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Original Articles

Carbon footprint of dryland winter wheat under film mulching during summer-fallow season and sowing method on the Loess Plateau

Jian-Fu Xue[a], Ya-Qi Yuan[a], Hai-Lin Zhang[b], Ai-Xia Ren[a], Wen Lin[a], Min Sun[a], Zhi-Qiang Gao[a,*], Da-Sheng Sun[c]

[a] College of Agriculture, Shanxi Agricultural University, Shanxi 030801, China
[b] College of Agronomy and Biotechnology, China Agricultural University, Key Laboratory of Farming System, Ministry of Agriculture, Beijing 100193, China
[c] College of Resources and Environment, Shanxi Agricultural University, Shanxi 030801, China

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ABSTRACT

To identify more carbon (C)-friendly agricultural technology, we studied the coupling impact of film mulching during summer fallow and sowing method on carbon footprint (CF) of dryland winter wheat (*Triticum aestivum* L.) on the Loess Plateau. From 2011 to 2014, a two-factor split block design was conducted with the following treatments: water-permeable film mulching in the summer fallow season (FM) or no mulching in the summer fallow season (FM0) with either conventional drill sowing (DS) or drill sowing beside a common film (DSF). The greenhouse gases (GHG) emissions associated with agricultural inputs were 7013.3, 5908.3, 5298.5, and 4193.5 kg CO_2-eq·ha^{-1}·yr^{-1} for FM × DSF, FM0 × DSF, FM × DS, and FM0 × DS treatments, respectively, which contributed > 80% of total GHG emissions during the winter wheat production. Fertilizer, especially P_2O_5 fertilizer, was the largest contributor to GHG emissions from agricultural inputs. The CF of dryland winter wheat was 1.14 to 3.60 kg CO_2-eq kg^{-1}, which was the lowest under the FM × DS treatment while the largest under the FM × DSF treatment. Film mulching during summer fallow with drill sowing (FM × DS) could be a C-friendly technology for winter wheat production on the Loess Plateau.

1. Introduction

Climate change resulting from anthropogenic greenhouse gases (GHG) emissions has captured the attention of scientists, policy-makers, and even the public. Dryland accounts for 47.2% of the world's land area (Lal, 2004b), and which may increase by 11% and 23% under representative concentration pathways (RCP) 4.5 and RCP 8.5, respectively (Huang et al., 2016). Generally, agriculture has been regarded as both a source of CO_2 (e.g., plant respiration and the decomposition of dead plant biomass and soil organic carbon [SOC]) and sink of CO_2 (e.g., SOC sequestration and plant carbon fixation) (Smith et al., 2014). In addition, agricultural soil is a primary N_2O emission source (Smith et al., 2014). Dryland agriculture plays a predominant role in the global food supply. Therefore, quantifying GHG emissions from agricultural production in drylands plays a central role for the development of cleaner, more C-friendly technology and the mitigation of agriculture's impact on climate change.

Recently, carbon footprints (CFs) have been adopted as an environmental performance indicator for climate change. GHG emissions are summarized by CF measurements, permitting the quantification of the whole life cycle of a product manufactured within a certain system. The CF is defined as the direct and indirect CO_2 emission of a product or service in the life cycle process from cradle to grave (Wiedmann and Minx, 2008). The CF can be assessed by measuring CO_2 equivalents (CO_2-eq) of all GHG emissions (Hillier et al., 2009). To resolve the divergence in the concepts, content, and calculation methods of CF among researchers, the International Organization for Standardization (ISO) has defined the CF for a specific product as the sum of GHG emissions and removals in the whole product process expressed as CO_2-eq based on a life cycle assessment (LCA) using the single impact category of climate change (ISO, 2013).

Recently, increasing research has focused on CF assessments for crop products. Cheng et al. (2015) evaluated the CF of four main food crops in China, paddy rice, wheat, maize, and soybean, which had CFs of 0.58, 0.22, 0.19, and 0.17 kg CO_2-eq kg^{-1}, respectively. Moreover, the spatial and temporal variations of CFs for three main grain crops (rice, wheat, and maize) were affected by environmental and socio-economic factors in China (Xu and Lan, 2017). Most of studies indicate that GHG emissions from agricultural materials inputs (e.g., fertilizers, machinery energy consumption, pesticides) contributed substantially to

* Corresponding author.
E-mail address: gaosxau@163.com (Z.-Q. Gao).

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Table 1
Precipitation occurring at the experimental site from 2011 to 2014 (in mm).

Year	Summer fallow[#]	Sowing to pre-wintering	Pre-wintering to jointing	Jointing to anthesis	Anthesis to mature	Total
2002–2014	301.7 ± 95.6	48.2 ± 17.9	38.6 ± 24.2	32.6 ± 11.1	62.9 ± 24.8	484.0 ± 106.8
2011–2012	459.9	137.4	28.2	20.5	27.1	673.1
2012–2013	171.1	19.8	26.3	20.8	104.9	342.9
2013–2014	283.7	43.7	19.3	63.8	63.7	474.2

[#] The precipitation data sourced from Wenxi Meteorological Bureau. Summer fallow ranges from the middle of June to late September, sowing to pre-wintering ranges from early October to late November, pre-wintering to jointing ranges from early December to early April, jointing to anthesis ranges from the middle of April to early May, and anthesis to mature ranges from the middle of May to early June.

