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Intercropping maize and wheat with conservation agriculture principles improves water harvesting and reduces carbon emissions in dry areas

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ABSTRACT

In arid and populated areas or countries, water shortage and heavy carbon emissions are threatening agricultural sustainability with food security severely, and becoming a major issue. It is unclear whether improved farming systems can be developed to tackle those issues through a sustainable agriculture. Here three farming practices that have proven to be essential and successful, which were: (a) crop intensification through strip intercropping, (b) water harvesting through conservation tillage; and (c) carbon sequestration through improved crop residue management options, were integrated in one cropping system. We hypothesize that the integrated system allows the increase of crop yields with improved water use efficiency, while reducing carbon emissions from farming. The hypothesis was tested in field experiments at Hexi Corridor (37°96′N, 102°64′E) in northwest China. We found that the integrated system increased soil moisture (mm) by 7.4% before sowing, 10.3% during the wheat–maize co-growth period, 8.3% after wheat harvest, and 9.2% after maize harvest, compared to the conventional sole cropping systems. The wheat/maize intercrops increased net primary production by 68% and net ecosystem production by 72%; and when combined with straw mulching on the soil surface, it decreased carbon emissions by 16%, compared to the monoculture maize without mulch. The wheat/maize intercrops used more water but increased grain yields by 142% over the monoculture wheat and by 23% over the monoculture maize, thus, enhancing water use efficiency by an average of 26%. We conclude that integrating strip intercropping, conservation tillage as well as straw mulching in one cropping system can significantly boost crop yields, improve the use efficiency of the limited water resources in arid areas, while, lowering the carbon emissions from farming. The integrated system may be considered in the development of strategies for alleviating food security issues currently experienced in the environment-damaged and water-shortage areas.

1. Introduction

Ever-growing human population on the planet requires the continuous supplies of sufficient quantity of grains to meet the needs for food, feed, and fuel (Godfray et al., 2010). This has been a real challenge in highly-populated countries such as China and India (Tilman et al., 2011). Yet, in those developing nations, crop cultivation typically uses suboptimal farming practices that cause serious soil degradation (Snyder et al., 2009), rapid decline of soil fertility, and large amounts of greenhouse gas emissions (West et al., 2010). An added challenge in the arid and semiarid areas is water shortage, which threatens agricultural sustainability (Wani et al., 2008). A typical example is northwestern China, where average freshwater availability is about 760 m^3 per capita per year, a level 25% below the internationally-accepted threshold of water scarcity (Shalizi, 2006). Annual precipitation is between 50 mm and 150 mm, while annual evaporation is greater than 2400 mm. The quantity of freshwater available for agriculture has been declining in recent years (Brown and Halweil, 1998). Rapid-growing urbanization creates much competition for limited freshwater resources between agriculture and other industries (Kendy et al., 2007). Furthermore,

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high-input farming systems typical in the populated areas (Garnett et al., 2013; Li et al., 2010) have been shown to increase production costs (Garnett et al., 2013) with negative climatic consequences (Challinor et al., 2014), as higher cropping inputs (such as inorganic fertilizers, pesticides) generate more greenhouse gases (Brock et al., 2012; Burney et al., 2010; Li et al., 2010). Therefore, strategies are urgently needed in order to meet the goals of increasing crop productivity with the limited water availability, while reducing carbon emissions from farming. An important question is—can we develop an improved farming system that can address those issues simultaneously, and to achieve a sustainable agriculture in those highly-populated, resource-limited areas.

Intensified intercropping system, a practice that has been used in many parts of the world for increasing crop productivity (Chai et al., 2013), or closing yield gaps between current yield levels and their potentials (Mueller et al., 2012). Predominantly, it is due to the yield advantages over monoculture systems: (a) improved light interception by crop canopy (Munz et al., 2014; Yang et al., 2014), (b) reduced disease pressure in some crop species (Fernández-Aparicio et al., 2010; Qin et al., 2013b), and (c) enhanced supplementary effects of the inter-species during their co-growth period (Chai et al., 2013). Also, intensified systems have been recognized as a key farming strategy for reducing the carbon footprint of crop production (Gan et al., 2014; Qin et al., 2013a). However, traditional intercropping with minor improvements has stroked its main difficulties in the practical translation to modern farming and logistics especially in recent years. Even with such a vital problem, intercropping plays an important role in producing sufficient food and high-efficient use of resources in developing countries (Fan et al., 2012). Therefore, major approaches, such as conservation agriculture principles, should be employed in the system in order to adapt the modern mechanized farming.

