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Multi-site assessment of the effects of plastic-film mulch on the soil organic carbon balance in semiarid areas of China

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ABSTRACT

Plastic-film mulch is widely used to increase soil temperature and reduce water evaporation in vegetable production. In China, it is also extensively used for growing grain crops, especially in temperature and rainfall limited areas. However, it remains unclear whether the technology is sustainable in terms of maintenance of soil organic carbon (SOC) balance. We assessed the effects of plastic-film mulch on the SOC balance in maize (*Zea mays* L.) production in a range of cold semiarid environments. We imposed four treatments: (i) no plastic-film mulch or straw incorporation, (ii) plastic-film mulch, (iii) straw incorporation in soil without mulch, and (v) straw incorporation plus mulch, in ridge–furrow prepared fields at five sites along a hydrothermal gradient for up to six years. Maize root biomass across sites increased by 23–38% in mulched plots associated with the increase in aboveground biomass, indicating an increased SOC input, compared to that in non-mulched plots. The plastic-film mulch increased SOC mineralization, indicated by the stimulated decomposition of buried maize straw, and a 4–5% reduction in the concentration of light-fraction SOC (<1.8 g cm^{-3}), but the total SOC concentration and stock in the 0–0.15 m soil layer did not change relative to no mulch after six years of continuous cropping. Plastic-film mulch did not affect the total non-cellulosic sugar content; however, it significantly increased the contribution of microbial-synthesized sugars to the total non-cellulosic sugars, indicating an intensified microbial action on the SOC pool compared to no mulch. Straw incorporation increased the root biomass, light and total SOC concentrations and non-cellulosic sugars, and changed the non-cellulosic sugar composition. We conclude that the increase in soil temperature and moisture by use of plastic-film mulch enhances productivity, but importantly maintains the SOC level in temperature- and rainfall-limited semiarid regions by balancing the increased SOC mineralization with increased root-derived C input.

1. Introduction

Plastic-film mulch is a technology used worldwide for vegetable production (Clarkson, 1960; Lamont, 1993; Díaz-Pérez et al., 2004; Anikwe et al., 2007; Berger et al., 2013). In China, plastic-film mulch is not only used for vegetable production, but also in maize (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), potato (*Solanum tuberosum* L.), wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) production, particularly to enable earlier planting in regions with cold and long winter. In 2014, the total production of plastic-film in China was 1.42 million t and about 19% (25 million ha) of total arable land (130 million ha) in China was cultivated under plastic-film mulch (http://www.ampcn.com/news/content.asp?newsid=103593). The large scale use of plastic-film mulch in China originates from its severe shortages of arable land and water resources for agriculture (Zhang et al., 2013); only 0.1 ha of cropland is available for each of China's 1.3 billion people, less than 1/6 of the per capita cropland area in the USA (0.64 ha in 2000; Lal, 2002). Therefore, meeting the demand for increased grain production requires improved productivity of existing cropping systems (Godfray et al., 2010; Tilman et al., 2011; Zhang et al., 2013), but not at the expense of long-term degradation of the soil resources. Improved productivity without environmental degradation is termed sustainable intensification (Garnett et al., 2013).

Insufficient precipitation and shortages of irrigation water are major constraints to increasing crop productivity in semiarid areas while low air temperatures in spring are limitations in high altitude and/or high latitude regions. Plastic-film mulch provides a

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way of reducing these soil and water limitations by simultaneously increasing soil temperatures and decreasing soil water evaporation (Li et al., 2007; Gan et al., 2013; Chai et al., 2014; Liu et al., 2014a,b). On the Loess Plateau in northwest China, plastic-film mulch increases the upper (0–0.15 or 0.20 m) soil temperatures by 2–7 °C in the early growth of maize or wheat (Li et al., 2004, 2013a; Liu et al., 2014a,b; Wang et al., 2015, 2016). By blocking soil water evaporation, plastic-film mulch significantly increases soil moisture (Li et al., 2007, 2013b; Liu et al., 2014b; Wang et al., 2016). Crops grown under plastic-film mulch typically have increased yields of 50–100% in drought years or cold sites, 30–90% in an average-rainfall year or warmer sites, and 10–40% in a wetter-than-normal year and milder temperatures, compared non-mulched crops (Gan et al., 2013; Wang et al., 2016). In maize, the increased yields in mulched-systems are typically a combination of increases in various yield components, such as more fertile cobs per plant, increased 1000-seed weight, and more seeds per head (Li et al., 1999; Niu et al., 2004; Ren et al., 2009).

Any increase in crop productivity must not be at the expense of soil quality, as measured by soil organic carbon (SOC) and must not exacerbate greenhouse gas emissions in the face of rapid global change (Godfray et al., 2010; Cui et al., 2013). While the impacts of commonly-employed practices such as treatment of straw and stubble residues, application of mineral fertilizers, improvement of cultivars, species and tillage on food production and global climate change have been extensively studied (Ciais et al., 2011), the impact of plastic-film mulch on the carbon balance is less known. The basic principal of using plastic-film mulch in crop production is to simultaneously increase soil temperature and moisture (Liu et al., 2010; Gan et al., 2013; Chai et al., 2014), which is well known to stimulate mineralization and loss of SOC (Yin et al., 2013; Hadden and Grelle, 2016). The SOC level not only determines the productivity and sustainability of a cropping system, but also affects the CO_2 fluxes between the soil and atmosphere (Lal, 2004; Luo et al., 2011; Liu et al., 2015). The change in the SOC level in the soil is the result of inputs from plant-derived organic sources and losses by microbial decomposition (Lal, 2004; Liu et al., 2015). Sporadic data has shown that plastic-film mulch increases soil microbial biomass (Li et al., 2004; Wang et al., 2014; Hai et al., 2015), soil enzymatic activity (Wang et al., 2014; Liu et al., 2014a), nitrogen mineralization and availability (Chen and Katan, 1980; Zhang et al., 2012; Hai et al., 2015), and decreases labile SOC pools after one growing season (Wang et al., 2014). This implies that by increasing soil temperature and moisture plastic-film mulch may increase SOC mineralization and thus negatively affect the SOC balance if the increased mineralization is not balanced by increased inputs. However, despite plastic-film mulch being widely adopted, its effect on the SOC balance has not been rigorously assessed. It remains unclear if the plastic-film mulch is a technology of sustainable intensification, in terms of the SOC balance.

