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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

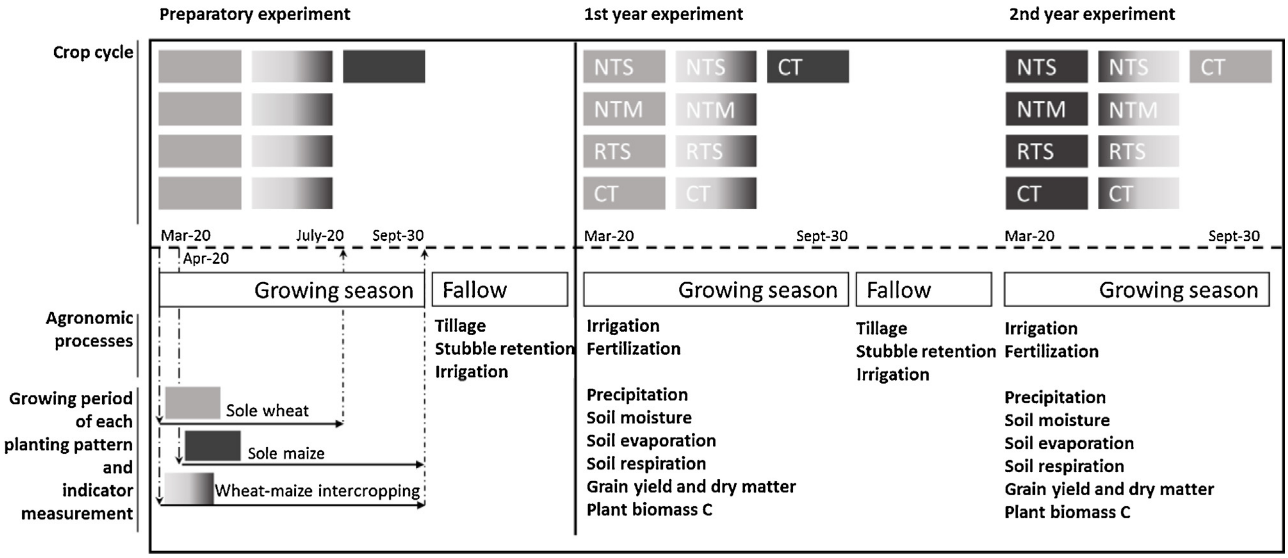

Fig. 1. Yearly calendar diagram which sets out the annual cycle of wheat and maize with the illustration of particular agronomic processes, growing period and indicator measurement in a 3 years experiment at Wuwei experimental station, northwestern China, in 2010–2012.

were implemented: (a) no-till with 25 cm wheat stubble standing in the field (NTS, stubble standing), (b) no-till with 25 cm height of wheat stubble chopped and spread evenly on the soil surface (NTM, stubble mulching), (c) reduced tillage with 25 cm height of stubble was incorporated into the soil (RTS, stubble incorporated), and (d) conventional tillage (CT, tillage without stubble retention as the control). We applied four tillage and stubble management in monoculture treatments as inter-annual arrangement where sole wheat applied them in 2011, while sole maize applied in 2012 (Fig. 1). In the control treatment, crop straw was removed to mimic the local agricultural systems with crop straw transported to households for feeding and heating use. Also, a tillage operation (30 cm deep) the previous fall was used for weed control (applied in CT and RTS) and a pre-seeding rotary tillage (10 cm deep) was used for seedbed preparation (in no-till plots). The different tillage and stubble retention patterns were applied to the wheat strips of the wheat/maize intercropping the previous fall. In all treatments, maize stalks were removed out of the fields for animal feeding. In the 2nd year experiment, sole (or monoculture) maize and sole wheat were alternated among years (i.e. the plots grown with sole maize the previous year were planted with sole wheat the current year, and vice versa). Similarly, in the wheat–maize intercropping, the maize strips the previous year were planted with wheat the current year, and vice versa. These inter-strip rotations were designed for maximizing the intercropping benefits and minimizing monoculture disadvantages.

Supplemental irrigation was applied due to low precipitation at the testing areas (less than 150 mm annually). We employed the irrigation schedule as local farmers. All plots received an amount of 120 mm of irrigation the previous fall just before soil freezing, and then required irrigation quotas were applied to the crops during the growing season (Table 1). A hydrant pipe system was used for irrigation, and a flow meter was installed at the discharging end of the pipe to measure and record the irrigation amounts entering each plot.

Spring wheat (cv. Yong-liang 4) and maize (cv. Wu-ke 2) were relay planted in 2011 and 2012 (Table 1). Each plot was 48 m^2 (4.8 m × 10 m) in size with a 40 cm wide by 30 cm high ridge plus a 30–40 cm width walkway beside the ridges were built between two neighboring plots to eliminate potential water movement. Maize strips were mulched with plastic films at seeding, an innovative technology for boosting maize productivity in arid environments (Gan et al., 2013). Planting density was 6750,000 plants ha^{-1} for wheat and 82,500 plants ha^{-1} for maize, the same densities used for the intercropped crops and the monoculture crops. Urea (46-0-0 of N-P_2O_5-K_2O) and diammonium phosphate (18-46-0 of N-P_2O_5-K_2O) were broadcast and then incorporated to the soil prior to seeding. Sole wheat received 225 kg N ha^{-1} and 66 kg P_2O_5 ha^{-1}; sole maize at 360 kg N ha^{-1} and 158 kg P_2O_5 ha^{-1}. The two intercrops each received the same rate of fertilizers as the sole crops on a per hectare basis, i.e., the N and P rates were halved for each intercrop because each species in the intercropping occupied1/2 of the total land areas (Table 1). All N and P were applied as base fertilizers to wheat, while maize received 30% of N as base fertilizer at sowing, 60% at jointing, and the remaining 10% at grain filling. For the last two N applications, a 3-cm diameter hole (10-cm deep) was made 4–5 cm away from the maize stem, and fertilizer was applied into the hole, and the hole was compacted with soil.

