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Tillage effects on carbon footprint and ecosystem services of climate regulation in a winter wheat–summer maize cropping system of the North China Plain

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ABSTRACT

Inappropriate farm practices can increase greenhouse gases (GHGs) emissions and reduce soil organic carbon (SOC) sequestration, thereby increasing carbon footprints (CFs), jeopardizing ecosystem services, and affecting climate change. Therefore, the objectives of this study were to assess the effects of different tillage systems on CFs, GHGs emissions, and ecosystem service (ES) values of climate regulation and to identify climate-resilient tillage practices for a winter wheat (*Triticum aestivum* L.)-summer maize (*Zea mays* L.) cropping system in the North China Plain (NCP). The experiment was established in 2008 involving no-till with residue retention (NT), rotary tillage with residue incorporation (RT), sub-soiling with residue incorporation (ST), and plow tillage with residue incorporation (PT). The results showed that GHGs emissions from agricultural inputs were 6432.3–6527.3 kg CO_2-eq ha^{-1} yr^{-1} during the entire growing season, respectively. The GHGs emission from chemical fertilizers and irrigation accounted for >80% of that from agricultural inputs during the entire growing season. The GHGs emission from agricultural inputs were >2.3 times larger in winter wheat than that in the summer maize season. The CFs at yield-scale during the entire growing season were 0.431, 0.425, 0.427, and 0.427 without and 0.286, 0.364, 0.360, and 0.334 kg CO_2-eq kg^{-1} yr^{-1} with SOC sequestration under NT, RT, ST, and PT, respectively. Regardless of SOC sequestration, the CFs of winter wheat was larger than that of summer maize. Agricultural inputs and SOC change contributed mainly to the component of CFs of winter wheat and summer maize. The ES value of climate regulation under NT was ¥159.2, 515.6, and 478.1 ha^{-1} yr^{-1} higher than that under RT, ST, and PT during the entire growing season. Therefore, NT could be a preferred "Climate-resilient" technology for lowering CFs and enhancing ecosystem services of climate regulation for the winter wheat–summer maize system in the NCP.

1. Introduction

Increased atmospheric concentrations of greenhouse gases (GHGs) have resulted in global warming, and drawn global attention of scientists and policymakers. Agriculture is one of the largest source of GHGs (IPCC, 2013). However, agro-ecosystem is also an important solution to mitigation of climate change through sequestering atmospheric CO_2 in soil and biota (Lal, 2004a), contributing to numerous important ecosystem service (ES), e.g., food, feed, fiber, and climate regulation (Kroeger and Casey, 2007). Agricultural management practices can affect emission of GHGs, directly and indirectly, from agricultural inputs that include seeds, fertilizer, irrigation, seeding, tillage, storage, and harvest (Lal, 2004a; Cheng et al., 2011). It is the right time to design and explore some appropriate cleaner and climate-resilient technologies for agriculture to mitigate GHGs emissions and increase ESs (Lal, 2004b; Lal, 2013). Recommended management practices

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Abbreviations: BD, soil bulk density; CF, carbon footprint; ES, ecosystem service; GHGs, greenhouse gases; LCA, life cycle assessment; NCP, North China Plain; NT, no-till with residue retention; PT, plow tillage with residue incorporation; RMPs, recommended management practices; RT, rotary tillage with residue incorporation; SCS, soil organic carbon storage; SOC, soil organic carbon; ST, subsoiling with residue incorporation.

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(RMPs) (e.g., conservation tillage and integrated nutrient management) can reduce GHGs emissions and carbon footprint (CF) (Stavi and Lal, 2013), increase soil organic carbon (SOC) sequestration (Lal et al., 1999; Zhu et al., 2015), and thus enhance ESs (Lal, 2013; Xue et al., 2014). Therefore, assessment of CFs and ESs associated with climate regulation can provide climate-resilient options for mitigating and adapting to climate change.

The term CF refers to the total set of GHGs emissions caused by an organization, event, product, or person, which can be assessed by using a life cycle assessment (LCA) approach (ISO, 2013). As an environmental indicator of an agro-ecosystem, CF of agricultural products can be used to identify cleaner and climate-resilient technologies, and can enhance understanding of the mitigation potential of a particular technology (Gan et al., 2012a; Hadian and Madani, 2015). The implementation of RMPs can effectively decrease the CF of agricultural products (Gan et al., 2012b). The ES is the benefits people obtain from ecosystems, including four categories as supporting service, provisioning service, regulating service, and cultural service (Millennium Ecosystem Assessment, MEA, 2005; Costanza et al., 1997). In addition, the ES of climate regulation derives from ecological processes that contributes to or mitigates the build-up of GHGs in the atmosphere (MEA, 2005). The agro-ecosystem is meritorious for its provisioning of climate regulation through crop C fixation, SOC sequestration and GHGs emissions (Palm et al., 2014). Xue et al. (2014) reported that no-till (NT) can increase the ES value of climate regulation in the double paddy cropping system. However, little information associated with ES assessment of climate regulation due to tillage practices has been assessed for other regions.

