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Effects of combined application of organic amendments and fertilizers on crop yield and soil organic matter: An integrated analysis of long-term experiments

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ABSTRACT

A comprehensive synthesis of 32 long-term experiments in China is performed by comparing yields and SOM contents and their time by nutrient management responses (TNMR) to determine whether and to what extent combined application of organics amendments and fertilizers (organics + fertilizers) can increase productivity and soil organic matter (SOM) content and enhance the sustainability of diverse cropping systems. TNMR is defined as percentage changes over time in yields and SOM contents in external nutrient input treatments relative to initial and control plots and represents the net effects of nutrient management strategies on yields and SOM contents. Organics + fertilizers significantly increased yields over three crops (wheat, maize and rice) on average by 29% relative to sole organics and 8% to fertilizer only. Higher TNMR values in yields were found with organics + fertilizers in the sequence wheat (53%) > maize (40%) > rice (8%). Significant and positive time trends in TNMR of organics + fertilizers in wheat and maize yield may imply enhanced sustainability of cropping systems. Addition of organics (alone or combined with fertilizers) increased SOM contents and their TNMR over fertilizers applied alone. However, benefits varied between organics and organics + fertilizers by land use type. The latter led to higher SOM contents than (for dry land) and similar to the former (for dry-flooded and flooded systems). 2.3 and 1.4 times higher TNMR of organics + fertilizers in SOM content in dry land than dry-flooded and flooded systems implies that dry land was more responsive in SOM content increase upon adoption of organics + fertilizers than the latter. Overall, despite variation in the quantitative magnitude in crop or land use type, compared with application of organics or fertilizers only, a combination of both represents the most effective way to produce more food, build up SOM and enhance sustainability, especially in dry land cropping systems.

1. Introduction

Intensification of crop production over the last 50 years has come to be known as the ‘green revolution’ and has proved to be very successful. This, combined with increased soil productivity, has allowed China to feed 22% of the global population using only 7% of the global arable land area (Zhang, 2011; Fan et al., 2013). However, environmental degradation resulting from excessive application of fertilizers has led to the development of more integrated approach to farming and plant nutrient management (Tilman, 1998; Fan et al., 2012; Chen et al., 2014).

Recycling of agricultural organics is an old but relevant and increasingly popular technology for maintaining soil productivity and saving fertilizers in response to the search for cost-effective nutrient management (Rasmussen et al., 1998; Fan et al., 2012; Misselbrook et al., 2012; Rosegrant et al., 2014). However, application of organics alone usually results in lower crop productivity levels than application of fertilizers (Trewavas, 2001; Seufert et al., 2012). The combined application of organic amendments and fertilizers (organics + fertilizers) has been gaining increasing recognition as a feasible and practical approach in boosting crop yields in the short term and enhancing soil organic matter (SOM) in the long term (Morris and Winter, 1999; Palm et al., 2001; Vanlauwe et al., 2001a,b; Dawe et al., 2003; Zhang et al., 2009; Diacono and Montemurro, 2010; Chivenge et al., 2011; Zhang et al., 2012; Liang et al., 2012; Yan et al., 2012). However, the

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extent to which the benefits in increased productivity and enhanced SOM across diverse cropping systems can be realized remains to be determined.

It is widely accepted that long-term cropping experiments (LTEs) remain the only reliable source of information in evaluating sustainable agricultural management systems and predicting future trends (Rasmussen et al., 1998; Dobermann et al., 2000). Since the 1980s numerous LTEs have focused on different cropping systems within China and have formed the basis of studies assessing crop productivity and SOM of various nutrient management strategies (Xu et al., 2006; Zhao et al., 2010, 2012). However, most studies have been restricted to the locations of the field experiments with few synthesizing the information on a national scale. A comprehensive analysis nationally will offer important advantages including overcoming limited (or absence of) replication by using years and/or sites as a substitute for true replication and conducting comparison between different cropping systems. Furthermore, the methods used often compare the absolute values and/or dynamic changes in yields and SOM among treatments. This approach, however, does not take into consideration changes in measurements over time in the absence of external nutrient applications and the impact of changes in other management factors (e.g. tillage, crop variety and management) and biophysical factors such as climate change. This may mask the net effects and the contribution of organics + fertilizers to crop productivity and SOM.

