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ORIGINAL PAPER

Integrated double mulching practices optimizes soil temperature and improves soil water utilization in arid environments

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Abstract Water shortage threatens agricultural sustainability in many arid and semiarid areas of the world. It is unknown whether improved water conservation practices can be developed to alleviate this issue while increasing crop productivity. In this study, we developed a "double mulching" system, i.e., plastic film coupled with straw mulch, integrated together with intensified strip intercropping. We determined (i) the responses of soil evaporation and moisture conservation to the integrated double mulching system and (ii) the change of soil temperature during key plant growth stages under the integrated systems. Experiments were carried out in northwest China in 2009 to 2011. Results show that wheat-maize strip intercropping in combination with plastic film and straw covering on the soil surface increased soil moisture (mm) by an average of 3.8 % before sowing, 5.3 % during the wheat and maize co-growth period, 4.4 % after wheat harvest, and 4.9 % after maize harvest, compared to conventional practice (control). The double mulching decreased total evapotranspiration of the two intercrops by an average of 4.6 % ($P < 0.05$), compared to control. An added feature was that the double mulching system decreased soil temperature in the top 10-cm depth by 1.26 to 1.31 °C in the strips of the cool-season wheat, and by 1.31 to 1.51 °C in the strips of the warm-season maize through the 2 years. Soil temperature of maize strips higher as 1.25 to 1.94 °C than that of wheat strips in the top 10-cm soil depth under intercropping with the double mulching system; especially higher as 1.58 to 2.11 °C under intercropping with the conventional tillage; this allows the two intercrops to grow in a well "collaborative" status under the double mulching system during their co-growth period. The improvement of soil moisture and the optimization of soil temperature for the two intercrops allow us to conclude that wheat-maize intensification with the double mulching system can be used as an effective farming model in alleviating water shortage issues experiencing in water shortage areas.

Keywords Intercropping · Reduced tillage · Straw covering · Plastic mulch · Drought stress · Evapotranspiration · Oasis region

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Introduction

Water is the most abundant compound on Earth, and yet, water deficit is a single most important factor affecting all the lives on the planet. In many areas and regions, water shortages threaten economic development and environmental sustainability. It is estimated that nearly 800 million people on the planet lack access to safe drinking water and 2.5 billion have no proper sanitation (Schiermeier 2014). The Hexi Corridor of northwestern China is one of the areas facing serious water problems. In this region, annual precipitation is between 50 and 150 mm, with more than 60 % falling during the monsoon months of July to September, while annual evaporation is between 2100 and 2400 mm. Shortages of water resources

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and uneven distribution of available water across regions restrict agricultural development (Chai et al. 2014a).

Plastic film mulch has been used to conserve soil water and reduce soil evaporation and increasing topsoil temperature in early spring when soil is cold in many arid and semiarid areas, especially where irrigation is not available (Liu et al. 2001). Also, plastic mulching has been shown to improve the infiltration of rainwater into the soil (Ramakrishna et al. 2006), enhance soil water retention (Ghosh et al. 2006), and accelerate crop growth and increase crop yields (Tiwari et al. 2003; Xie et al. 2005; Zhou et al. 2009). However, plastic film commercially available for soil mulching is non-biodegradable. The widespread use of plastic over the years has potential to damage the sustainability of agro-ecosystems and cause serious soil and environmental pollution (Briassoulis 2006; Scarascia-Mugnozza et al. 2006). Also, high soil temperature in the root zone at the blossom and grain filling stage of crops grown with plastic mulch can lead to crop root and leaf senescence, and decrease crop yield (Bu et al. 2013). Therefore, the development of environmentally friendly mulching practices is needed in order to improve soil moisture conservation with minimized negative impacts on the environment.

Crop straw mulch is one of the alternatives to plastic mulch. Straw mulch in combination with no-till or reduced tillage has become a popular conservation practice in the world. It is increasingly used for crop production due to their environmental advantages over moldboard plow (Al-Kaisi and Yin 2005). In northwestern China, this technology has been introduced, tested, and extended since the 1970s (Xie et al. 2007), and it has been considered as an important tool for ecological protection and sustainable development (Li et al. 2011). Studies have shown that conservation tillage can effectively keep soil moisture, reduce water and wind erosion, decrease soil temperature and water consumption, and increase crop yields (Li et al. 2011; Monneveux et al. 2006; Huang et al. 2008). Crop residue is an important component in the package of conservation practices that leave about 30 % of crop residues on the soil surface at planting (Jourdain et al. 2001). These crop residues form a mulch cover that protects the soil against runoff and erosion, and increases the capacity of the soil to intercept rainfall. Also, crop residues left on the soil surface helps improve soil roughness, soil surface porosity, and hydraulic conductivity. An added value is that straw mulching reduces temperature extremes (Shinner et al. 1994). However, low soil temperature caused by crop residues can delay seedling emergence, especially when soil temperature is low in spring. In some cases, delayed seedling emergence may decreases crop yield (Chen et al. 2011). Therefore, the practice of straw mulching has also been questioned by farmers whether or not this practice can be more sustainable as compared to plastic mulching.

Wheat (*Triticum aestivum*) is a cool-season crop while maize (*Zea mays*) is a thermophilic crop. In arid northwestern China, the two crops are usually "intercropped" together in an intensified cropping system (Qin et al. 2013a). Cool-season spring wheat is planted in strips soon after spring thaw to capture the early part of the growing season, and then warm-season maize is planted in alternate strips in the same field accompanying the growing wheat plants (Fig. 1). After wheat harvest, maize plants continue their growth until freeze-up. This intercropping system allows the production of two crops within a single season in areas where one crop after another has not been possible due to limited frost-free days. However, this intensified intercropping system typically uses substantially more water than monoculture crops. An important question is, can we develop an advanced mulching system that allows maintain and increase crop productivity while minimizing the use of soil water? Based on many years of experimentation on the regulation mechanisms for soil temperature and moisture, we propose a "double mulching" system in which plastic film mulch is integrated together with crop straw mulch in the wheat-maize intercropping system. The central hypothesis of this double mulching technique is that both plastic film and straw mulch are applied to the maize strips to balance and optimize soil temperatures for both the thermophilic maize and the cool-season wheat crops. We further propose that heat intercepted on the soil surface can be transferred from maize strips to wheat strips in the mid to late part of the growing season to provide a heat "buffering effect" between the two crop strips. Consequently, the integration of plastic film with straw mulch will significantly improve microenvironments, thus increasing crop yields and resource use efficiency.

If this integrated double mulching system works well at this testing site, a typical Oasis agricultural region with annual evaporation of about 2400 mm and annual precipitation less than 150 mm (Chai et al. 2014b), then this system could be employed in the other arid and semiarid regions of the world. In testing the hypothesis, we determined (a) the responses of soil evaporation and moisture conservation to the integrated double mulching system by determining soil evaporation (E), evapotranspiration (ET), and the E/ET ratio, and (ii) the change of soil temperature during key plant growth stages under the integrated systems.

Materials and methods

Experimental site

Field experiments were conducted at the Wuwei experimental station (37° 96′ N, 102° 64′ E) of Gansu Agricultural University, in 2009–2011 (a preparatory experiment was laid out in 2009 to generate different wheat stubble fields for the implementation of the treatments in 2010–2011). The experimental area, located in the eastern part of Hexi Corridor of

Fig. 1 Wheat-maize intercropping system tested at Wuwei experimental station, China, with **a** the wheat jointing stage/maize seedling stage, **b** wheat heading stage/maize jointing stage, at their co-growth period, **c** wheat straw of 25 cm high that was chopped and evenly spread on the soil surface, and **d** wheat straw removed off the field, at wheat harvesting

northwestern China, is a typical temperate arid zone of the continent, with average annual sunshine duration higher than 2945 h, annual mean air temperature 7.2 °C, accumulated air temperature above 10 °C higher than 2985 °C, and the frost-free period of 155 days. Mean annual precipitation is below 150 mm, and potential evaporation 2400 mm. The soil at the experimental site is classified as a desert soil containing a large amount of calcareous particles. During the two study years, rainfall was 122.8 mm in 2010 and 201.4 mm in 2011 throughout the whole year, which in the wheat growing season (1 March–31 July) was 58.8 mm in 2010 and 65.8 mm in 2011; the maize growing season (1 April–30 September) rainfall was 94.7 mm in 2010 and 179.1 mm in 2011. It should be pointed out that rainfall concentrated in late July to October; therefore, it is very urgent for restraining the invalid evaporation after wheat harvest in Hexi Corridor of northwestern China.