The North China Plain (NCP) is an important food grain base in China. Intensive farming is the principal characteristic of a cropping system in the NCP. The rate of chemical fertilizer has increased from 100 to 600 kg ha^{-1} yr^{-1} since 1980s (Chen et al., 2001). Such a rapid increase in fertilizer input and intensive farming have increased GHGs emissions (Gao et al., 2011) and other environmental problems. Intensive farming also has increased the costs of farm management and requires more resources, particularly water resources. In the context of climate change, big challenges lie ahead for agricultural development in the NCP. Therefore, it is critical to assess and identify climate-resilient technologies with low GHGs emissions and CF, high SOC sequestration capacity, and high ES value. The objectives of this study were to evaluate the tillage effects on the GHGs emissions from agricultural inputs, the CF of crop production, and the ES value of climate regulation, and identify the climate-resilient tillage system for the winter wheat–summer maize system of the NCP.

2. Materials and methods

2.1. Site description

The data were collected from a tillage experiment from 2008 to 2013. This study was conducted at the Wuqiao Experimental Station of the China Agricultural University (37°36′N, 116°21′E, 17 m a.s.l.), Hebei Province. The region has a temperate continental climate with an average annual temperature of ~12.6 °C, the mean annual precipitation of ~500 mm, of which 60–70% is received during July and August. Soil texture for 0–20 cm depth is silt loam with 177 g kg^{-1} of sand, 614 g kg^{-1} of silt, and 154 g kg^{-1} of clay. Principal soil properties of for 0–20 cm depth are as follows: 10.34 g kg^{-1} of SOC, 0.79 g kg^{-1} of total nitrogen (N), 94.2 mg kg^{-1} of available potassium (K), and 44.6 mg kg^{-1} of available phosphorus (P), and pH of 7.6. The typical cropping system in this region is winter wheat (*Triticum aestivum* L., from the middle of October to early June) and summer maize (*Zea mays* L., from early June to the middle of October).

2.2. Experimental design and farm management

The field experiment was initiated in 2008 with four treatments and three replications per treatment: no-till with residue retention (NT), rotary tillage with residue incorporation (RT), sub-soiling with residue incorporation (ST), and plow tillage with residue incorporation (PT). The net area of each plot was 215 m^2. Tillage practices were only implemented after the summer maize had been harvested, and NT was performed during the summer maize season for all treatments. Prior to tillage implementation, maize residues were returned to the soil and chopped into small pieces (5–10 cm) after the summer maize harvest. The PT plots were plowed once to 15–20 cm depth, and maize residues incorporated with a moldboard plow, and then rotovated once with a rotary tiller to ~10 cm depth. The NT plots were sown with an NT seeder (Nonghaha Machinery Group, Shijiazhuang, Hebei Province, China) without any other seedbed preparation. The ST plots were sub-soiled to 30 cm depth and rotovated once to 10 cm depth with a rotary cultivator. The RT plots were rotovated twice with a rotary tiller to 10 cm depth. Fertilizers in NT plots were applied at sowing, but broadcast over the field and mixed into the soil by tillage in the other three treatments. Winter wheat was harvested with a combine harvester, and residues (20–30 cm high) were retained on the soil surface. Summer maize was seeded with an NT seeder. The amounts of residues retained were approximately 12,598.8 and 9894.6 kg ha^{-1} yr^{-1} in the summer maize and winter wheat growing seasons, respectively.

All farming management practices in the experiment were implemented as per the locally recommended practices. Winter wheat variety Jimai 22 was seeded at a rate of 337.5 kg ha^{-1} in the NT treatment, and 300 kg ha^{-1} in the other three treatments. The higher seeding rate in NT was used to ensure a good crop stand. Summer maize variety Zhengdan 958 was sown at a seeding rate of 60 kg ha^{-1} from 2009 to 2012 and at 30 kg ha^{-1} in 2013. All plots received urea, diammonium phosphate, and potassium sulfate at the rate of 450, 225, and 75 kg ha^{-1}, respectively, when the winter wheat was sown. Furthermore, urea was applied at a rate of 150 kg ha^{-1} in each plot when irrigated at the jointing stage. All plots were top-dressed with compound fertilizer ($N:P_2O_5:K_2O = 28:15:10$) at the rate of 525 kg ha^{-1} during the summer maize growing season. Tribenuron-methyl was applied at 225 g ha^{-1} during the seedling stage of winter wheat. Nicosulfuron + atrazine was applied at a rate of 1500 g ha^{-1} during the seedling stage of summer maize. All plots were irrigated with deep well water by pumping, prior to seeding of the winter wheat and again at the jointing and heading stages, with a total electricity consumption of 1590.3 kWh ha^{-1}. Irrigation in the summer maize season consumed 675 kWh ha^{-1} of electricity in 2008–2011; however, no irrigation was applied in 2012 and 2013 due to an adequate amount of precipitation. Diesel consumption by the farm machinery during the 5 years was as follows: 41.5, 51.0, 77.25, and 73.5 kg ha^{-1} for tillage and sowing under NT, RT, ST, and PT, respectively, and 42.5 kg ha^{-1} for winter wheat harvesting under all treatments. In addition, the diesel consumption was 13.5 and 38.5 kg ha^{-1} for sowing and harvesting, respectively, for all treatments during the summer maize season.

2.3. Data collection

2.3.1. The GHGs emissions from agricultural inputs

The system boundary in the study included all stage of winter wheat or summer maize production from raw material exploitation, manufacture, transportation of agricultural inputs