2.2. *Measurement and calculation*

2.2.1. *Soil evaporation (E) and soil water content*

Micro-lysimeters were used to measure soil evaporation from the inter-rows of crops. All micro-lysimeters were constructed using polyvinyl chloride (PVC) tube with the length of 150 mm and, internal diameter of 110 mm and external diameter of 115 mm. The base of the tubes was sealed with waterproof tape. Micro-lysimeters were situated in the central rows of wheat strips and maize strips in intercropping and in the center of each monoculture plot. The lysimeters were filled with soil and placed in a larger (internal diameter 120 mm) PVC tube which was installed in the field position prior. Micro-lysimeters were weighed at 18:00 each day, and daily evaporation was calculated from the weight loss of the micro-lysimeters that was recorded using a portable balance weighing to ±0.2 g (1 g change was equivalent to 0.1053 mm soil evaporation). In each measurement, the soil evaporation value for a plot was represented by the mean value of three lysimeters' readings. In each cropping pattern, only in-growing-season (from sowing to harvesting) evaporation was measured.

Soil water content was measured at 20 days interval by using oven-drying method for the top 0–10-cm, 10–20-cm, and 20–30-cm soil layers, whereas a neutron probe (NMM503DR, USA) was used to measure soil water content from 30 to 120 cm depth by 30 cm increments. The probes were installed in the center of wheat

Table 1
Sowing and harvesting dates, fallow water supply, in growing season rainfall, irrigation quota, fertilization status, and rooting depth in sole and intercropping systems at Wuwei experimental station, northwestern China, 2011–2012.

Item	Year	Cropping pattern	Wheat	Maize
Sowing	2011	Sole or intercrops	28-March	17-April
	2012		19-March	20-April
Harvesting	2011		22-July	29-September
	2012		18-July	30-September
Fallow water supply (rainfall + irrigation)	2010	Sole or intercrops	25 + 120[b]	
	2011		18 + 120	
In growing season rainfall[a] (mm)	2011	Sole	65.8	179.1
		Intercrops	**200.6**[c]	
	2012	Sole	40.5	128.5
		Intercrops	**146.9**	
Irrigation quota (mm)	2011–2012	Sole	240	400
		Intercrops	**480**	
N fertilizer ($kg\,N\,ha^{-1}$)	2011–2012	Sole	225	360
		Intercrops	112.5	180
P fertilizer ($kg\,P_2O_5\,ha^{-1}$)	2011–2012	Sole	66	158
		Intercrops	33	79
Rooting depth (cm)	2011–2012	Sole	90–100	108–114
		Intercrops	95–100	105–110

[a] In growing season rainfall of intercropping was measured from wheat sowing to maize harvest.
[b] All plots received the same amount of water supply.
[c] Data in bold type represents the rainfall or irrigation amount for the intercropping system.

strips and maize strips for intercropping plots (the averaged value of two intercropped strips was used for an intercropping plot), whereas the probes installed in the central rows of each plot were used for monocultures. Apart from the regular measurements, soil water content was also measured before and after each irrigation.

2.2.2. Evapotranspiration (ET)

The evapotranspiration (ET) (mm) was determined using water balance method (Yang et al., 2011):

$$ET = P + I + WS_s - WS_h \tag{1}$$

where P is the effective precipitation (mm), determined by USDA soil conservation services method, I the irrigation quota (mm), WS_s and WS_h are soil water storage (mm) at the 0–120 cm depth before sowing and after harvesting. Ground water table depth is consistently below 14–18 m, and upward and downward flow was also negligible at the experimental site (Yang et al., 2011). Runoff was negligible due to small rains, and irrigation was controlled by raised ridges and walkway (with total width of 70–80 cm separation) between plots.

2.2.3. Soil respiration and carbon emission

CO_2 efflux was measured with a CFX-2 system (Soil CO_2 Flux System, CFX-2, PP System Hitchin, UK) connected with a proprietary respiration chamber. At each measurement, all crop residues and other litters on the soil surface were carefully removed. At 12 h before CO_2 readings, a hole with diameter the same as the respiration chamber size was made on the plastic film of the maize strips (which was applied prior to seeding); this was to release the stored CO_2 efflux from the plastic-covered soil. The chamber, with a sharp edging point at the bottom, was placed on the soil surface and then pushed to the depth of 2 cm. Measurements were made at three spots randomly selected in each plot, 5 readings were recorded for each spots within 3 min., and the average value of the 15 readings (5 readings at each spot × 3 spots) was used for each plot. For intercropping, measurements were taken from each strip and the averages of the two strips were used for each plot. The diurnal soil respiration was measured at 2 h interval from 8:00 am to 8:00 pm on the selected dates, started from 21 April in 2011 and 22 April in 2012, and completed by the end of September in each year.

Carbon emission ($kg\,ha^{-1}$) was estimated based on soil respiration ($g\,CO_2\,m^{-2}\,h^{-1}$) using the following equation described by Zhai et al. (2011):

$$CE = \sum \left[\frac{Rs(i+1) + Rsi}{2} \left[t(i+1) - ti \right] \times \frac{12}{44} \right] \times 24 \times 10 \tag{2}$$

where Rs was soil respiration ($g\,CO_2\,m^{-2}\,h^{-1}$) measured at 20 days interval during the growing season and post-harvest period, $i+1$ and i were the previous and the current sampling date, respectively, t was days after sowing.

2.2.4. Carbon sequestration

Net ecosystem production (NEP) represents the C flux from the atmosphere to the soil-plant system, and was calculated as follows (Iqbal et al., 2009):

$$NEP = GPP - Ra - Rs \tag{3}$$

$$NPP = GPP - Ra - Rr \tag{4}$$

Combining Eqs. (3) and (4):

$$NEP = NPP + Rr - Rs \tag{5}$$

where NPP is the net primary productivity; GPP is the gross primary productivity; Ra is the above ground respiration of the plants; Rs is the soil respiration; Rr is the root respiration of the plants. By using Eq. (5), C flux from the atmosphere to the soil-plant system was calculated by measuring the NPP, Rr and Rs . The NPP of the wheat and maize was estimated by the equation: $C\,(kg) = 0.446 \times DW(kg) - 67$, as documented by Osaki et al. (1992). The Rr was estimated using the equation: $RC = -0.66 + 0.16\ln(Rs)$, $R^2 = 0.38$, $P < 0.001$, where RC means the annual relative contribution of Rr to Rs (Bond-Lamberty et al., 2004). Carbon sequestration capacity was calculated by taking the difference between NEP and the amount of carbon in harvested crops (Iqbal et al., 2009).

