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Stover retention rather than no-till decreases the global warming potential of rainfed continuous maize cropland

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ABSTRACT

During the past two decades, conservation management practices to sequester soil carbon have been recommended to mitigate greenhouse gas (GHG) emissions. However, the long-term effects of no-till, stover retention, and their interaction on soil organic carbon (SOC) stocks and GHG emissions from rainfed croplands remain uncertain. In this study, tillage practice and stover management effects were investigated in a long-term rainfed continuous maize cropping system. Measurements of soil nitrous oxide (N_2O) and methane (CH_4) fluxes and SOC change were conducted in four treatments: conventional tillage with stover removal (CT), conventional tillage with stover retention (CS), no tillage with stover removal (NT) and no tillage with stover retention (NS). Annual N_2O emissions with stover retention (CS and NS, 0.52–0.74 kg N ha^{-1} yr^{-1}) were significantly higher ($P < 0.0001$) than those with stover removal (CT and NT, 0.40–0.55 kg N ha^{-1} yr^{-1}), but N_2O emissions were not affected by tillage practice. Net CH_4 consumption occurred in all treatments, but no significant effect of tillage practice or stover management was found. Surface (0–20 cm) SOC stocks decreased with both stover removal and no tillage practice, while deep SOC (20–100 cm) was not affected by tillage practice or stover management over ten years. Stover retention led to a net GHG sink with annual global warming potential (GWP) values of -2.52 ± 0.05 and -1.03 ± 0.02 Mg CO_2-eq. ha^{-1} yr^{-1} for CS and NS, respectively, but stover removal practices were a net GHG source with annual GWP values of 0.83 ± 0.04 and 1.40 ± 0.04 Mg CO_2-eq. ha^{-1} yr^{-1} for CT and NT, respectively. Our results highlight the importance of C input from crop residues for increasing SOC stocks and mitigating GHG emissions. Therefore, conventional tillage with crop residue return is the most promising management system for simultaneously achieving maximum yield and minimum GWP.

1. Introduction

Agriculture plays a major role in regulating the exchange of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) between soils and the atmosphere, which accounts for 10–12% of global anthropogenic greenhouse gas (GHG) emissions (Smith et al., 2014). The United Nations Environment Programme (UNEP) estimates a global mitigation potential of 1.1–4.3 Gt CO_2-eq. yr^{-1} by 2020 for the agriculture sector, 89% of which could be realized through implementation of improved management practices, including conservation tillage, more efficient use of water and fertilizers, and addition of biochar to the soil (UNEP, 2013). Conservation tillage was initially promoted to reduce soil erosion risk and energy consumption, but more recently has been widely recommended to increase soil organic carbon (SOC) content, enhance carbon (C) sequestration, and mitigate GHG emissions (Lal et al., 1998; Six et al., 2000; Smith et al., 2008).

The impact of conservation tillage on SOC concentration and the SOC pool is still controversial, although hundreds of experimental studies and several meta-analyses have been conducted to quantify the impact. During the past two decades, many studies have suggested that no-till generally results in increased SOC storage through C sequestration when compared with conventional tillage (e.g. Lal, 2004; Ogle et al., 2005; Schmer et al., 2014). By conducting a global meta-analysis of 67 long-term agricultural experiments, West and Post (2002)

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concluded that a change from conventional tillage to no-till can sequester 57 ± 14 g C m^{-2} yr^{-1}. Ogle et al. (2005) found that converting from conventional tillage to no-till increases SOC storage over 20 years, ranging from a 10% increase for temperate dry regions to a 23% increase for tropical moist climates. However, they also noticed that 10% of the experimental no-till treatments did not increase SOC from their meta-analysis (Ogle et al., 2005). Furthermore, Luo et al. (2010) suggested that conversion from conventional tillage to no-till changes the C distribution in the soil profile, but does not increase the SOC stock in the 0–40 cm soil profile in double cropping systems.

On the other hand, the effects of conservation tillage on non-CO_2 GHG emissions depend on climate conditions, soil properties, and other site-specific factors (Chen et al., 2013; van Kessel et al., 2013). Some studies have suggested that soil N_2O emissions are expected to be greater in no-till systems compared with conventional tillage systems due to increased mineral N derived from residues, greater soil moisture, and less aeration in no-till practices, consequently leading to more N_2O production by nitrification and/or denitrification (Linn and Doran, 1984; Ball et al., 1999; Rochette, 2008). However, others studies have shown a decrease in N_2O emissions with no-till (Mosier et al., 2006; Guzman et al., 2015) or no difference between no-till and conventional tillage (Lemke et al., 1998). A global meta-analysis by Six et al. (2004) suggested that no-till generally increases N_2O emissions in poorly aerated soils during the initial several years after conversion from conventional tillage and thereafter N_2O fluxes tend to decrease, but this was only significant in humid climates. By conducting a global meta-analysis, van Kessel et al. (2013) concluded that no-till for more than ten years significantly reduces N_2O emissions only in dry climates, while short-term no-till operations in dry climates increases N_2O emissions by 38% relative to conventional tillage. The SOC increases resulting from residue and tillage management practices could be substantially offset by N_2O and/or CH_4 emissions (Six et al., 2004; Mutegi et al., 2010; Wang et al., 2011; Chen et al., 2013; Schmer et al., 2014). Therefore, a comprehensive assessment of the effects of management practices on soil GHG fluxes needs to take into account N_2O and CH_4 emissions in addition to SOC stock change.

