Effects of Irrigation and Straw Mulching on Microclimate Characteristics and Water Use Efficiency of Winter Wheat in North China

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Abstract: In North China, irrigation is required to obtain a high yield from winter wheat; this results in rapid aquifer depletion. The primary objective of this study was to investigate the influencing mechanisms of irrigation and straw mulching in preserving the soil moisture. Maize straw (3−5 cm) was mulched immediately after sowing winter wheat, and irrigation water was supplied at 60 mm, controlled by using a flow meter, during the jointing, heading, or milking stages of the crop. The results revealed that irrigation decreased the eddy thermal diffusivity, sensible heat flux, and soil heat flux, but increased the latent heat flux. In contrast, straw mulching enhanced the eddy thermal diffusivity and sensible heat flux, but decreased the latent heat flux. Straw mulching increased the soil temperature at 5 cm depth form January to February, but decreased the soil temperature before January and after February. There were no significant differences in the total evapotranspiration between mulched and non-mulched treatments, however, there was a statistically significant difference in the evapotranspiration among the different growing seasons. Straw mulching reduced the evapotranspiration from the seeding stage to the regrowing stage, and the evapotranspiration with mulching was less than that non-mulching 47.4 mm. Further, straw mulching significantly reduced the number of spikes in the crop. Both irrigation and straw mulching increased the number of kernels, but had no visible effects on the thousand kernel weight. These results indicate that straw mulching may decrease the yield and water use efficiency (WUE) of winter wheat in North China.

Key words: Irrigation, Microclimate, Straw mulching, Water use efficiency, Winter wheat.
reduce soil evaporation and to increase the WUE. Researchers have studied the relationships between straw mulching and WUE of winter wheat (Anderson and Kemper, 1964; Unger, 1978; Limon-Otetga et al., 2000). But only few researchers could interpret the relationship between straw mulching mechanisms and evapotranspiration characteristics of crops. However, the underlying mechanisms that control the effect of mulch on crop evapotranspiration characteristics are not completely understood. This study aims to determine: (i) the effect of irrigation and straw mulching on the microclimate characteristics of winter wheat farmland; (ii) the changes in soil evaporation and transpiration in the winter wheat season; and (iii) the effect of irrigation and straw mulching on the yield and WUE of winter wheat.

Materials and Methods

1. Experimental site
The experiment was conducted at the pool cultures of Yucheng Comprehensive Experimental Station (36° 57’ E, 116° 38’ N, 20 m above the sea level) of the Chinese Academy of Sciences in Shandong Province, north China. It is 1 of the 34 agricultural ecosystem stations of Chinese Ecological Research Network. The area of the pool cultures is 6.7 m$^2$, with a depth of 1.5 m, its walls are concrete, and a neutron access tube has been installed in the center. The soil is formed from the sediments of the Yellow River and is calcareous, alkaline, and rich in phosphorus and potassium. Agriculture in this area is intensified by a double cropping system with a high-yielding cultivar and high fertilizer and water inputs. The site is characterized by a summer monsoon climate with a mean annual precipitation of 515 mm, of which 70−80% is in the summer maize growing season (July to late September) and only 20−30% is in the winter wheat growing season (October to early June). During 2002−2003, the precipitation in the winter wheat season was 222.2 mm. Winter wheat was sown on October 4, 2002. At the time of sowing, 30.0 g m$^{-2}$ of triple superphosphate, 30.0 g m$^{-2}$ of urea and 7.5 g m$^{-2}$ of potassium chloride were applied. The heading stage and harvesting stage of winter wheat commenced on April 26, 2003 and June 2, 2003, respectively.

2. Experimental design
This study was based on the experiment conducted between 2001 and 2002 (Fang et al., 2004). 4 selected irrigation treatments were used: no supplemental irrigation throughout the entire growth cycle of winter wheat; applying irrigation at the jointing stage, applying irrigation at the jointing and heading stages; applying irrigation at the jointing, heading and milking stages. On October 4, 2002, straw mulching was carried out on selected plots by applying 1.1 kg m$^{-2}$ maize straw that was chopped to 3−5 cm and contained 80% dry-matter. Treatments were randomized using a complete factorial design and were replicated 3 times. An outline of the treatments applied is presented in Table 1. The amount of irrigation was controlled at 60 mm. Basin irrigation, which is widely used in the region, was used in the experiments. The water was supplied from the outlet of a pump to the pool cultures via plastic pipes, and a flow meter was used to measure the amount of water used.