Experimental design

In the study, we integrated two components together in alternative cropping systems: (i) crop intensification with wheat-maize intercropping and (ii) double mulching with plastic film and crop straw (i.e., both plastic film and straw were used to cover the maize strips). Plastic film mulched with colorless plastic film (polyethylene film 0.008-mm thick, made in Lanzhou Green Garden Corporation of China, Lanzhou) of 80-cm wide, and it was laid out by hand over the plot where the width of plastic film covering on the crop straw surface was 60 cm. Moreover, three approaches were implemented for water conservation and soil temperature optimization; they were (i) no-till with straw covering (i.e., NTS), where no-till was combined with wheat straw of 25 cm high that was chopped and evenly spread on the soil surface at wheat harvesting the previous fall; (ii) reduced tillage with straw incorporation (i.e., TIS), where 25-cm high of wheat straw was incorporated into the soil through tillage at wheat harvesting the previous fall; and (iii) conventional tillage (i.e., CT, control), where conventional deep plowing was applied to the plot with straw removed off the field (Fig. 1). These three straw mulching approaches were applied to the wheat-maize intercropping systems (Table 1), with three replicates in a total of nine plots. In late October to early November, wheat strips were managed as described earlier, and maize strips were deep plowed and raked. In the next spring, first, fertilizing, harrowing, smoothing, and compacting at the maize-preceded strips were done; then, a wheat crop was planted on the maize-preceded strips by strip rotary tillage wheat seeder; meanwhile, plastic film covering on the wheat straw surface in the wheat-preceded strips, and maize planted on the wheat-preceded strips by dibbler. Wheat strips were rotated with maize strips in alternate years (Table 1); this was to provide the crops with an "intra-field strip rotation" to avoid potential weakness or problems that may occur with continuous cultivation. Also, the intra-field strip rotation may help balance soil nutrients required by the two different crops in the alternate years.

Spring wheat (cv. *Yong-liang 4*, a popularly-grown cultivar) was planted on 20 March in 2010 and 28 March in 2011; maize (cv. *Wu-ke 2*, a popular-grown hybrid) was planted on

Table 1 The detailed description of treatments in 2010 and 2011

Treatment abbreviation	Description of tillage and straw management	Inter-strips rotation[a]		
		Year 1	Year 2	Year 3
NTS	No-till with 25 cm wheat straw covering on the soil surface	Wheat	Maize	Wheat
		Maize	Wheat	Maize
TIS	Reduced tillage with 25 cm wheat straw incorporated into the soil	Wheat	Maize	Wheat
		Maize	Wheat	Maize
CT (control)	Conventional tillage with no straw covering	Wheat	Maize	Wheat
		Maize	Wheat	Maize

[a] A preparatory experiment was conducted in 2009 to provide various wheat straw management options for the treatments to be implemented in 2010 and 2011

22 April in 2010 and on 17 April in 2011. Each plot was 48 m^2 (10 m × 4.8 m) with a 0.5-m wide by 0.3-m high ridge built between two neighboring plots to eliminate potential movement of irrigation water. Wheat and maize crops were alternated in sets of 160-cm-wide strips. Each wheat strip (80-cm wide) consisted of six rows of wheat plants spaced at 12 cm between rows, and maize strip (80-cm wide) had two rows of maize plants with 40-cm row spacing (Fig. 2). Planting density was 3,750,000 plants ha^{-1} for wheat and 52,500 plants ha^{-1} for maize. 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 incorporated into the soil at sowing. The N rates to wheat and maize were 113 and 190 kg ha^{-1}; P rates were 75 and 143 kg ha^{-1}, respectively. All N and P were applied as base fertilizers for wheat, while for maize crops, 30 % of N was applied at sowing, 60 % top-dressed at jointing, and the remaining 10 % top-dressed at grain filling.

Due to low precipitation, irrigation was applied to the crops according to the recommendation for optimizing crop production in the local areas (Chai et al. 2014b). All plots received an amount of 120 mm of irrigation the previous winter just before soil freezing, and then various irrigation quotas were applied at the different growth stages the current year. A hydrant pipe system was used for the irrigation, and a flow meter was

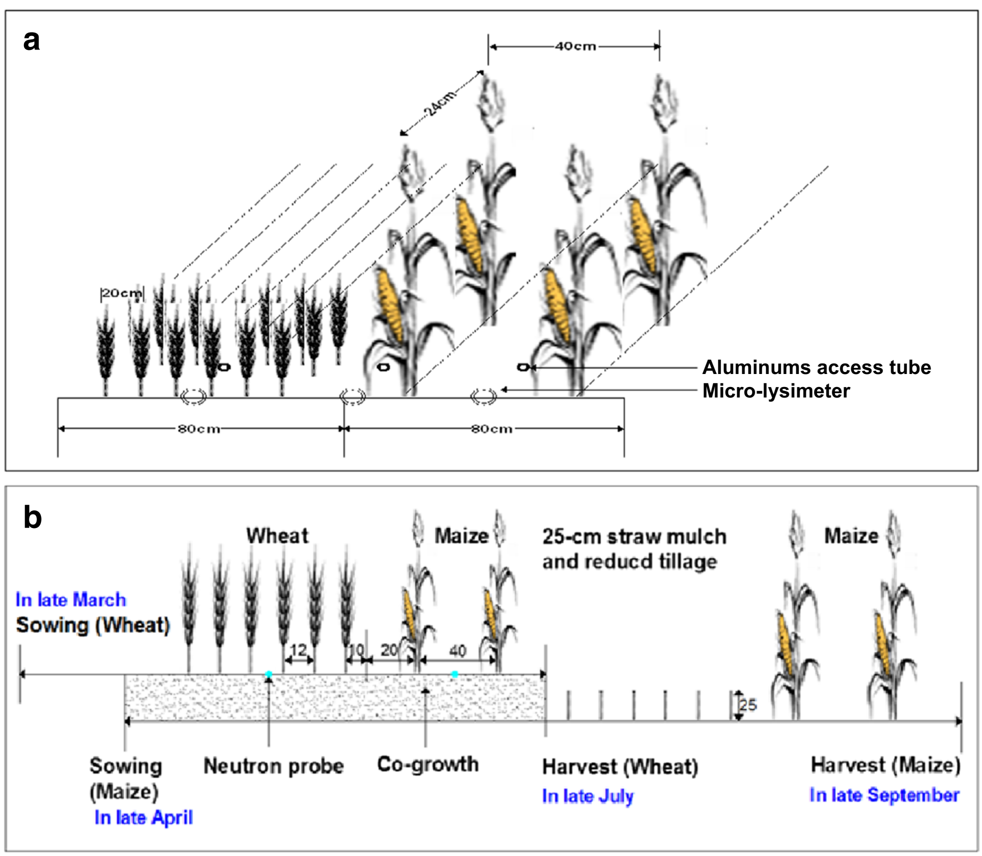

Fig 2 The spatial arrangement (**a**) and temporal arrangement (**b**) in wheat-maize intercropping, and the field locations where soil moisture and evaporation were measured in each plot

installed at discharging end of the pipe to record the irrigation amounts entering each plot.

