Innovation in alternate mulch with straw and plastic management bolsters yield and water use efficiency in wheat-maize intercropping in arid conditions

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In arid regions, higher irrigation quota for conventional farming causes substantial conflict between water supply and demand for crop production. Innovations in cropping systems are needed to alleviate this issue. A field experiment was conducted in northwestern China to assess whether straw and plastic managements in wheat/maize intercropping could alleviate these issues. Integrating no tillage with two-year plastic and straw mulching (NTM2) improved grain yields by 13.8–17.1%, compared to conventional tillage without straw residue and annual new plastic mulching (CTI). The NTM2 treatment reduced soil evaporation by 9.0–17.3% and the proportion of evaporation to evapotranspiration (E/ET) by 8.6–17.5%, compared to CTI. The NTM2 treatment weakened wheat competition of soil moisture from maize strip during wheat growth period, and enhanced wheat compensation of soil moisture for maize growth after wheat harvest, compared with CTI. Thus, soil water movement potential of NTM2 was lowest during wheat growth period, but it was highest during maize-independent growth stage after wheat harvest. The NTM2 treatment increased evapotranspiration before maize silking, decreased from maize silking to early-filling stage, and increased after the early-filling stage of maize, this effectively coordinated water demand contradiction of intercrops at early and late stages. The NTM2 treatment improved WUE by 12.4–17.2%, compared with CTI. The improved crop yields and WUE was attributed to the coordinated water competition and compensation, and the decreased soil evaporation and E/ET.

In densely populated countries, such as Indonesia, India, and China, most of the rural population lives on self-sufficient and small-scale family farms that produce the majority of the country's grain1. To meet the demand of a growing population, grain production must be greatly increased while optimizing the utilization of the limited resources. Small-scale family farms are threatened by deterioration and shortage of natural resources2, availability of water resources to compete with urbanization or other sectors3, and soil degradation due to unsustainable agronomic practices4. Thus, small-scale family farms must adopt innovative cropping patterns that are more productive use resources more efficiently, and have a lighter ecological footprint5.

A prominent issue threatening the sustainability of crop production is water use, especially in areas such as northwestern China where available freshwater is 25% less than the internationally-recognized threshold for water shortages6. Here, average precipitation over many years is less than 160 mm but annual potential soil evaporation exceeds 2000 mm, causing crop production to rely on irrigation7. In the main grain producing areas of northwestern China such as the Hexi oasis irrigation region, the quantity of water available for crop production
has seriously declined due to overexploitation of groundwater and uneven distribution across regions, thereby threatening the productivity of current farming systems. Maize and wheat are the two major food crops planted in arid areas of northwestern China. Both are usually produced with strip intercropping, which allows two crops to be grown within a single season in the same field. This intercropping pattern has been shown to boost crop yields, enhance resource use efficiency, and produce greater economic benefits, compared to the corresponding monoculture crops. However, high yields with this system have been attributed to the large amount of water supplied during the growing season compared to monocropping, creating conflict between increased yields through use of strip intercropping and reduced water consumption for agricultural production. Improvements to this system are needed to concurrently achieve high yields while reducing or optimizing utilization of the limited water resources. In a region with annual soil evaporation greater than 20 times precipitation, how can soil water be best captured with minimized soil evaporation?

Some innovative water-saving measures, such as plastic and straw, regulated deficit irrigation, and the implement of policies and bylaws in water management, have been used to promote effective use of water in agriculture. Although high yields with strip intercropping have been attributed to the large amount of water supplied, it is also one of the most effective methods to improve crop water use efficiency. The intercropping combined with regulated deficit irrigation or straw and plastic mulching, can improve water use efficiency in semiarid regions.

However, there is lack of the mechanism responsible for improved water use efficiency in intercropping system. Previous researches have shown that high water use efficiency is because of the increased total yields per unit of water supply. When two contrasting crops are cultivated together in alternate strips, aboveground interspecies interactions are beneficial to improve the stereo-structure availability in light capture between the intercrops and enhance photosynthetically active radiation transmittance. Moreover, underground interspecific competition and facilitation may occur simultaneously when two crops are cultivated together in arid regions with high soil water evaporation. It is likely that underground interspecific interactions lead to competition and compensation use of soil water in both intercrop strips, so soil water movement in the intercrops’ rooting zones may also occur. However, there is a lack of quantitative researches regarding the magnitude of soil water that may be competed for both two intercrop strips during their co-growth period and compensated for after early-maturing crop harvest. It is unknown whether the two intercrops compete for soil moisture and whether one intercrop may provide a compensation effect to the other intercrop. Current research is limited in soil water competition and compensation under highly efficient soil water-regulating agronomic measures, such as straw and plastic managements. Therefore, it is of great significance to elucidate the mechanism of high yield and efficient utilization of water in intercropping.