3. Measurements
Throughout the entire growth cycle of winter wheat, a single aluminum access tube was installed to a depth of 120 cm in each experimental plot, and soil volumetric water content was measured using a neutron moisture probe calibrated separately on the site. Counts for 10 cm depth increments were obtained for 64 sec, and measurements were repeated at approximately 5−7 days intervals. After irrigation or precipitation events, additional measurements were taken. During the course of the experiment, diurnal soil temperatures between 8 A.M. and 8 P.M. at soil depths of 0, 5, 10, 15 and 20 cm were measured.

| Treatments | Mulching | Jointing 02/04/06$^*$ (mm) | Heading 02/04/26 (mm) | Milking 02/05/15 (mm) | Total irrigation amount (mm) |
|------------|----------|-----------------------------|------------------------|------------------------|-----------------------------|
| N0         | Non-mulching | 0                           | 0                      | 0                      | 0                           |
| N1         | Non-mulching | 60                          | 0                      | 0                      | 60                          |
| N2         | Non-mulching | 60                          | 60                     | 0                      | 120                         |
| N3         | Non-mulching | 60                          | 60                     | 60                     | 180                         |
| M0         | Mulching   | 0                           | 0                      | 0                      | 0                           |
| M1         | Mulching   | 60                          | 0                      | 0                      | 60                          |
| M2         | Mulching   | 60                          | 60                     | 0                      | 120                         |
| M3         | Mulching   | 60                          | 60                     | 60                     | 180                         |

$^*$The format was YY/MM/DD.
on selected cloudy and sunny days. Between 8:00 and 20:00, relative humidity and air temperature were measured by determining the dry and wet bulb temperatures every hour at heights of 5, 20 and 50 cm above the ground level. The values of mean monthly precipitation and air humidity that were obtained from a weather station located near the experiment area are listed in Table 2.

Radiant energy absorbed by the earth’s surface was mostly used for increasing the air temperature, soil evaporation, and soil temperature as follows:

\[ R = H + LE + G \] (1)

In equation (1), \( R \) is the net radiation flux; \( H \), sensible heat flux; \( LE \), latent heat flux; and \( G \), soil heat flux. In China, eddy thermal diffusivity, sensible heat flux, latent heat flux, and soil heat flux are typically calculated by using the equations presented below (Weng et al., 1981):

Eddy thermal diffusivity is calculated using the following equation:

\[ K(z) = k^2 (u_2 - u_1) / \ln(z_2/z_1) [1 + (T_1 - T_2)/(u_2 - u_1)]^2 \ln[(z_2/z_1)]/Z \] (2)

In equation (2), \( K(z) \) is the eddy thermal diffusivity at \( z \) height; \( k = 0.38 \) is a constant; \( z_1 = 0.05 \) m and \( z_2 = 0.50 \) m; \( T_1 \), \( T_2 \) and \( u_1 \), \( u_2 \) are air temperatures and wind speeds at 0.05 and 0.50 m, respectively; \( Z \) is some height between \( z_1 \) and \( z_2 \), and \( z = 0.20 \) m in this experiment.

Sensible heat flux is calculated as follows:

\[ H = -\rho c_p K \frac{\partial T}{\partial z} \] (3)

In equation (3), \( H \) is the sensible heat flux (W m\(^{-2}\)); \( \rho = 0.00129 \) g m\(^{-3}\) and \( c_p = 1.008 \) J g\(^{-1}\) C\(^{-1}\) are constants; \( K \) is the eddy thermal diffusivity; and \( \frac{\partial T}{\partial z} \) is the lapse rate.

After conversion, equation (3) appears as follows:

\[ H = 5\rho c_p K_{\text{a}} (T_1 - T_2) / \ln(Z_2/Z_1) \] (4)

In equation (4), \( K_{\text{a}} \) is the eddy thermal diffusivity at 0.20 m; and \( T_1 \) and \( T_2 \) are the temperatures at 0.05 and 0.50 m, respectively.

Latent heat flux is calculated using the following equation:

\[ LE = 5\rho L K_{\text{a}} (q_1 - q_2) / \ln(Z_2/Z_1) \] (5)

In equation (5), \( E \) is the vaporizing water quantity (g); \( L \), vaporizing latent heat; and \( q \), air specific humidity (g kg\(^{-1}\)).

