., 2016; Zhong et al., 2010) and globally (Hati et al., 2006; Maltas et al., 2018; Singh et al., 2019). This trend indicates a vast potential for SOC storage in Chinese croplands through the input of organic fertilizers. For instance, when UMF inputs were combined with organic sources (straw or manure) (UMOF), the mean SOC storage across different climatic zones increased greatly (400%), compared with that of the sole UMF practices (Fig. 2). A direct source of carbon through organic fertilizers increases SOC storage (García‐Orenes et al., 2016; Li et al., 2018) and also provides additional nutrients (N, P, S, etc.) to the soil. These nutrients are essential to form a fine fraction of soil organic matter (<0.4 mm) which makes up 70–80% of the organic matter (Kögel-Knabner, 2002). Beside this, additional crop residues, litter, and root-associated carbon from higher biomass production with BMOF treatment enhanced C input in soils under all climates (Fig. 3) Thus, BMOF was able to store maximum SOC in soils across all climatic zones of China, compared with other nutrient management practices.

Increase in grain yield

Climate influences crop productivity and thereby crop yields varied significantly in different climatic zones for each treatment. For fertilizer inputs, crop yields relative to control were greater in the warm climate zone compared with cool regions of China (Fig. 3). An annual temperature 10-18°C seems to benefit crop productivity in China. Climate-warming can influence crop productivity positively or negatively, depending on whether current temperature is lower or higher than the optimum temperature for crop productivity (Wang et al., 2019). An ANOVA indicated that changes in SOC storage significantly influence crop yield values (Table S2). Past studies conducted globally (Oldfield et al., 2019), and in China (Han et al., 2018) have linked increase in SOC storage with improved crop production. Additional SOC storage explains higher crop yields in warm climate regions compared with cool climate regions. Likewise, crop yield benefits were lower in the CM climate zone, due to least SOC storage for fertilizer treatments compared with other climatic zones of China (Fig. 2).

Unbalanced application of plant nutrients is also causing yield reductions in other parts of the world. For example, unbalanced use of N and P reduced crop yield in Africa by 10-40% (Van Der Velde et al., 2014). Globally, insufficient and unbalanced fertilization may lead to a potential production loss of 1,136 Tg yr^{-1} (Tan et al., 2005). Therefore, China and other nations must help smallholder farmers to address soil nutrient management problems. Unbalanced mineral fertilizers showed a small impact on crop yields across different climate zones. However, yield benefits were increased by 132%, 19%, 49%, and 169% in WD, WM, CD, and CM climate zones, respectively, when unbalanced mineral nutrients were used in combination with organic inputs. This increase was primarily attributed to the improved availability of plant nutrients with the application of manure (Dai et al., 2019; Maltas et al., 2018). BMF produced high grain yields but had a little impact on SOC. Contrastingly, using OF showed less impact on crop production but had a large impact on SOC across different climatic conditions (Fig. 1&2). Analyzing global farming systems, Seufert et al. (2012) reported that organic agriculture could reduce crop yield by 5-34%, compared with that of the mineral fertilizers. Higher crop yields over the years can only be produced with balanced and integrated nutrient management. Increasingly intensive crop production with modern cultivars (e.g., summer maize-winter wheat rotation in the North and annually three rice crops in the South China) and excessive mineral fertilizer applications reduce the inherent capacity of the soil to provide nutrients. Intensive farming induces micronutrient deficiency due to high nutrient uptake, which is aggravated by leaching and the prevalent irrigation practices (Sun et al., 2018; Yousaf et al., 2017). Addition of organic inputs like manure can attenuate these risks (Singh et al., 2018; Tang et al., 2019). The highest crop yield relative to the control across all the climatic regions was observed with the BMOF treatment. Thus, BMOF effectively met the nutrient demands of crop production in diverse climatic conditions of China. Further, increase in crop yield by BMOF compared with those from other treatments may be attributed to high SOC storage (Fig. 2), even across all the climatic zones. Increase in SOC increases crop yield by supplying plant nutrients, improving soil health, increasing microbial diversity, and enhancing soil moisture retention capacity (Lal, 2004; Oldfield et al., 2018).