2.3. Statistical analysis

Data were analyzed using the Mixed model of Statistical Analysis Software (SPSS software, 16.0, SPSS Institute Inc., USA), and treatment effects were determined using the Duncan's multiple-range test. Due to significant treatment by year interactions for most of the variables evaluated in the study, the treatment effect was assessed for each year separately. Significances were declared at the probability level of 0.05, unless otherwise stated.

3. Results

The results of the two-year study (2011 and 2012) were consistent with small variation between years. For crop yield, water use efficiency, and carbon emissions and sequestration, we compared the integrated system with the conventional farming system (i.e., the CT control). Also, we analyzed each of the three key components of the system by comparing (i) intercropping with monoculture crops, (ii) differences among the residue management options, and (iii) conventional tillage versus no-till.

3.1. *The integrated system improves soil moisture status*

The integrated system (i.e., the wheat–maize intercropping with the NTS, NTM, or RTS straw management options) conserved more soil moisture than the monoculture wheat or monoculture maize under the CT system. In 2011, the integrated system increased soil moisture by an average (mm) 8.4% before sowing, 13.1% during the wheat–maize co-growth period, 5.4% after wheat harvest, and 4.7% after maize harvest, compared to the monoculture wheat CT control (Table 2). Similarly, in 2012, the integrated system increased average soil moisture (mm) by 6.4% before sowing, 7.5% during the wheat–maize co-growth period, 11.3% after wheat harvest, and 13.7% after maize harvest, compared to the monoculture maize CT control. The improved straw management options (applied in the previous fall) not only influenced the soil moisture status at spring seeding the following year, but also the soil moisture during the entire growing season.

A close examination of the three key components of the integrated system revealed that in 2011 about 31% of the increased soil moisture during the co-growth period was attributable to the first component (i.e., the use of intercropping), 16% contributing to no-till, and the remaining 53% was attributable to straw mulching; similarly, in 2012, these three values were, respectively, 57%, 33%, and 10%. In 2011, straw mulching had a more important role than crop intensification on harvesting soil water, whereas in 2012, intercropping contributed more to the increased soil moisture than straw mulching.

Among the water harvesting approaches, no-till in combination with straw mulching (i.e., the NTM system) conserved the highest soil moisture during the wheat–maize co-growth period, which was increased by 8% in 2011 and 9% in 2012 for the wheat–maize intercropping (Table 2). Similarly, the residue retention on the soil surface increased soil moisture by 10% in 2011 and 14% in 2012 for the monoculture maize and monoculture wheat. After wheat harvesting, straw mulching with no-till increased soil moisture (mm) by 16% compared to the CT control. After maize harvesting, straw mulching with no-till increased soil moisture by an average of 8% compared to the CT control.

3.2. *The integrated system balances soil evaporation with crop yield and water use*

In the present study, soil evaporation was measured only from planting to harvesting and potential evaporation prior to planting or after harvesting was not recorded. On average, wheat was harvested 72 days earlier than the maize crops. Owing to the relay cropping of wheat and maize, the wheat–maize intercropping had a 30–46 days longer growing season than the monoculture wheat or monoculture maize. Thus, soil evaporation accumulated during the growth periods of the intercrops was higher compared to the monoculture crops (Fig. 2). Averaged across the two years, monoculture wheat evaporated 139–56 mm of water during its growth period, significantly ($P < 0.05$) less than monoculture maize at 232–248 mm or the intercrops at 250–270 mm. However, because of the different length of the growth period, these comparisons may have little biological meaning.

A valid comparison for water harvesting capability is between the four straw mulching-tillage combinations under the wheat–maize intercropping or the monoculture systems. Under the intercropping systems, no matter how the crop residue was managed to stand in the field (NTS), mulched on the soil surface (NTM), or incorporated into the soil (RTS), it greatly reduced soil evaporation (Fig. 2). Among them, no-till coupled with straw mulching on the soil surface (i.e., the NTM system) decreased soil evaporation along with E/T significantly in both 2011 (by 9% and 8%) and in 2012 (by 13% and 16%) compared to the same intercropping under the CT system (Table 2). In monoculture systems, the NTM system also reduced soil evaporation and E/T by 11% and 9% in 2011, and both 7% in 2012 compared to the CT control.

Total water consumption (mm) of the two intercrops with the NTM system was decreased ($P < 0.01$) by 4.5% in 2011 and 3.6% in 2012 as compared to the CT control (data revealed in a previous study by Hu et al., 2015). Reduced tillage with stubble incorporated in the soil (RTS) barely had a consistent influence on water consumption either in the intercropping or the monoculture, in either year. The wheat–maize intercropping had crop water consumption ranging from 736 to 771 mm in 2011, and from 670 to 695 mm in 2012; whereas sole wheat consumed 378–416 mm and sole maize 589–644 mm. However, the wheat–maize intercropping systems had an average grain yield of 15.6 t ha^{-1} in 2011, which was 23% greater than the monoculture maize and 136% greater than the monoculture wheat (data shown in the previous study). Similarly, in 2012, the wheat–maize intercropping yielded 15.2 t kg ha^{-1}, or 22% greater than the monoculture maize and 147% greater than the monoculture wheat. As a result, the integrated system had an average TUE and WUE, respectively, of 37 kg ha^{-1} mm^{-1} and 22 kg ha^{-1} mm^{-1}, much higher than each monoculture crops (Table 2). Compared to the monoculture wheat, TUE and WUE of this integrated system were respectively increased by 44% and 33% in 2011, similarly the values were 5% and 8% compared to monoculture maize in 2012. In the same cropping pattern, NTM system received the highest TUE and WUE. Compared to CT control of each cropping pattern, TUE was improved by 9%, 13% and 13% respectively under sole wheat, sole maize and wheat–maize intercropping.

