Quantification of maize water uptake from different layers and root zones under alternate furrow irrigation using stable oxygen isotope

Youjie Wu a, Taisheng Du a,*, Fusheng Li b, Sien Li a, Risheng Ding a, Ling Tong a

a Center for Agricultural Water Research in China, China Agricultural University, Beijing 100083, China
b College of Agriculture, Guangxi University, Nanning, Guangxi 530005, China

**A R T I C L E   I N F O**

Article history:
Received 15 May 2015
Received in revised form 14 January 2016
Accepted 23 January 2016

Keywords:
Alternate furrow irrigation
Stable isotope
Maize
Root water uptake
IsoSource model

**A B S T R A C T**

How to quantify the root water uptake from different soil layers under alternate furrow irrigation (AFI) condition accurately, is still of great challenge. In this study, the stable hydrogen and oxygen (δD and δ18O) isotopes of soil water, stem water, rainfall and irrigation water (groundwater) in the maize field system under AFI condition were measured during 2013–2014. The root water uptake was estimated by the multi-source mass balance method (IsoSource model). Results showed that δ18O distribution varied significantly between the ridge (R) and furrow (F) near soil surface, and between ridge surface and wet furrow under AFI, δ18O in stem water had better response to soil water variation at wet side, and soil water in wet side was firstly absorbed by maize root and then transported to the dry side. Maize water uptake was mainly from the depths of 20–40 cm at the late jointing stage, 40–60 cm at the late heading stage and 40–80 cm at the filling stage, with relative contribution of 84, 80 and 66%, respectively. Maize water uptake from different soil zones varied remarkably at AFI. For example, at the filling stage, 16–52% of maize water uptake was from the depth of 60–80 cm below the ridge (dry side) before irrigation, 32–78 and 14–64% from the surface soil (0–20 cm) of wet furrow and the ridge at 1 day after irrigation, 14–60 and 8–54% from the depths of 20–40 cm below the ridge side and 40–60 cm below wet furrow at 3 day after irrigation, and 6–80 and 30–60% from the depths of 60–80 cm below the ridge and 40–60 cm below the ridge side at 7 day after irrigation. Thus maize root water uptake was from deeper soil with the advance of growth stage, and it was mainly from the deeper soil in dry side and the shallow soil in wet side under AFI.

© 2016 Elsevier B.V. All rights reserved.

1. **Introduction**

There was no hydrogen and oxygen isotope fractionation after water absorbed by plant root system, so the isotopic composition of plant stem water is consistent with that of water source (Zimmermann et al., 1968; White et al., 1985; Flanagan and Ehleringer, 1991; Dawson and Ehleringer, 1991). Because plant water uptake can be considered from the mixture of different water sources, plant water uptake from different water sources can be assessed by comparing stable hydrogen and oxygen isotopes of plant stem water and those of possible water sources (Brunel et al., 1995; Dawson et al., 2002; Wang et al., 2010). Using stable isotope technique, researchers found that plants mainly absorb deeper soil water in dry season but shallower soil water in wet season (Dawson and Pate, 1996). Although the upward flux of water in soil is adequate, lucerne prefers to absorb ‘fresh’ water such as rainfall and irrigation water near the surface rather than soil water (Zhang et al., 1999). The maize and prairie species obtained 45 and 36% of the water from the 0–20 cm soil layer (Asbjornsen et al., 2007). And most of C3 species absorb more water from deeper soil than the C4 grasses, but plants in the uplands absorb more shallow soil water than those in the lowlands in dry seasons (Nippert and Knapp, 2007). The subalpine non-phreatophytic shrubs utilized soil water primarily from the 0–30 cm layer (Liu et al., 2011). And Haloxylon ammodendron mainly absorbs groundwater while Haloxylon persicum mainly absorbs deeper soil water in summer (Dai et al., 2014).