The increasing global food demand and climate change both require sustainable agricultural production practices that maximize crop productivity and minimize environmental issues (Grassini and Cassman, 2012). By conducting a global meta-analysis, Pittelkow et al. (2015) found that no-till overall decreases crop yields by 5.7%, although under certain conditions it produces equivalent or even greater yields than conventional tillage systems. Powlson et al. (2014) also argued that the quantity of additional organic C in soil under no-till is relatively small and that the role of no-till in GHG mitigation has been widely overstated. Therefore, caution is needed in proposing no-till as a best management practice (BMP) for C sequestration and reducing GHG emissions, and further research is required to design site-specific BMPs for different regions. Furthermore, it has been argued that soil surface cover by plant residue is an essential part of the definition of no-till because residues provide additional help in preventing soil erosion and increasing water-use efficiency (Derpsch et al., 2014). However, maize residue or stover is increasingly being harvested and used as forage for cattle feeding as well as feedstock for the cellulosic biofuel industry (Klopfenstein et al., 2013; Dong et al., 2015). It is necessary to identify the effects of tillage practice, residue management, and their interaction on crop productivity, GHG emissions, and their mitigation potential.

In this paper, we present *in situ* field results of a two-year study, in which N_2O and CH_4 fluxes were intensively measured and SOC changes were estimated in a long-term rainfed continuous maize system that had been under continuous different stover managements (removal and retention) and tillage practices (no tillage and conventional tillage) for about ten years. The objectives of this study were to: (1) determine annual N_2O and CH_4 fluxes across different cropping years and their key regulating factors; (2) evaluate the impacts of tillage practice and stover management and their interaction on N_2O and CH_4 fluxes, SOC stock change, and the resulting global warming potential (GWP); and (3) identify the BMP that minimizes the GWP while sustaining maize yield in the rainfed system.

2. Materials and methods

2.1. Site description

The experiment was conducted at the Changwu State Key Agro-Ecological Experimental Station of the Loess Plateau, Shaanxi Province, China (35°14′N, 107°40′ E; altitude 1206 m). The study region has a warm temperate continental monsoon climate, with an annual mean air temperature of 9.1 °C, an annual accumulative temperature (> 10 °C) of 3029 °C, an annual sunshine duration of 2230 h, an annual total radiation of 484 kJ cm^{-2}, and an annual frost-free period of 171 days. The average annual precipitation is 578 mm, with 55% falling between July and September. The open pan evaporation is 1440 mm.

The study site was located in a typical rainfed cropping region of the Loess Plateau highland in Northwest China. The soil is characterized by a silt loam texture with 35% clay, 62% silt, and 3% sand, and classified as Cumulic Haplustoll based on the USDA soil taxonomy. The soil (0–20 cm) before the experiment in 2002 had a pH of 8.3, bulk density of 1.34 g cm^{-3}, and contained 6.94 g kg^{-1} organic C, 0.87 g kg^{-1} total N, 16.22 mg kg^{-1} available P, and 147.35 mg kg^{-1} available K.

2.2. Experimental design

Continuous spring maize (*Zea mays* L.) experiment was established in 2002 to investigate the effects of different management practices on crop yields and soil properties. Four treatments were included: conventional tillage with stover removal (CT), conventional tillage with stover retention (CS), no tillage with stover removal (NT), and no tillage with stover retention (NS). Each treatment was replicated three times with an area of 7 × 5 m^2. Fertilizers were applied at a rate of 150 kg N ha^{-1} (as urea) and 90 kg P_2O_5 ha^{-1} (as calcium superphosphate) before seeding each year. Fertilizers were uniformly spread onto the soil surface by hand and incorporated into the plowed soil (0–20 cm) by tillage for conventional tillage treatments, and were applied in shallow furrows and covered with soil for no-till treatments. Maize (cultivar Shendan 10) was planted at a density of ~45,700 plants ha^{-1} on April 20 in 2011 and April 28 in 2012 respectively, by using a hole-sowing tool by hand for all treatments. During the fertilizing and sowing operations, straw was moved aside temporarily and carefully returned back to the same plot for the stover-retention (i.e. CS and NS) treatments. Mature maize was harvested by hand on September 25 in 2011 and September 28 in 2012, respectively. Samples of maize grain and stover were oven-dried at 60 °C to constant weights to obtain the grain yield and aboveground biomass.

2.3. Soil greenhouse gas measurements

Soil CO_2, N_2O, and CH_4 fluxes were measured using the closed chamber method over a two-year period, from 3 October 2010 to 30 September 2012. In September 2010, chamber bases were installed in each plot to observe the effect of tillage and stover retention on GHG emissions. A rectangular PVC base frame (30 cm × 30 cm × 15 cm), with a groove (5 cm in width) around the upper edge, was permanently inserted 5 cm into the soil and allowed to equilibrate for two weeks before gas sampling. A chamber (30 cm × 30 cm × 10 cm) was fitted to the frame by inserting it into the groove; this was filled with water to ensure a gas-tight seal during gas sampling. Samples were taken twice per week during the growing season and weekly after harvest, resulting in 74 and 71 sampling times in 2010–2011 and 2011–2012, respectively. Sampling was carried out in the morning between 09:00 and 12:00 to minimize the diurnal variation in GHG flux patterns and to