Table 1. Total grain yield of wheat and maize by cropping pattern and treatment in 2014–2016. Within a column for a given year, means followed by different lowercase letters are significantly different at P < 0.05.

| Cropping pattern                     | Treatment | Year | 2014   | 2015   | 2016   |
|--------------------------------------|-----------|------|--------|--------|--------|
| Monoculture wheat                    | NTSW      | 2014 | 7.37de | 7.08cd | 7.89c  |
|                                      | NTM2      | 2015 | 7.62d  | 7.20c  | 8.04c  |
|                                      | TSW       | 2016 | 6.96e  | 6.69d  | 7.49d  |
|                                      | CTW       |      | 6.28f  | 6.07e  | 6.31e  |
| Monoculture maize                    | NTM2      | 2014 | 14.32c | 14.24b | 14.41b |
|                                      | CTM       | 2015 | 14.89bc| 14.52b | 14.62b |
| Wheat-maize intercropping            | NTSI      | 2014 | 16.82a | 16.49a | 17.23a |
|                                      | NTM2      | 2015 | 16.90a | 16.63a | 17.49a |
|                                      | TSI       | 2016 | 16.97a | 16.50a | 16.86a |
|                                      | CTI       |      | 14.86bc| 14.61b | 14.93b |

Results

Effects of straw and plastic management on crop yields of intercropping systems. Wheat/maize strip intercropping produced significantly greater total grain yield than the monocultures across the three years studied (Table 1). Averaged across years and treatments, intercropping systems produced a total grain yield of 16.4 Mg ha⁻¹, which was 11.7–14.5% greater than that of monoculture maize treatments and 1.2- to 1.4-fold greater than that of the monoculture wheat treatments.
No-tillage with straw returned to the field significantly boosted grain yield of monoculture wheat (Table 1). Grain yield of the no tillage with straw standing (i.e., NTSW), no tillage with straw mulching (i.e., NTMW), and tillage with straw incorporation (i.e., TSW) treatments was improved by 16.6–24.9%, 18.6–27.3%, and 10.2–18.7%, respectively, compared to the conventional tillage treatment (i.e., CTW); especially for the NTMW treatment which produced 7.2–9.5% greater grain yield than the TSW treatment. No tillage with two-year plastic mulching had no significant effect on grain yield of monoculture maize in comparison to conventional tillage with new plastic film mulch applied annually. However, no tillage with straw residue in wheat strips and two-year plastic film mulching in maize strips boosted total grain yield of intercropped wheat and maize. Compared to the conventional intercropping treatment (i.e., CTI), No tillage with wheat straw standing in wheat strips combined with two-year plastic mulching in maize strips (i.e., NTSI2), no tillage with wheat straw mulching in wheat strips combined with two-year plastic mulching in maize strips (i.e., NTMI2), and tillage with straw was incorporated in wheat strips and annual new plastic mulching in maize strips (TSI) increased total grain yields by 13.7–16.5%, 16.0–20.2%, and 16.7–18.3%, respectively.

Soil evaporation. Soil evaporation of different cropping systems. Strip intercropping significantly increased soil evaporation by 44.8–78.5% (higher 72–115 mm) and 17.6–26.2% (34–54 mm) compared to monoculture wheat and maize, respectively (Fig. 1). Straw retention significantly reduced soil evaporation of monoculture wheat. The NTSW, NTMW, and TSW treatments reduced soil evaporation by 9.3–17.4%, 10.8–23.3%, and 4.3–13.4%, compared to the CTW treatment, respectively, and soil evaporation of the NTSW and NTMW treatments was 4.0–5.8% and 5.6–11.4% less than that of the TSW treatment, respectively. Within monoculture maize, soil evaporation was not affected by plastic film mulching approach. However, NTMI2 treatment significantly reduced total soil evaporation by 9.0–17.0% compared to the CTI treatment.

Effects of straw and plastic management on soil evaporation of intercropping strips. The NTMI2 treatment inhibited the soil evaporation significantly compared to the CTI (Fig. 2). In 2014–2016, soil evaporation with the NTMI2 treatment was reduced by 7.1–21.6%, 6.4–11.1%, and 11.0–22.0% compared to the control during the wheat-independent growth period, the two crops co-growth period, and the maize-independent period, respectively. These results show that no tillage, in combination with straw mulching the soil surface in wheat strips and two-year plastic mulching in maize strips, was an effective measure to reduce soil evaporation in the intercropping.

During the wheat-independent growth period, soil evaporation in the wheat strips was 32.0–39.3%, 8.9–44.8%, 75.8–121.2%, and 103.2–141.0% higher than that in the maize strips for the NTSI2, NTMI2, TSI and CTI, respectively (Fig. 2). Compared to the CTI, soil evaporation in wheat strips of the NTSI2 and NTMI2 was...
Effects of straw and plastic management on soil water potential of intercropping strips. The difference in the soil water potential of the wheat and maize strips in the intercropping systems is reflected in three growth periods, including the wheat-independent growth period, the intercrops’ co-growth period, and the maize-independent growth period (Fig. 4). During the wheat-independent growth period, soil water potential of maize strips across

Figure 2. Soil evaporation (E, mm) and soil water movement potential (WMP, mm) of the intercropped wheat and maize strips, along with precipitation (P, mm) and irrigation (I, mm), by crop growing period in 2014–2016. The WMP in the intercropping systems is defined as one-half of the high soil water storage (SWS, mm) minus the low SWS of crop strips for the 0–120 cm soil depth and includes E from the two crop strips, the arrow to the left indicates that soil water has a tendency of moving from wheat to maize strips, the arrow to the right indicates that soil water has a tendency of moving from maize to wheat strips. Within a column for a given year, means followed by different lowercase letters are significantly different at $P < 0.05$.

17.2–22.1% and 25.3–40.9% less, respectively; however, in maize strips it was 22.0–42.3% and 21.5–30.6% greater, respectively.

During wheat-maize co-growth, soil evaporation in wheat strips was 28.5–39.2%, 27.4–29.7%, 40.7–47.5%, and 30.2–58.9% higher than that in maize strips for NTSI2, NTM12, TSI, and CTI, respectively (Fig. 2). Compared to the CTI, soil evaporation in wheat strips of NTSI2 and NTM12 was 6.7–7.0% and 7.4–18.9% less, respectively; however, it was not significantly different in maize strips.