Soil heat flux is calculated using the following equation:

\[ SE = \frac{C_v}{\Delta t} \left| S_1 - \frac{k}{10} S_2 \right| [\text{mm}] \] (6)

In equation (6), \( SE \) is the soil heat flux of 0–0.20 m soil profiles in \( \Delta t \) time; \( C_v \), soil volume heat capacity; \( k \), conduct temperature ratio per day; \( \Delta t \), intervals between two observation hours; and \( S_1 \) and \( S_2 \), temperature variation in 0–0.20 m and 0.10–0.20 m soil profiles, respectively.

Before the winter wheat season, the leaf area index (LAI) of winter wheat was small, and soil evaporation constituted most of the evapotranspiration under field conditions. Soil evaporation was estimated using the relationship proposed by Liu et al. (1998):

\[ E/ET = 1.157361 + 0.525615 (\ln \theta_v) \] (7)

In equation (7), \( E \) is soil evaporation; \( ET \), evapotranspiration; and \( \theta_v \), soil moisture content at a depth of 0–0.10 m measured using the gravimetrical method. The following water balance relationship was used for estimating ET from the moisture and irrigation data (Zhang et al., 1998):

\[ ET = I + P - R - D - \Delta W \] (8)

In equation (8), \( ET \) is evapotranspiration (mm); \( I \), the amount of irrigation water (mm); \( P \), precipitation (mm); \( R \), surface runoff (mm); \( D \), drainage and deep percolation (mm); and \( \Delta W \), the change in soil moisture between maturity and seeding seasons (mm).

There were no major precipitation events throughout the growth cycle of winter wheat, therefore, surface runoff was assumed to be non-significant. Since the water table depth at the Yu Cheng experimental station exceeded 5 m, capillary rise could be omitted from the |Climatic variables| Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | June |   |
|---|---|---|---|---|---|---|---|---|---|---|
| Precipitation (mm) | 8.7 | 20.0 | 3.3 | 23.9 | 12.4 | 31.8 | 63.2 | 44.1 | 14.8 |   |
| Humidity (%) | 66 | 63 | 85 | 74 | 68 | 67 | 70 | 75 | 69 |   |
| ET\(_0\) (mm day\(^{-1}\)) | / | / | / | / | / | 2.4 | 2.6 | 3.3 | 4.2 |   |

\(^{a}\)Precipitation and air humidity in October were the mean monthly from sown day to Oct 31.  
\(^{b}\)Precipitation and air humidity in June were the mean monthly from June 1 to harvested day.  
\(^{c}\)ET\(_0\) was monthly reference evapotranspiration computed using FAO Penman-Monteith method (Allen et al, 1998).
equations. Therefore,

\[ \text{ET} = I + P - \Delta W \]  

(9)

After regrowing in the spring season, according to the models of Kang et al. (1995) that were based on energy balance,

\[ \frac{T}{E_{Tc}} = 1 - e^{-K (1.0 + A \cdot \sin(t - 13) / 12) \cdot \text{LAI}} \]  

(10)

\[ \frac{E_s}{E_{Tc}} = e^{-K (1.0 + A \cdot \sin(t - 13) / 12) \cdot \text{LAI}} \]  

(11)

In equations (10) and (11), \( E_{Tc} \), \( T \), and \( E_s \) are crop evapotranspiration under standard conditions, transpiration, and soil evaporation, respectively; \( K = 0.3973 \) and \( A = 0.10364 \) are experimental coefficients; \( t \) is the time; LAI is computed as the product of specific leaf area and the total leaf mass divided by the sample area (320 cm\(^2\)), the LAI of every treatment is shown in Table 3.

\( K_c \) is the crop coefficient (Table 4) calculated using equation (12) mentioned below (Abdelhadi et al., 2000):

\[ K_c = \frac{E_{Tc}}{E_T} \]  

(12)

In equation (12), \( E_T \) is the reference crop evapotranspiration calculated using the FAO Penman-Monteith equation (Allen et al., 1998).