Yield sustainability

Results indicated YSI (%) varies under different climatic conditions. The YSI data presented herein were derived from actual crop yields over the long-term duration of the experiments conducted across different climatic conditions of China. For all treatments, highest YSI was noted in CM climate region compared to other climatic zones. Most importantly for no fertilized control treatment, YSI was more in CM climate. This scenario hints that CM climate crop yields were less exposed to biotic and abiotic stresses, season variations, and pest attacks may be due to beneficial influence of high SOC stocks in the soils. Initial SOC stock levels significantly influence YSI among different fertilization practices (Table S3). The high YSI indicated better nutrient management practices capable of sustaining high yields over the years. Highest variation in grain yields (less YSI) were observed in the control and UMF treatments across different climatic conditions of China. It implies that under these practices, crops were prone to the nutrient deficit, and therefore more susceptible to biotic and abiotic stresses (Waqas et al., 2019). Practicing OF management also exhibited low YS at the end of experiments. The data from the present study indicate that YSI declines, with complete reliance on the inherent soil fertility, as was also concluded by Zhang et al. (2016). Soils of different climatic regions managed by BMOF exhibited sustainable productivity over the years. The increase in SOC content, with probable improvement in nutrient availability and water holding capacity, for the BMOF-amended soil likely contributed to more stable yields of rice, wheat, and maize (Chen et al., 2018). Crop growth and yield were not only affected by improvement in soil fertility but also adapted better to changing and uncertain climate over the years, with the integrated management of plant nutrients. In general, the temporal variability in crop yield due to climatic factors can affect regional and global food availability, food prices, and socio-economic conditions of the population involved. Therefore, it is crucial to adopt those fertilizer management practices that support agriculture sustainability over the long-term period.

Critical SOC stocks for crop production

It is difficult to quantify the impacts of SOC stocks on crop yields because: (1) nutrient managements vary in their influence on SOC, and consequent changes in SOC influence (2) nutrient cycling (3) plant available water by influencing soil physical properties like soil aggregate stability, retention pores, porosity etc. and (4) soil structure. Further, long-term agricultural experiments conducted in different climatic zones exhibit large variations in crop yields due to seasonal variations, variety change, and crop production practices. In the current study, these variations were minimized by demonstrating actual attained grain yield under a treatment relative to maximum attained grain yield at a particular experimental site. To obtain maximum yield responsive SOC stock (C_{opt}) for rice, wheat, and maize, data of top soil SOC stock was plotted against relative grain yield. A past study estimated critical SOC concentration of 1.9-2.2% for optimal grain yield of cereals (Musinguzi et al., 2016). But often in the literature, a top soil SOC concentration of 2% is considered critical, beyond which benefits are level off. It is important that the range measured in the current analysis is below that critical level of SOC (2%).

C_{opt} for the rice crop was higher than for wheat and maize (Fig. 5). It implies rice was less responsive to increase in SOC storage in terms of increase in grain yield compared with those of wheat and maize. Similar findings, also presented by Lal (2006), may be attributed to the fact that rice is generally grown in conditons that are very different from those for wheat and maize. SOC stocks reported in the current study can be targeted for optimal grain production. However, economic analyses in future are essential to ascertain critical SOC stocks with optimal returns for smallholder farmers.