During the maize-independent growth period, soil evaporation in wheat strips was 88.9–141.9%, 53.4–124.1%, 81.8–134.7%, and 111.9–181.3% higher than that in maize strips for the NTSI2, NTM12, TSI, and CTI treatments, respectively (Fig. 2). Compared to the CTI treatment, soil evaporation in wheat strips of the NTSI2, NTM12 and TSI treatments was 8.9–10.4%, 16.6–30.5%, and 10.1–20.5% less, respectively; however, in maize strips it was 5.9–9.0% and 4.7–6.5% greater, respectively. These results show that reducing soil evaporation from wheat strips is important in wheat-maize intercropping, especially after wheat harvest.

Water competition and compensation between intercropping strips. Soil water potential in the 0 to 120 cm soil profile of different cropping systems. Strip intercropping maintained high soil water potential of 0–60 cm and 60–120 cm soil profile in comparison with monocultures, and strip intercropping integrated with straw retention and plastic further improved soil water potential (Fig. 3). Intercropping had 13.2–18.6% and 14.9–18.2% in the 0–60 cm and 11.2–12.1% and 8.2–10.3% in 60 to 120 cm soil profile, greater soil water potential than monoculture wheat and maize treatments, respectively. NTSI2 and NTM12 increased soil water potential by 22.9–25.5% and 26.7–29.6% compared to CTW, respectively, by 18.3–20.5% and 21.8–25.2% in comparison to CTM, respectively, and by 10.2 to 11.0% and 14.8 to 17.5%, compared to CTI, respectively, in 0 to 60 cm soil profile. From 60 to 120 cm soil profile, NTSI2 and NTM12 increased soil water potential by 16.3–19.0% and 20.4–22.3% compared to CTW, and by 11.5–14.0% and 15.7–18.3% compared to CTM, and by 7.5–8.6% and 11.9–13.2% compared to CTI, respectively.

Effects of straw and plastic management on soil water potential of intercropping strips. The difference in the soil water potential of the wheat and maize strips in the intercropping systems is reflected in three growth periods, including the wheat-independent growth period, the intercrops’ co-growth period, and the maize-independent growth period (Fig. 4). During the wheat-independent growth period, soil water potential of maize strips across
0–60 cm soil depth averaged 11.9–23.5%, 12.6–25.4%, 16.7–22.7%, and 12.9–23.7% higher than that of wheat strips in the NTSI2, NTMI2, TSI, and CTI treatments, also, by 10.7–19.0%, 4.3–11.9%, 7.5–17.9%, and 7.4–21.7% across 60–120 cm, respectively. Similarly, during the intercrops’ co-growth period, soil water potential of maize strips of the NTSI2, NTMI2, TSI, and CTI treatments was 17.2–19.5%, 16.6–18.6%, 20.0–21.2%, and 20.3–21.6% higher than that of wheat strips in 0–60 cm, and by 11.0–21.7%, 14.8–21.2%, 17.4–20.6%, and 17.2–22.8%, in 60–120 cm, respectively, and the difference in soil water potential between intercrops strips was reduced with NTMI2. These findings indicate that soil moisture had a tendency to flow from maize to wheat strips, and that NTMI2 reduced the movement potential of soil moisture between intercrops strips compared to CTI, during the wheat growth period.

However, during the maize-independent growth period, soil water potential of wheat strips across 0–60 cm soil depth averaged 25.6–28.1%, 32.8–34.4%, 31.5–33.4%, and 24.8–27.2% higher than that of maize strips in the NTSI2, NTMI2, TSI, and CTI treatments, and by 17.7–27.7%, 27.5–31.5%, 26.2–30.9%, and 13.8–28.2%, respectively, and the difference in soil water potential between intercrops strips was enhanced with NTMI2. These data indicate that soil moisture had a tendency to flow from wheat to maize strips, and that NTMI2 enhanced the movement potential of soil moisture between intercrops strips compared to CTI, during the wheat growth period.

During the three periods of crop growth, soil water potential of wheat and maize strips was greater with NTSI2, NTMI2, and TSI than CTI (Fig. 4). Across the four intercropping treatments, the NTMI2 treatment had the greatest soil water potential of wheat and maize strips. These results show that integrated water conservation practices (no-tillage with two-year plastic mulching in maize strips coupled with straw mulching the soil surface in wheat strips, i.e., the NTMI2 treatment) kept a relatively high soil water potential, thereby enhancing the soil water environment for intercropping.

Effects of straw and plastic management on soil water movement potential of intercropping strips. Soil water status was monitored in each intercrop strip across the entire growing season, including wheat-independent period, intercrops’ co-growth period, and maize-independent period, to quantify soil water competition and compensation effect of both intercropped strips. Soil water movement potential between wheat and maize strips was expressed as one-half of the difference between the high soil water storage strip and the low soil water storage strip divided by soil evaporation of both strips in intercropping system (Fig. 2). During the wheat-independent growth period, in 2014–2016, soil water moved from maize strip to wheat strip by 20.4–26.4, 14.5–20.7, 21.1–23.2, and 25.6–29.8 mm in the NTSI2, NTMI2, TSI, and CTI treatments, respectively. During the intercrops’ co-growth period, soil water moved from maize strip to wheat strip by 40.6–52.5, 27.4–38.7, 46.9–56.3, and 61.8–69.5 mm in the above four intercropping treatments, respectively. Across the four intercropping treatments, the NTMI2 treatment had the least amount of soil water moved from wheat strip to maize strip, with wheat strip having the lowest level of competition for soil water. Here, we show that intercropping
coupled with straw mulching the soil surface and two-year plastic mulching can significantly reduce soil water losses from wheat strips and lower the competition for soil water from the adjacent maize strips during the co-growth period.

