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A synthetic analysis of livestock manure substitution effects on organic carbon changes in China's arable topsoil

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ABSTRACT

Application of livestock manure has been recognized as an important strategy for enhancing soil organic carbon (SOC) stocks. However, the magnitude of manure application impacts on SOC changes as compared with conventional mineral fertilizers still needs to be better assessed. In this study, we conducted a meta-analysis to address the effects of various fertilization practices on SOC changes in China's arable topsoil. The analysis was based on 148 peer reviewed articles reporting 69 sites and 729 observations with an average experimental duration of 18 years across China. We compared the response of SOC content to application of manure alone (M) or manure plus mineral fertilizers (NPKM) with the SOC response to NPK or no fertilizers (Control). We systematically analyzed how SOC responses were influenced by different environmental and management factors (land use, climate and soil properties, etc.). First, the retention coefficient of manure was used to present the percentage of C input from manure "converted" to SOC. Compared to Control, on average, manure had C-retention coefficients of 31% ± 12% (95% Confidence Interval, CI) and 18% ± 2% for the experimental duration of ≤10 years and > 10 years, respectively. When compared to NPK, manure had C-retention coefficients of 29% ± 13% and 9% ± 3% for the experimental duration of ≤10 years and > 10 years, respectively. In addition, compared to Control and NPK, application of manure increased SOC content by 0.23–0.26 and 0.18–0.19 g kg^{-1} yr^{-1}, respectively. The results also indicated that the mean differences of SOC change between the treatments with or without manure application were mainly controlled by soil properties (28–43%) and anthropogenic farming practices (21–27%). Our results highlight the significance of improving or maintaining SOC stocks by manure applications, and provide insights for making manure application recommendations or guidelines to improve SOC stocks of China's cropland based on soil properties, climatic conditions and management practices.

1. Introduction

China has been facing the challenges of increasing demand of food while degradation of soil fertility. In order to gain a high crop production, natural soils that are rich in soil organic carbon (SOC) were converted to croplands (Song et al., 2005), and changes in land use type and crop rotation can markedly influence SOC (Song et al., 2005; Li et al., 2000; Wu et al., 2003). In addition, a critical phenomenon has frequently occurred on many farms since 1980s, which is excessive use of mineral nitrogen (N) fertilizers and intensive agricultural land use associated with a sharp decline in manure usage (Ju et al., 2005; Lai, 2002; Wu et al., 2003). This might be one of the key factors that led to significant degradation of soil fertility in particular decline in SOC which is a key factor benefitting soil physical, chemical and biological functions (Han et al., 2016; Ju et al., 2005; Pan et al., 2009; Xu and Liang, 2006). On the other hand, more than four billion tons of manure per year is produced from livestock sector but only a small proportion of the manure is appropriately applied to croplands because of high labor costs associated with manure transport and spreading (Fan et al., 2017; Ju et al., 2005), while application of livestock manure is widely

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recommended with the aim to promote SOC and reduce carbon (C) losses to counteract SOC decreases (Chen et al., 2014; Gattinger et al., 2013). Indeed, manure application is currently expected as a cost-effective and environmentally friendly strategy to maintain or improve soil fertility and crop productivity (Ahmad et al., 2007; Leite et al., 2010). Thus, manure application has been regarded as an important strategy to ensure global food security.

Individual studies and rare reviews have demonstrated that SOC could be enhanced by manure application in some regions of China (Ding et al., 2012; Wang et al., 2015). However, there is still a lack of studies on quantitative comparisons of SOC changes derived by manure application and conventional mineral fertilizers across the entire China's cropland. In comparison to mineral fertilizers, manures were shown to be generally more efficient on SOC sequestration (Wang et al., 2015; Yu et al., 2012; Zhang et al., 2012), but the differences in SOC changes resulting from manure application and mineral fertilizer application varied largely in different studies. For instance, the change in SOC stock following manure application was reported to be two-fold higher than that following mineral fertilizer application in upland soils of the temperate monsoon climatic region (Fang et al., 2006), while only 15% higher in paddy soils of the subtropical monsoon climatic region (Wang et al., 2015). In other studies, on the contrary, manure applications were reported to result in an 8% lower SOC concentration than mineral fertilizers in a Mollisol soil (Li et al., 2012), and a 10% lower in a brown soil (Lan et al., 2016). These uncertain and inconsistent results represent a large knowledge gap in the discrepancy of SOC changes between manures and mineral fertilizers at the national scale.

