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Tillage and residue management for long-term wheat-maize cropping in the North China Plain: I. Crop yield and integrated soil fertility index

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ABSTRACT

Conservation tillage has been gaining increasing recognition for its role in improving soil quality and maintaining agricultural sustainability. This is the first in a series of papers describing the impacts of reduced/no-tillage with and without residue based on the field experiment in the North China Plain. The experiment was established in 2006 on a sandy loam soil and involved a winter wheat-summer maize rotation system per year. The objective of this study was to investigate the impacts of different conservation tillage systems on crop yield and soil fertility that was quantified by a minimum data set and integrated index. Soil samples were collected since 2011, and the stocks of soil organic matter (SOM), total nitrogen (TN), alkali-hydrolyzale nitrogen (AN), total phosphorus (TP), available phosphorus (AP), total potassium (TK) and available potassium (AK) were measured for each year as well as soil aggregates were fractionated for 2016. Compared to continuous tillage, the reduced/no-tillage, regardless of residue, significantly increased the macroaggregate mass and soil nutrient stocks at the 0–10 cm depth, while further improvements in these soil attributes apart from TK were observed at the 0–10 and 10–20 cm depths for residue returning relative to residue removing. The accumulations of soil nutrients were closely related to soil macroaggregation. The path analysis revealed that TN was the most important soil attribute to directly determine wheat and maize yields while other soil attributes apart for TK primarily made indirect contributions to the yields. The first two factors extracted using 8 soil attributes through factor analysis were selected as the integrated indicators for the minimum data set, and their integrated score was calculated to quantify soil fertility. It was found that reduced/no-tillage did not improved soil fertility at the 0–20 cm depth. Consequently, an average 6.9% decrease in wheat yield across all years was observed under no-tillage while reduced tillage only increased the yield in the first two years in a periodic reduced tillage event. No significant difference was observed for the mean maize yield among the three tillage regimes averaged across all years and residue managements. Wheat and maize yields were significantly correlated with the integrated score for soil fertility, and thus significant increases in grain yields of wheat and maize were observed for residue returning. It can be concluded that grain yields of wheat and maize within a given residue management practice were not significantly higher for reduced/no-tillage than continuous tillage, regardless of the effects of tillage on aggregates and soil nutrients.

1. Introduction

Conservation tillage is a viable management alternative with increasing global adoption due to its potential for conserving soil, improving crop productivity and reducing input cost (Powlson et al., 2016; Margenot et al., 2017; Jiang et al., 2011). The most extreme form of conservation tillage, and one that is becoming more common, is no-tillage with crop residues left on the soil surface (Neto et al., 2010). He et al. (2009) and Deubel et al. (2011) demonstrated that all relevant soil properties including soil organic matter (SOM), nitrogen (N), phosphorus (P) and potassium (K), bulk density, porosity and macroaggregation under conservation tillage, were improved and led to higher yields and greater water use efficiency compared to continuous tillage.

Accumulated evidences (Kautz et al., 2013; Ding et al., 2013) suggest that continuous tillage makes the soil vulnerable to losses of organic matter and other nutrients, and potentially leads to a reduction in soil fertility. The results from long-term field experiments (Martínez et al., 2016; Wiebold and Fritschi, 2011; Deubel et al., 2011) showed significant SOM and NPK accumulations near the soil surface under

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conservation tillage associated with crop residue retention on the surface. The fact that soil is not tilled and remains residue retention favors to improve soil physical, chemical (Serraj and Siddique, 2012; Xue et al., 2015; Huang et al., 2012) and biological properties (Derpsch et al., 2014; Spedding et al., 2004), resulting in increasing crop productivity (Serraj and Siddique, 2012). A meta-analysis by Pittelkow et al. (2015) revealed negative yield responses to continuous tillage in humid climates irrespective of residue management and crop rotation, whereas no-tillage coupling with residue retention and crop rotation exerted significant increases in crop yields in dry climates.

Soil aggregate structure is a fundamental attribute of productive soils, which can largely contribute to soil fertility as it mediates the transport of water and gas, nutrient cycling, and the provision of microhabitat for fauna and microorganisms (Wang et al., 2015), but it is also influenced by different tillage and residue managements. The use of different tillage systems affects soil aggregation directly by physical disruption of the macroaggregates, and indirectly through altering biological and chemical factors (Barto et al., 2010). Additionally, residue retention can also promote a favorable soil environment and is the most important factor that facilitates soil structural development and soil aggregation improvement (Bhattacharyya et al., 2009). A promotion in soil macroaggregation will help to retain soil nutrients and sustain primary production (Six et al., 2004). Six et al. (2002) and Kautz et al. (2013) reported that soil structure determined the root ability as well as the distribution of gases, water, solutes and organisms in soils, thus influencing nutrient accessibility and nutrient mobilization processes. The physical protection provided by macroaggregates stabilizes SOM, organic N and organic P against degradation through compartmentalizing substrates and microbial biomass, reducing the microbial activity within aggregates, and separating microbial biomass from grazers (Six et al., 2002). On the other hand, the formation of macroaggregates can decrease the relative surface area and thus reduces the reactive sites for soil P and K sorption, leading to the accumulations of available nutrients in soil (Ranatunga et al., 2013; Horn and Taubner, 1989). Soil macroaggregation and the following nutrient accumulation in soil as well as the organic inputs from crop residues collectively contribute to the soil fertility and crop yields in response to conservation tillage.