During the maize-independent growth period, in 2014–2016, soil water moved from the maize strips to the wheat strips by 65.6–81.7, 81.6–96.4, 75.7–89.8, and 50.8–66.5 mm in the NTSI2, NTMI2, TSI, and CTI treatments, respectively (Fig. 2). This movement of soil moisture from wheat to maize strips after wheat harvest was consistent at all treatments and compensated the growing maize. Across the four intercropping treatments, the NTMI2 treatment allowed the greatest amount of the remaining, unused water to be moved from wheat to maize strips, while the CTI treatment allowed the least. This study shows that the treatment with no tillage and straw mulching the soil surface after wheat harvest reduces soil water competition and enhances water compensation for maintaining water balance of two strips in the intercropping system.

Effects of straw and plastic management on soil water balance characteristics of intercropping strips. Rainfall and irrigation were the two main water sources in this study. Field evapotranspiration mainly included soil

Figure 4. Soil water potential in the 0–60 cm and 60–120 cm soil depth for the intercropped wheat and maize strips in 2014–2016. Within a year and growing period, different letters indicate significant differences ($P < 0.05$) among treatments. Error bars are standard errors.
| Year | Treatment | ET1 (mm) | ET1/ET (%) | ET2 (mm) | ET2/ET (%) | ET3 (mm) | ET3/ET (%) | ET4 (mm) | ET4/ET (%) | ET5 (mm) | ET5/ET (%) | ET6 (mm) | ET6/ET (%) | ET (mm) |
|------|-----------|----------|------------|----------|------------|----------|------------|----------|------------|----------|------------|----------|------------|--------|
| 2014 | NTSI2 | 37a 4.8a | 132b 17.1b | 125a 16.2a | 138a 17.8a | 60a 7.7a | 280c 36.3c | 772a |
|      | NTMI2 | 37a 4.8b | 132b 17.2b | 124a 16.3a | 140a 18.3a | 59a 7.7a | 276c 36.1c | 764a |
|      | TSI | 33b 4.3b | 138a 17.8a | 122a 15.7a | 141a 18.2a | 50b 6.5b | 292b 37.7b | 776a |
|      | CTI | 30c 3.9c | 135ab 17.1b | 114b 14.5b | 144a 18.3a | 48b 6.2b | 315a 40.1a | 787a |
| 2015 | NTSI2 | 40a 5.6a | 166a 23.3ab | 116b 16.3b | 116a 16.3a | 58c 8.1c | 217a 30.4a | 712a |
|      | NTMI2 | 37b 4.8b | 163ab 23.6a | 121ab 17.4a | 102b 14.7c | 67a 9.7a | 207b 29.9a | 693ab |
|      | TSI | 36b 5.3b | 162ab 23.9a | 123a 18.0a | 105b 15.5b | 62b 9.1b | 192c 28.2b | 680b |
|      | CTI | 33c 4.8c | 163ab 23.6a | 121ab 17.4a | 102b 14.7c | 67a 9.7a | 207b 29.9a | 693ab |
| 2016 | NTSI2 | 48b 6.4a | 176a 23.4ab | 108b 14.3b | 136a 18.1a | 55c 7.3c | 230ab 30.5b | 753a |
|      | NTMI2 | 47b 6.4a | 176a 23.2b | 111a 14.9b | 134a 17.9a | 48d 6.4d | 254a 31.3a | 747a |
|      | TSI | 45b 6.0b | 178a 24.0a | 114a 15.4a | 128b 17.2b | 59b 7.9b | 218c 29.4c | 742a |
|      | CTI | 41c 5.5c | 179a 24.1a | 112a 15.0b | 127b 17.1b | 64a 8.6a | 221bc 29.7bc | 745a |

Table 2. Evapotranspiration and evapotranspiration modulus coefficient of wheat-maize intercropping at each of growth stage under different straw and plastic managements in 2014–2016. The sampling dates were 18 March, 22 April, 27 May, 19 June, 23 July, 6 August, and 1 October in 2014, 28 March, 23 April, 30 May, 21 June, 27 July, 9 August, and 30 September in 2015, and 29 March, 19 April, 28 May, 26 June, 20 July, 8 August, and 20 September in 2016. Within a column for a given year, means followed by different lowercase letters are significantly different at \( P < 0.05 \).

Evapotranspiration and evapotranspiration modulus coefficient of intercropping at each of growth stage. Strip intercropping treatments had greater total evapotranspiration (ET) than monoculture wheat and maize treatments due to a longer crop growth period (Table 2). The straw and plastic management had no significant effect on total ET during the entire crop growth period in 2014 and 2016; but in 2015 the NTMI2 treatment reduced total ET by 4.7% compared to CTI.

In 2014, there was no consistent trend on the ET and evapotranspiration modulus coefficient (EC) among intercropping systems and was likely because cumulative precipitation during the growing season (262 mm) was 90 cm greater than long-term (1960–2015) average, at entire growth period (Table 2). In 2015 and 2016 during the wheat-independent growth period, compared to CTI, NTSI2 and NTMI2 increased ET by 16.2–22.3% and 10.2–22.1%, and increased EC by 14.9–24.7% and 13.5–20.5%, respectively. From maize sowing to the pre-heading stage, straw and plastic management had no significant effect on ET and EC of four intercropping treatments. From the pre-heading to early-filling stages in maize, the NTSI2 and NTMI2 treatments increased ET by 6.8–14.0% and 4.9–10.5%, and increased EC by 4.7–6.4% and 4.5–9.1%, respectively, compared to CTI. From maize silking to the early-filling stage, the NTSI2 and NTMI2 treatments increased ET by 13.6–14.2% and 11.2–24.8%, and decreased EC by 14.5–16.5% and 20.2–25.1%, respectively, in comparison to CTI. However, from maize filling to harvesting stage after wheat harvest, NTSI2 and NTMI2 had 3.8–4.6% and 3.5–5.6% greater ET than CTI, respectively; and greater ET by 5.3–12.9% and 7.2–10.6%, greater EC by 3.7–7.8%, 6.4–7.2%, than TSI, respectively.