the CF of crop products (Cheng et al., 2011, 2015; Huang et al., 2017c; Zhang et al., 2017). Furthermore, agricultural practices (e.g., soil tillage, fertilizer use, and film management) influence the physical, chemical and biological properties of soils, resulting in changes in crop yield and soil GHG emissions, which ultimately affect crop CFs. Some pivotal farming tactics (e.g., using diversified cropping systems, improving N fertilizer use efficiency, adopting intensified rotation, using reduced tillage with crop residue retention) have been proven to be effective in improving crop yields while lowering the CF (Liu et al., 2016a). The CFs of main staple crops (e.g., wheat, rice, and maize) were assessed under different agricultural management practices across various regions, e.g., soil tillage (Xue et al., 2014; Zhang et al., 2016), and nitrogen (N) fertilizer rates (Gan et al., 2012a; Wang et al., 2015). With accelerated dryland expansion due to more sensitive and vulnerable to GHG-included climate change, water shortage in dryland could become more severe (Huang et al., 2016, 2017a), resulting in that crop yield fluctuation would be more prominent issues on the Loess Plateau. Film mulching and optimal sowing methods have been adopted to increase soil water content and maintain crop yield (Chen et al., 2015; He et al., 2016; Li et al., 2013a; Liu et al., 2016b), however, such practices may also resulted in the increase of soil GHG emissions in dryland agriculture systems of the Loess Plateau due to the improvement of microbial activity under greater soil water and temperature (Chen et al., 2017; Wang et al., 2016). The variation in crop yield accounted for the majority of the variation in the CF (Heidari et al., 2017). Therefore, it is necessary to assess the CF of crops under different film mulching and sowing methods.

Wheat (*Triticum aestivum* L.) is one of the three largest food staples in China, and it therefore plays a critical role in the food security of China. Dryland winter wheat accounts for ~60% of the total wheat planting area in southern Shanxi Province on the Loess Plateau (Li et al., 2013b). However, numerous problems threaten dryland wheat production on the Loess Plateau, e.g., water shortages coupled with lower water use efficiency (WUE), the degradation of soil fertility, and lower yields due to large climate fluctuations in different years. To address these issues and ensure food safety, film mulching has been used to increase WUE and improve yields of dryland winter wheat production in southern Shanxi Province. Film mulching during the summer-fallow season and the crop growing stage has been shown to substantially increase soil water storage, and improve the yield of winter wheat (Gao et al., 2015; Zhao et al., 2013). Differences in soil water content may affect yields and soil GHG emissions, altering the CF of wheat. Moreover, sowing methods, including conventional drill sowing or/and drill sowing beside a common plastic film, could also influence soil water content and wheat yield, thus change soil GHG emissions. The CF of dryland winter wheat is potentially affected by film mulching and the sowing method, and its assessment may be important in reducing GHG emissions and developing C-friendly farming technology.

Thus, the objectives of this study were to (i) quantify the GHG emissions associated with agricultural inputs using the life cycle assessment method under different treatments, (ii) evaluate the CF and its components under different film mulching during the summer fallow season and sowing method among different years, and (iii) identity the C-friendly farming technology for dryland winter wheat production on the Loess Plateau.

2. Materials and methods

2.1. Site description

This study was conducted from 2011 to 2014 at the Wenxi Experimental Station of the Shanxi Agricultural University (111°28′E, 35°35′N) in Shanxi Province, located on the Loess Plateau in China. The region has a temperate continental monsoon climate with a mean annual temperature of 12.6 °C, mean annual precipitation of ~440 mm, mean annual potential evapotranspiration of 1838.9 mm, and mean annual sunshine duration of 2461 h. Table 1 provides a summary of 2002–2014 precipitation data at the experimental site, most of which is received from June to September (i.e., during the summer fallow season) in this region. According to the average precipitation from 2002 to 2014, the three experimental years were divided into wet, normal, and dry years using a common method developed by Zhang et al. (2008). Winter wheat, with a single cropping per year and a summer fallow period, is the principal cropping system in this region. The experiments described herein were laid out in different fields in three wheat cropping seasons. The soil properties at 0–20 cm depth were 8.72 g kg^{-1} of soil organic matter (SOM), 0.78 g kg^{-1} of total N, 40.16 mg kg^{-1} of available N, and 19.87 mg kg^{-1} of available phosphorus (P) in June 10, 2011; 11.88 g kg^{-1} of SOM, 38.62 mg kg^{-1} of available N, 14.61 mg kg^{-1} of available P in June10, 2012; and 10.18 g kg^{-1} of SOM, 39.32 mg kg^{-1} of available N, 16.62 mg kg^{-1} of available P in June 10, 2013.

2.2. Experimental design and management

The treatments were implemented in a two-factor split-block design with water-permeable film mulching (FM) or no mulching (FM0) during the summer fallow season in the main plots, with either conventional drill sowing (DS) or drill sowing beside a common plastic film (DSF) in the sub-plots. The 1400 mm wide and 0.006 mm thick water-permeable film was supplied by the Shanxi Academy of Agricultural Sciences. Both water-permeable film and the common plastic film are made from polyethylene. Four treatments combinations were established in 2011–2014, including water-permeable film mulching in the summer fallow season with conventional drill sowing (FM × DS), water-permeable film mulching in the summer fallow season with drill sowing beside a common film (FM × DSF), no mulching in the summer fallow season with conventional drill sowing (FM0 × DS), and no mulching in summer fallow season with drill sowing beside a common film (FM0 × DSF). Each treatment was replicated three times, and the plot size was 50 m × 3 m.

Generally, wheat plant remnants were retained, with ~20–30 cm of stubble remaining for all treatments after winter wheat was harvested by a combine harvester in early June, which was plowed to a depth of ~25–30 cm after heavy rain in early- to mid-July. In addition, all plots received 1500 kg ha^{-1} of commercial organic fertilizer (≥20% SOM, ≥12-0-3% N-P_2O_5-K_2O) before plowing. After plowing, all plots were