Data collection

Soil temperature

Soil temperature in each plot was measured at an interval of 3 days from sowing to harvesting. At each measurement, two readings were taken in each of the wheat and maize strips, and the average value of two strips represents the intercropping plot. Soil temperatures in the 5-, 10-, 15-, 20-, and 25-cm soil depths were measured using curved pipe geothermometer at 8, 14, and 18 o'clock on the measurement day.

Soil water content

Soil water content (%) in each plot was measured at an interval of 20 days during the entire growing season. At each measurement, two readings were taken from each of the wheat and maize strips in the intercrop plots. Water content in the 0 to 10, 10 to 20, and 20 to 30 cm depths were measured using oven-drying method; soil was taken out by soil drill, and filled into aluminum box, first, weighing the aluminum box and wet soil (W_1) by electronic balance, then continuing to the drying of 12 h in the constant temperature of 105 °C, until constant weight, weighing the dry soil and aluminum box (W_2) by electronic balance, next, weighing the aluminum box (W_3) by electronic balance, finally, calculating soil water content using the equation as follows:

$$\theta\% = \frac{W_1 - W_2}{W_2 - W_3}$$

where θ is the soil water content; W_1 is the weight of the aluminum box and wet soil, W_2 is the weight of dry soil and aluminum box, and W_3 is the weight of aluminum box.

A neutron probe (NMM503DR, CA, USA) was used to measure soil water contents in the 30 to 50, 50 to 80, and 80 to 110 cm soil depths. The probes were installed in wheat and maize strips in the intercropping plot, and between the two central rows in the monoculture plots. The average value from the maize and wheat strips was used for the intercropping plot. Soil water content was also measured prior to and after each irrigation, before sowing, and after harvest.

Standard curves of soil water content were established using the numerical method as follows:

$$\theta\% = \left(0.3308 \times \frac{R}{R_0} + 0.0319\right) \times 100\% \quad r = 0.986$$

where θ is the soil water content, 0.3308 is the coefficient of 1 ° term, R is the actual numerical readings in the various soil depths at various crop stages measured by neutron probe, R_0 is the basic numerical readings of the neutron probe, 0.0319 is constant term, and r is the correlation coefficient. The linear regression was used to determine the relationship between the numerical readings of neutron probes and soil water content.

Soil evaporation

Micro-lysimeters were used to measure soil evaporation from the inter-rows of crops, a method similar to that used by other researchers (Plauborg 1995). All micro-lysimeters were constructed using polyvinyl chloride (PVC) tubes with the length of 150 mm, 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, maize, and between wheat and maize strips. Micro-lysimeter was filled with soil and placed into a larger (internal diameter 120 mm) PVC tube which was installed in the field position prior. Micro-lysimeters were weighed at 18 o'clock each day, and daily evaporation was recorded and calculated from the weight loss of the micro-lysimeters. The weight loss of the micro-lysimeters was the value between the weights of the micro-lysimeters last time minus that of next time. Weight loss was recorded at the plot site using a portable balance that weighed to ±0.2 g (1 g change was equivalent to 0.1053-mm of soil evaporation). Soil evaporation was measured from sowing to harvesting in each plot. At each measurement, two readings were taken in each of the wheat and maize strips, and the average of the two strips was used for the intercropping plot.

Evapotranspiration

Evapotranspiration was determined using the equation as follows (Chai et al. 2014a):

$$\mathrm{ET} = P_C + I + U - R - \mathrm{Dw} - \Delta S$$

Where P_c is the effective precipitation (mm), determined by the USDA soil conservation services method (Kuo et al. 2006), I is the irrigation quota (mm), U is the upward capillary flow from the root zone (mm), R is the runoff (mm), Dw is the downward drainage out the root zone (mm), and ΔS is the change of soil water stored in the 0–120 cm layer (mm). The upward and downward flows were measured previously at a nearby field, and these two items have been found to be negligible in this semiarid area (Jin et al. 2007; Xie et al. 2005). Runoff was also negligible due to small rains, and irrigation was controlled by raised ridges between plots. Therefore, the reduced equation is as follows:

$$\mathrm{ET} = P_C + I - \Delta \mathrm{S}$$

Statistic analysis

Data were analyzed using the mixed effect of the SPSS statistical analysis software (SPSS software, 17.0, SPSS Inst. Ltd., USA) with the treatment as the fixed effect and replicate as random effect. Due to significant year by treatment interactions for most of the variables evaluated in the study, the treatment effect was assessed separately for each year. All statistical significances were declared at the probability level of 0.05.

Results

Optimize soil temperature

Soil temperature in different periods of the day

Soil temperatures at the 25-cm soil depth were recorded for the wheat-maize intercropping under different mulching treatments (Fig. 3). At 8 and 18 o'clock, soil temperature of NTS was significantly greater than that of TIS or control. However, at 14 o'clock, soil temperature of NTS was significantly lower than that of control. At 8 o'clock, soil temperature in the NTS field was 0.78 °C greater than TIS and 1.27 °C greater than control in 2010 (Fig. 3x); 0.73 and 1.35 °C greater, respectively, in 2011 (Fig. 3y); at 18 o'clock, soil temperature in the NTS field was 0.94 and 1.17 °C greater than TIS and control, respectively, in 2010; and 1.04 and 1.49 °C greater in 2011. However, at 14 o'clock, NTS had 1.54 °C lower soil temperature than control in 2010, and 1.62 °C lower in 2011.

The NTS treatment increased soil temperature of wheat strips by 0.73 and 1.15 °C compared to TIS and control at 0800 hours, respectively, in 2010 (Fig. 3a); and by 0.88 and 1.25 °C, respectively, in 2011 (Fig. 3b); similarly, it increased soil temperature of maize strips by 0.83 and 1.38 °C in 2010 and by 0.58 and 1.45 °C in 2011, respectively (Fig. 3c, 3d). The soil temperature measured at 1800 hours followed a similar trend as those measured at 0800 hours (described earlier). However, at 1400 hours, NTS decreased soil temperature significantly compared to TIS and control of wheat or maize strips in both years. Overall, plastic film and no-till with straw covering on the soil surface played an important role in optimizing soil