Organics and fertilizers bring different advantages to soil management; a combination of both may lead to positive interactive effects in crop productivity (Vanlauwe et al., 2001b). However, added benefits of organics + fertilizers on cereal yields in Chinese LTEs remain to be tested.

Here, a comprehensive synthesis of the current scientific literature on Chinese LTEs at national scale is conducted in an attempt to understand to what extent organics + fertilizers can increase productivity and SOM and enhance the sustainability of diverse cropping systems. The specific objectives were to determine the yields and SOM contents of various cereal cropping systems or land use types in both absolute terms and changes relative to initial values and in controls upon application of organics, fertilizers and organics + fertilizers at application rates representing best local practices, and the added benefits of organics + fertilizers on grain yields.

2. Materials and methods

2.1. Data sources

We have included all the available long-term data from 32 long-term experiments conducted throughout China. The experiments range in duration from 13 to 31 years and represent a wide range of climatic zones, soil types, cropping systems, and management practices. Detailed location information is presented in Appendix Table 1 in the online supporting information. Cropping systems involved are wheat–maize, wheat-rice and rice-rice double cropping, rice-based triple cropping, and wheat or maize single cropping, representing the major high productivity cereal-based cropping systems in the country. In total they account for 95% of total wheat, 64% of maize, and 90% of rice production. The nitrogen (N), phosphorus (P) and potassium (K) inputs from fertilizers and N from organics are listed in Appendix Table 1. Crop, water and pest management followed the best local recommendations but differ among sites. Further details on the management and sampling procedures used are given in the publications referring to the specific locations.

All long-term studies that met the following criteria were included.

1. The experiments included at least one cereal crop (wheat, maize or rice).
2. The same type of organics was applied in both the organics only and organics + fertilizers treatments within the same experiment. Organics used in current LTEs are manures, straw, green manures or composts.
3. At least three of the following treatments were included within a study: control, organics, fertilizers and organics + fertilizers. Fertilizer treatments comprised applied chemical NPK plots. In organics + fertilizers, application of organics served either as a supplement to the fertilizer NPK in most of LTEs, or as a partial substitute for NPK, usually with half of the recommended N rate as fertilizer and the other half as organics (e.g. in 6 LTEs). However, there were no experiments which included treatments in which NPK rates were the same in the fertilizers, organics and organics + fertilizers treatments. In cropping systems with more than one crop grown each year, organics were applied once a year (9 sites) or to both crops (13 sites). Control treatments received neither organics nor fertilizers. However, control plots received the same control measures in terms of weeds, insects and diseases, and supplemental irrigation as external nutrient input treatments (organics, fertilizers, and organics + fertilizers).
4. The same soil sampling methods to the same depths and the same methods for determination of SOM/C concentrations were used across all treatments within a study. The SOM/C data are reported as concentrations based on soil weight, e.g. g kg^{-1} or percentage (%). A conversion factor of 1.742 was used to convert SOC data to SOM.

2.2. Data grouping

All the datasets were divided according to cropping systems for crop yield analysis: winter wheat in north and northwest China and the Yangtze River Basin in east China, maize in north and northeast China, and rice in the Yangtze River Basin and south China; and land use type for SOM content analysis: dry, dry-flooded, and flooded systems. It should be noted that dry lands are represented as winter wheat-summer maize rotation systems on the North China Plain, wheat (or maize) cropping systems in the northwest and maize (or wheat and soybean) cropping systems in northeast China. Dry-flooded systems include rice-wheat/barley rotation systems in the Yangtze River Basin. Flooded systems are dominated by single, double or triple rice systems. Seventeen, ten and eight of the experiments involved wheat, maize, and rice, respectively, and thirteen, six and six were dry, dry-flooded and flooded systems.

2.3. Data manipulation

We first compared mean crop yield and SOM content in absolute terms among control, organics, fertilizers and organics + fertilizers plots across all land use types. Then the percentage changes in crop yield and SOM content in external nutrient input treatments relative to initial and control plots, referred to as time by nutrient management response (TNMR), were further compared using Eq 1.

$$TNMR = \left[\frac{(Af-fertilized - Ai-fertilized)}{Ai-fertilized}\right] \times 100 - \left[\frac{(Af-control - Ai-control)}{Ai-control}\right] \times 100 \quad (1)$$

A_f-fertilized and A_f-control represent the yield or SOM content in each year for external nutrient input treatments and controls