When compared to the CTI treatment, evapotranspiration with the NTSI2 and NTMI2 treatments was increased until maize silking, decreased from maize silking to the early-filling stage, and increased after the early-filling stage of maize. This effectively coordinated water demand contradiction of intercrops at early and late stages, and a greater extent with the NTMI2 treatment.

**E/ET ratio.** E/ET ratio of different cropping systems. Strip intercropping significantly reduced the ratio of soil evaporation to evapotranspiration (E/ET) by 8.7–15.6%, compared to monoculture wheat, but improved the E/ET ratio by 5.7–12.6%, compared to monoculture maize, during the entire crop growth period (Fig. 1). During the entire crop growth period, NTMW reduced the E/ET ratio of monoculture wheat by 6.9–21.3% compared to CTW; similarly, NTMI2 significantly reduced the E/ET ratio of intercropping by 8.6–17.5% compared to CTI.
Plastic mulching and straw residue are the two common soil water conservation measures which can enhance water infiltration and increase soil water retention\(^{28,29}\). The findings of previous researches showed that no tillage treatments (NTSII and NTMI2) significantly reduced the E/ET by 20.3–20.9% and 19.1–31.9%, compared to CTI, respectively, and TSI reduced the E/ET ratio by 6.8–12.1% (Table 3). Meanwhile, NTSII and NTMI2 reduced the E/ET ratio by 10.1–14.5% and 8.0–26.9% compared to TSI, respectively. However, from maize sowing to jointing stage, the E/ET ratio of NTSII and NTMI2 was increased by 9.2–14.8% and 7.2–10.9% compared to CTI, and was increased by 9.1–21.1% and 10.3–15.1% compared to TSI, respectively. From maize jointing to silking stage, NTSII and NTMI2 reduced the E/ET ratio by 10.1–22.6% and 4.4–29.3% compared to CTI, respectively. During the maize-filling stage in 2015 and 2016, the E/ET ratio of NTSII and NTMI2 was reduced by 5.9–7.0% and 11.6–25.2% compared to CTI, respectively, and the E/ET ratio of NTMI2 was reduced by 12.8–14.7% compared to TSI.

**Effects of straw and plastic management on water use efficiency (WUE) of intercropping systems.** Strip intercropping significantly enhanced WUE, no tillage with straw retention in wheat strips and two-year plastic mulching in maize strips (i.e., NTSII and NTMI2) further improved WUE by 5.5–6.6% and 23.0–44.2% compared to monoculture maize and wheat, respectively. For the monoculture wheat, NTSW, NTMW, and TSW treatments improved WUE by 21.1–28.3%, 26.6–30.6%, and 13.1–20.3% in comparison to CTW during the three study years (Fig. 5). Plastic film mulching patterns did not significantly affect WUE of monoculture maize. Within wheat-maize intercropping, NTSII, NTMI2, and TSI significantly improved WUE by 9.9–15.3%, 12.4–17.2%, and 13.4–15.8%, respectively, compared to CTI. At maize harvest, the effect of NTMI2 on conserving soil water was apparent. Here, we suggest that straw and two-year plastic mulching the soil surface are an indispensable component of wheat/maize strip intercropping. The increased soil water with straw coverage and two-year plastic mulching can partly offset the water deficit in intensified cropping systems. When combined with intercropping,
the alternative strip mulching pattern can be an ideal measure for empowering the capacity of soil moisture conservation in arid environments.

The findings of the current research clearly demonstrate that two-year plastic mulching measure integrated into wheat/maize intercropping with straw residue can decrease soil evaporation, especially wheat strips after wheat harvest. This is because crop residues and plastic mulching the soil surface typically form a barrier against evaporation, thus, maintaining the water storage in the crop root zone19,33. Also, straw mulching can reduce soil evaporation via the decreasing of soil temperature34,35. In wheat-maize intercropping, the two intercrops have different sensitivity to soil temperature. Wheat is in favor of cooler soil temperature whereas maize is in favor of warmer soil temperature. Optimizing soil temperature to satisfy the requirements for growth of these two intercrops simultaneously has been a challenge. Crop residues left on the soil surface help improve soil roughness, soil surface porosity, and hydraulic conductivity34. An added value is that straw mulching reduces soil temperature extremes36. Plastic mulch can significantly increase soil temperature37, in many cases, the use of plastic can markedly increase soil temperature compared to straw mulch38,39. In the present research, two-year plastic mulch is integrated together with wheat straw mulch in wheat-maize intercropping; the innovative technique is that plastic mulching is applied to the maize strips and straw mulch is applied to the wheat strips to balance and optimize soil temperature for the thermophilic maize and the cool-season wheat crops. Solar radiation intercepted on the soil surface can be transferred from maize to wheat strips in the mid to late part of the growing season to provide a heat “buffering effect” between the two crop strips40. Consequently, the integration of plastic film with straw mulch can significantly improve microenvironments, thus increasing crop productivity and water utilization. This further confirms the possibility of two-year plastic mulching measure applied to wheat/maize intercropping at a semiarid region. It suggests that the practice of mulching the soil with straw at wheat harvest can be used to glean more precipitation in rainfed farming areas or reduce irrigation amount in irrigated farming areas. Straw residue is a traditional conservation practice, but we found that this traditional technique coupled with two-year plastic mulching in an intensified intercropping system, can be extremely effective for improving yield and water use efficiency in an arid region of water shortage.