A major weakness of equations (10) and (11) is the inaccuracy of estimating soil evaporation when soil moisture is a limited factor. FAO showed that the relationship between \( E_T \) and \( E_{T0} \) (Richard and Allen, 1998) was as follows:

\[ E_{Tc} = K_c \times E_{T0} \]  

(13)

\[ E_{Tadj} = K_s \times E_{Tc} \]  

(14)

In equations (13) and (14), \( E_{Tadj} \) is crop evapotranspiration under nonstandard conditions; \( K_c \), crop coefficient; and \( K_s \), water stress coefficient, that was expressed by the relative water content and calculated using the following formula:

\[ K_s = \frac{\theta_a - \theta_{wp}}{\theta_s - \theta_{wp}} \]  

(15)

In equation (15), \( \theta_a \) is the actual soil moisture content; \( \theta_{wp} \), wilting soil volumetric moisture content (8%); and \( \theta_s \), saturated soil volumetric moisture content (25%).

If \( \theta_{wp} < \theta_a < \theta_s \), then equations (10) and (11) could be modified as follows:

\[ T = (1 - e^{-K (1.0 + A \cdot \sin(t - 13) / 12) \cdot \text{LAI}}) \times e^{-\left(\frac{\theta_a - \theta_{wp}}{\theta_s - \theta_{wp}} - 1\right) \times E_{T0} \times K_s} \]  

(16)

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**Table 3. LAI in winter wheat growing season.**

| Treatments | 02/12/08* | 03/02/07 | 03/03/09 | 03/04/09 | 03/05/08 | 03/06/02 |
|------------|-----------|-----------|-----------|-----------|-----------|-----------|
| N0         | 0.42a     | 0.56a     | 1.29b     | 2.29c     | 1.89h     | 0.89f     |
| N1         | 0.40a     | 0.57a     | 1.33a     | 2.79a     | 2.69e     | 1.47e     |
| N2         | 0.39a     | 0.55ab    | 1.31ab    | 2.75ab    | 2.79d     | 1.60c     |
| N3         | 0.38ab    | 0.57a     | 1.35a     | 2.72a     | 3.06c     | 1.64c     |
| M0         | 0.35c     | 0.46cd    | 1.18c     | 1.57e     | 2.51f     | 0.81g     |
| M1         | 0.32c     | 0.48c     | 1.15cd    | 1.71d     | 2.27g     | 1.55d     |
| M2         | 0.30c     | 0.44cd    | 1.12d     | 1.74d     | 3.44b     | 1.90b     |
| M3         | 0.36bc    | 0.45cd    | 1.14d     | 1.70d     | 3.57a     | 2.16a     |

*The format was YY/MM/DD. Figures followed by the same letters are not significantly different and that followed by different letters are significantly different at P < 0.05 based on LSD test.

**Table 4. Kc in winter wheat growing season.**

| Treatments | 02/12/08* | 03/02/07 | 03/03/09 | 03/04/09 | 03/05/08 | 03/06/02 |
|------------|-----------|-----------|-----------|-----------|-----------|-----------|
| N0         | 0.49a     | 0.59a     | 0.81c     | 1.44e     | 1.04f     | 0.55g     |
| N1         | 0.41b     | 0.59a     | 0.80c     | 2.45c     | 1.21d     | 0.52h     |
| N2         | 0.47a     | 0.60a     | 0.82c     | 2.40c     | 1.88b     | 0.77d     |
| N3         | 0.45ab    | 0.61a     | 0.81c     | 2.41c     | 1.84b     | 1.27b     |
| M0         | 0.28cd    | 0.34c     | 1.13b     | 1.70d     | 1.05c     | 0.65f     |
| M1         | 0.27d     | 0.36bc    | 1.11a     | 2.66ab    | 1.21c     | 0.68e     |
| M2         | 0.30c     | 0.37b     | 1.15a     | 2.61b     | 1.89a     | 0.88c     |
| M3         | 0.29c     | 0.35bc    | 1.13a     | 2.67a     | 1.85a     | 1.39a     |

*The format was YY/MM/DD. Figures followed by the same letters are not significantly different and that followed by different letters are significantly different at P < 0.05 based on LSD test.
If $\theta_s > \theta_a$ in equation (10) and $\theta_a < \theta_{wp}$ in equation (11), then equations (16) and (17) could be modified as follows:

$$ E_s = 0 \quad (19) $$

Based on equations (16), (17), (18), and (19), the effects of winter wheat on soil evaporation and transpiration could be estimated. In this study, soil evaporation was determined based on the soil moisture content at a depth of 0 - 0.10 m, and transpiration was determined based on the soil moisture content at a depth of 0 - 0.90 cm.

WUE was defined as follows (Zhang et al., 1999; Mahrup et al., 2005):

$$ WUE = \frac{Y}{ET} \quad (20) $$

In equation (20), $Y$ is the grain yield and $ET$ is the total seasonal evapotranspiration.