Based on water balance principle and isotopic mass conservation, a linear mixed model was established to calculate plant water uptake from different water sources (Flanagan and Ehleringer, 1991; Ogle and Reynolds, 2004). But in this model, at least ‘n’ isotopes are need if there are ‘n+1’ potential water sources, thus stable hydrogen and oxygen isotopes are limited to solve plant water uptake from two or three water sources. For more than

---

* Corresponding author. Fax: +86 10 62738398.
E-mail address: dutaisheng@cau.edu.cn (T. Du).
three-layer mixing model, the calculation is complex and uncertain answer can be obtained. Under the uncertain condition, Phillips et al. (2003, 2005) put forward a multi-source mass balance method (IsoSource model) to determine the contribution of each water source. Using this method, recent research indicated that maize used 45% of the water from the 0–20 cm soil layer, and oak trees growing in the savanna and woodland obtained 40% and 20% of the water from the upper 20 cm and 60% and 80% of the water from deeper soil (>60 cm), respectively (Asbjørnsen et al., 2007). Summer maize used 96–99% of water from the 0–20 cm layer at the jointing stage, 58–85% of water from the 20–50 cm layer at the flowering stage and 69–76% of water from the 0–20 cm layer at full ripening stage, and cotton uses 27–49% of water from the 0–20 cm layer at the seedling stage, 79–84% of water from the 20–50 cm layer at the bud stage, 30–92% of water from the 50–90 cm layer at the blooming stage and 69–82% of water from the more than 90 cm layer at boll open stage (Wang et al., 2010). And Populus euphratica and Tamarix chimensis obtained more than 93% and 90% of the water from groundwater, but Sophora alopecuroides obtained more than 97% of the water from the soil layer about 80 cm in depth (Zhao et al., 2008). Celtis wightii seedlings suffered stronger water stress and greatly relied on fog moisture (23.8% on average), but adult trees had little or negligible water uptake from fog moisture (3–7% on average) and obtained about 63–85% of the water from bedrock sources (Liu et al., 2014).

Alternate furrow irrigation (AFI) is a method that parts of the root zone are dried and wetted alternately, which has been tested to be an effective water-saving irrigation technique (Kang and Zhang, 2004). AFI increases water use efficiency by stimulating crop root water uptake, optimizing the stomatal behavior and reducing the luxury transpiration loss, and it is relatively easy to be applied in the field (Kang et al., 2000; Kang and Zhang, 2004). Now the effects of AFI are focused on water physiology and consumption, yield, soil infiltrative parameters and irrigation water advancing. But some problems such as quantifying plant water uptake from different soil layers and zones under AFI have not been systematically investigated. Mechanisms of plant water uptake play an important role in the water cycle of the soil-plant-atmosphere continuum. It determines not only the plant’s ability to absorb water resource, but also the response mechanism of plant to the change of water resource conditions (Wang et al., 2010). As for the AFI, it also provides the theoretical basis for making proper irrigation schedule and agricultural water management. Thus, if the problem of quantifying plant water uptake from different soil layers and zones under AFI could be solved commendably, the water use efficiency will be further improved effectively and the AFI method will be popularized widely.

Therefore, two-year experiments were conducted to measure stable hydrogen and oxygen (δD and δ18O) isotopes of soil water, stem water, rainfall and irrigation water under AFI, and to assess plant water uptake from different layers and root-zones using the multi-source mass balance method (IsoSource model) in this study, the objectives were to (1) clarify whether soil water in the wet side was firstly absorbed by roots or transported to dry sides under AFI; (2) quantify maize water uptake from which soil layers at different growth stages; and (3) analyze the changing of maize water uptake from different root-zones (horizontal and two-dimensional profile) before and after irrigation, so as to provide the scientific basis in understanding the mechanism of improving water use efficiency under alternate furrow irrigation.

2. Materials and methods

2.1. Experimental site

The experiments were conducted during April to September in 2013 and 2014 at Shiyanghe Experimental Station of China Agricultural University, located in Wuwei City, Gansu Province of northwest China (37°52’ N, 102°51’ E, altitude 1581 m). The site is in a typical continental temperate climate zone. It is rich in sunlight resource with a mean annual sunshine duration over 3000 h, mean annual temperature of 8 °C and annual accumulated temperature (>0 °C) of 3550 °C. However, the region is scarce in water resource with a mean annual precipitation of 164 mm and mean annual evaporation from a free water surface of 2000 mm. The groundwater table is 30–40 m below the ground surface. Soil texture is shown in Table 1.