3.3. *The integrated system lowers carbon emissions and enhances carbon sequestration*

In maize monoculture, soil respiration declined sharply after the peak, while in the wheat–maize intercropping and wheat monoculture, the decline was gradually and slowly, which induced a significant difference in the absolute value of soil respiration between the systems (Fig. 3). On average, wheat–maize intercropping had a mean soil respiration value of 0.8 μmol m^{-2} s^{-1}, which was 46% lower ($P < 0.01$) compared to the monoculture maize (1.6 μmol m^{-2} s^{-1}) (Table 3). In particular, soil respiration in the wheat–maize intercropping with residue retention on the soil surface (i.e., NTM treatment) was decreased by 54% compared to the CT control. Wheat–maize intercropping, consequently, decreased carbon emissions significantly compared to the monoculture crops. On average, the annual emission for intercropping was estimated to be 2411 kg C ha^{-1}, or 10% lower ($P < 0.01$) compared to maize monoculture (2525 kg C ha^{-1}) (Table 3).

Carbon sequestration can be estimated using various parameters such as net primary production (NPP, g C m^{-2} season^{-1}), net ecosystem production (NEP, g C m^{-2} season^{-1}), or carbon in har-

Table 2
Soil moisture (mm) before sowing, in co-growth period, after wheat and maize harvesting within the 0–120 cm depth, the ratio of evaporation and transpiration (E/T), and transpiration use efficiency (TUE) in sole wheat, sole maize, and wheat/maize intercropping systems in an Oasis region, in 2011 and 2012.

Treatment	Before sowing (mm)		Co-growth period[d] (mm)		After wheat/maize harvesting (mm)		E/T		TUE kg ha^{-1} mm^{-1}	
	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
Monoculture[a]										
NTS[b]	366	334	286	228	278/297	272/256	0.50	0.69	24.3	36.9
NTM	364	333	289	240	279/298	280/272	0.53	0.67	26.0	37.9
RTS	364	338	282	212	277/290	247/255	0.54	0.70	23.6	35.2
CT	344	338	262	210	274/289	241/250	0.58	0.72	23.8	33.9
Intercropping										
NTS	381	365	294	226	286/302	269/287	0.65	0.63	27.9	37.6
NTM	375	360	305	232	296/304	272/283	0.66	0.61	36.4	39.5
RTS	363	354	290	219	284/302	264/283	0.68	0.67	34.5	36.3
CT	358	357	283	212	285/298	264/264	0.71	0.73	32.6	35.7
p-value[c]	0.068	0.001	0.014	0.000	0.159/0.262	0.000/0.000	0.000	0.000	0.000	0.000
LSD (0.05)	NS	9	12	7	NS/NS	9/7	0.03	0.02	0.6	1.1

[a] Conservation practices which applied in monoculture crops were implemented in an alternative arrangement, i.e. applied in sole wheat in 2011 and then applied in maize in 2012.

[b] NTS no-till with stubble standing; NTM no-till with stubble mulching; RTS reduced tillage with stubble incorporated in the soil; CT conventional tillage without stubble retention.

[d] Data for the monoculture crops means the measurement was taken in those monoculture plots at wheat/maize intercropping co-growth period.

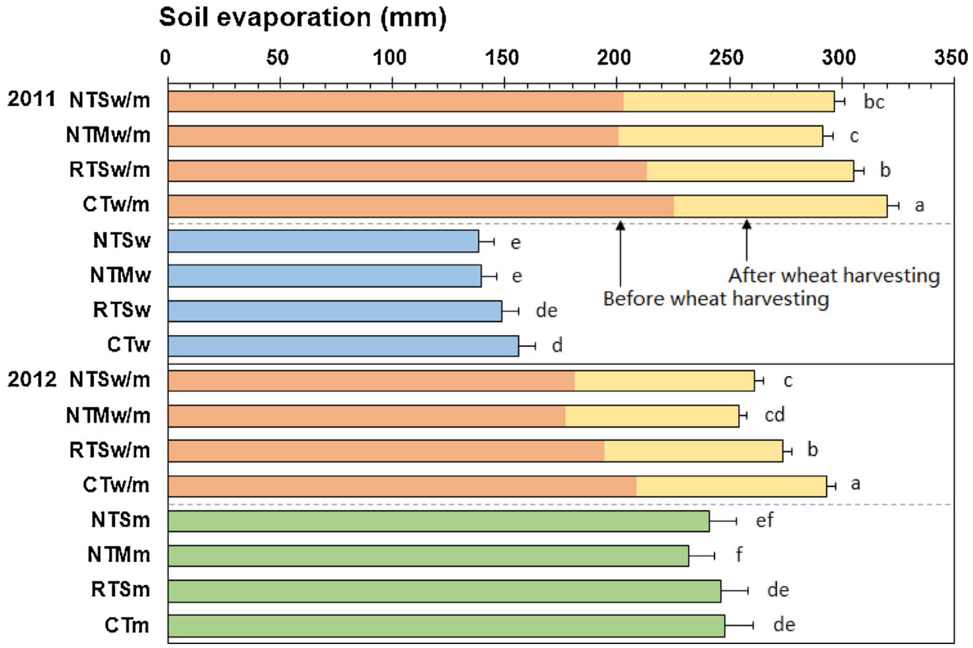

Fig. 2. Soil evaporation (E) for sole crops and intercrops during the growing season in an Oasis region, in 2011 and 2012. NTS, no-till with stubble standing; NTM, no-till with stubble mulching; RTS, reduced tillage with stubble incorporated in the soil; CT, conventional tillage without stubble retention; w, wheat; m, maize; w/m, wheat/maize intercropping. The soil evaporation of intercropping was calculated from wheat sowing to maize harvesting. Different letters indicate significant differences ($P < 0.05$) among treatments within a year and the smaller bars are standard errors.

vested crops (Harvest-C, g C m^{-2} season^{-1}). In the present study, the integrated system showed significant ($P < 0.01$) benefits in sequestering carbon (Table 3). Compared to the monoculture wheat under the CT control, the favorable system increased NPP by 112%, NEP by 171%, and harvest-C by 123%. In a less magnitude, the integrated system increased NPP by 25%, NEP by 28%, and harvest-C by 21% as compared to the monoculture maize under the CT system. However, the values of net carbon sequestration were mostly negative for all the systems evaluated in the study, which indicate that carbon loss by soil respiration was not compensated by the amount of residue returned to the soil. Maize stubble was removed out of the field for animal feed; this was the main reason of having a negative carbon input to the soil.

