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Organic amendments increase crop yields by improving microbe-mediated soil functioning of agroecosystems: A meta-analysis

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ABSTRACT

Although numerous studies suggest that organic amendments are better at maintaining soil fertility and crop production than mineral-only fertilization, it is unclear if this occurs in different agricultural systems on a global scale. Here we report a comprehensive meta-analysis of 690 independent experiments comparing the performance of organic amendments and mineral-only fertilization on crop yields, the soil organic carbon (SOC) and total nitrogen (TN) contents, soil nutrient dynamics and biological properties. Our analysis shows that organic amendments increased crop yields on average of 27% than mineral-only fertilization. Farmyard manure (FYM) had the highest effect (49% increase) and this was especially clear in wheat croplands (40% increase). Organic amendment increased the amount of SOC (38%), TN (20%), microbial biomass carbon (MBC; 51%) and microbial biomass nitrogen (MBN; 24%) than mineral-only fertilization. Organic amendments also increased the soil microbiome enzyme activity in terms of soil hydrolytic C acquisition (C-acq; 39%), N acquisition (N-acq; 22%), P acquisition (P-acq; 48%) and oxidative decomposition (OX; 58%). Increased nutrient acquisition and oxidative decomposition could explain the positive effects of organic amendment on crop yields. These observed patterns were consistent for most organic amendments and cropping systems in diverse regions of the world. In summary, our analysis suggests that organic amendments can improve microbe-mediated soil ecosystem functioning, long-term soil fertility and crop productivity, relative to mineral fertilization, on a global scale.

1. Introduction

Optimal management strategies are essential for maintaining good soil quality and the long-term sustainability of agricultural production (Li et al., 2015; Deng et al., 2006; Ramesh et al., 2009). Over the past decade, intensive agriculture has caused a clear decrease in soil fertility, which is a major concern for the long-term agricultural productivity and stability (Sarma et al., 2017; Agegnehu et al., 2014). Despite playing a critical role in feeding the global population (Jensen et al., 2011), excessive use of mineral fertilizers is one of the main drivers behind the loss in soil fertility (Chen et al., 2014; Zhang et al., 2016). Organic materials, such as farmyard manure, straw or mixture of manure and compost, have been proposed as alternatives for mineral fertilization (Bodirsky et al., 2014; Gu et al., 2015). However, it remains largely unknown if organic amendments can provide equally comprehensive and continuous nutrition for plant growth and functioning of agroecosystems across different farming systems (Thangarajan et al., 2013; Ling et al., 2016). Here we address this problem with a meta-analysis of data from 690 independent measurements from around the world that were published in the scientific literature.

Numerous previous studies have demonstrated that organic amendments can provide various benefits over mineral fertilization such as improved soil structure (Thangarajan et al., 2013), enhanced soil fertility (Chaparro et al., 2012), long-term maintenance of soil health (Xie et al., 2014), and particularly, similar or even higher crop yields in certain cases (Lin et al., 2009; Seufert et al., 2012). These benefits have primarily been associated with responses in soil biological and biochemical properties (Hueso et al., 2011; Ling et al., 2016). Common responses include increased soil extracellular enzyme activity (EEAs) (Thangarajan et al., 2013) and microbial biomass (MB) (Kallenbach and Grandy, 2011), which are important factors behind the soil carbon (C), nitrogen (N) and phosphorus (P) turnover and dynamics (Agegnehu et al., 2016; Xia et al., 2017). Soil MB also facilitates key ecosystem functions and services such as microbial community-

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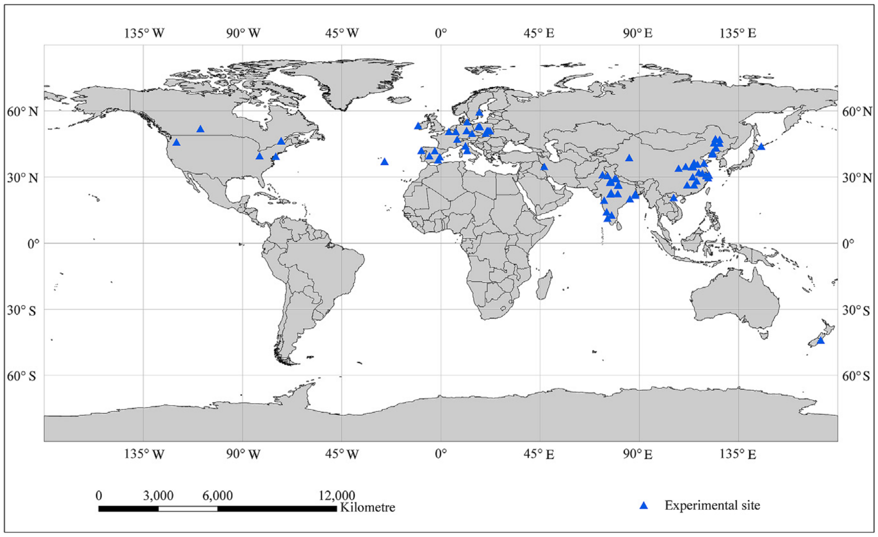

Fig. 1. World map showing the sites included in 106 studies (covering 690 experiments) that were used in meta-analysis.