2.2. Experimental design

Maize was sown in two-rows on each ridge (Fig. 1). Growing stages of maize was listed in Table 2, the five growth stages were divided according to Ritchie et al. (1993) and Ding et al. (2010). According to Du et al. (2010), irrigation scheduling was designed as shown in Table 3. The effective precipitation and irrigation quota during the whole growing stage of maize were 68.8 mm and 285 mm in 2013, and 241.0 mm and 175 mm in 2014, respectively. Fertilizer supply during the growing season was consistent with the local management.

2.3. Sampling and measurements

Stable hydrogen and oxygen isotopes of soil water, maize stem water, rainfall and irrigation water were measured respectively.

2.3.1. Stem water

To avoid the isolate fractionation caused by plant transpiration, maize stem containing no chlorophyll at 5 cm above soil surface were chosen during 12:00–14:00 on several sunny days. Then plant samplings were stored in the valve bag and water was extracted using the vacuum extraction system (LI-2000, LICA, China).

2.3.2. Soil water

Sampling time was the same as maize stem, and the sampling points were shown in Fig. 1. Three locations (interval 20 m) along the furrow direction were evenly chosen to take soil samplings from each layer (0–5 cm, 5–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm and 80–110 cm) using a soil auger. Then the soil samples were stored and water was extracted using the same method.

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>Soil texture</th>
<th>Bulk density (g/cm³)</th>
<th>Saturated water content (%)</th>
<th>Field capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–20</td>
<td>Loamy soil</td>
<td>1.47</td>
<td>48.01</td>
<td>28.4</td>
</tr>
<tr>
<td>20–40</td>
<td>Loamy soil</td>
<td>1.51</td>
<td>46.77</td>
<td>27.9</td>
</tr>
<tr>
<td>40–60</td>
<td>Sandy loam soil</td>
<td>1.62</td>
<td>39.83</td>
<td>25.8</td>
</tr>
<tr>
<td>60–80</td>
<td>Sandy loam soil</td>
<td>1.55</td>
<td>44.38</td>
<td>26.4</td>
</tr>
<tr>
<td>80–100</td>
<td>Sandy loam soil</td>
<td>1.56</td>
<td>44.26</td>
<td>26.7</td>
</tr>
<tr>
<td>100–120</td>
<td>Clay</td>
<td>1.38</td>
<td>51.03</td>
<td>32.6</td>
</tr>
</tbody>
</table>

Table 1
Details of soil texture in study area.
2.3.3. Rainfall and irrigation water

Rainfall and irrigation water (groundwater) were collected using sample bottles, and then filtered.

To avoid evaporation and isotope fractionation, four water sources were stored in airtight glass with 4 °C. The stable hydrogen and oxygen isotope values (δ, ‰) of the water samples were measured using Liquid-Water Isotope Analyzer (PICARRO L2130-I, Picarro, USA). According to the Vienna Standard Mean Ocean Water, the isotope compositions (δ18O or δD) were calculated as follows:

\[
\delta^{18}O (\text{or} \delta D) = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000
\]

where \(R_{\text{sample}}\) and \(R_{\text{standard}}\) are the \(^{18}\text{O}/^{16}\text{O}\) (or D/H) molar ratios of the sample and standard water (V-SMOW), the analytical precision was <2.0‰ for δD and <0.1‰ for δ18O.

2.3.4. Soil water content

Soil water content of each plot was measured by gravimetric method. Sampling time and points were the same as isotopes sampling of soil water. Because of the difference of soil bulk density in different soil layers (Table 1), the volumetric soil water content was shown in this study, volumetric soil water content were calculated as follows:

\[
\theta_v = \theta_w \times \gamma
\]

where \(\theta_v\) is volumetric soil water content (vol.%), \(\theta_w\) is soil gravimetric water content (w/w%), \(\gamma\) is soil bulk density (g/cm³).

2.4. Data analysis method

Maize water uptake from different layers and root-zones was assessed using the multi-source mass balance model (IsoSource model) (Phillips and Gregg, 2003; Phillips et al., 2005).