4. Discussion

4.1. System approaches

Increasing awareness of food security and climate change is spurring interest to policy-makers, researchers, producers, and the society as a whole, to investigate how farming systems can be improved to produce high-quality and affordable food in sufficient quantities while minimizing potentially negative impacts on the environment (Chen et al., 2011; Vermeulen et al., 2012). In heavily-populated regions or counties with the shortage of natural resources, this issue needs to be addressed urgently. The present study demonstrates that each individual farming practice has its own role in affecting crop productivity, but packaging individually-proven key farming practices together in an improved system can

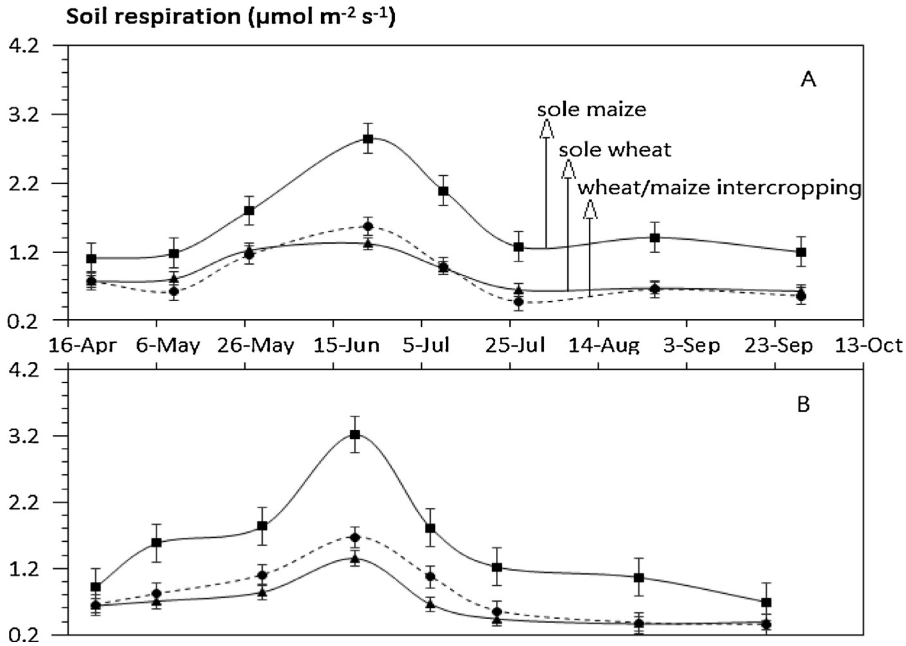

Fig. 3. Seasonal variations of soil respiration rates measured from 16 April to 13 October for sole crops and wheat–maize intercrops in 2011 (A), and 2012 (B). The smaller bars are standard errors.

Table 3
Carbon emission (CE, g C m^{-2} $season^{-1}$), averaged soil respiration (Rs, μmol m^{-2} s^{-1}), net primary production (NPP, g C m^{-2} $season^{-1}$), net ecosystem production (NEP, g C m^{-2} $season^{-1}$), carbon in harvested crops (Harvest-C, g C m^{-2} $season^{-1}$), and carbon sequestration (g C m^{-2} $season^{-1}$) in sole wheat, sole maize, and wheat/maize intercropping systems in an Oasis region.

Treatment [a]	CE	Rs	NPP	NEP	Harvest-C	C sequestration
Wheat monoculture						
NTS	112	0.94	729	669	685	−16
NTM	95	0.77	758	705	712	−7
RTS	102	0.87	705	649	662	−13
CT	110	0.93	713	653	670	−16
Maize monoculture						
NTS	261	1.63	1285	1180	1318	−137
NTM	235	1.34	1334	1239	1368	−128
RTS	250	1.56	1208	1110	1239	−129
CT	264	1.65	1205	1099	1236	−137
Wheat/maize intercropping[b]						
NTS	259	0.90	1517	1413	1499	−86
NTM	222	0.76	1545	1451	1532	−81
RTS	230	0.80	1462	1365	1446	−81
CT	254	0.91	1403	1301	1388	−88
p-value[c]	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
LSD (0.05)	1.1	0.03	32	32	34	24

[a] NTS no-till with stubble standing; NTM no-till with stubble mulching; RTS reduced tillage with stubble incorporated in the soil; CT conventional tillage without stubble retention. Wheat/maize intercropping with the values being averaged in 2011 and 2012.

[b] Data were the average of 2011 and 2012 since there was no significant treatment by year interaction.

[c] The *p*-value and the LSD (0.05) were for all the treatments in same column.

enable the increase of crop yields while concurrently reducing the impact of farming on the environment. The integrated system we developed and tested in this study has three key components, namely (a) crop intensification through strip intercropping, (b) the use of no-till or reduced tillage, and (c) crop residue management options. It was consistent across the testing years that the integration of improved farming practices using a system approach can significantly boost crop yields, harvest more soil water in the arid environments, and decrease carbon emissions from cropping.

The concept of using a system approach to increase crop productivity, while decreasing environmental impacts of farming, is supported strongly by researches conducted by others. For example, in Australia, as wheat crop yield increases from 3.5 to 5.0 tons per hectare due to the employment of improved farming systems, the carbon footprint of wheat grains was reduced by 25% (Brock et al., 2012). In the UK, the use of improved pesticide management approaches increased wheat grain yield, and at the same time, decreasing greenhouse gas emissions substantially (Berry et al., 2008). In western Canada, the use of a suite of improved farming practices enhanced soil carbon sequestration and decreased carbon emission associated with per kg of grain produced (Gan et al., 2014). In Denmark, with optimized fertilization and improved agronomic practices, winter wheat increased grain yield by 7.9% while greenhouse gas emissions during the production was reduced by 1.7 g CO_2eq MJ^{-1} of ethanol produced (Elsgaard et al., 2013).