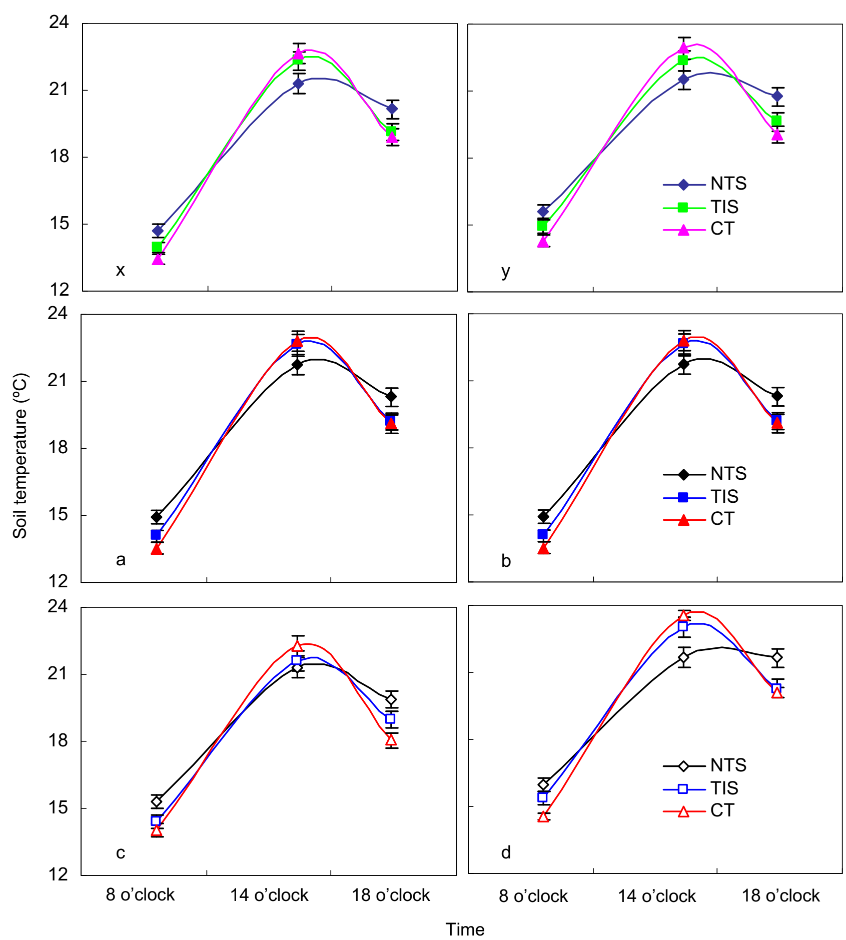

Fig. 3 Dynamics of soil temperature in a day measured in the wheat-maize intercropping under different mulching approaches. Soil temperature of wheat-maize intercropping in 2010 (**x**) and 2011 (**y**). Soil temperature of wheat strips in 2010 (**a**) and 2011 (**b**). Soil temperature of maize strips in 2010 (**c**) and 2011 (**d**). *Smaller bars* are standard errors ($P \leq 0.05$) among treatments at the given measurement. The treatment names *NTS*, *TIS*, and *CT* are the same as those defined in Table 1

temperature during the period of the day for both maize and wheat strips (more details in the "Discussion" section).

Soil temperature across the soil profile

Across the 0 to 25 cm soil profile, soil temperature decreased with the soil depth for all the mulching treatments evaluated in the study (Fig. 4). All treatments followed a similar trend, but at a given depth, soil temperature of NTS was significantly lower than that of TIS and control. In the 5-cm soil depth, soil temperature in the NTS field was 0.65 °C lower than TIS and 1.23 °C lower than control in 2010 (Fig. 4x), and it was 1.00 and 1.55 °C lower, respectively, in 2011 (Fig. 4y); similarly, in the 10-cm depth, NTS was 0.92 and 1.24 °C lower in 2010 and 1.33 and 1.28 °C lower in 2011 compared to TIS and control, respectively. The treatment effects on soil temperature in the 15-, 20-, and 25-cm soil depths followed a similar trend as those in the top 10-cm soil layer described earlier. These values showed that NTS treatment reduced soil temperature at all soil depths, with the largest differences between the treatments occurring in the 0 to 10 cm depth.

Compared to control, the NTS treatment decreased soil temperature of the wheat strips by an average of 1.26 °C in the top 10-cm depth in 2010 (Fig. 4a) and 1.31 °C in 2011 (Fig. 4b). Also, the NTS treatment decreased soil temperature of the maize strips by 1.31 °C in 2010 (Fig. 4c) and 1.51 °C in 2011 (Fig. 4d).

Between the maize and wheat strips, soil temperature in the maize strips was 1.94 °C higher compared to the wheat strips in the 0 to 10 cm depth with plastic film and straw mulch system (i.e., NTS, TIS) in 2011, and 1.25 °C higher in 2011; similarly, soil temperature in the maize strips was 2.11 °C higher compared to the wheat strips under control in 2010, and 1.58 °C higher in 2011. These results suggest that soil temperature between wheat and maize strips can be regulated well through the adoption of the double mulching evaluated in the present study.

Improve soil water content across the soil profile

Across the 0 to 110 cm soil profile, soil water content at sowing was increased with the soil depth for all the treatments evaluated in the study (Fig. 5). At a given soil depth, the integrated double mulching system conserved more soil moisture than the conventional farming system.

In the top 30-cm soil depth, the two integrated double mulching systems increased average soil water content by 5.7 % in 2010 and 7.7 % in 2011 compared to control (Fig. 5x, y); similarly, in the 50 to 80 cm depth, NTS increased soil water content by 4.8 % in 2010 and 7.5 % in 2011; in the 80 to 110 cm depth. NTS increased soil water content by 3.0 % in 2010 and 3.6 % in 2011 compared to control. All those increases of soil water content, albeit small values, were statistically significant.

A close examination of the wheat and maize strips revealed that compared to control, the two integrated double mulching systems increased soil water content of the wheat strips in the top 30-cm soil layer by an average of 9.7 % in 2010 (Fig. 5a) and 8.1 % in 2011 (Fig. 5b). The same effect was found in the maize strips, the double mulching increased soil water content by 9.6 % in 2010 and 8.2 % in 2011 (Fig. 5c, d). The treatment

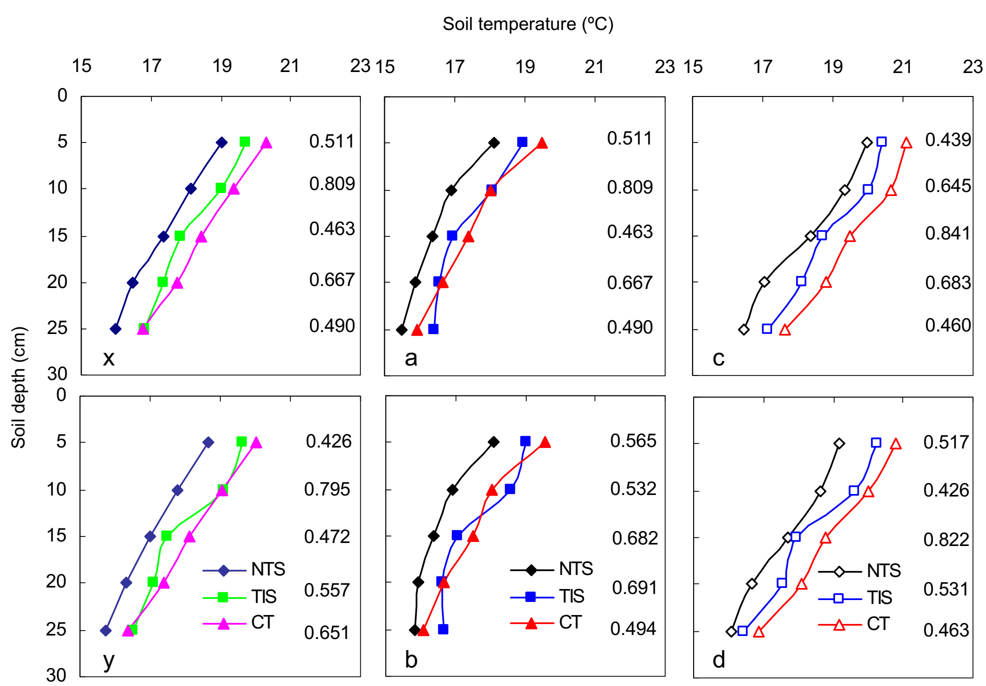

Fig. 4 Soil temperature in the 0 to 25 cm depth measured in the wheat and maize strips under different straw mulching approaches. Soil temperature of the wheat and maize intercropping in 2010 (**x**) and 2011 (**y**). Soil temperature of wheat strips under intercropping treatment in 2010 (**a**) and 2011 (**b**). Soil temperature of maize strips in 2010 (**c**) and 2011 (**d**). The *numbers* on the very *right* are *LSD* values between the treatments at the given soil depth ($P \leq 0.05$), with *NS* referring to no significant differences. The treatment names *NTS, TIS*, and *CT* are the same as those defined in Table 1