The contribution of each potential source is increased incrementally, and an isotopic mass-balance is performed at each increment to determine if the result compares well with the isotopic composition of stem water. The sum of the isotopic composition in stem water within a small tolerance is considered to be feasible combination. The total number of suitable solutions depends on the isotopic values of the sources, the number of water sources, the isotopic value of mixed stem water, the increment employed, and the uncertainty level.

\[
N = \left[ \left( \frac{100}{i} \right) + (S - 1) \right] \times \left[ \left( \frac{100}{i} \right) + (S - 1) \right]
\]

where \(N\) is the number of feasible combination, \(i\) is increment (%); \(S\) is the number of sources.

The water sources were defined as the soil waters in each layer and root-zone, and mean isotopic values of each layer and root-zone were used to represent the potential water sources. The mixture of this model was determined by analyzing mean isotopic values of maize stem water. The increment was set at 1%, the tolerances of the sum at 0.01‰ and the uncertainty level at 0.2.

3. Results

3.1. Hydrogen and oxygen isotopic values of water samples

It shows linear relationship between δD and δ18O of the water samples in 2013–2014 (Fig. 2). The linear fitting between δD and δ18O in local precipitation (δD = 7.2 δ18O + 9.8) was close to the globe meteoric water line (δD = 8δ18O + 10) (Craig, 1961). Mean values of δD and δ18O in surface soil water were −0.48‰ and −25.02‰, and its enrichment results from the fractionation of hydrogen and oxygen isotope due to soil water evaporation (Barnes and Allison, 1983; English et al., 2007). δD and δ18O in stem water had similar values to those of subsoil water (>20 cm) and groundwater, and δD ranged from −86.52‰ to −52.42‰ and δ18O from −13.41‰ to −7.77‰.

Due to significant linear relationship between the hydrogen and oxygen in all water samples and similar fractionation of isotope in
the water cycle, the distribution of δD and δ18O in various water samples showed a good uniformity. But the difference of relative mass between 18O and 16O was lower than that between D and H, so the fractionation of oxygen isotope was less significant than that of hydrogen isotope (Lin, 2013). Thus the data of 18O was selected to do analysis in this study.

3.2. Maize water uptake from different soil layers at different growth stages

Based on the theory that there is no fractionation of stable oxygen isotope during the process of root water uptake (Zimmermann et al., 1968; White et al., 1985), if the composition of stable oxygen isotope in maize stem water had similar to that of soil water at a certain layer, it can be considered that the maize water uptake mainly comes from this layer.

Fig. 3 shows δ18O in soil water at the profile and stem water during late jointing stage. The δ18O in soil water decreased with the increased depth, but it varied significantly in the furrow surface (R(S)) after irrigation (Fig. 3b). The intersection of δ18O in stem water with that in soil water at the profile is considered to be root water uptake from the layer. δ18O in stem water had the intersection with that in soil water at 20–40 cm layer (Fig. 3a), so root water uptake was from this layer before irrigation. And root water uptake was from soil water at 20–40 cm layer under the ridge and 0–10 cm under furrow after irrigation (Fig. 3b).

Fig. 4 shows δ18O in soil water at the profile, stem water and corresponding volumetric soil water content in the profile. Comparing the data with the isotopic gradients in the profile and assuming that maize absorbed water from single dominant source, δ18O in stem water had the intersection with that of soil water at 40, 60 and 70 cm layer for three growth stages (Fig. 4a), suggesting that maize water uptake was primarily from the 20–40 cm at the late jointing stage, 40–60 cm at the late heading stage and 60–80 cm at the mid-filling stage, respectively. However, the corresponding soil water content in the profile increased slightly with the increased depth (Fig. 4d–f), and soil water content below 80 cm was close to the field capacity.

Frequency histograms produced from the IsoSource multiple source mass–balance models can estimate the proportion of total water uptake from each layer (Fig. 5). At different growing stages of maize, the histogram patterns were relatively convergence at some depths, but broad and diffuse at other depths. At the late jointing stage (Fig. 5a), the histogram patterns were relatively convergence at the 20–40 cm layer, but broader and more diffuse at other depths, and root water uptake was mainly from soil water at the 20–40 cm layer, accounting for 74–92% (crest value was 84%) of total water uptake. Similarly, maize primarily absorbed water from the 40–60 cm layer at the late heading stage, accounting for 62–90% (crest value was 80%) of total water uptake (Fig. 5b), and from 40–60 cm layer at the filling stage, accounting for 16–68% of total water uptake (Fig. 5c). Considering root water uptake from soil water at the 20–40 cm layer (Fig. 5c) was also larger (18%) at the filling stage, suggesting that root water uptake was mainly from soil water at the 40–80 cm layer, accounting for 66% approximately of total root water uptake.