Reduced tillage or no-till has been increasingly used worldwide due to their environmental advantages and lower labour inputs (Kirkegaard et al., 2014a) over traditional systems. Most studies have declared that no-till decreases soil disturbance (Alletto et al., 2010) along with inhabitation of soil microbial community functionalities (Bainard et al., 2014), and lowers CO_2 emission from the soil (Boeckx et al., 2011). Nevertheless, others demonstrated no significant differences between no-till and conventional tillage (Elder and Lal, 2008), and even opposite (Hendrix et al., 1988). Some recent reports also addressed faithful question on the potential of no-till in reducing greenhouse gas emissions and C-sequestration (Kirkegaard et al., 2014a). The incorporation of suitable crop residue management practices to no-till would be somewhat valid solution to sustain lesser CO_2 emission (Fuentes et al., 2011), and in some cases increase C-sequestration (Alletto et al., 2010). A combination of crop residue retention with no-till will also increase the water infiltration (Elliott and Efetha, 1999; Kirkegaard et al., 2014b), reduce water loss by restraining evaporation (Govaerts et al., 2006), and improve crop water use efficiency (Fan et al., 2012).

Crop residue retained on the soil surface will minimize the time that the soil is bare and exposed to wind, rainfall and runoff (Palm et al., 2014). Thus will simply forms a barrier that help reduce the reaction between atmosphere and surface soil, therefore, result in restraining soil evaporation (Lichter et al., 2008) and sequestering greenhouse gas emissions (Patiño-Zúñiga et al., 2009). In arid and semiarid areas, less soil evaporation often means increased crop productivity (Kumar and Goh, 2002). In terms of soil C storage, most studies confirmed that crop residue returned back to fields helps sequester more carbon (Ghimire et al., 2012; Alletto et al., 2010), and improve soil quality (Elliott and Efetha, 1999). While others proved that there had little or no relevance between residue input and soil C concentration (Paul et al., 2013). The divergence results on increasing soil C mainly depends on whether the returned residue is sufficient or not (Palm et al., 2014). However, more crop residue input to soil, in another side, may led to more CO_2 emission when soil organic matter decomposition occurs. Therefore, it is paramount to understand and address these contradictions in order to employ conservation agriculture principles wisely and maintain productivity while protecting the resource base (Kirkegaard et al., 2014a).

With above concerns in mind, we tried to tackle these issues through establishing a new farming system approach, where three key components, i.e. intercropping, conservation tillage and stubble retention were integrated together. Although conservation tillage has been a well-known practice for decades, most of the published studies are concentrated on monoculture crops and little attention has been paid to intercropping. To which, comprehensive cropping managements are required, and adoption of conservation tillage in intercropping systems has not been easy. There still lack of theoretical and practical basis on yield response, environment impact (e.g. CO_2 emission), and resources use status of such an integrated system. The improved practices we evaluated in the present study may begin to fill this gap. We hypothesize that integrating of the three key farming practices in a well-designed alternative cropping system can allow the increase of crop yield and improvement of water use efficiency, while, at the same time, reducing carbon emissions from farming. An ideal location to test this hypothesis is the Hexi Corridor of northwest China, a typical Oasis agricultural region, with annual evaporation more than 2400 mm and annual precipitation less than 150 mm (Chai et al., 2013). We further hypothesize that if the integrated system works well at this extremely stressful site, this system-approach model could be employed in the other arid and semiarid regions of the world. In testing the hypothesis, we determined (i) soil moisture conservation responses under this integrated system, (ii) the balances of soil evaporation and crop water use, and (iii) CO_2 efflux, carbon emissions and carbon sequestration under different components of this system.

2. Materials and methods

The experiment was carried out at the Gansu Agricultural University Research Station, in Wuwei (37°96′N, 102°64′E, and 1506 m a.s.l). Located in the eastern part of the Hexi Corridor of northwestern China, this station is at the temperate arid zone in the hinterland of the Eurasia Continent. The soil was classified as an Aridisol (FAO/UNESCO, 1988) with soil bulk density in the 0–110 cm soil depth averaging 1.40 g cm^{-3}. For various soil layer (i.e. 0–20, 20–40, 40–70, 70–100 cm), wilting point ranges from 6.7 to 11.4% by weight, and field capacity from 22.2 to 27.8% (Chen et al., 2014). Total nitrogen (N), phosphorous (P) and organic matter in the top (0–60 cm) soil are 0.78 g kg^{-1}, 1.14 g kg^{-1} and 14.3 g kg^{-1}, respectively. Long term (1960–2009) solar radiation is 6000 MJ m^{-2}, annual sunshine duration is >2945 h, annual mean temperature is 7.2 °C with accumulated temperature above 0 °C > 3513 °C and above 10 °C > 2985 °C, and the frost-free period 155 days. Mean annual precipitation is rarely greater than 150 mm, occurring mainly in June to September, and potential evaporation is higher than 2400 mm.

2.1. The system design and plot management

The experiment was conducted with a randomized, complete block design and with three replicates. A preparatory experiment was conducted in 2010 to create proper stubble fields; this was to provide plot bases for the implementation of various treatments in the following years. In 2011 and 2012, wheat–maize intercropping was planted in strips with six rows of wheat (12-cm row space) alternated with two rows of maize (40-cm inter-row) in the set of 80:80 cm strips (Fig. 1). Four tillage and stubble retention patterns