Conclusions

This study evaluated the impact of different nutrient managements on SOC storage and crop yields under different climatic conditions. Overall, the influence of fertilizer management on SOC storage, crop yield and yield sustainability differed between distinct climate zones. Use of UMF, and BMF enhanced the SOC storage in three (WD, WM, and CD) of the four climatic zone, and indicated SOC losses in the CM climate region. UMOF, OF, and BMOF, on the other hand, enhanced SOC storage across all climates. The largest increase in SOC storage in all four climatic zone is possible with BMOF. Thus, climate feedback should be considered in future cropland management and conservation policies. Likewise, for fertilizer treatments, increase in crop productivity relative to control treatments was lower in the CM climate compared with other climates. Relative crop yields were larger in warm climates. However, yield sustainability was higher in the CM climate, which indicates more resilience to seasonal variations, biotic and abiotic factors, and pest attacks may be due to the positive influence of higher initial SOC stocks in soils of the CM region. Therefore, the best nutrient management strategy needs to be tailored to attain high and stable crop yields without the loss of SOC. BMOF inputs produced high and sustainable crop yields over the years in all four climates compared with other nutrients management regimes. Enhancements in SOC storage with nutrient management support crop production up to a limit. Further increase in SOC beyond optimum SOC stocks (C_{opt}) results in little of no additional benefit. We calculate that C_{opt} (Mg C ha^{-1}) for rice, wheat, and maize is 45.51, 36.40, and 33.43, respectively. C_{opt} can be targeted for increasing crop production and soil quality. Future studies should also include an economic analyses to ascertain critical SOC stocks with optimal returns for smallholder farmers.

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References

Alam, M.K., Bell, R.W., Biswas, W.K., 2019. Increases in soil sequestered carbon under conservation agriculture cropping decrease the estimated greenhouse gas emissions of wetland rice using life cycle assessment. Journal of cleaner production 224, 72-87. https://doi.org/10.1016/j.jclepro.2019.03.215.

Arnhold, E., 2019. easyreg: Easy Regression. R Package Version 4.0.

Bai, Z., Li, H., Yang, X., Zhou, B., Shi, X., Wang, B., Li, D., Shen, J., Chen, Q., Qin, W., 2013. The critical soil P levels for crop yield, soil fertility and environmental safety in different soil types. Plant and Soil 372(1-2), 27-37. https://doi.org/10.1007/s11104-013-1800-3.

Borenstein, M., Hedges, L.V., Higgins, J.P., Rothstein, H.R., 2011. Introduction to meta-analysis. John Wiley & Sons, Chichester, UK. https://www.meta-analysis-workshops.com/download/bookChapterSample.pdf.

Chen, H., Deng, A., Zhang, W., Li, W., Qiao, Y., Yang, T., Zheng, C., Cao, C., Chen, F., 2018. Long-term inorganic plus organic fertilization increases yield and yield stability of winter wheat. The Crop Journal 6(6), 589-599. https://doi.org/10.1016/j.cj.2018.06.002.

Chivenge, P., Vanlauwe, B., Six, J., 2011. Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. Plant and Soil 342(1-2), 1-30. https://doi.org/10.1007/s11104-010-0626-5.

Dai, H., Chen, Y., Liu, K., Li, Z., Qian, X., Zang, H., Yang, X., Zhao, Y., Shen, Y., Li, Z., 2019. Water-stable aggregates and carbon accumulation in barren sandy soil depend on organic amendment method: A three-year field study. Journal of cleaner production 212, 393-400. https://doi.org/10.1016/j.jclepro.2018.12.013.

Fan, M., Christie, P., Zhang, W., Zhang, F., 2010. Crop productivity, fertilizer use, and soil quality in China. Food Security and Soil Quality (Advances in Soil Science), CRC Press, Boca Raton, FL, USA, 87-107.

Farrell, M., Macdonald, L.M., Hill, P.W., Wanniarachchi, S.D., Farrar, J., Bardgett, R.D., Jones, D.L., 2014. Amino acid dynamics across a grassland altitudinal gradient. Soil Biology and Biochemistry 76, 179-182. https://doi.org/10.1016/j.soilbio.2014.05.015.

Fischer, G., Van Velthuizen, H., Shah, M., & Nachtergaele, F. O. (2002). Global agro-ecological assessment for agriculture in the 21st century: methodology and results. In. IIASA RR-02-02: IIASA. Laxenburg, Austria. http://pure.iiasa.ac.at/id/eprint/6667/.