Combining Figs. 4 and 5 and considering the successive root growth during an irrigation cycle, the appropriate wetting depth for each stage was suggested as 40–50 cm before the jointing stage, 60–70 cm at the heading stage and 70–80 cm during and after the filling stage, and the corresponding irrigation quota was 33–40, 40–47 and 53–60 mm on the basis of Tables 1 and 3 during the three growth stages.

3.3. Maize water uptake from different soil zones after irrigation

Our research shows the dynamic distribution of δ18O in soil water at horizontal and vertical direction and stem water. δ18O in soil water varied obviously at the vertical direction but slightly in horizontal direction before irrigation (Fig. 6). Due to significant dilution effect of irrigation water (δ18O = −10.13‰ ± 0.2‰) on soil water, δ18O in soil water at furrow surface and sides decreased rapidly at 1 day after irrigation (Fig. 6f and g). At 3 day after irrigation, δ18O in soil water at the 0–40 cm soil layer increased slowly due to the evaporation (Fig. 6k and l). At the same time, the δ18O in soil water at the 40–60 cm soil layer was affected by water infiltr-
Fig. 3. $\delta^{18}$O in soil water at the profile and maize stem water. R: Ridge, F: Furrow, S: South, N: North. (a) 1 day before irrigation, (b) 1 day after irrigation. The sampling dates were June 22 and 24 2013 (late jointing stage). Irrigation in F(S) on June 23 2013, with irrigation quota of 55 mm. The depth of 20 cm is the surface of furrow because ridge is 20 cm higher than furrow.

Fig. 4. $\delta^{18}$O in soil water at the profile and maize stem water and volumetric soil water content in the profile. June 28 (a and d), July 17 (b and e) and August 17 (c and f), 2014.

Combining soil water at horizontal and vertical direction, a range of maize water uptake from each soil zone of two-
dimensional profile under AFI was estimated using multiple-source mass balance assessment (IsoSource) (Fig. 7). Maize obtained water primarily from the 40–80 cm layer before irrigation at the filling stage, with 12–50, 16–52 and 8–30% of maize water uptake from the 60–80 cm layer below R1, R2 and R3, respectively (Fig. 7a), indicating that maize water uptake was mainly from deeper soil. At 1 day after irrigation, 32–78, 14–64 and 18–60% of maize water uptake was from the 0–20 cm layer below R3, 20–40 cm layer below F1 and F2, respectively (Fig. 7b), and maize water uptake was mainly from shallow soil in the wet furrow. At 3 day after irrigation, with the water infiltration, 14–60, 8–54 and 8–52% of maize water uptake was from the 20 to 40 cm layer below R3, 40–60 cm layer below F1 and F2, respectively (Fig. 7c). At 7 day after irrigation, 0–70, 30–60 and 6–80% of maize water uptake was from the 40–60 cm layer below R1 and R3, and 60–80 cm layer below R2, respectively (Fig. 7d).

Fig. 8 shows the distribution of soil water content at horizontal and vertical direction. The soil water contents varied in the two neighboring furrows of AFI, with higher water content (27–28%) in the deep soil of previously irrigated furrow (Fig. 7a). Combining with Fig. 7, maize water uptake from different root-zones varied with the change of soil water content within the irrigation cycle.