4.2. *Effectiveness of the integrated system*

It was consistent across the testing years that the integration of wheat–maize intercropping with crop residue retention on the soil surface in combination with no-till was highly effective in increasing crop yield, improving water use efficiency, and reducing carbon emissions. The test site—the Hexi Corridor of northwest China is in an area with extremely low water availability, which has been the foremost factor threatening agricultural sustainability. We feel confident that this system-approach model will perform well in other arid and semiarid areas where water shortage is a major concern.

Among water harvesting approaches evaluated in the study, no-till in combination with straw mulching on the soil surface (i.e., the NTM system) conserved more water during the wheat–maize co-growth period so as to supply the most vigorous growth of maize in late stage. This was mainly attributed to optimized water balance. A lower value of E/T and lower total water consumption under NTM practice, either in monoculture or intercropping, indicates improved water use by crops. More water was consumed through transpiration to supporting crop growth rather than directly evaporated. Besides, the higher TUE of NTM practices demonstrated that water loss from transpiration has generated considerable production of each planting pattern. Therefore, the conserved soil moisture under straw cover could lost slowly and the available water could maintained for a longer period of time for late-sowing crop to uptake. After wheat harvesting in the maize–wheat intercropping system, straw mulching with no-till had a significant effect on the moisture storage in the maize strips which was improved by 16% compared to the control. Our results clearly show that straw mulching with no-till serve as an ideal practice for harvesting soil water in the arid environment, and that the increased soil moisture with straw mulching with no-till can partly offset water deficit occurring in intensified cropping systems.

Among the four straw mulching-tillage combination options, the crop residue standing in the field (NTS), mulched on the soil surface (NTM), or incorporated into the soil (RTS) all decreased soil evaporation along with E/T significantly. Of which, no-till in combination with straw mulching on the soil surface (i.e., the NTM system) decreased soil evaporation and E/T most in both years, and under both intercropping and monoculture systems. Our results clearly demonstrate that no-till with straw mulching on the soil surface in combination with intensified intercropping can improve the capacity of soil water harvesting and optimization of water balance in arid environments.

Another important aspect in the evaluation of the feasibility of the integrated system is crop water consumption and water use efficiency. Yield advantage of intercropping system has been proved in many studies (Li et al., 2001; Yang et al., 2011; Fan et al., 2012; Chai et al., 2013). Where, the sub-dominant crop, e.g. wheat in this study, had severe competition to maize in order to meet the stimulated growth (Li et al., 2001). While maize could receive a valid complementary growth after early-sowing crop was harvested (Li et al., 1999). Therefore, competition and facilitation both enhanced area-based productivity of each component crop than grown alone (Li et al., 2001). With combination of no-till and stubble retention, the integrated system achieved beneficial yield response through: (i) optimized water balance in co-growth period allowing more water used for transpiration to supporting wheat growth; and (ii) conserved more water to meet the vigorous maize complementary growth. The two years of results were consistent that although the intensified wheat–maize intercropping systems used more water than the monoculture crops, the intercropping system significantly increased crop yield (by 22–147%) and improved water use efficiency (by 14–37%) compared to the monoculture crops. Our study provides strong encouragement that the adaptation of the intensified, well-managed intercropping system will alleviate the water shortage issue in arid and semiarid areas while meeting the ever-growing demands for grains.

Wheat–maize intercropping decreased CO_2 efflux significantly compared to the monoculture crops, where CO_2 efflux was directly related to soil respiration. The integrated system was shown to decrease carbon emissions by decreasing soil respiration and limiting CO_2 efflux effectively; this suggests that the adoption of integrated farming models can significantly reduce potentially negative impacts of farming on the environment. To meet the global carbon cycle and carbon budget, developing low-carbon agriculture systems to store as much C as possible in soils is considered an urgent issue in the 21 century (Fedoroff et al., 2010). A key strategy in reducing carbon emission from agricultural soils is to adopt improved farming practices in crop production (Gan et al., 2011). The present study clearly shows that wheat–maize intercropping with crop residue retention in combination with no-till that form the integrated system is an effective cropping system. It can be employed as a sustainable cropping model for increasing the productivity of the agricultural systems while contributing to the mitigation of global climate change. For broader use of this system-approach model in the future, long-term estimation and more comprehensive ‘Life cycle assessment’ (Cao et al., 2014) or ‘carbon footprint determination’ (Gan et al., 2014) may be needed in order to evaluate the systematic effects.

5. Conclusions

The integrated system performed successfully in the Hexi Corridor of northwestern China, a typical Oasis agricultural region with annual precipitation less than 150 mm and evaporation greater than 2400 mm. The system approach helped conserve more soil moisture throughout the growing season (by 7.4–10.3%), increased net primary production by 68% and net ecosystem production by 72%, increased grain yields by 21 to 144%, and enhanced water use efficiency by 26%. An added feature of this system approach is that carbon emission was decreased by 16% compared to the conventional sole maize. Success at the study site with extremely low ratio of precipitation to evaporation provides strong encouragement that this model can be employed in other arid and semiarid regions with high confidence. Estimate of carbon emissions with the use of soil respiration may need to be refined. More research on soil respiration and its relation to soil temperature and moisture, crop growth characteristics, and the other sources of carbon emissions is required to further evaluate the effect of this integrated farming system under various growing conditions.

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References

Alletto, L., Coquet, Y., Benoit, P., Heddadj, D., Barriuso, E., 2010. Tillage management effects on pesticide fate in soils. A review. Agron. Sustain. Dev. 30, 367–400.

Bainard, L.D., Bainard, J.D., Hamel, C., Gan, Y., 2014. Spatial and temporal structuring of arbuscular mycorrhizal communities is differentially influenced by abiotic factors and host crop in a semi-arid prairie agroecosystem. FEMS Microbiol. Ecol. 88, 333–344.

Berry, P.M., Kindred, D.R., Paveley, N.D., 2008. Quantifying the effects of fungicides and disease resistance on greenhouse gas emissions associated with wheat production. Plant Pathol. 57, 1000–1008.

Boeckx, P., Van Nieuland, K., Van Cleemput, O., 2011. Short-term effect of tillage intensity on N_2O and CO_2 emissions. Agron. Sustain. Dev. 31, 453–461.

Bond-Lamberty, B., Wang, C., Gower, S.T., 2004. A global relationship between the heterotrophic and autotrophic components of soil respiration? Global Change Biol. 10, 1756–1766.

