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Review Paper

Conservation agriculture practices increase soil microbial biomass carbon and nitrogen in agricultural soils: A global meta-analysis

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ABSTRACT

Conservation agriculture through the use of crop residue retention and no-tillage (NT) has been widely practiced to improve agricultural soil quality, such as to increase soil organic carbon (C) content and the microbial population size. However, there has been no quantitative analysis on the effect of conservation agriculture, particularly in relation to crop residue retention, on soil microbial biomass C (C_{mic}) and nitrogen (N_{mic}), and the microbial quotient (qMIC, C_{mic}-to-organic C ratio), which are frequently used as indicators of soil health under different agricultural practices. The objective of this study was to evaluate the influence of conservation agriculture practices on soil C_{mic}, N_{mic} and qMIC on a global scale using meta-analysis based on data from 96 recent publications. Relative to conventional tillage (CT) without residue retention, NT without residue retention (NTR0) increased C_{mic} by 33% ($P < 0.05$), while NT with residue retention (NTR) increased ($P < 0.05$) C_{mic}, N_{mic}, and qMIC by 25, 64, and 57%, respectively. Greater C_{mic} and N_{mic} were found in the NT than in the CT treatment, regardless of the soil condition (e.g., soil pH and texture), experimental duration, and climate (e.g., mean annual temperature and precipitation). Particularly, NTR was a promising conservation agriculture practice to increase C_{mic} and N_{mic} in global farmlands, and NTR0 can be an alternate strategy for loam soils in the subhumid (600–1000 mm mean annual precipitation) region, or under long-term (> 20 yr) conservation agriculture practices. We conclude that NTR should be an important strategy that could be used to increase C_{mic} and N_{mic} contents and improve soil quality in global farmlands.

1. Introduction

Cropland management is one of the key drivers of global change through its influence on carbon (C) and nitrogen (N) cycling and greenhouse gas emissions, and is one of the most notable factors that directly impact the properties of agricultural soils (Smith et al., 2016). Conservation agriculture (CA), typically represented by crop residue retention, and no-tillage (NT) or reduced tillage (RT), has been widely practiced to mitigate the negative effect of conventional soil management practices; such negative effects include soil erosion, loss of nutrients and soil organic matter (SOM), and agricultural soil carbon dioxide emission (Johnson and Hoyt, 1999; Abdalla et al., 2016; Zuber and Villamil, 2016). Currently, CA is practiced on nearly 155 million hectares worldwide, which is about 11% of the global arable cropland (Kassam et al., 2014). The use of tillage practices and residue retention can influence the soil microclimate, the distribution and decomposition of crop residue, and the mineralization and immobilization of nutrients (Cheng et al., 2017); such changes can alter soil microbial biomass (SMB) and microbial community structure (Carter and Rennie, 1982; Johnson and Hoyt, 1999). Thus, cropland management practices can markedly affect microbial activity, the rate of organic matter turnover, and ultimately soil C and N cycling.

Soil microbial biomass C (C_{mic}) and N (N_{mic}) play a significant role in enhancing soil aggregation, and promoting C and N turnover and thus nutrient cycling (Mader et al., 2002; Coleman et al., 2004; Zuber and Villamil, 2016; Zhang et al., 2017). Despite its small size, the SMB pool is an important labile fraction of SOM. It is not only a proxy for the transformation and cycling of SOM, but also as a sink/source of plant nutrients (Mader et al., 2002; Kallenbach and Grandy, 2011; Zhang et al., 2017). For instance, plant nutrient availability and crop

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productivity of agro-ecosystems depend primarily on the size of C_{mic} and N_{mic} as well as the activity of the soil microbial population (Friedel et al., 1996). Also, SMB responds quickly to changes in cropland management practices. Thus SMB could serve as an indicator of early changes in soil C stability following land use change, benefiting from the short turnover time and high sensitivity of SMB to changes in the soil environment (Kallenbach and Grandy, 2011). The dynamics of SOM is partly affected by the microbial community structure (Acosta-Martínez et al., 2003), and the active fractions of SOM, e.g., C_{mic}, are responsive to cropland management (Liu et al., 2014). In this regard, the metabolic quotient (qMIC), C_{mic}-to-organic C (SOC) ratio, provides a measure of the activity of microbial communities (Anderson and Domsch, 1978).

The response of C_{mic} and N_{mic} to changes in tillage practices and residue retention has been extensively studied, but results from these studies vary considerably. For example, many reported greater microbial biomass under NT due to more favorable microclimates in comparison with conventional tillage (CT) (Johnson and Hoyt, 1999; Martens, 2001; Balota et al., 2004; Das et al., 2014). Whereas, no difference between NT and CT was found for soils planted to common bean (*Phaseolus vulgaris*) (de Gennaro et al., 2014), bell pepper (the *Capsicum annuum* Group) (Jokela and Nair, 2016), or under a maize (*Zea mays*) - soybean (*Glycine max*) crop rotation (Ferreira et al., 2007). The qMIC was lower under NT than under CT (Balota et al., 2004), indicating that microbes were more active in the CT system. Meanwhile, although a meta-analysis using results from a global dataset with more than 60 experiments found that SMB was generally greater under NT than under CT (Zuber and Villamil, 2016), there has been no analysis of the effect of tillage practices on SMB and microbial activity, with regards to residue management such as the removal vs. retention of crop residue.