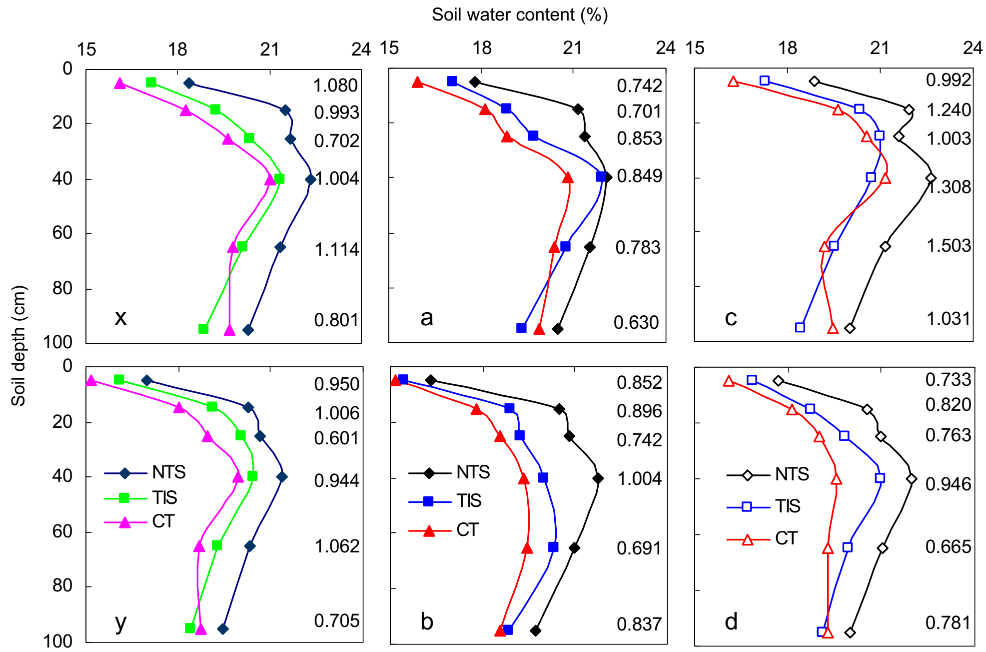

Fig. 5 Soil water contents in the 0 to 110 cm depth measured in the wheat and maize strips under different straw mulching approaches before sowing. Soil water content of the wheat-maize intercropping in 2010 (**x**) and 2011 (**y**). Soil water content of wheat strips in 2010 (**a**) and 2011 (**b**). Soil water content of maize strips in 2010 (**c**) and 2011 (**d**). The *numbers* on the very *right* are *LSD* values between the treatments at the given soil depth ($P \leq 0.05$), with *NS* referring to no significant differences. The treatment names *NTS*, *TIS*, and *CT* are the same as those defined in Table 1

effects on soil moisture in the 50 to 80 and the 80 to 110 cm soil depths followed a similar trend as those in the other soil layers described earlier.

Soil water content changed after the wheat was harvested (Fig. 6). Soil water content of the two intercrops under the NTS treatment was significantly greater than that of TIS and control with the largest differences being in the 0 to 80 cm soil depth. In the 0 to 30 cm soil depth, NTS increased soil water content by 10.0 and 17.8 %, compared to TIS and control, respectively, in 2010 (Fig. 6x); and by 8.0 and 15.9 % in 2011 (Fig. 6y); similarly, in the 50 to 80 cm depth, increased by 5.0 and 9.1 % in 2010, and by 7.3 and 10.8 % in 2011, respectively.

In 0 to 30 cm soil depth, the double mulching systems increased soil water content by an average of 12.9 % in the wheat strips in 2010 (Fig. 6a) and 13.5 % in 2011, compared to control (Fig. 6b), and increased by 11.9 and 9.8 % in the maize strips, respectively, in the 2 years (Fig. 6c, d). In the 30 to 80 cm soil depth, NIS increased soil water content by an average of 5.0 and 8.0 % in the wheat strips over TIS and control in 2010, 6.9 and 8.9 % in 2011, respectively; similarly,

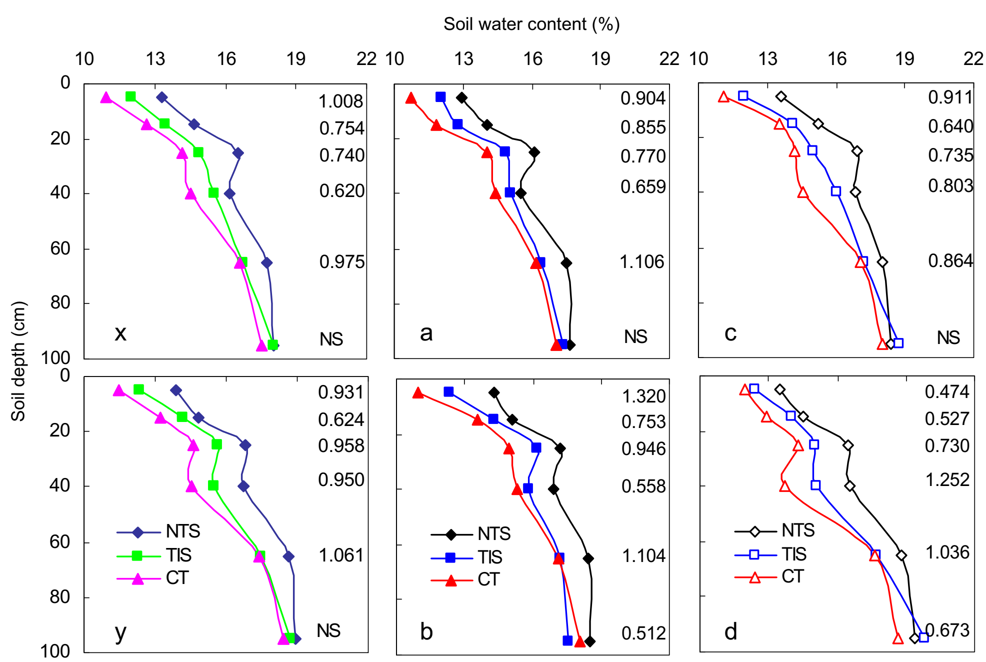

Fig. 6 Soil water content in the 0 to 110 cm depth measured in the wheat and maize strips under different straw mulching approaches after wheat harvest. Soil water content of the intercropping in 2010 (**x**) and 2011 (**y**). Soil water content of wheat strips in 2010 (**a**) and 2011 (**b**). Soil water content of maize strips in 2010 (**c**) and 2011 (**d**). The *numbers* on the very right are *LSD* values between the treatments at the given soil depth ($P \leq 0.05$), with *NS* referring to no significant differences. The treatment names *NTS*, *TIS*, and *CT* are the same as those defined in Table 1

it increased by 5.1 and 10.1 % in the maize strips in 2010, and 7.8 and 12.8 % in 2011, respectively.

The ample evidence clearly shows that plastic film coupled with straw covering on the soil surface has an overwhelming effect on water status across the 0–110 cm soil profile. It was consistent in both years that double mulching systems increased soil moisture significantly compared to the control. Averaged across the 2 years, the NTS treatment increased soil water (in mm) by 3.9 % before sowing, 8.6 % during the wheat and maize co-growth period, 5.2 % after wheat harvest, and 5.7 % after maize harvest, compared to control (Table 2). Straw mulching applied in the previous fall not only increased soil moisture at spring seeding the following year, but also the soil moisture during the entire growing season.

Balance soil evaporation and evapotranspiration

Evapotranspiration

Total ET (in mm) of the wheat-maize intercropping in the NTS system was decreased ($P < 0.05$) by 4.6 % in 2010 and 4.5 % in 2011 as compared to control (Table 2). Using the time when the wheat was harvested as a "break" line, the ET measured before the wheat harvest accounted for 60.0 % of the total ET of the wheat strips in 2010 and 58.5 % in 2011 (Fig. 7). In the maize strips, the ET measured before the wheat harvest accounted for 49.9 % of the total ET of the maize strips in 2010 and 47.5 % in 2011. During the period before the wheat harvest, total ET in the wheat strips was higher than that in the maize strips. However, after wheat harvest, total ET in the maize strips was significantly higher than that in the wheat strips, which resulted from strong transpiration of maize in the vigorous growth period. Moreover, the evapotranspiration of wheat and maize in 2011 had higher than that in 2010 after wheat harvest, which is due to the rainfall after wheat harvest in 2011 (rainfall was 131.6 mm) was obviously higher than that in 2010 (rainfall was 28.0 mm).