4. Statistical analysis

The treatments were analyzed using the analysis of variance (ANOVA). For ANOVA, $\alpha = 0.05$ was set as the level of significance to determine whether significant differences existed among the means of the various treatments. Multiple comparisons were performed for significant effects with the LSD test at $\alpha = 0.05$.

Results

1. Effects of irrigation and straw mulching on microclimate elements of winter wheat fields

Straw mulching could provide a physical barrier between the soil and atmosphere and consequently improve soil moisture retention and heat conditions of the soil surface. Fig. 1 was based on the data of May 6, 2003; similar patterns were obtained even from the data of other days. Irrespective of whether irrigation was applied, the eddy thermal diffusivity was higher in the mulched treatments than in the non-mulched treatments (Fig. 1 A), this was because caused by the presence of straw mulch increased the air temperature near the ground surface. Irrespective of whether mulching was performed, irrigation reduced the turbulence coefficient to 0.20 m and the effect of the increase in air temperature near the ground surface was reduced.

The heat used for increasing the air temperature was considerably greater in the mulched treatments than in the non-mulched treatments (Fig. 1 B). At noon, sensible heat flux attained its maximum value: it was higher in M0 than in N0 by 69 W m\(^{-2}\) and higher in M3 than in N3 by 63 W m\(^{-2}\). Therefore, for the non-irrigated treatments, more heat was required for increasing the air temperature near the ground surface.

Before 11 A.M., irrespective of whether irrigation was applied, the latent heat flux in the mulched treatments was substantially higher than that in the

$$ T = (1 - e^{-(1.0 + 0.5 \sin(t - 13)/12) \times LAI}) \times e^{(\theta_s - \theta_{wp})/\theta_{wp} - 1} \times ET_0 \times K_c \quad (17) $$

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Before 11 A.M., irrespective of whether irrigation was applied, the latent heat flux in the mulched treatments was substantially higher than that in the
non-mulched treatments (Fig. 1 C), this was probably due to the morning dew on the straw. After sunrise, the air temperature increased and the dew evaporated. Later during the day, the latent heat flux was considerably higher in the non-mulched treatments than in the mulched treatments, and it was higher in the irrigation treatments than in the non-irrigation treatments. These results indicated that the heat used for evaporation was considerably lower in the mulched treatments than in the non-mulched treatments, and it was considerably higher in the irrigation treatments than in the non-irrigation treatments.

Soil heat flux is the heat used for increasing soil temperature. Before 2 P.M., the soil heat flux was lower in the mulched treatments than in the non-mulched treatments (Fig. 1 D): this is because the maize straw blocks the solar rays. After 2 P.M., the results were adverse.

2. Effect of straw mulching on soil temperature of winter wheat farmland

With the increase in the air temperature, the soil temperature at a depth of 5 cm also increased (Fig. 2). However, compared to the effect of air temperature, the increase in soil temperature exhibited an hysteretic effects. The effect of straw mulching on the soil temperature has two sides: from January to February, the soil temperature was considerably higher in the mulched treatments than in the non-mulched treatments (Fig. 1 D): this is because the maize straw blocks the solar rays. After 2 P.M., the results were adverse.

3. Effects of irrigation and straw mulching on evaporation and transpiration of winter wheat

Based on energy balance, straw mulching could reduce the latent heat flux; therefore, soil evaporation could be decreased appreciably by the mulched treatments (Fig. 3 A). The results showed that from November 2002 to February 2003, soil evaporation was relatively low in all the treatments, particularly in mulched treatments wherein soil evaporation was approximately zero. Although soil evaporation was low during this period, the effects of straw mulching in reducing soil evaporation were rather pronounced because this period was considerably long. After February 2003, the air temperature increased gradually and let to an increase in soil evaporation: the soil evaporation intensity was higher in the non-mulched treatments than in the mulched treatments. On April 9, 2003, with the jointing stage irrigation, soil evaporation rates in N3 and M3 increased considerably. The maximum values in N3 and N0 were 2.1 and 1.6 mm d\(^{-1}\), respectively, and irrigation increased the soil evaporation rates by approximately 30%.