Compared to residue removal, residue retention has been found to increase soil organic C (SOC) (Duiker and Lal, 1999) and labile C contents (Chen et al., 2009). Residue retention not only increases soil C input but also affects soil physical and chemical properties (Johnson and Hoyt, 1999). For example, SMB increased with the increasing rate of residue retention (Salinas-Garcí;a et al., 2002; Govaerts et al., 2007). Additionally, a meta-analysis showed that, in comparison with inorganic fertilizer application, organic input increased C_{mic} and N_{mic} by 36 and 27%, respectively (Kallenbach and Grandy, 2011); however, synthetic analysis focusing on the effect of residue retention vs. removal in combination with tillage practices on SMB and microbial activity is lacking.

Understanding the effect of cropland management on SMB dynamics is fundamental for designing better management practices to restore soil function in intensively managed agricultural systems. However, management practices affect the soil environment and the microbial habitat in a variety of ways (Johnson and Hoyt, 1999; Zuber and Villamil, 2016), causing complex relationships between environmental conditions and management practices in these studies (Zuber and Villamil, 2016). As a result, the inter-relationship between SMB and environmental factors has not been fully assessed. The meta-analysis approach provides an excellent tool for synthesizing results from multiple data sets to assess the effect size of CA, the response pattern of SMB to CA, and sources of variation (Gurevitch and Hedges, 1999). Understanding how the SMB pool responds to CA is critical for sustainable cropland management. To test the hypothesis that CA practices increase SMB, and the combination of NT or RT and crop residue retention is more effective in increasing SMB than NT or RT alone, we conducted a meta-analysis to: 1) determine the direction and magnitude of change of C_{mic}, N_{mic} and qMIC in response to different CA practices; and 2) evaluate the effect of environmental conditions and management practices on the source of variability in C_{mic}, N_{mic} and qMIC.

2. Materials and methods

2.1. Data collection

Based on the number of related publications, and the quality of figures and tables, which are important for data extraction, journal articles published from 1990 to 2017 were searched using the ISI Web of Science database (http://apps.webofknowledge.com/) and the China Knowledge Resource Integrated Database (http://www.cnki.net/). Specific practices chosen for comparison in this study were RT and two kinds of NT (NT) practices: NT with residue retention (NTR) and NT without residue retention (NTR0, surface residue is removed after harvest). The NTR0, NTR and RT practices (in this study, reduced tillage refers to tillage systems that are less intensive, with fewer trips in the field than CT, with or without residue retention) were compared to CT as the control in side-by-side paired-plot experiments. In this study, CT mainly represents tillage practices that till the soil to 20–25 cm deep using a plow or harrow, with or without residue retention. There has been research on RT with or without residue retention, and NTR vs. NTR0 in our dataset, and the effect of residue retention on C_{mic} and N_{mic} content and qMIC were analyzed; however, there were not enough data to do a subgroup meta-analysis to evaluate the effect of environmental conditions and management practices on the source of variability in Cmic, Nmic and qMIC as a result of residue retention as compared with no residue retention. Due to insufficient data, straw retention rate, straw type, and the initial SOC concentration were not considered in our subgroup meta-analysis.

The SMB data used in the analysis were obtained from published articles (in tables and within the text), and some data were extracted from published figures using the Get-Data Graph Digitizer software (ver. 2.24, Russian Federation). To minimize any bias, the following criteria were used when selecting paired experiments: (1) each experiment had similar topography and soil type, in addition to having a control (CT); (2) the mean and standard deviation (or standard error) of C_{mic} and N_{mic} and qMIC were provided, with the number of replicates described either in the experimental design or in figure captions, and at least two replications were used in the experiment; and (3) tillage and residue management were included as treatments and other agronomic practices such as cropping intensity and irrigation were similar. The details of the selected studies and associated references are presented in the supplementary material. In total, 96 published papers, among which 95 had C_{mic} data, 48 had N_{mic} data, 82 had qMIC data, and 34 had both C_{mic} and N_{mic} data under different conservation tillage practices, are included in this meta-analysis (the references used are listed in the supplementary material).

From each publication, we extracted information on soil properties (texture, pH and initial SOC concentration), climatic condition (mean annual precipitation (MAP) and mean annual temperature (MAT)), and the duration of the experiment. The dataset was organized based on the experimental duration (< 6, 6–10, 11–20, and > 20 years) (Zhang et al., 2017), MAP (< 600, 600–1000, and > 1000 mm yr^{-1}), MAT [frigid (< 8 °C), mesic (8–15 °C), and thermic (> 15 °C) temperature regimes] (Knorr et al., 2005), soil texture (clay, silt loam, loam, and sandy loam) (Jian et al., 2016; Zhang et al., 2017), and soil pH (≤7, and > 7) (Zhao et al., 2016).

2.2. Data analysis

The response ratio (RR) of SMB between the treatment and control or the effect of NT and RT relative to CT management on C_{mic} and N_{mic} were analyzed according to Equation (1) (Osenberg et al., 1999).

$$RR = \ln\left(\frac{\overline{X_t}}{\overline{X_c}}\right) = \ln(\overline{X}_t) - \ln(\overline{X}_c) \quad (1)$$

where RR is the response ratio, X_t and X_c are the means of the treatment