Brock, P., Madden, P., Schwenke, G., Herridge, D., 2012. Greenhouse gas emissions profile for 1 tonne of wheat produced in Central Zone (East) New South Wales: a life cycle assessment approach. Crop Pasture Sci. 63, 319–329.

Brown, L.R., Halweil, B., 1998. China's water shortage could shake world food security. World Watch 11, 10–16.

Burney, J.A., Davis, S.J., Lobell, D.B., 2010. Greenhouse gas mitigation by agricultural intensification. Proc. Natl. Acad. Sci. U. S. A. 107, 12052–12057.

Cao, L.M., Li, M.B., Wang, X.Q., Zhao, Z.P., Pan, X.H., 2014. Life cycle assessment of carbon footprint for rice production in shanghai. Shengtai Xuebao/Acta Ecol. Sin. 34, 491–499.

Chai, Q., Qin, A.Z., Gan, Y.T., Yu, A.Z., 2013. Higher yield and lower carbon emission by intercropping maize with rape, pea, and wheat in arid irrigation areas. Agron. Sustain. Dev. 34, 535–543.

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R., Chhetri, N., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change 4, 287–291.

Chen, X.P., Cui, Z.L., Vitousek, P.M., Cassman, K.G., Matson, P.A., Bai, J.S., Meng, Q.F., Hou, P., Yue, S.C., Römheld, V., Zhang, F.S., 2011. Integrated soil-crop system management for food security. Proc. Natl. Acad. Sci. U. S. A. 108, 6399–6404.

Chen, H.W., Qin, A.Z., Chai, Q., Gan, T., Liu, Z.D., 2014. Quantification of soil water competition and compensation using soil water differences between strips of intercropping. Agric. Res. 3, 321–330.

Elder, J.W., Lal, R., 2008. Tillage effects on gaseous emissions from an intensively farmed organic soil in North Central Ohio. Soil Till. Res. 98, 45–55.

Elliott, J.A., Efetha, A.A., 1999. Influence of tillage and cropping system on soil organic matter, structure and infiltration in a rolling landscape. Can. J. Soil Sci. 79, 457–463.

Elsgaard, L., Olesen, J.E., Hermansen, J.E., Kristensen, I.T., Børgesen, C.D., 2013. Regional greenhouse gas emissions from cultivation of winter wheat and winter rapeseed for biofuels in Denmark. Acta Agric. Scand. Sect. B: Soil Plant Sci. 63, 219–230.

Fan, Z.L., Chai, Q., Huang, G.B., Yu, A.Z., Huang, P., Yang, C.H., Tao, Z.Q., Liu, H.L., 2012. Yield and water consumption characteristics of wheat/maize intercropping with reduced tillage in an Oasis region. Eur. J. Agron. 25121, 1–7.

FAO/UNESCO, 1988. Soil map of the world: revised legend/prepared by the Food and Agriculture Organization of the United Nations. UNESCO.

Fedoroff, N.V., Battisti, D.S., Beachy, R.N., Cooper, P.J.M., Fischhoff, D.A., Hodges, C.N., Knauf, V.C., Lobell, D., Mazur, B.J., Molden, D., Reynolds, M.P., Ronald, P.C., Rosegrant, M.W., Sanchez, P.A., Vonshak, A., Zhu, J.K., 2010. Radically rethinking agriculture for the 21st century. Science 327, 833–834.

Fernández-Aparicio, M., Amri, M., Kharrat, M., Rubiales, D., 2010. Intercropping reduces *Mycosphaerella pinodes* severity and delays upward progress on the pea plant. Crop Prot. 29, 744–750.

Fuentes, M., Hidalgo, C., Etchevers, J., De León, F., Guerrero, A., Dendooven, L., Verhulst, N., Govaerts, B., 2011. Conservation agriculture, increased organic carbon in the top-soil macro-aggregates and reduced soil CO_2 emissions. Plant Soil 355, 183–197.

Gan, Y., Liang, C., Chai, Q., Lemke, R.L., Campbell, C.A., Zentner, R.P., 2014. Improving farming practices reduce the carbon footprint of spring wheat production. Nat. Commun. 5, 5012, http://dx.doi.org/10.1038/ncomms6012.

Gan, Y.T., Liang, C., Wang, X.Y., McConkey, B., 2011. Lowering carbon footprint of durum wheat by diversifying cropping systems. Field Crops Res. 122, 199–206.

Gan, Y.T., Siddique, K.H.M., Turner, N.C., Li, X.G., Niu, J.Y., Yang, C., Liu, L.P., Chai, Q., 2013. Chapter seven—ridge-furrow mulching systems-an innovative technique for boosting crop productivity in semiarid rain-fed environments. In: Donald, L.S. (Ed.), Advances in Agronomy. Academic Press, pp. 429–476.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J., Godfray, H.C.J., 2013. Sustainable intensification in agriculture: premises and policies. Science 341, 33–34.

Ghimire, R., Adhikari, K.R., Chen, Z.-S., Shah, S.C., Dahal, K.R., 2012. Soil organic carbon sequestration as affected by tillage, crop residue, and nitrogen application in rice-wheat rotation system. Paddy Water Environ. 10, 95–102.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–818.

Govaerts, B., Sayre, K.D., Ceballos-Ramirez, J.M., Luna-Guido, M.L., Limon-Ortega, A., Deckers, J., Dendooven, L., 2006. Conventionally tilled and permanent raised beds with different crop residue management effects on soil C and N dynamics. Plant Soil 280, 143–155.

Hendrix, P.F., Han, C.R., Groffman, P.M., 1988. Soil respiration in conventional and no-tillage agroecosystems under different winter cover crop rotations. Soil Till. Res. 12, 135–148.

Hu, F.L., Chai, Q., Yu, A.Z., Yin, W., Cui, H.Y., Gan, Y.T., 2015. Less carbon emissions of wheat–maize intercropping under reduced tillage in arid areas. Agron. Sustain. Dev 35, 701–711.

Iqbal, J., Hua, R., Lin, S., Hatano, R., Feng, M., Lu, L., Ahamadou, B., Du, L., 2009. CO_2 emission in a subtropical red paddy soil (Ultisol) as affected by straw and N-fertilizer applications a case study in Southern China. Agric. Ecosyst. Environ. 131, 292–302.