García‐Orenes, F., Roldán, A., Morugán‐Coronado, A., Linares, C., Cerdà, A., Caravaca, F., 2016. Organic fertilization in traditional mediterranean grapevine orchards mediates changes in soil microbial community structure and enhances soil fertility. Land Degradation & Development 27(6), 1622-1628. https://doi.org/10.1002/ldr.2496.

Gonçalves, D.R.P., de Moraes Sá, J.C., Mishra, U., Fornari, A.J., Furlan, F.J.F., Ferreira, L.A., Inagaki, T.M., Romaniw, J., de Oliveira Ferreira, A., Briedis, C., 2019. Conservation agriculture based on diversified and high-performance production system leads to soil carbon sequestration in subtropical environments. Journal of Cleaner Production 219, 136-147. https://doi.org/10.1016/j.jclepro.2019.01.263.

Han, P., Zhang, W., Wang, G., Sun, W., Huang, Y., 2016. Changes in soil organic carbon in croplands subjected to fertilizer management: a global meta-analysis. Scientific reports 6, 27199. https://doi.org/10.1038/srep27199.

Han, X., Xu, C., Dungait, J.A., Bol, R., Wang, X., Wu, W., Meng, F., 2018. Straw incorporation increases crop yield and soil organic carbon sequestration but varies under different natural conditions and farming practices in China: a system analysis. Biogeosciences 15(7), 1933-1946. https://doi.org/10.5194/bg-2017-493-ac1.

Hati, K., Swarup, A., Singh, D., Misra, A., Ghosh, P., 2006. Long-term continuous cropping, fertilisation, and manuring effects on physical properties and organic carbon content of a sandy loam soil. Soil Research 44(5), 487-495. https://doi.org/10.1016/j.agee.2006.06.017.

Hu, J., Guo, H., Xue, Y., Gao, M.-t., Zhang, S., Tsang, Y.F., Li, J., Wang, Y.-n., Wang, L., 2019. Using a mixture of microalgae, biochar, and organic manure to increase the capacity of soil to act as carbon sink. Journal of Soils and Sediments, 1-10. https://doi.org/10.1007/s11368-019-02337-z.

Ji, Q., Zhao, S.-X., Li, Z.-H., Ma, Y.-Y., Wang, X.-D., 2016. Effects of Biochar-straw on soil aggregation, organic carbon distribution, and wheat growth. Agronomy Journal 108(5), 2129-2136. https://doi.org/10.2134/agronj2016.02.0121.

Johnston, A., Poulton, P., 2018. The importance of long‐term experiments in agriculture: their management to ensure continued crop production and soil fertility; the Rothamsted experience. European journal of soil science 69(1), 113-125. https://doi.org/10.1111/ejss.12521.

Kögel-Knabner, I., 2002. The macromolecular organic composition of plant and microbial residues as inputs to soil organic matter. Soil Biology and Biochemistry 34(2), 139-162. https://doi.org/10.1016/s0038-0717(01)00158-4.

Lal, B., Gautam, P., Nayak, A., Panda, B., Bihari, P., Tripathi, R., Shahid, M., Guru, P., Chatterjee, D., Kumar, U., 2019. Energy and carbon budgeting of tillage for environmentally clean and resilient soil health of rice-maize cropping system. Journal of Cleaner Production 226, 815-830. https://doi.org/10.1016/j.jclepro.2019.04.041.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. science 304(5677), 1623-1627. https://doi.org/10.1126/science.1097396.

Lal, R., 2006. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. Land Degradation & Development 17(2), 197-209.

Lal, R., 2013. Intensive agriculture and the soil carbon pool. Journal of Crop Improvement 27(6), 735-751. https://doi.org/10.1002/ldr.696.

Lal, R., 2018. Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. Global change biology 24, 3285–3301. https://doi.org/10.1111/gcb.14054.

Li, Y.e., Shi, S., Waqas, M.A., Zhou, X., Li, J., Wan, Y., Qin, X., Gao, Q., Liu, S., Wilkes, A., 2018. Long-term (⩾ 20 years) application of fertilizers and straw return enhances soil carbon storage: a meta-analysis.