Previously we showed that the continuous use of plastic-film mulch along a hydrothermal gradient significantly increased the grain yield and aboveground biomass of maize compared with non-mulched plots at five semiarid sites varying in temperature and precipitation (Wang et al., 2016). Additionally, we showed that straw incorporation increased the yield and aboveground biomass of maize by 7–12% and 8–12%, respectively (Wang et al., 2016). The objective of the present study was to examine the effect of the plastic-film mulch and straw incorporation on SOC balance under maize at the same five sites. We hypothesized that: (i) the plastic-film mulch and straw incorporation would increase the input of SOC from increased belowground biomass associated with the increased aboveground biomass; (ii) the plastic-film mulch would increase the microbial mineralization of SOC; and (iii) the increase in belowground biomass with the use of plastic-film mulch would counterbalance the loss of SOC from the increased mineralization. To test our first hypothesis, we measured the root biomass production of maize in plastic-film mulched and non-mulched plots and with and without straw incorporation. There should be more roots in the mulched treatments because of the increased water content in the top soil. To test our second hypothesis, we measured the decomposition of maize straw buried in soil to indicate SOC mineralization as affected by plastic-film mulch, because the direct measurement of SOC mineralization is difficult due to the low SOC content of the local soils. Finally, we measured the changes in total and light-fraction SOC pools and non-cellulosic carbohydrates in different treatments to assess the effect of plastic-film mulch and straw incorporation on SOC levels and composition. The light-fraction SOC and carbohydrates are readily-available carbon and energy sources for microorganisms and are sensitive to changes in soil management practices (Gregorich et al., 1994; Haynes, 2005). In addition, the analysis of the respective contribution of hexoses, pentoses, and desoxy-hexoses to the neutral sugar pool allows an assessment of changes in the polysaccharide sources (microbial versus plant-derived polysaccharides) when subjected to the different treatments (Murayama, 1984; Oades, 1984; Schmidt et al., 2015).

2. Materials and methods

2.1. Site and experimental design

The study was conducted at five sites in Gansu Province, China, varying in altitude, temperature and precipitation: Ningxian, Chongxin, Tongwei, Huining and Yuzhong (Table 1). The five sites increased in altitude from Ningxian through Chongxin, Tongwei and Huining to Yuzhong, while mean annual rainfall and mean temperature (1982–2012) decreased from Ningxian through Chongxin, Tongwei, and Huining to Yuzhong (Table 1). At each site, the experiments were conducted on a flat field that had been cropped for many years. The soils across all five sites are classified as Mollisols at Ningxian and Chongxin, and Entisols at Tongwei, Huining and Yuzhong, developed from wind-blown loess that has a deposition thickness of more than 100 m above the bedrock. They have a silt loam texture (2–0.05 mm 3.5–6.7%; 0.05–0.002 mm 71.1–74.8%; <0.002 mm 21.6–22.0%), a bulk density ranging from 1.00 to 1.14 g cm^{-3} and pH values (water:soil = 2.5:1) from 8.0 to 8.2 in the upper 0.15-m soil profile. At the start of the experiment in October 2008, the total SOC varied from 9.1 to 12.2 g kg^{-1}, total soil nitrogen (N) varied from 1.02 to 1.23 g kg^{-1}, mineral N varied from 23 to 128 mg kg^{-1}, and Olsen phosphorus varied from 7 to 56 mg kg^{-1} across the five sites (Wang et al., 2016).

A detailed description of the experimental sites and experimental design are given in Wang et al. (2016). At each site, four treatments with three replicates were imposed in October in a ridge-furrow field: (1) control (no plastic-film mulch and no straw incorporation), (2) plastic-film mulch over ridges and furrows (without straw incorporation), (3) straw incorporation (without plastic-film mulch), and (4) plastic-film mulch with straw incorporation. The experiment was conducted continuously in the same field at each site for three years (2009–2011) at Ningxian, four years (2009–2012) at Chongxin and six years (2009–2014) at Tongwei, Huining and Yuzhong. At each site, maize straw (stems and leaves, <0.06 m in length) was applied in late October on the straw-incorporation plots. The amount of maize straw incorporated was between 5 and 7.5 t ha^{-1} (constant mass at 60 °C) per year (2.4–3.6 t C ha^{-1} y^{-1}) at Ningxian, Tongwei, Huining and Yuzhong, and between 4 and 6 t ha^{-1} y^{-1} (1.9–2.9 t C ha^{-1} y^{-1}) at Chongxin. Urea at 276 kg N ha^{-1} and superphosphate at 37 kg soluble phosphorus ha^{-1} were broadcast on each plot before plowing to a depth of 0.15 m with a spade. Afterwards, alternate narrow