mediated nitrogen-use efficiency (NUE) and carbon-use efficiency (CUE) (Mooshammer et al., 2014; Kallenbach and Grandy, 2011). Fertilizer-mediated microbial activity can further lead to changes in C and N dynamics (Mooshammer et al., 2014; Brilli et al., 2017), which can regulate the balance between NUE and CUE (Zhong et al., 2015). Microorganisms have the ability to adjust their CUE and NUE according to soil nutritional conditions and it has been shown that high environmental N can lead to low NUE and high CUE (Mooshammer et al., 2014). High CUE has been found to promote microbial growth and stabilization of C in soils, while low CUE has been found to favor respiration (Manzoni et al., 2012). Microbial growth will not only affect the number of cells but also their metabolism and the concentration of EEAs (Burns et al., 2013; Joergensen and Wichern, 2018). Moreover, changes in EEAs and MB are more dynamic and faster than changes in soil physiochemical properties providing immediate information on the activity of agriculturally important microbial processes (Dick and Tabatabai, 1993; Ros et al., 2003). It remains unclear, however, if these patterns hold across different agricultural systems and geographic locations.

In general, EEAs have been widely used as indicators of soil quality (Loeppmann et al., 2016), ecosystem functioning (Bastida et al., 2016) and productivity (Zhao et al., 2009). A wide range of EEAs has been associated with soil organic C, N and P decomposition and oxidation and these are largely dependent on soil C and N availability (Burns et al., 2013; Chen et al., 2016; Sinsabaugh et al., 2008). For example, the cellulases, including β-1,4-xylosidase (BX), β-1,4-glucosidase (BG) and β-D-cellobiosidase (CBH), are a group of hydrolytic enzymes produced by soil microbes that are used to decompose polysaccharides (Deng and Tabatabai, 1994). Key enzymes associated with microbial N acquisition include β-1,4-N-acetyl-glucosaminidase (NAG), leucine aminopeptidase (LAP) and urease (UREA) that target chitin, protein, and urea, respectively (Tabatabai and Bremner, 1972). The enzymes associated with P acquisition cleave PO_4^{3-} from P-containing organic compounds and include acidic (ACP) and alkaline (ALP) phosphatases (Eivazi and Tabatabai, 1977). Phenol oxidase (PhOx) and peroxidase (PEO) are the two most frequently assayed oxidases responsible for decomposing insoluble materials such as lignin and aromatic compounds (Sinsabaugh, 2010; Wang et al., 2012). Thus far, soil extracellular enzyme activities have been reported to both decrease and increase in response to organic amendments with varying magnitude (Burns et al., 2013; Henry, 2013; Geisseler and Scow, 2014; Sinsabaugh et al., 2014). Generally, the responses of EEAs to fertilization management are affected by the types of crops and organic amendments, soil pH and texture, as well as climate conditions (Jian et al., 2016; Ramesh et al., 2009). Analyzing these patterns on a global scale, therefore, is important for identifying key abiotic and biotic drivers that have positive effects on soil EEAs and crop yields.

Here we performed a comprehensive meta-analysis where we compared the effects of organic amendments versus mineral fertilizers on crop yields, soil organic carbon (SOC), soil total nitrogen (TN) and soil biological properties using 690 independent studies published in > 100 journals between 2000 and 2016. We hypothesized that: (i) Organic amendments could support similar or higher crop yields than mineral-only fertilization on average but that this effect is likely to depend on the particular crop type, abiotic environment or other factors. Moreover, we expected that (ii) when organic amendments are observed to have a more positive effect on crop yields than mineral fertilizers, this could correlate positively with the soil EEAs and MB pools having positive effect on the functioning of agroecosystems.

2. Materials and methods

2.1. Data extraction and compilation

We collected a total of 106 peer-reviewed papers published between 2000 and 2016 listed in the ISI Web of Science (www.isiknowledge.com) and Google Scholar (scholar.google.com). Through this search, we found 690 individual records (Fig. 1) that included at least two of our targeted search terms: “soil extracellular enzyme”, “exoenzyme”, “crop yields” and either “farmyard manure (FYM)”, “manure”, “compost”, “waste”, “straw” or “solid waste”. Data were extracted and compiled according to three following criteria: (1) If the data of interest were only shown in graphs or figures, both the standard deviation (SD) and the means were extracted by using ImageJ 1.50i and the standard errors (SE) converted to SD using following equation: $SD = SE \times \sqrt{n}$ (n, replicate numbers) (Jian et al., 2016); (2) If one paper reported various independent experiments (e.g., two experiments at separate locations), each of them was considered as an individual study and incorporated as an independent observation into our dataset (García-Palacios et al., 2015). (3) If one paper contained results from various sampling dates and soil depths, we used the data from the latest sampling time-point and from the sample collected from the uppermost layer of soil. The complete dataset is included as supplementary material and contains 24 parameters linked with crop yields, soil EEAs, SOC, TN and MB pools. The effects of other management factors were considered when selecting the literature for our meta-analysis by choosing only studies that focused on comparing the impacts of organic amendments and mineral-only fertilization under otherwise similar management practices such as