Soil evaporation

The NTS and TIS treatments restrained soil evaporation significantly as compared to control. In 2010, NTS and TIS evaporated 240 and 254 mm of water during the entire growth period, respectively, and control treatment evaporated 276 mm. In 2011, NTS and TIS evaporated 292 and 305 mm of water, respectively, and control treatment evaporated 320 mm. On average, NTS and TIS decreased soil evaporation by 13.1 and 8.0 % in 2010 and 8.9 and 4.7 % in 2011, respectively, compared to control.

Soil evaporation before wheat harvest accounted for 64.1 and 68.4 % of the total soil evaporation in the wheat strips in 2010 and 2011, respectively (Fig. 8); similarly, it accounted for 78.9 and 71.1 % in the maize strips in 2010 and 2011, respectively. Before wheat harvest, soil evaporation in the wheat strips was lower (by 25.2 to 34.0 % in 2010 and 21.4 to 28.8 % in 2011) than that in the maize strips; soil evaporation of NTS was significantly lower (by 13.7 and 18.5 % in 2010 and 11.1 and 15.1 % in 2011) compared to TIS and control in the wheat strips; similarly, they were lower (by 8.8 and 6.7 % in 2010, 7.5 and 5.8 % in 2011) in the maize

Table 2 Soil moisture (mm) before sowing, during the wheat-maize co-growth period, after wheat harvesting, after maize harvesting within the 0–110 cm depth, and evapotranspiration (including growing season precipitation, mm) in the wheat-maize intercropping system in an Oasis region, in 2010 and 2011

Year	Treatment[a]	Before sowing	Co-growth period	After wheat harvest	After maize harvest	Evapotranspiration[b]
2010	mm					
	NTS	313	230	262	269	585
	TIS	322	217	254	263	611
	CT	304	210	246	246	613
	P value [c]	0.002	0.001	0.001	0.001	0.000
	LSD (0.05)	9	7	9	7	15
2011	NTS	375	305	296	304	736
	TIS	363	290	284	302	756
	CT	358	283	285	298	771
	P value	0.03	0.014	0.159	0.262	0.001
	LSD (0.05)	16	12	NS	NS	14

[a] Treatment abbreviations are the same as those shown in table 1

[b] Wheat growing season (March–July) rainfall was 58.8 mm in 2010 and 65.8 mm in 2011; Maize growing season (April–September) rainfall was 94.7 mm in 2010 and 179.1 mm in 2011

[c] The *P* value and the LSD (0.05) were for all the treatments in the same column within a year

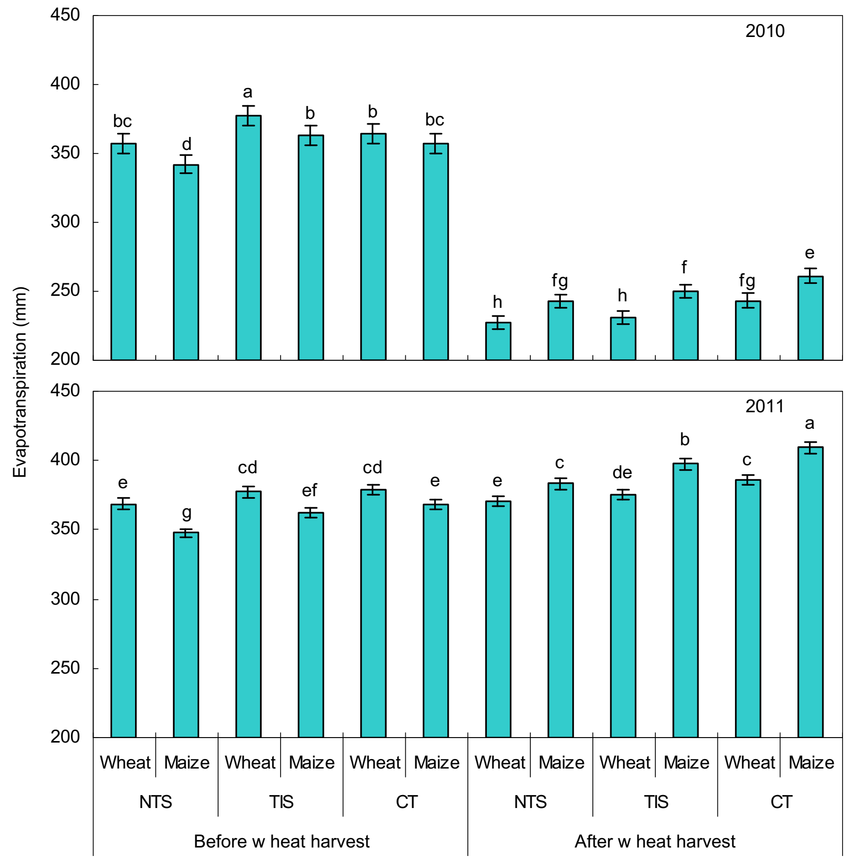

Fig. 7 Evapotranspiration (rainfall plus irrigation) before wheat harvest and after wheat harvest for the wheat-maize intercropping tested in 2010 and 2011 at an Oasis region. Different *letters* indicate significant differences ($P \leq 0.05$) among treatment within a year and the *smaller bars* are standard errors. The treatment names *NTS, TIS,* and *CT* are the same as those defined in Table 1

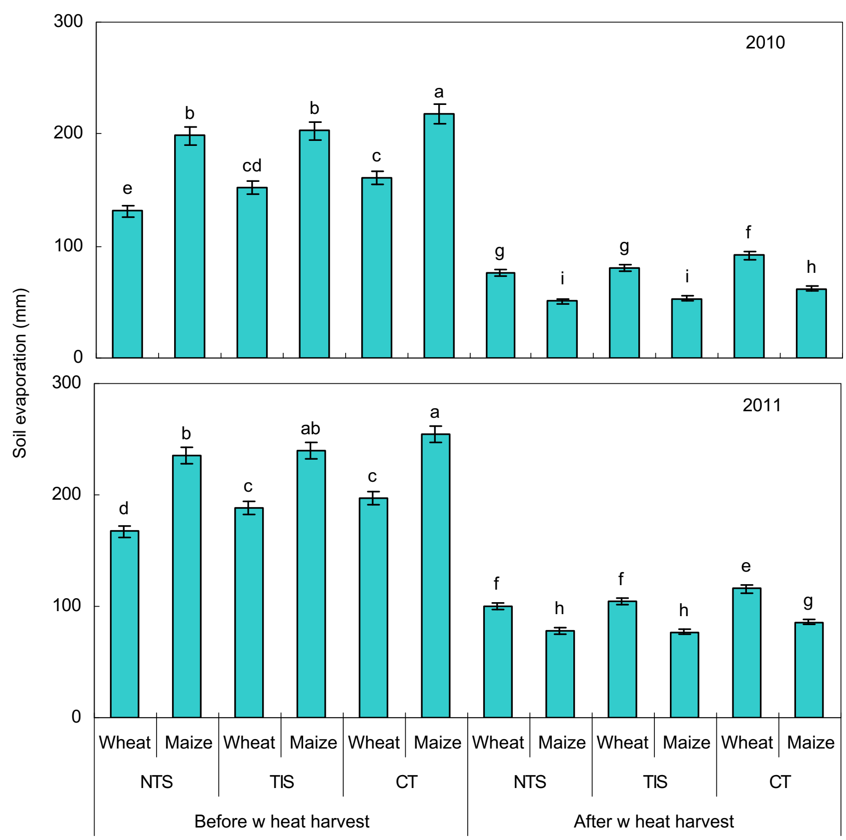

Fig. 8 Soil evaporation (E) before wheat harvest and after wheat harvest in the wheat-maize intercropping in 2010 and 2011 at an Oasis region. Different *letters* indicate significant differences ($P \leq 0.05$) among treatment and the *smaller bars* are standard errors. The treatment names *NTS*, *TIS*, and *CT* are the same as those defined in Table 1

strips. After wheat harvest, soil evaporation in the wheat strips was higher (by 48.4 to 51.6 % in 2010 and 28.7 to 35.5 % in 2011) than that in the maize strips. Again, soil evaporation with NTS and TIS was significantly lower (by 16.9 and 12.7 % in 2010, 13.4 and 10.1 % in 2011) than that of control in the wheat strips, similarly, they were lower (by 17.7 and 14.6 % in 2010, 9.2 and 10.5 % in 2011) in the maize strips.