Mitigation and adaptation strategies for global change 23(4), 603-619. https://doi.org/10.1007/s11027-017-9751-2.

Lu, F., 2015. How can straw incorporation management impact on soil carbon storage? A meta-analysis. Mitigation and Adaptation Strategies for Global Change 20(8), 1545-1568. https://doi.org/10.1007/s11027-014-9564-5.

Maltas, A., Kebli, H., Oberholzer, H.R., Weisskopf, P., Sinaj, S., 2018. The effects of organic and mineral fertilizers on carbon sequestration, soil properties, and crop yields from a long‐term field experiment under a Swiss conventional farming system. Land Degradation & Development 29(4), 926-938. https://doi.org/10.1002/ldr.2913.

Manna, M., Swarup, A., Wanjari, R., Ravankar, H., Mishra, B., Saha, M., Singh, Y., Sahi, D., Sarap, P., 2005. Long-term effect of fertilizer and manure application on soil organic carbon storage, soil quality and yield sustainability under sub-humid and semi-arid tropical India. Field crops research 93(2-3), 264-280. https://doi.org/10.1016/j.fcr.2004.10.006.

Musinguzi, P., Ebanyat, P., Tenywa, J.S., Basamba, T.A., Tenywa, M.M., Mubiru, D.N., 2016. Critical soil organic carbon range for optimal crop response to mineral fertiliser nitrogen on a ferralsol. Experimental Agriculture 52(4), 635-653. https://doi.org/10.1017/s0014479715000307.

National Statistical Bureau, N., 2018. National Statistics yearbook. China Statistics Press. Beijing, China. http://www.stats.gov.cn/english/.

Ogle, S.M., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F.J., McConkey, B., Regina, K., Vazquez-Amabile, G.G., 2019. climate and Soil characteristics Determine Where no-till Management can Store carbon in Soils and Mitigate Greenhouse Gas emissions. Scientific reports 9(1), 1-8. https://doi.org/10.1038/s41598-019-47861-7.

Oldfield, E.E., Bradford, M.A., Wood, S.A., 2019. Global meta-analysis of the relationship between soil organic matter and crop yields. Soil 5(1), 15-32. https://doi.org/10.5194/soil-5-15-2019.

Oldfield, E.E., Wood, S.A., Bradford, M.A., 2018. Direct effects of soil organic matter on productivity mirror those observed with organic amendments. Plant and Soil 423(1-2), 363-373. https://doi.org/10.1007/s11104-017-3513-5.

Pan, J., Zhang, L., He, X., Chen, X., Cui, Z., 2019. Long‐term optimization of crop yield while concurrently improving soil quality. Land Degradation & Development 30(8), 897-909. https://doi.org/10.1002/ldr.3276.

Ren, F., Zhang, X., Liu, J., Sun, N., Sun, Z., Wu, L., Xu, M., 2018. A synthetic analysis of livestock manure substitution effects on organic carbon changes in China's arable topsoil. Catena 171, 1-10. https://doi.org/10.1016/j.catena.2018.06.036.

Rosenberg, M.S., Adams, D.C., Gurevitch, J., 2000. MetaWin: statistical software for meta-analysis. Sinauer Associates, Sunderland, MA, USA.

Seufert, V., Ramankutty, N., Foley, J.A., 2012. Comparing the yields of organic and conventional agriculture. Nature 485(7397), 229. https://doi.org/10.1038/nature11069.

Sheldrick, W.F., Syers, J.K., Lingard, J., 2003. Soil nutrient audits for China to estimate nutrient balances and output/input relationships. Agriculture, ecosystems & environment 94(3), 341-354. https://doi.org/10.1016/s0167-8809(02)00038-5.

Šimanský, V., Juriga, M., Jonczak, J., Uzarowicz, Ł., Stępień, W., 2019. How relationships between soil organic matter parameters and soil structure characteristics are affected by the long-term fertilization of a sandy soil. Geoderma 342, 75-84. https://doi.org/10.1016/j.geoderma.2019.02.020.