Kendy, E., Wang, J., Molden, D.J., Zheng, C., Liu, C., Steenhuis, T.S., 2007. Can urbanization solve inter-sector water conflicts? Insight from a case study in Hebei Province, North China Plain. Water Policy 9, 75–93.

Kirkegaard, J.A., Conyers, M.K., Hunt, J.R., Kirkby, C.A., Watt, M., Rebetzke, G.J., 2014a. Sense and nonsense in conservation agriculture: principles, pragmatism and productivity in Australian mixed farming systems. Agric. Ecosyst. Environ. 187, 133–145.

Kirkegaard, J.A., Hunt,J, R., McBeath, T.M., Lilley, J.M., Moore, A., Verburg, K., Robertson, M., Oliver, Y., Ward, P.R., Milroy, S., Whitbread, A.M., 2014b. Improving water productivity in the Australian Grains industry—a nationally coordinated approach. Crop Pasture Sci. 65, 583–601.

Kumar, K., Goh, K.M., 2002. Management practices of antecedent leguminous and non-leguminous crop residues in relation to winter wheat yields, nitrogen uptake, soil nitrogen mineralization and simple nitrogen balance. Eur. J. Agron. 16, 295–308.

Li, H., Qiu, J., Wang, L., Tang, H., Li, C., Van Ranst, E., 2010. Modelling impacts of alternative farming management practices on greenhouse gas emissions from a winter wheat–maize rotation system in China. Agric. Ecosyst. Environ. 135, 24–33.

Li, L., Sun, J.H., Zhang, F.S., Li, X.L., Yang, S.C., Rengel, Z., 2001. Wheat/maize or wheat/soybean strip intercropping I. Yield advantage and interspecific interrations on nutrients. Field Crops Res. 71, 123–137.

Li, L., Yang, S.C., Li, X.L., Zhang, F.S., Christie, P., 1999. Interspecific complementary and competitive interactions between intercropped maize and faba bean. Plant Soil 212, 105–114.

Lichter, K., Govaerts, B., Six, J., Sayre, K.D., Deckers, J., Dendooven, L., 2008. Aggregation and C and N contents of soil organic matter fractions in a permanent raised-bed planting system in the Highlands of Central Mexico. Plant Soil 305, 237–252.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257.

Munz, S., Graeff–Hönninger, S., Lizaso, J.I., Chen, Q., Claupein, W., 2014. Modeling light availability for a subordinate crop within a strip-intercropping system. Field Crops Res. 155, 77–89.

Osaki, M., Shinano, T., Tadano, T., 1992. Carbon-nitrogen interaction in field crop production. Soil Sci. Plant Nutr. 38, 553–564.

Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L., Grace, Peter, 2014. Conservation agriculture and ecosystem services: an overview. Agric. Ecosyst. Environ. 187, 87–105.

Patiño-Zúñiga, L., Ceja-Navarro, J.A., Govaerts, B., Luna-Guido, M., Sayre, K.D., Dendooven, L., 2009. The effect of different tillage and residue management practices on soil characteristics, inorganic N dynamics and emissions of N_2O, CO_2 and CH_4 in the central highlands of Mexico: a laboratory study. Plant Soil 314, 231–241.

Paul, B.K., Vanlauwe, B., Ayuke, F., Gassner, A., Hoogmoed, M., Hurisso, T.T., Koala, S., Lelei, D., Ndabamenye, T., Six, J., Pulleman, M.M., 2013. Medium-term impactof tillage and residue management on soil aggregate stabilitysoil carbon, andcrop productivity. Agric. Ecosyst. Environ. 164, 14–22.

Qin, A.Z., Huang, G.B., Chai, Q., Yu, A.Z., Huang, P., 2013a. Grain yield and soil respiratory response to intercropping systems on arid land. Field Crops Res. 144, 1–10.

Qin, J., He, H., Luo, S., Li, H., 2013b. Effects of rice-water chestnut intercropping on rice sheath blight and rice blast diseases. Crop Prot. 43, 89–93.

Shalizi, Z., 2006. Addressing China's Growing Water Shortages and Associated Social and Environmental Consequences. World Bank, Washington D.C., USA.

Snyder, C.S., Bruulsema, T.W., Jensen, T.L., Fixen, P.E., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric. Ecosyst. Environ. 133, 247–266.

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. U. S. A. 108, 20260–20264.

Vermeulen, S.J., Aggarwal, P.K., Ainslie, A., Angelone, C., Campbell, B.M., Challinor, A.J., Hansen, J.W., Ingram, J.S.I., Jarvis, A., Kristjanson, P., Lau, C., Nelson, G.C., Thornton, P.K., Wollenberg, E., 2012. Options for support to agriculture and food security under climate change. Environ. Sci. Policy 15, 136–144.

Wani, M.H., Baba, S.H., Wani, S.A., 2008. Land degradation in cold arid eco-region of Ladakh—extent implications and strategies for sustainable land management. Indian J. Agric. Econ. 63, 448–455.

West, P.C., Gibbs, H.K., Monfreda, C., Wagner, J., Barford, C.C., Carpenter, S.R., Foley, J.A., 2010. Trading carbon for food: global comparison of carbon stocks vs. crop yields on agricultural land. Proc. Natl. Acad. Sci. U. S. A. 107, 19645–19648.

Yang, C.H., Huang, G.B., Chai, Q., Luo, Z.X., 2011. Water use and yield of wheat/maize intercropping under alternate irrigation in the oasis field of northwest China. Field Crops Res. 124, 426–432.

Yang, F., Huang, S., Gao, R., Liu, W., Yong, T., Wang, X., Wu, X., Yang, W., 2014. Growth of soybean seedlings in relay strip intercropping systems in relation to light quantity and red: Far-red ratio. Field Crops Res. 155, 245–253.

Zhai, L.M., Liu, H.B., Zhang, J.Z., Huang, J., Wang, B.R., 2011. Long-term application of organic manure and mineral fertilizer on N_2O and CO_2 emissions in a red soil from cultivated maize–wheat rotation in China. J. Integr. Agric. 10, 1748–1757.