Interspecific competition and facilitation are the two main types of interactions in intercropping systems that coexist in mixed systems13. Facilitation occurs in most cereal/cereal intercropping systems and occurs as one component species enhances the growth of another species9. The competition and compensation of underground nutrients and water is a manifestation of interspecies relationship. In the present study, we determined the soil water competition and compensation for wheat/maize intercropping and found that soil water storage in wheat strips was significantly lower than that in maize strips during the wheat growing season. This was largely due to superior growth of the intercropped wheat compared to the adjacent maize. The cool-season wheat was sown about 30 days earlier than the warm-season maize, providing wheat with a time-advantage for uptake of more available water. Also, it might be possible that greater soil evaporation may have occurred in wheat strips.

Figure 5. Water use efficiency of various treatments under different cropping patterns in 2014–2016. Within a year, different letters indicate significant differences (P < 0.05) among treatments. Error bars are standard errors.
In strip intercropping systems, during the early-maturing crop growing period, early-maturing crop roots may extend into the territory of the late-maturing crop, enabling the early-maturity crop to compete for soil water in late-maturing crops. However, roots of the late-maturing crop will extend into the early-maturing crop’s rooting regions after the early-maturing crop has been harvested, thereby absorbing some of the remaining but unused soil water, resulting in a water compensation effect to the late-maturing crop. Previous researches have shown that the altered soil water potential is closely related to differences in soil water content, especially in dry soil layers. A horizontal driving force is generated between adjacent crop strips due to the differences in soil water content at a given soil depth, thus resulting in a supply of available water for the neighboring crops.

Therefore, strip intercropping contributes to an increasing ability to utilize soil water through the gradient difference in soil water storage between intercrop strips for a given soil layer. Asymmetric root systems in intercropping force soil water movement between rooting zones of the intercrops. In intercropping, roots of the early-maturing crop are initially deeper than the late-maturing crop, and after harvest of the early-maturing crop, early-maturing crop roots are fallow and roots of the late-maturing crop are dominant in the soil profile. Hence, improving cereals resource utilization by optimizing crop combination and cultivation measures to improve root morphology. Straw mulching has been shown to effectively conserve soil water and decrease soil temperature and water consumption. In addition, straw mulching has been shown to decrease the depth of crop roots in some cases, leading to weakened root interaction and competition of intercrops during their co-growth period. Therefore, in this study, wheat/maize strip intercropping with wheat straw mulching in wheat strips and two-year plastic mulching in maize strips resulted in the least amount of soil water movement to wheat from maize strips, with the wheat strip having the lowest level of competition for soil water.

After intercropped wheat has been harvested, straw mulching the soil surface can conserve more soil water in wheat strip, and more soil water can then move from wheat to maize strip. This movement compensates for the water requirement for growth of intercropped maize. Intercropping with no-tillage and straw mulching the soil surface in wheat strips and two-year plastic mulching in maize strips allowed the greatest amount of the remaining, unused water to be moved from wheat to maize strips, and conventional tillage treatment allowed the least. Here, we show that no tillage with straw mulching the soil surface in wheat strips combined with two-year plastic mulching in maize strips can weaken soil water competition during the wheat growth period and strengthen water compensation during maize-independent growth after wheat harvest, and thereby maintain water balance between intercrops strips. Hence, these improved practices can result in efficient utilization of water by regulating the water competition and complementary utilization relationship.

Conclusions
Wheat/maize strip intercropping combined with straw residue and plastic mulching can reduce soil evaporation, decrease the proportion of evaporation to evapotranspiration (E/ET), and improve crop yields and water use efficiency compared to conventional monoculture and intercropping treatments. Strip intercropping combined with straw mulching the soil surface in wheat strips and two-year plastic mulching in maize strips (i.e., NTM12) was most significant and decreased soil evaporation and the E/ET ratio by 9.0–17.3% and 8.6–17.5% compared to the conventional intercropping treatment (i.e., CTI) across the studies years. During the wheat growth period, wheat strips competed for soil water from the neighboring maize strips of intercropping. After intercropped wheat harvest, maize extracted soil water from wheat strips, which compensated water competition between intercropped strips. The NTM12 treatment favorably reduced the wheat strip competed soil water from the maize strip and enhanced the wheat strip compensated soil water for the maize strip, compared to CTI. Meanwhile, NTM12 boosted grain yields by 13.5–19.6% compared to conventional monoculture maize, by 1.7- to 1.8-fold compared to conventional monoculture wheat, and by 13.8–17.1% compared to the conventional intercropping treatment, and improved WUE by 3.2–5.7%, 40.8–64.9%, and 12.4–17.2%, respectively. The 3 year of field experiment showed consistent results that straw and two-year plastic mulching practices applied to wheat/maize intercropping can serve an effective water conservation technique for improving crop yields and WUE in arid irrigation areas.