Before February 7, 2003, there was only slight transpiration in every treatment (Fig. 3 B). From February 7, 2003 to April 9, 2003, although the LAI was significantly lower in the mulched treatments than in the non-mulched treatments (Table 3), transpiration in the former was substantially higher. On May 8, irrespective of whether irrigation was applied, the LAI was higher in the mulched treatments than in the non-mulched treatments. Accordingly, transpiration reached the maximum value of the entire growing seasons: the values in M3 and N3 were 5.6 mm d\(^{-1}\) and 4.5 mm d\(^{-1}\), respectively, while those
in M0 and N0 were only 1.8 mm d\(^{-1}\) and 1.7 mm d\(^{-1}\), respectively. Subsequently, the transpiration decreased in every treatment. On June 2, 2003, transpiration was higher in M3 than in N3 by 0.8 mm d\(^{-1}\), while it was lower in M0 than in N0 by 0.4 mm d\(^{-1}\), accordingly, LAI was significantly lower. This suggests that under the conditions of non-irrigation, straw mulching could decrease winter wheat transpiration in the later growing season.

4. Evapotranspiration in different growing seasons of winter wheat

From the seeding to the regrowing stage, evapotranspiration in the non-mulched treatments was 47.4 mm higher than that in the mulched treatments (Table 5). During these stages, evaporation accounts for the majority of the overall water loss. During these growth stages, the air temperature was very low and evaporation was limited. This period lasted for was 137 days (56.8% of the growing seasons): therefore, the benefit of straw mulching in preserving soil moisture was more pronounced. After the jointing stage, soil evaporation reduced gradually and transpiration increased. Therefore, the maximum soil moisture consumption in winter wheat farmland was by transpiration. After March 2003, there was little difference between N0 and M0 with regard to transpiration, but transpiration in M3 was considerably higher than that in N3 (Fig. 3 B), indicating that with irrigation, straw mulching could substantially increase the transpiration of winter wheat. Hence, with the increase in transpiration, evapotranspiration in the mulched treatments during the jointing-heading stages, heading-filling stages and filling-maturity stages also significantly increased, and the values were higher than those in the non-mulched treatments.

5. Evapotranspiration of winter wheat farmland

With the increase in the application rates of

### Table 5. Evapotranspiration in different growing seasons of winter wheat.

| Treatments     | Seeding-Regrowing | Regrowing-Jointing | Jointing-Heading | Heading-Filling | Filling-Maturity |
|----------------|--------------------|--------------------|------------------|-----------------|------------------|
|                | 02/10/04−03/02/18* | 03/02/18−03/04/03   | 03/04/03−03/04/26| 03/04/26−03/05/15| 03/05/15−03/06/02|
|                | 137days            | 44days             | 23days           | 19days          | 18days           |
| N0             | 50.2a              | 53.8b              | 87.1d            | 57.0e           | 39.4g            |
| N1             | 49.1a              | 50.2bc             | 143.1b           | 59.2c           | 32.8h            |
| N2             | 51.0a              | 51.0b              | 144.8b           | 100.3b          | 55.8d            |
| N3             | 52.1a              | 53.8b              | 148.0b           | 102.2b          | 95.6b            |
| M0             | 3.1b               | 71.3a              | 101.8c           | 57.7d           | 44.5e            |
| M1             | 2.3b               | 70.0a              | 160.2a           | 62.6c           | 40.1f            |
| M2             | 5.0b               | 70.6a              | 158.3a           | 102.3a          | 64.4c            |
| M3             | 2.5b               | 71.9a              | 161.5a           | 103.4a          | 97.9a            |

*The format was YY/MM/DD. Figures followed by the same letters are not significantly different and that followed by different letters are significantly different at P < 0.05 based on LSD test.

### Table 6. Evapotranspiration of winter wheat farmland from 02/10/04 to 03/06/02 : 241 days.

| Treatments | Change in soil moisture (mm) | Precipitation (mm) | Irrigation (mm) | Evapotranspiration (mm) |
|------------|------------------------------|--------------------|-----------------|-------------------------|
| N0         | 65.3a                        | 222.2              | 0               | 287.5e                  |
| N1         | 52.2f                        | 222.2              | 60              | 334.4d                  |
| N2         | 56.7c                        | 222.2              | 120             | 398.9c                  |
| N3         | 49.5g                        | 222.2              | 180             | 451.7a                  |
| M0         | 56.2d                        | 222.2              | 0               | 278.4e                  |
| M1         | 53.0e                        | 222.2              | 60              | 335.2d                  |
| M2         | 58.4b                        | 222.2              | 120             | 400.6c                  |
| M3         | 35.0h                        | 222.2              | 180             | 437.2b                  |