The North China Plain is the second largest plain in China where produces almost 60–80% of China's wheat and 35–40% of China's maize every year (Kong et al., 2014). Cultivated tracts in the plain are dominated by fluvo-aquic soils that are characterized by poor structures and low contents of organic matter. Soil N and P have been considered to be the critically limiting nutrients for crop production although these soils are rich in K. In past several decades, intensive and continuous tillage and the removal of postharvest residues from conventional tillage practice have further degraded the soil and reduced crop productivity. It has been suggested that conservation tillage systems including reduced or no-tillage coupling with residue returning could effectively promote soil macroaggregation and reverse the disadvantages of conventional tillage in depleting soil nutrients, resulting in the improvement of soil fertility and crop yields (Neto et al., 2010; Wang et al., 2015; Pittelkow et al., 2015). To date, numerous studies have focused in the impacts of different tillage and residue managements on soil properties and crop productivity (White and Rice, 2009; Neto et al., 2010; Wang et al., 2015; Pittelkow et al., 2015). However, the information about identifying the best conservation tillage system to achieve the optimal yield based on an integrated soil fertility is limited. To investigate the effects of conservation tillage on soil fertility and crop yields, the present study was conducted based on a continuous 10-year conservation tillage experiment in the North China Plain. Furthermore, considering the limited measured indicators, the soil fertility was evaluated based on the macroaggregation and 7 stocks of soil nutrients including SOM, total NPK and available NPK, although soil fertility is an integration of soil physical, chemical and biological properties. Thus, the main objectives of this study were to (1) establish the minimum data set and integrated index to quantify soil fertility through factor analysis, and (2) investigate the responses of soil fertility index and crop yields to various tillage and residue managements in rainfed agricultural ecosystems.

2. Materials and methods

2.1. Site description and experimental design

The long-term field experiment was established in June 2006 as a demonstration site at the Fengqiu State Key Agro-Ecological Experimental Station (35°00′N, 114°24′E) in Fengqiu, Henan Province, China. The soil is classified as an Aquic Inceptisol (USDA classification), has a sandy loam texture with 52% sand, 33% silt and 15% clay. The area belongs to semi-arid with a warm temperate continental monsoon climate. The mean annual precipitation was 615 mm (mainly from July to September) and the mean annual temperature was 13.9 °C in last 30 years. The field trial was set up in a well-drained area where winter wheat (*Triticum aestivum* L.) has been annually rotated with summer maize (*Zea mays* L.). At the beginning of the experiment, soil had been cultivated for > 50 years in a similar agricultural cropping system, so the heterogeneity of soil fertility was considered to be minimal. In 2006, soil had an average pH of 8.31, 6.09 g organic C kg^{-1}, 0.55 g total N kg^{-1}, 0.81 g total P kg^{-1}, 18.08 g total K kg^{-1}, 57.39 mg alkali-hydrolyzale N kg^{-1}, 9.67 mg available P kg^{-1} (extracted by 0.5 mol L^{-1} $NaHCO_3$), and 36.14 mg available K kg^{-1} (extracted by 1.0 mol L^{-1} CH_3COONH_4).

The experiment was performed in a completely randomized design with six treatments in triplicates including two factors. The first factor was tillage regime including T (continuous tillage), RT (tillage every four years or reduced tillage) and NT (no-tillage); and no residue (-S) or all crop residues (+S) were added to the soils of three tillage practices and regarded as the second factor. Different tillage regimes were performed only in the wheat planting season and the soil was never tilled in the maize planting season. T treatment involved one moldboard plowing (20–22 cm) in October followed by secondary seedbed preparation (7.5–10 cm) with a disk harrow. Under NT treatment, the soil was undisturbed except when the crop was planted using a no-till planter. In the RT, moldboard plowing was employed in the tillage-year, whereas no tillage disturbance occurred in the no-tillage-year. After harvesting, residues were crushed into 2–3 cm pieces for maize residue and 6–7 cm pieces for wheat residue, and were then returned to the soil surface under +S treatments. The residue amounts were related to the crop yield in each plot. And under −S treatments, all crop residues were removed from the plots. The plot size was 7 m × 6.5 m. Each treatment plot received the same amount of fertilizer. Further details of fertilizer application have been reported by Zhang et al. (2017). The amounts of seed and irrigation water were also recorded in this experiment and kept the same among treatments.

2.2. Sampling and analytical procedures

At maturity, all of the aboveground crop parts were harvested manually from each plot, and the grain yield was obtained. In September immediately after the maize harvest, mixed soil samples (0–10 cm and 10–20 cm) from five points in each plot were taken using a coring tube (3 cm in diameter) for physical and chemical analyses. The samples were air-dried, and the visible roots, organic residues and rock fragments were discarded. By dividing each soil sample into two subsamples, one subsample was ground and passed through a 2-mm sieve for the analyses of alkali-hydrolyzale nitrogen (AN), available phosphorus (AP) and available potassium (AK), and the other was passed through < 0.15-mm sieve for the analyses of soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP) and total potassium (TK). Since we began to measure soil physical and chemical properties and crop productivity systematically in June 2011, the crop grains and