Materials and Methods
Site description. The field experiment was conducted at the Wuwei Agricultural Experimental Station of Gansu Agricultural University near Wuwei City, Gansu Province, China (37°34’N, 102°94’E, 1506 m asl), from 2013–2016. Long-term (1960–2016) annual precipitation is less than 200 mm and annual potential evaporation is greater than 2000 mm. Average annual sunshine duration is 2945 h, solar radiation is 6000 MJ m⁻², and the frost-free period is 156 d. Heat conditions at this site are suitable for intercropping spring wheat and maize, with an average annual accumulated air temperature ≥ 10°C of 2985°C and annual mean air temperature of 7.2°C. In 2015 and 2016, weather conditions were similar to the long-term average. Precipitation throughout the growth period of the intercrops was 176 mm in 2015 and 196 mm in 2016, whereas in 2014, the growing season precipitation (262 mm) was greater than the long-term average (172 mm). The soil was classified as an Aridisol with soil bulk density in the 0–110 cm soil depth averaging 1.44 g cm⁻³.

Experimental design. The experiment was conducted using a randomized complete block design with three replicates. Treatments were applied to the same plots annually. In 2013, treatments involving different wheat straw management methods combined with two-year plastic film mulching were established in the field prior to the experimental study years 2014, 2015, and 2016. Four wheat straw management approaches were imposed after wheat grain harvest in the late fall of 2013, 2014, and 2015: (i) no tillage with 25–30 cm high wheat straw standing (NTS); (ii) no tillage with 25–30 cm high wheat straw cut 3 cm above the soil surface and evenly distributed over the soil surface (NTM); (iii) conventional tillage (tillage depth of 30–33 cm) using chisel plow with 25–30 cm high
China and were planted in all treatments of this experiment during the three testing years. The sole crop and
with a manual duckbill punch roller dibbler.

(tic was installed on the soil surface in maize strips of the conventional tillage treatments and maize was planted
pacted; then, spring wheat crop was planted with a strip rotary tillage wheat seeder. At the same time, a new plas-

spring in the conventional tillage treatments, soil in the wheat strips was fertilized, harrowed, leveled, and com-
mulching (CTM), and (ii) no tillage with two-year plastic mulching (NTM2). This resulted in 10 treatments. Each
returned (CTW). The two sole maize treatments were as follows: (i) conventional tillage with annual new plastic
incorporation or without straw residue and annual new plastic film mulching produced two conventional tillage
wheat/maize intercropping treatments: (i) conventional tillage with 25–30 cm high wheat straw was incorporated
into the soil in wheat strips and annual new plastic mulching in maize strips (TSI); and (ii) conventional tillage
without straw residue in wheat strips and annual new plastic mulching in maize strips (CTI). The straw retention
measures applied to sole wheat produced four treatments: (i) no tillage with 25–30 cm high wheat straw stand-
ning (NTSW) and (ii) no tillage with 25–30 cm high wheat straw mulching the soil surface (NTMW); (iii) tillage
with straw mulching. Two types of no tillage with wheat straw retention and two-year plastic mulching produced two no
wheat/maize intercropping treatments: (i) no tillage with 25–30 cm high straw standing in wheat strips and
two-year plastic mulching in maize strips (NTSI2) and (ii) no tillage with 25–30 cm high straw mulching the soil
surface in wheat strips and two-year plastic mulching in maize strips (NTM2). Conventional tillage with straw
incorporation or without straw residue and annual new plastic film mulching produced two conventional tillage
wheat/maize intercropping treatments: (i) conventional tillage with 25–30 cm high wheat straw was incorporated
into the soil in wheat strips and annual new plastic mulching in maize strips (TSI); and (ii) conventional tillage
without straw residue in wheat strips and annual new plastic mulching in maize strips (CTI). The straw retention
measures applied to sole wheat produced four treatments: (i) no tillage with 25–30 cm high wheat straw stand-
ning (NTSW) and (ii) no tillage with 25–30 cm high wheat straw mulching the soil surface (NTMW); (iii) tillage
with 25–30 cm high of wheat straw incorporation (TSW); and (iv) conventional tillage without the wheat straw
returned (CTW). The two sole maize treatments were as follows: (i) conventional tillage with annual new plastic
mulching (CTM), and (ii) no tillage with two-year plastic mulching (NTM2). This resulted in 10 treatments. Each
spring in the conventional tillage treatments, soil in the wheat strips was fertilized, harrowed, leveled, and com-
pacted; then, spring wheat crop was planted with a strip rotary tillage wheat seeder. At the same time, a new plast-
ic was installed on the soil surface in maize strips of the conventional tillage treatments and maize was planted
with a manual duckbill punch roller dibbler.