Figures followed by the same letters are not significantly different and that followed by different letters are significantly different at P < 0.05 based on LSD test.
irrigation, the change in soil moisture had decreased, and the overall volumetric soil moisture variation in N0, N1, N2, and N3 accounted for 22.7%, 15.6%, 14.2%, and 11.0% of the total evapotranspiration, respectively (Table 6). During all the growing seasons of winter wheat, the main water supply resources were precipitation and irrigation, and irrigation largely affected most of the differences in evapotranspiration. With the increase in the amount of irrigation, evapotranspiration of winter wheat also increased. Differences in the total evapotranspiration between M3 and N3, M2 and N2, M1 and N1, and M0 and N0 were 14.5, 1.7, 0.8, and 9.1 mm, respectively. However, the differences between only M3 and N3 were statistically significant. Therefore, with an increase in the amount of irrigation, the effects of straw mulching on protecting soil moisture also improved.

6. Effects of irrigation and straw mulching on the yield of winter wheat

When the same amount of irrigation water was applied, straw mulching reduced the yield greatly: the differences between N0 and M0, N1 and M1, N2 and M2, and N3 and M3 were statistically significant (Table 7). Among the yield compositions, the largest effect of straw mulching was on the number of spikes, and this number was significantly lower in the mulched treatments. Irrigation and straw mulching had a large effect on the number of kernels of winter wheat. When the amount of irrigation water was constant, the number of kernels was much higher in the mulched treatments than in the non-mulched treatments. The effects of irrigation and straw mulching on the thousand kernels weight were not significantly different between any 2 treatments except between M3 and M0.

7. The relationship of evapotranspiration with yield and WUE of winter wheat under various conditions of irrigation and straw mulching

In the non-mulched treatments (Fig. 4), evapotranspiration of winter wheat ranged from 276.4 to 453.1 mm and yield (Yw) as a function of crop evapotranspiration (ET) could be described as follows: \[ Y_w = -32.033 + 2.5288ET - 0.0025ET^2 \] (r²=0.9742, n=16). Based on this quadratic equation, the maximum yield could be attained if evapotranspiration was 453.1 mm, which translates to

![Figure 4](image1.png)  
**Fig. 4.** Relationship between evapotranspiration and yield of winter wheat.

![Figure 5](image2.png)  
**Fig. 5.** Relationship between evapotranspiration and WUE of winter wheat.

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| Treatments | Spike numbers (hundred m⁻²) | Kernel numbers (kernel spike⁻¹) | Thousand kernels Weight (g) | Yield (g m⁻²) |
|------------|-----------------------------|---------------------------------|-----------------------------|---------------|
| N0         | 4.1d                        | 45.3f                           | 29.4b                       | 499.0cd       |
| N1         | 4.2c                        | 48.7e                           | 29.6ab                      | 528.7bc       |
| N2         | 4.3b                        | 49.9de                          | 30.7ab                      | 540.5bc       |
| N3         | 4.5a                        | 51.7c                           | 31.3ab                      | 598.6a        |
| M0         | 3.8h                        | 48.6e                           | 29.5b                       | 460.0e        |
| M1         | 3.8g                        | 51.2cd                          | 30.4ab                      | 466.7d        |
| M2         | 3.9f                        | 55.2b                           | 31.0ab                      | 501.2d        |
| M3         | 4.0e                        | 57.1a                           | 31.7a                       | 554.0b        |

Figures followed by the same letters are not significantly different and that followed by different letters are significantly different at P<0.05 based on LSD test.
a yield of 600.5 g m$^{-2}$. In the mulched treatments (Fig. 4), evapotranspiration ranged from 273.4 to 443.1 mm, and the corresponding yield equation was as follows: 
$Y_{M} = 53.34 + 1.812ET - 0.0015ET^2$  \((r^2 = 0.9838, n = 16)\), the optimum yield would be 561.7 g m$^{-2}$ at a cumulative crop ET of 443.1 mm.