Singh, R., Srivastava, P., Singh, P., Sharma, A.K., Singh, H., Raghubanshi, A.S., 2018. Impact of rice-husk ash on the soil biophysical and agronomic parameters of wheat crop under a dry tropical ecosystem. Ecological Indicators 105, 505-515. https://doi.org/10.1016/j.ecolind.2018.04.043.

Singh, V., Dwivedi, B., Mishra, R., Shukla, A., Timsina, J., Upadhyay, P., Shekhawat, K., Majumdar, K., Panwar, A., 2019. Yields, soil health and farm profits under a rice-wheat system: Long-term effect of fertilizers and organic manures applied alone and in combination. Agronomy 9(1), 1. https://doi.org/10.3390/agronomy9010001.

Smith, P., Soussana, J.F., Angers, D., Schipper, L., Chenu, C., Rasse, D.P., Batjes, N.H., van Egmond, F., McNeill, S., Kuhnert, M., 2019. How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. Global change biology 00, 1–23. https://doi.org/10.1111/gcb.14815.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Annals of internal medicine 151(4), 264-269. https://doi.org/10.7326/0003-4819-151-4-200908180-00135.

Song, X. D., Wu, H. Y., Ju, B., Liu, F., Yang, F., Li, D. C., ... & Zhang, G. L. (2020). Pedoclimatic zone-based three-dimensional soil organic carbon mapping in China. Geoderma 363, 1-15. https://doi.org/10.1016/j.geoderma.2019.114145.

Sun, M., Huo, Z., Zheng, Y., Dai, X., Feng, S., Mao, X., 2018. Quantifying long-term responses of crop yield and nitrate leaching in an intensive farmland using agro-eco-environmental model. Science of the Total Environment 613, 1003-1012. https://doi.org/10.1016/j.scitotenv.2017.09.080.

Tan, Z., Lal, R., Wiebe, K.D., 2005. Global soil nutrient depletion and yield reduction. Journal of Sustainable Agriculture 26(1), 123-146. https://doi.org/10.1300/j064v26n01_10.

Tang, Q., Ti, C., Xia, L., Xia, Y., Wei, Z., Yan, X., 2019. Ecosystem services of partial organic substitution for chemical fertilizer in a peri-urban zone in China. Journal of Cleaner Production 224, 779-788. https://doi.org/10.1016/j.jclepro.2019.03.201.

Tian, K., Zhao, Y., Xu, X., Hai, N., Huang, B., Deng, W., 2015. Effects of long-term fertilization and residue management on soil organic carbon changes in paddy soils of China: A meta-analysis. Agriculture, Ecosystems & Environment 204, 40-50. https://doi.org/10.1016/j.agee.2015.02.008.

Tubiello, F.N., Salvatore, M., Ferrara, A.F., House, J., Federici, S., Rossi, S., Biancalani, R., Condor Golec, R.D., Jacobs, H., Flammini, A., 2015. The contribution of agriculture, forestry and other land use activities to global warming, 1990–2012. Global change biology 21(7), 2655-2660. https://doi.org/10.1111/gcb.12865.

Van Der Velde, M., Folberth, C., Balkovič, J., Ciais, P., Fritz, S., Janssens, I.A., Obersteiner, M., See, L., Skalský, R., Xiong, W., 2014. African crop yield reductions due to increasingly unbalanced Nitrogen and Phosphorus consumption. Global Change Biology 20(4), 1278-1288. https://doi.org/10.1111/gcb.12481.

Wang, B., Li, J., Wan, Y., Cai, W., Guo, C., You, S., Li, R., Qin, X., Gao, Q., Zhou, S., 2019. Variable effects of 2° C air warming on yield formation under elevated [CO2] in a Chinese double rice cropping system. Agricultural and Forest Meteorology 278, 107662. https://doi.org/10.1016/j.agrformet.2019.107662.

Wang, G., Luo, Z., Han, P., Chen, H., Xu, J., 2016. Critical carbon input to maintain current soil organic carbon stocks in global wheat systems. Scientific reports 6, 19327. https://doi.org/10.1038/srep19327.