Spring wheat cultivar Ning-chun No. 2 and maize cultivar Xian-yu No. 335 are widely grown in northwestern
China and were planted in all treatments of this experiment during the three testing years. The sole crop and
strip intercropping treatments were sown and harvested on the same date for both wheat and maize. Spring
wheat was planted on 21 March, 29 March, 30 March and harvested on 24 July, 28 July, 21 July in 2014–2016,
respectively. Maize was planted on 25 April, 24 April, and 20 April and harvested on 1 October, 28 September, and
20 September of the three test years, respectively. The phenological stages of wheat and maize in intercropping
system was shown in Table 4. The experimental plot size was 48 m² (10 × 4.8 m). Intercropped wheat and maize
were alternated within 160-cm-wide strips and three of these strips constituted one intercropping plot. Each
160-cm-wide intercropped strip consisted of an 80-cm-wide wheat strip with six rows spaced 12 cm apart and an
80-cm-wide maize strip with two rows spaced 40 cm apart. Sole wheat and maize were established at 675 and 8.25
plants m⁻², respectively, and intercropped wheat and maize were established at 375 and 5.25 plants m⁻², respect-
ively. Nitrogen and phosphorus were applied using urea and diammonium phosphate. For intercropping treat-
ments, each crop received the same area-based rate of fertilizer as the corresponding sole crop. Nitrogen fertilizer
for wheat and maize was applied at 225 and 450 kg ha⁻¹, respectively. Phosphorus fertilizer for wheat and maize
was applied at 150 and 225 kg P2O5 ha⁻¹, respectively. All N and P fertilizer for wheat and all P fertilizer for maize
was broadcast and incorporated prior to sowing. For maize, 30% of N was broadcast and incorporated prior to
sowing, 60% was topdressed at the jointing stage, and the remaining 10% was topdressed at the filling stage. All
plots received 1200 m³ ha⁻¹ of irrigation water in the early winter after crops were harvested but before tillage
treatments and plastic mulch treatments were applied. Then, all plots received 750, 900, and 750 m³ ha⁻¹ of irriga-
tion at the seedling, booting, and beginning grain filling stage of monoculture wheat, respectively. Monoculture
and intercropped maize received 900, 750, 900, 750, and 750 m³ ha⁻¹ of irrigation at the jointing, pre-heading,
silking, flowering, and filling stage of monoculture maize; additionally, 750 m³ ha⁻¹ of irrigation was applied to
intercropped maize at the seedling stage. Polyvinyl chloride (PVC) pipes (15 cm diameter) were used for plot
flooding irrigation. A flow meter was installed to record irrigation amount of each plot.

Measurement and calculation. Soil water potential. Soil water potential (kPa) in each plot was measured
from the 0–120 cm layer in 30-cm increments using a set of mechanical tensiometers with accuracy of 0.1 Pa

| Crop growth period       | Crop | Wheat | Maize |
|--------------------------|------|-------|-------|
| Wheat-independent growth period | Sowing | Sowing | --     |
|                           | Jointing stage | Seeding stage |          |
| Wheat-maize co-growth period | Booting stage | Jointing stage |          |
|                           | Heading stage | Post-jointing stage |          |
|                           | Flowering stage | Pre-heading stage |          |
|                           | Filling stage | Heading stage |          |
|                           | Full-ripening stage (harvesting) | Silking stage |          |
| Maize-independent growth period | -- | Flowering stage |          |
|                           | -- | Filling stage |          |
|                           | -- | Full-ripening stage (harvesting) |          |

Table 4. The phenological stages of wheat and maize in intercropping system.
of each plot was calculated using the water balance equation as follows:

\[ \text{ET} = P_e + I + U - R - D_w - \Delta S \]  

where \( P_e \) is effective precipitation (mm), determined by the USDA Natural Resources Conservation Service in the late 1990s, \( I \) is irrigation quota (mm), \( U \) is upward capillary flow from the root zone (mm), \( R \) is runoff (mm), \( D_w \) is downward drainage out of the root zone (mm), and \( \Delta S \) is the change in soil water storage in the 0–120 cm layer (mm), from sowing to harvest of crops. Upward and downward flow was measured previously at a nearby field and was found to be negligible in this semiarid region. Runoff was also negligible due to small quantities of precipitation and irrigation that was controlled by raised ridges between plots.

Soil water movement potential (SWMP, mm) in the intercropping systems is defined as two-thirds of the high soil water storage (SWS, mm) minus the low SWS of crop strips at 0–120 cm soil depths and includes soil evaporation from the two crop strips. In addition to soil evaporation from the wheat and maize strips, if the late-maturing maize strips have greater soil water storage than the early-maturing wheat strips at a given soil depth, then, there is water competition from wheat strips to maize strips, and water competition is defined as the amount of soil water absorbed by wheat plants from the maize strips during the co-growth period. Alternately, if the early-maturing wheat strips have greater soil water storage than the late-maturing maize strips, then, there is water compensation from wheat strips to maize strips, and water compensation is defined as the amount of soil water absorbed by maize plants from the wheat strips after wheat harvest. Soil water movement potential is calculated as follows:

\[ \text{SWMP} = (\text{SWS}_{\text{high}} - \text{SWS}_{\text{low}} - E_W - E_M)/2 \]  

where \( \text{SWS}_{\text{high}} \) and \( \text{SWS}_{\text{low}} \) are high and low soil water storage of intercrop strips, respectively, and \( E_W \) and \( E_M \) are soil evaporation of intercropped wheat and maize strips, respectively.

Grain yield and water use efficiency (WUE). All plots were harvested artificially when wheat and maize reached physiological maturity, and the grain yields based on air-dried weight were obtained for each crop of the various treatment groups.

WUE was determined using the following equation:

\[ \text{WUE} = \frac{\text{GY}}{\text{ET}} \]  

where \( \text{GY} \) is grain yield (kg ha\(^{-1}\)) and \( \text{ET} \) is total evapotranspiration over the whole growing season (mm), calculated from Eq. (1) described above.
Statistical analysis. The SPSS program (SPSS software, 17.0, IBM Company, USA) was used to conduct analysis of variance. Treatment means were compared using Duncan’s multiple-range test at the 0.05 probability level. Treatment as fixed factor, because the treatment factors were applied in the same experimental plots during the 3 years of research, year and year × treatment as random factors. If the interaction of Treatment and Year was found significant, data were analyzed in separate years.

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Author Contributions
Qiang Chai designed the research; Wen Yin, Zhilong Fan, Falong Hu, Aizhong Yu, and Cai Zhao performed the research; Wen Yin analyzed the data; Wen Yin wrote the manuscript; Qiang Chai and Jeffrey A. Coulter reviewed and edited the manuscript.

Additional Information
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