In the mulched treatments (Fig. 5), the relationship between evapotranspiration (ET) and WUE (YM) was 
$Y_{M} = -0.000005ET^2 + 0.0014ET + 1.6729$  \((r^2 = 0.9919, n = 16)\). Since the range of data in ET is from 273.4 to 443.1 mm, when ET was 273.4 mm, the highest WUE was 1.62 g m$^{-2}$ mm$^{-1}$; In the non-mulched treatments (Fig. 5), the relationship between evapotranspiration (ET) and WUE (YM) was 
$Y_{N} = -0.000004ET^2 + 0.0009ET + 1.6729$  \((r^2 = 0.9838, n = 16)\). Since the range of data in ET is from 276.4 to 453.1 mm, when ET was 276.4 mm, the highest WUE was 1.67 g m$^{-2}$ mm$^{-1}$. Therefore, straw mulching could considerably reduce the maximum WUE of winter wheat greatly.

**Discussion**

Many researchers considered that straw mulching could considerably increase the yield and WUE of winter wheat (Zhao et al., 1996; Gu et al., 1998). In this experiment, the soil temperature was substantially lower in the mulched treatments than in the non-mulched treatments after February. Within a range of 0–40˚C, higher soil temperature is beneficial for root system expansion (Ksapar and Bland, 1992; Bai et al., 1996). A low temperature probably affects the ability of the root system to absorb soil moisture and nutritional elements (Chen et al., 2002). Hence, many tillers could not develop (Li et al., 2006a), and the number of spikes were considerably lower in the mulched treatments than in the non-mulched treatments. Briefly, straw mulching exhibited effects on the growth and development of winter wheat in the later growing season.

From March to April 2003, LAI was quite lower in the mulched treatments than in the non-mulched treatments, but transpiration was higher in the former than in the later. During the proceeding of photosynthesis, transpiration could be highly affected by water, temperature, wind and radiation regimes which often interact to induce a number of responses on the biological systems. The increased vapor pressure deficit would increase the atmospheric gradient for transpiration and would lead to increased crop water use from the soil (Hatfield and Prueger, 1996). Forseth and Teramura (1987) found that transpiration showed an initial increase at intermediate water vapor deficits. Li and Tang (2006) discovered that transpiration was significantly and positively related to PAR and air temperature, while it was negatively related to relative humidity. Straw mulching placed on the soil surface induce a variety of dynamic changes in the microclimate of the soil and the atmosphere near the soil surface. In the later growing season of winter wheat, straw mulching reduced transmittance and reflectance of PAR, and therefore the PAR capture ratio increased (Li et al., 2006a). Heat used for evaporation in the mulched treatments was much lower than that in the non-mulched treatments, and more heat was being used for increasing air temperature than in the non-mulched treatments. Then in the straw mulching conditions, the air humidity at 5 cm above the ground had decreased, while the air temperature at 5 cm above the ground had increased (Li et al., 2006b). These factors may be responsible for the higher transpiration in the mulched treatments than in the non-mulched treatments in these growing seasons. After April 2003, dry matter accumulation and total solar energy utilization efficiency was much better in the mulched treatments than in the non-mulched treatments (Li et al., 2006a), indicating that later in the growing season, straw mulching improved the above-ground microclimate, an effect that was beneficial for increasing the yield and WUE.

Another positive effect of straw mulching was the decrease in soil evaporation. The experiment showed that straw mulching could reduce the latent heat flux, thereby leading to decrease soil evaporation. Hence, a large amount of soil moisture could accumulate in the soil, and this moisture could be absorbed by winter wheat in the later growing season. Vapor losses were mostly centralized among the bare rows, and there is little soil moisture evaporation in the inner rows due to the crops covering the soil surface. The authors believe that the crop’s straw should be mulched among the bare rows of winter wheat, this would not only avoid the detrimental effects on both soil temperature and tillers of winter wheat but also restrain soil moisture evaporation. In the Huanghuaihai Plain of north China, the most widespread planting pattern of winter wheat is “20+40”, i.e., the narrow row measures 20 cm and the wide row measures 40 cm (Chen et al., 2003). In the later growing seasons of winter wheat, the narrow rows are completely covered with leaves, and therefore there is only little soil evaporation. However, since leaves can not completely cover the wide rows, soil evaporation in the wide rows is extremely large. If the crop’s straw are mulched over the wide rows in the “20+40” planting pattern of winter wheat, then soil evaporation could be effectively restrained.

This experiment showed that straw mulching exhibited not only some positive effects on the yield and WUE of winter wheat, but also some negative effects. Among the elements comprising a yield, only the spike numbers had reduced. If effective measures are taken to prevent this decrease in the number of spikes, straw mulching could definitely increase the yield and WUE of winter wheat.
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