Waqas, M. A., Li, Y. E., Lal, R., Wang, X., Shi, S., Zhu, Y., ... & Gao, Q., 2020. When Does Nutrient Management Sequester More Carbon In Soils And Produce High And Stable Grain Yields In China?. Land Degradation & Development 2020, 1–16. https://doi.org/10.1002/ldr.3567.

Waqas, M. A., Kaya, C., Riaz, A., & Li, Y. E. (2019). Potential Mechanisms of Abiotic Stress Tolerance in Crop Plants Induced by Thiourea. Frontiers in plant science 10, 1-14. doi: 10.3389/fpls.2019.01336.

Wu, Y., Xi, X., Tang, X., Luo, D., Gu, B., Lam, S.K., Vitousek, P.M., Chen, D., 2018. Policy distortions, farm size, and the overuse of agricultural chemicals in China. Proceedings of the National Academy of Sciences 115(27), 7010-7015. https://doi.org/10.1073/pnas.1806645115.

Xie, Z., Zhu, J., Liu, G., Cadisch, G., Hasegawa, T., Chen, C., Sun, H., Tang, H., Zeng, Q., 2007. Soil organic carbon stocks in China and changes from 1980s to 2000s. Global Change Biology 13(9), 1989-2007. https://doi.org/10.1111/j.1365-2486.2007.01409.x.

Yang, Y., Mohammat, A., Feng, J., Zhou, R., Fang, J., 2007. Storage, patterns and environmental controls of soil organic carbon in China. Biogeochemistry 84(2), 131-141. https://doi.org/10.1007/s10533-007-9109-z.

Yousaf, M., Li, J., Lu, J., Ren, T., Cong, R., Fahad, S., Li, X., 2017. Effects of fertilization on crop production and nutrient-supplying capacity under rice-oilseed rape rotation system. Scientific reports 7(1), 1270. https://doi.org/10.1038/s41598-017-01412-0.

Zalles, V., Hansen, M.C., Potapov, P.V., Stehman, S.V., Tyukavina, A., Pickens, A., Song, X.-P., Adusei, B., Okpa, C., Aguilar, R., 2019. Near doubling of Brazil’s intensive row crop area since 2000. Proceedings of the National Academy of Sciences 116(2), 428-435. https://doi.org/10.1073/pnas.1810301115.

Zhang, D., Wang, H., Pan, J., Luo, J., Liu, J., Gu, B., Liu, S., Zhai, L., Lindsey, S., Zhang, Y., 2018. Nitrogen application rates need to be reduced for half of the rice paddy fields in China. Agriculture, Ecosystems & Environment 265, 8-14. https://doi.org/10.1016/j.agee.2018.05.023.

Zhang, T., Zhang, Y., Guo, Y., Ma, N., Dai, D., Song, H., Qu, D., Gao, H., 2019. Controls of stable isotopes in precipitation on the central Tibetan Plateau: A seasonal perspective. Quaternary International 513, 66-79. https://doi.org/10.1016/j.quaint.2019.03.031.

Zhang, X., Sun, N., Wu, L., Xu, M., Bingham, I.J., Li, Z., 2016. Effects of enhancing soil organic carbon sequestration in the topsoil by fertilization on crop productivity and stability: Evidence from long-term experiments with wheat-maize cropping systems in China. Science of the Total Environment 562, 247-259. https://doi.org/10.1016/j.scitotenv.2016.03.193.

Zhong, W., Gu, T., Wang, W., Zhang, B., Lin, X., Huang, Q., Shen, W., 2010. The effects of mineral fertilizer and organic manure on soil microbial community and diversity. Plant and soil 326(1-2), 511-522. https://doi.org/10.1007/s11104-009-9988-y.

Zhu, L., Li, J., Tao, B., Hu, N., 2015. Effect of different fertilization modes on soil organic carbon sequestration in paddy fields in South China: a meta-analysis. Ecological indicators 53, 144-153. https://doi.org/10.1016/j.ecolind.2015.01.038.