To date, there are increasing interests in quantitatively assessing the contribution of manure application to SOC changes as a basis for making guidance to farmers and parameterizing the relevant C models (Maillard and Angers, 2014). The retention coefficient of manure, which is defined as the percentage of C input from manure "converted" to SOC, is a key factor for SOC sequestration assessment (Henin and Dupuis, 1945). However, the retention coefficient of cumulative C input from manure has not been systemic analyzed and inconsistent with regard to the large variations of the values. For instance, the retention coefficient of cumulative C input from manure ranged from 6.8% to 31% and from 4.4% to 5.1% in croplands in the North and South of China, respectively (Zhang et al., 2015; Zhang et al., 2010). The inconsistent results in the literatures indicate that a further systematic assessment is highly necessary to figure out the variations of manure-C retention coefficient in arable topsoil across China.

The response of SOC change to manure application vary widely at different spatial and temporal scales, which leads to difficulties in assessing the contribution of manure to SOC changes across the China's cropland (Tao et al., 2013). The magnitude of SOC change induced by manure is largely influenced by soil properties, climate types (Zhang et al., 2015), amounts of manure C and N input to the soil (Silver and Miya, 2001), land use types (Huang et al., 2012), and length of experimental duration (Gerzabek et al., 1997). However, very rare studies in existing literature have quantified the effects of these explanatory factors at the national scale in China. There is, therefore, a need for establishing a reliable and verifiable database of SOC change in response to manure applications at various climates, land uses and soil conditions (Banger et al., 2010; Campbell et al., 1991a; Ding et al., 2014; Smith et al., 1997).

Meta-analysis is a formal statistical method commonly used to quantify the results of a large number of individual and independent studies, and based on that to draw a general conclusion across nationwide or worldwide (Don et al., 2011; Gurevitch and Hedges, 1999). In this study, we adopted the meta-analysis methodology to assess the effects of manure applications on SOC changes in Chinese arable soils relative to mineral fertilizers or no fertilizer applications. To achieve such a goal, we integrated the results from published studies comparing the changes in SOC between manure applications and mineral fertilizers or no fertilizers across main crop production areas in China. In addition, we attempted to assess the effects of explanatory factors such as climate types, land use types, soil properties (initial SOC and soil pH), and manure-C input on the SOC changes induced by manure applications.

2. Materials and methods

2.1. Data sources

To fully cover the research on assessing the SOC changes in Chinese soils, the peer-reviewed articles indexed by the Web of Science (http://apps.webofknowledge.com/), ScienceDirect and the China Knowledge Resource Integrated Database (http://www.cnki.net/) were retrieved for the period from 1990 to 2017. The keywords of manure category (animal species: pig, cattle, hog, poultry, sheep and horse, etc.; manure types: composted, farmyard manure and fresh, etc.), and SOC content or soil organic matter (SOM) were used in the literature retrieval. Specifically, the following criteria were used to select the publications: 1) field experiments were carried out on cropland in China; 2) there were a minimum of three replications for each treatment; 3) treatments must include: no fertilizers (Control), balanced application of N, phosphorus (P) and potassium (K), manure applied alone (M) or M plus NPK; and 4) the initial and final SOC values were clearly reported. In summary, a total of 148 peer reviewed articles reporting 69 sites and 729 observations across China's arable topsoil were analyzed, and those studies had an average experimental duration of 18 years. The details of the selected published literatures are presented in Appendix 1.

In the selected publications, SOC was reported for soil depths ranging from 5 to 25 cm, with an average of 19.4 cm. To normalize the results, SOC was recorded or computed to a depth of 20 cm when needed. For each original study, the following information was compiled into the database: experimental location (longitude and latitude), duration of the experiment, soil acidity and alkalinity (pH), climate type, land use, manure-C input, manure-N input, and chemical N input. In some studies, when the SOM content was reported instead of SOC, a van Bemmelen factor of 0.58 was used to convert SOM to SOC (Han et al., 2016).

2.2. Choice of effect size index

The response value that calculated from the meta-analysis reflects the size of magnitude of the focused variable in the investigated treatments (NPKM or M) compared to reference treatments (Control or NPK) (Nony et al., 1995). For the observations in each selected publication, the index SOC_{RR} (relative SOC change rate; $g\,kg^{-1}\,yr^{-1}$) was used to evaluate SOC change in response to manure applications relative to reference treatments (Control or NPK) over time (Gattinger et al., 2012). We divided the entire database into two datasets with different reference treatments: the REF-zero dataset for the comparison of M and/or NPKM with the Control treatment; and the REF-min dataset for the comparison of M and/or NPKM with the NPK treatment. This study aimed at evaluating responses of SOC_{RR} to manure applications in comparison to Control and NPK, respectively.

Meta-analysis requires independent samples (Gurevitch and Hedges, 1999). As suggested by previous studies (Gurevitch and Hedges, 1999; Tian et al., 2015), only the SOC values at the initial and the final year from an individual site were therefore used to compare fertilization effects when SOC was repeatedly measured on a single site.

2.3. Data analysis

For each treatment, the mean annual SOC change rate ($g\,kg^{-1}\,yr^{-1}$) was calculated as:

$$MAC = \left(\frac{SOC_t - SOC_0}{t}\right) \quad (1)$$