The E/ET ratio

The E/ET ratio gives an indication of how much evaporated water that has been used for transpiration of crop plants. In the present study, NTS and TIS decreased the E to ET ratio (E/ET) significantly (Fig. 9). On average, the E/ET ratio of NTS and TIS was 8.9 and 7.7 % lower in 2010, 4.7 and 2.9 % lower in 2011, respectively, than that of control. Therefore, double mulching with plastic film and crop straw reduced the loss of soil water, providing more water for crop plant transpiration. The E/ET ratio varied during the growth period, averaged E/ET ratio in the wheat and maize strips was significantly higher before wheat harvest, compared to after wheat harvest. During the wheat-maize co-growth period (i.e., before wheat harvest), the E/ET ratio in the maize strips was significantly higher (by 37.8 to 53.7 % in 2010, 32.5 to 49.8 % in 2011) than in the wheat strips. Among the treatments, the NTS treatment had significantly lower E/ET ratio by (8.8 and 17.0 % in 2010, 9.5 and 15.6 % in 2011) than TIS and control in the wheat strips; in the maize strips, the E/ET ratio of NTS and TIS was also significantly lower than that of control (by 7.4 and 8.2 % in 2010, 4.7 and 6.8 % in 2011). After wheat harvest, E/ET of wheat strips was higher (by 59.1 to 63.9 % in 2010 and 33.2 to 43.5 % in 2011) than that of maize strips; E/ET of NTS and TIS was significantly lower (by 11.0 and 8.1 % in 2010, 7.5 and 5.2 % in 2011, respectively) than that of control in wheat strips; similarly, lower by 11.6 and 10.8 % in 2010, but it has no statistical differences in 2011.

Boost biomass of maize

The integrated double mulching system had not significant influence on biomass of wheat in wheat-maize intercropping system (data not presented), but it had significantly increased biomass of maize after wheat harvest (Fig. 10).

At wheat harvest stage, NTS and TIS increased biomass by 25.4 and 16.7 % in 2010, 17.1 and 11.8 % in 2011, respectively, compared to control. Similarly, they increased by 15.8 and 6.8 % in 2010, 33.4 and 14.4 % in 2011, respectively, at maize early filling stage; they increased by 19.3 and 9.6 % in 2010, 16.7 and 6.5 % in 2011, respectively, at maize late filling stage. At maturity, only NTS significantly increased biomass of maize by 7.0 % in 2010 and 5.9 % in 2011.

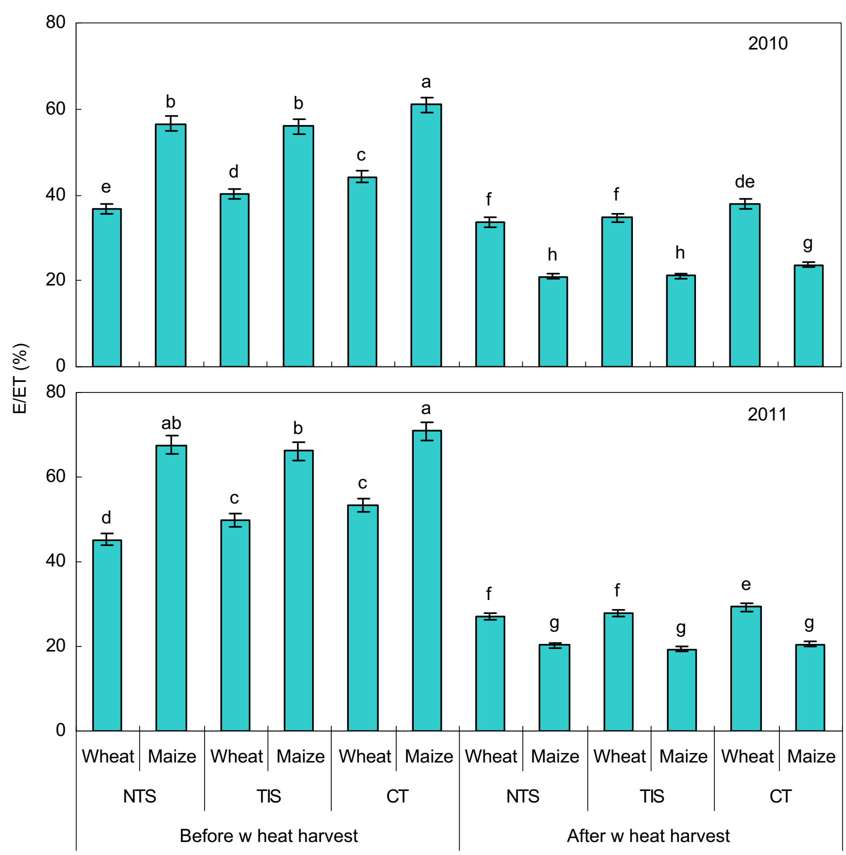

Fig. 9 The ratio of soil evaporation to evapotranspiration (E/ET) before wheat harvest and after wheat harvest in the wheat-maize intercropping in 2010 and 2011 at an Oasis region. Different *letters* indicate significant differences ($P \leq 0.05$) among treatment and the *smaller bars* are standard errors. The treatment names *NTS*, *TIS*, and *CT* are the same as those defined in Table 1

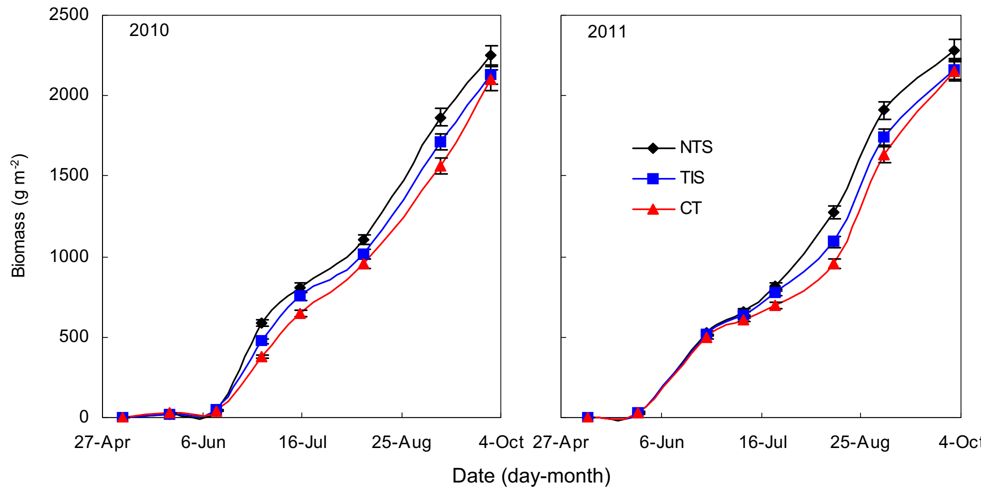

Fig. 10 Dynamics on biomass of maize in the wheat-maize intercropping under different mulching approaches in 2010 and 2011. *Smaller bars* are standard errors ($P \leq 0.05$) among treatments at the given measurement. The treatment names *NTS*, *TIS*, and *CT* are the same as those defined in Table 1

Discussion

Among the water conservation approaches evaluated in this study, no-till in combination with plastic film and straw covering on the surface (i.e., the NTS treatment) was most effective in conserving soil moisture during the wheat and maize co-growth period, which increased soil moisture by 9.5 % in 2010 and 7.8 % in 2011 for the averaged soil water content of wheat and maize strips. Soil moisture under plastic film and straw covering was lost slowly and the available water was maintained for a longer period of time that is available for crop plants. After wheat harvest, straw covering with no-till had a significant effect on the moisture storage that was improved by 6.5 % compared to control in 2010. After maize harvested, the effect of straw covering with no-till on soil moisture was apparent in 2010, increased by 9.3 %. Here, we suggest that straw covering on the soil surface serves an indispensable component of the integrated double mulching system. The increased soil moisture with straw covering can partly offset the water deficit in intensified cropping systems. When coupled with intercropping, the double mulching system can be an ideal practice for empowering the capacity of soil water conservation in this extremely arid environment.