4. Discussion

4.1. Maize water uptake from different soil layers at different growth stages

The difference of $\delta^{18}O$ in soil water between furrow and ridge were mainly in the shallow soil at AFI (Figs. 3 and 6). On one hand, such difference may result from the fractionation of hydrogen and oxygen isotope due to soil evaporation (Barnes and Allison, 1983; English et al., 2007), and on the other hand, it may result from rainfall and irrigation. Soil evaporation causes greater enrichment of $^{18}O$ in the shallow soil within longer period before irrigation (Allison and Leaney, 1982), but $\delta^{18}O$ in surface furrow water was significantly changed due to its dilution effect after irrigation (Figs. 3 b and 6g), and meanwhile, the lateral seepage caused $\delta^{18}O$ redistribution. Furthermore, isotope fractionation can influence $\delta^{18}O$ distribution to some extent during the process of water infiltration in soils (Araguás-Araguás et al., 1995). Rainwater harvesting in furrow also changed $\delta^{18}O$ distribution in soil water at the profile (Gazis and Feng, 2004). With the increased water infiltration under alternate furrow irrigation, $\delta^{18}O$ in soil water at the vertical direction changed greatly in a short period, and then stem water also varied rapidly (Figs. 3 b and 6), but $\delta^{18}O$ in soil water in the dry side changed slowly due to lower lateral seepage from the wet side. Meanwhile, maize water uptake was mainly from wet side soil after irrigation (Fig. 7b). Therefore, $\delta^{18}O$ in stem water had better response to the variation of soil water in wet side, and soil water in wet side was firstly absorbed by maize root and then transported to the dry side.

In this study, maize root water uptake was from deeper soil with the advance of growth stage (Figs. 4 and 5), because it was mostly related to the active absorbing area of root at different growth stages (Ehleringer et al., 1991). But Asbjornsen et al. (2007) and Wang et al. (2010) found that maize mainly absorbed soil water from the 0–20 cm layer during whole growing season under conventional irrigation, which was contrast with our result. It may result from the difference of irrigation methods, maize was a fibrous root crop whose roots were mostly in the 0–40 cm soil under traditional irrigation, which had been proved by previous studies (Coelho and Or, 1999; Liu et al., 2009). However, AFI changed the ways of moist soil, and stimulated of maize root distribution
deeper than regular irrigation strategies (Kang et al., 2004). Recent research also showed that the roots were mainly distributed on the ridge during the seedling stage of maize under AFI, and mainly distributed in soil layers of 20–60 cm during the middle growth stage, the depth with the maximum root density was 40–80 cm during the late growth stage (Li et al., 2011). Thus AFI stimulated fine root growth and roots into deeper soil, and increased root activity surface area, which might increase root water uptake from deeper soil (Kang et al., 2002; Li et al., 2011). Besides, deep roots were found to be very efficient in the uptake of water from deeper layers (Camposeo and Rubino, 2003). Combining the proportional contribution of maize water uptake from different soil layer during each growth stage (Fig. 5), the active absorbing area of root was deeper with the advance of growth stage under AFI.

Plant water uptake by root characteristics was similar to our result by isotopes. Root distribution was an important indicator of potential water uptake (Skinner et al., 1998; Coelho and Or, 1999), and the main depth of root water uptake gradually increased with the main root system distribution during the whole growth stage (Li et al., 2011; Liu et al., 2011). But some studies confirmed that soil water extraction by plants due to the depth and volume of root distribution may not be a reliable indicator of actual spatial and temporal water uptake dynamics (Ehleringer and Dawson, 1992; Dawson and Pate, 1996; Moreira et al., 2000). By contrast, our studies about isotope method should be an effective method to quantify maize water uptake from different layers, and the conclusion will be useful for agricultural water management and irrigation scheduling. Based on the conclusions, the irrigation schedules under AFI can be determined as follows: the appropriate wetting depth was suggested as 40–50 cm before the jointing stage, 60–70 cm at the heading stage and 70–80 cm during and after the filling stage, and the corresponding irrigation quota was 33–40, 40–47 and 53–60 mm during the three growth stages. Thus, the amount of water saving in AFI can be estimated as about 30% when compared to the traditional irrigation. Similar results were also found from Kang et al. (2002), which indicated AFI caused no significant yield reduction when the irrigation amount was reduced to 50%.