Studies have shown that there is a close relationship between soil temperature and soil water content, because soil water content can directly affect the transmission of the heat on the soil surface. In turn, soil temperature can affect soil evaporation (E) and evapotranspiration (ET). In the present study, we analyzed the relationship among ET, E, E/ET, and soil temperature for different systems before or after wheat harvest in intercropping systems. We found that there was a significant positive correlation between ET and soil temperature in the wheat and maize strips during the whole growth period and before or after the intercropped wheat harvest. Overall, ET was increased with the increase of soil temperature, which may be related to the differences on soil water content under different mulching treatments that affected the soil thermal conductivity. Similarly, there was a significantly positive correlation between E, E/ET, and soil temperature in wheat strips and intercropping systems during the whole growth period and before or after wheat harvest in 2011. However, the correlation between E, E/ET, and soil temperature was not significant after wheat harvest in maize strips. These results suggest that straw mulching reduces the soil evaporation and the E/ET ratio in the maize strips mainly after wheat harvest. The 2 years of the results were consistent, suggesting that straw covering is an approach effective for reducing the loss of soil water in the arid environment.

Previous studies have demonstrated that each individual farming practice has its own effect on crop productivity, but packaging individually proven key farming practices together in an improved system can enable the increase of crop yields and optimize resource use efficiency (Gan et al. 2014). In the present study, we developed the integrated double mulching system in which two key farming components are integrated together, namely (i) crop intensification through two-crop strip intercropping and (ii) the use of double mulching with plastic film and crop straw covering the maize strips. It was consistent across the testing years that this integrated cropping system can significantly boost crop yields, harvest more soil water in arid or semiarid environments, and decrease soil evaporation. In the scientific literature, some of the cropping systems require significant amount of input, while the others are complex enough and difficult for producers to use. The integrated double mulching system we tested in present study is simple and can be easily adopted by small-scale family farms or ordinary producers.

The first key component of the integrated double mulching system is two-crop strip intercropping which has been adopted in many parts of the world as a way of increasing crop productivity (Chai et al. 2014b; Mueller et al. 2012). Intensified cropping is an effective means to narrow the yield gaps between the current yield levels and their potentials (Mueller et al. 2012). The yield advantages of intercropping over monoculture has been found to be attributable to improved light conditions (Munz et al. 2014; Yang et al. 2014), increased resource use efficiency (Fang et al. 2010a), and reduced disease pressure in some crop species (Qin et al. 2013b; Fernández-Aparicio et al. 2010). Also, the two intercrops can provide each other with certain degrees of supplementary effects during their co-growth period (Chai et al. 2014b). Thereby, the adoption of intercropping has significant advantages on resource utilization and crop yield than conventional monoculture cropping (Fang et al. 2010b).

The second key component is double mulching with plastic film and crop straw. A combination of crop residue retention with reduced tillage or no-till management has been found to increase water infiltration (Elliott and Efetha 1999), reduce water loss by restraining evaporation (Govaerts et al. 2006) and evapotranspiration (Kang and Zhang 2004; Ussiri and Lal 2009), and improve crop water use efficiency (Fan et al. 2012). Crop residues on the soil surface typically form a barrier against evaporation, thus, maintaining the water storage in the plant root zone (Lichter et al. 2008). The findings of the present study clearly demonstrate that the integrated double mulching systems can significantly decrease evaporation and evapotranspiration during the entire growing season compared to conventional tillage practices. It suggests that the double mulching system can be used to harvest more rainwater in rainfed areas or reduce the amount of irrigation in irrigation areas. Straw mulching is a traditional conservation approach, but we found that this "old" technique, when combined with plastic film mulching together in intensified intercropping system, can be a means extremely effective for improving water use conservation in the arid, water shortage areas.

Soil temperature can significantly affect the growth and development of crop plants. In the wheat-maize intercropping system, the two crop species have different sensitivity to soil temperature. Wheat is in favor of cooler soil temperature whereas maize is in favor of warm soil temperature. Optimizing soil temperature to satisfy the requirements for the growth of the two crop species simultaneously has been a challenge. Plastic film mulch without straw mulch can significantly increase soil temperature (Choi and Chung 1997). In many cases, the use of plastic film can markedly increase soil temperature compared to straw mulch (Duhr and Dubas 1990). Our study shows that the plastic film mulch can serve as insulation more effectively than straw mulch in maize. However, it was apparent that from the silking to filling stage of maize, soil temperature was often higher than 40 °C at noon, causing leaf rolling and decreasing grain filling, thus reducing maize yield. In contrast, the double mulching (plastic film in combination with straw covering) regulated the soil temperature of the two intercrops in a more efficient way, and optimized the soil temperature in the wheat and maize strips. As a result, the growth of the two intercrops is in a well "collaborative" status during their co-growth period. In particular, during the period of maize tasseling to filling, soil temperature in the double mulching system was in the range of 23 to 26 °C, which is optimal for the growth and development of maize (Li et al. 2012).

Furthermore, plastic mulching in maize production has been reported to deteriorate soil organic carbon rapidly over time (Zhou et al. 2012), largely due to enhanced soil temperature by plastic film that promotes soil microbial activity and speeds up the decomposition of organic matter in the soil (Wang et al. 2014). Our study suggests that the double mulching with plastic film and crop straw covering on the soil surface can provide benefits in maintaining or increasing soil organic carbon content (due to crop straw input). Therefore, the double mulching can be employed as a sustainable cropping system for increasing crop productivity, meanwhile, improving soil quality. Overall, the integrated double mulching system plays a key role in balancing E, ET, and crop productivity. This is especially effective in Oasis agricultural regions such as the Hexi Corridor of China where water shortage is the foremost factor threatening agricultural sustainability (Guang and Wei 2002), and adapt of this type of crop intensification may alleviate the issue while meeting the ever-growing demands for grains (Fan et al. 2012).

Conclusions

The integrated double mulching system (i.e., plastic film and straw covering on the soil surface) in combination with cropping intensification through two-crop strip intercropping was shown to be effective in conserving soil moisture and optimizing soil temperature for the two intercrops. The improved soil moisture and optimized soil temperatures allowed the growth of the two intercrops in a well collaborative status during their co-growth period. In particular, the double mulching system significantly decreased ET and the E/ET ratio compared to the conventional practices. The reduced E and E/ET mainly occurred in the wheat strips after wheat harvest and in the maize strips during the co-growth period, suggesting that straw mulching provides an effective mode for reducing the water loss even after the wheat is harvested. Our results clearly demonstrate that the integrated system (i.e., the wheat-maize intercropping with plastic mulching and straw covering on the soil surface) can play an important role in the development of improved farming systems allowing to alleviate water shortage currently experiencing in the arid and semiarid areas.

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