### 4.2. Maize Water Uptake from Different Soil Zones After Irrigation

Maize water uptake from different root-zones varied with the change of soil water content within a short watering cycle (Figs. 7 and 8), and maize mainly absorbed water from surface soil of wet furrow and deeper soil at dry side (Fig. 7), which was similar to the previous results (Green and Clothier, 1995; Liu et al., 2011; Dai et al., 2014; Yang et al., 2015). They indicated that plants mainly absorbed shallow soil water when the upper soil water was abundant, but deep soil water and ground water when the upper soil water was depleted, and prefer to absorb near surface water after localized irrigation, indicating that soil water content was the leading factor influencing plant water uptake in a certain time. Green and Clothier (1999) showed that when the surface soil layers were uniformly wet, 70% of the trees water uptake occurred in the top 0.4 m of the root zone, but when a partial irrigation was applied to just one side of the root zone, the tree quickly shifted its pattern of water uptake with an almost two-fold increase.

![Fig. 6. Dynamic distribution of δ18O in the soil under AFI irrigation in F (N) on August 2 2014. F1, F2, R1, R2, R3, F3 and F4 in Fig. 1. The 20 figures (a-t) were the δ18O distribution in the corresponding soil layer at corresponding time, for example, Fig. 6b was the δ18O distribution of 20–40 cm soil layer at 1 day before irrigation.](image)
in uptake from the wetter soil parts and a corresponding reduction in uptake from the drier parts. As for the AFI, there was higher water content in the deep soil of previously irrigated furrow (Fig. 8), and the soil water content varied in the two neighboring furrows, with higher water content in the shallow soil of wet side and the deep soil of dry side. Thus maize water uptake pattern was mainly related to the soil water content. However, some studies indicated that plants absorbed the water mainly from deep soil water, even at times when water was available near the surface (Mensforth et al., 1994; Thorburn and Ehleringer, 1995). It might result from the difference of plant species and other environmental parameters, such as through-fall precipitation (Romero-Saltos et al., 2005) and leaf water potential (Stahl et al., 2013).

Our results showed that maize absorbed water with a large proportion from the wet side root-zone after irrigation. For example, 32–78% of maize water uptake was from the 0–20 cm layer below R3 at one day after irrigation, indicating that AFI increased the proportion of maize water uptake from wet side root soil zone of profile. Thus, it may increase the irrigation water use efficiency. Kang et al. (2002) conducted an experiment with maize plant under alternate furrow irrigation and conventional furrow irrigation (CFI), and found that the ratio of water uptake in the wet side with that in the same side of CFI was larger than 1.0 in most of periods for AFI, the ability of root water uptake under AFI exceeded that of CFI. So this might be a reason why the alternate furrow irrigation increased maize water use efficiency.

5. Conclusions

It can be concluded that varied significantly in δ18O distribution between the ridge and furrow near soil surface. δ18O in stem water had better response to soil water variation at wet side, and soil water in wet side was firstly absorbed by maize root and then transported to the dry side. Maize root water uptake was from deeper soil with the advance of growth stage. It obtained water mainly from the depths of 20–40 cm at the late jointing stage with relative contribution of 84%, 40–60 cm at the late heading stage (80%) and 40–80 cm at the filling stage (66%). Maize water uptake from different soil zones varied significantly at AFI, and it obtained water mainly from deeper soil in dry side and shallower soil in wet side. At the filling stage, 16–52% of maize water uptake was from soil of 60–80 cm below the ridge (dry side) before irrigation, 32–78 and 14–64% from the surface soil (0–20 cm) of wet furrow and the ridge at 1 day after irrigation, 14–60 and 8–54% from soil of 20–40 cm below the ridge side and 40–60 cm below wet furrow at 3 day after irrigation, and 6–80 and 30–60% from 60–80 cm below the ridge and 40–60 cm below the ridge side at 7 day after irrigation.
Fig. 8. Soil water content in the profile, (a) 1 day before irrigation, (b) 1 day after irrigation, (c) 3 day after irrigation, (d) 7 day after irrigation. Irrigation in F(N) on August 2 2014. F1, F2, R1, R2, R3, F3 and F4 in Fig. 1.

Acknowledgements

This research was funded by the research grants from the National Natural Science Foundation of China (91423002, 51439006, 51321001), the Research Projects of Public Welfare Industry in China (201503125, 201501017), Discipline Innovative Engineering Plan (111 Program, B14002) and Chinese Universities Scientific Fund (2015TC051).

References


