Effect of irrigation methods and quota on root water uptake and biomass of alfalfa in the Wulanbuhe sandy region of China

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Abstract

A field study was conducted in the Wulanbuhe sandy region to determine the effect of irrigation methods and quota on root water uptake and biomass of alfalfa (*Medicago sativa* L.). The results showed that water uptake rate by roots (*S*(*z*, *t*)) was closely related to the soil moisture content. Roots of local alfalfa would extract water mainly from the soil in the upper root zone if water content were appropriate. Otherwise, the peak of *S*(*z*, *t*) would move, usually down, to other places where moisture content was higher. *S*(*z*, *t*) gradually increased with the growth of alfalfa. Different water supply showed significant effects on shoot and root biomass of alfalfa. Insufficient water supply could stimulate development of roots. Compared with flooding irrigation, the sprinkler method resulted in more shoot biomass although the quota was 1/3–1/4 less, therefore, the sprinkler method would be suitable for extending the planting of alfalfa in this region.

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1. Introduction

The Wulanbuhe sandy region is situated at the intersection of north and northwest China, covering an area of $1 \times 10^6$ ha. This region has a typical arid climate, rare precipitation with frequent winds and sandstorms. The region and its neighbors, even the Northern China Plain, suffer greatly from the harsh climate. For example, Dengkou County of Inner Mongolia in the Wulanbuhe sandy region covers an area of only about $2.85 \times 10^5$ ha, with 52 km along the Yellow River, but it is estimated that $6 \times 10^7$ tonnes of sands are blown from this area.
into the river per year. The sandy region is extending southward and has been close to the Yellow River. In recent years, the desertification problem in this region has become more and more serious because of unreasonable and unscientific utilization of water resource. It is, therefore, urgent to prevent sandification and protect the ecological environment in this area.

Alfalfa, which has high adaptability, developed root system and high yield, is often called “the king of forage crop”. It is not only a forage crop of high quality, but also a plant which can ameliorate soil, control wind and fix sand. Thus, research on the relationship between the planting of alfalfa and water utilization is of significance for the scientific utilization of water resource and effective protection of the environment in this region.

Many reports have been done on the relationship between growth of alfalfa and water utilization (Ogata et al., 1960; James and Wright, 1988; Sheaffer, 1988; Smeal et al., 1991; Geng et al., 1995) and theorized that there is a positive linear relationship between the yield and transpiration capacity; Some researchers reported that water stress effected the transpiration ratio of alfalfa and morphology (Brown and Tanner, 1983; Matthias and Smith, 1997). These reports mainly concentrated on the relationship between the water utilization and shoot growth. However, the root system and plant canopy are an organic whole, so the relationship between plant growth and soil water use can be determined through research on the pattern of water uptake by roots.

There are many empirical and semi-mechanistic root water uptake models on soil water transport of annual crops (Feddes et al., 1978; Molz, 1981; Gardner, 1991; Zuo et al., 1998; Wu et al., 1999). Among them, the following water uptake model is typical which Feddes et al. (1978) advanced in case of water stress, and is given as the form

\[ S(z,t) = \alpha \times \psi(z,t) \times S_p(z,t) \]

where

\[ S_p(z,t) = T_p(t) \times \frac{\omega(z,t)}{\int_0^{\text{root}} \omega(z,t) \, dz} \]

where \( S(z,t) \) is water uptake rate by roots (h\(^{-1}\)), \( S_p(z,t) \) the potential uptake rate (h\(^{-1}\)), \( \omega(z,t) \) the root length distribution in soil, \( \psi(z,t) \) the experiential equation for potential uptake rate in case of water stress, \( T_p \) describes the potential transpiration (mm h\(^{-1}\)), \( z \) the depth in soil (cm), \( t \) the time (h) and \( \alpha \) is the experiential coefficient.

These water uptake models have mainly focused on annual crops, but little work on water uptake by roots of alfalfa has been done. The objectives of this study are (1) to understand the regularity of water uptake by roots of alfalfa and relationship between roots water uptake and yield in a dry sandy region; and (2) to provide scientific proof of the preservation and restoration of a sandy ecosystem based on the economy of water resource consumption.

2. Theory and methods

2.1. Study site

The experiment was carried out at the Dengkou Ecological Experimental Station (41°21’9.9’’N, 106°53’34.3’’E; elevation 1050 m) of China Agricultural University in Dengkou,
Table 1
Irrigation methods and quota of each treatment in 1999

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Method</th>
<th>Frequency</th>
<th>Total (mm)</th>
<th>Stage (D/M)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bifurcation</td>
<td>Flowering</td>
</tr>
<tr>
<td>W1</td>
<td>Flooding</td>
<td>3</td>
<td>133 (22/6)</td>
<td>(24/7)</td>
</tr>
<tr>
<td>W2</td>
<td>Sprinkler</td>
<td>3</td>
<td>103 (22/6)</td>
<td>(24/7)</td>
</tr>
<tr>
<td>W3</td>
<td>Sprinkler</td>
<td>1</td>
<td>43 (22/6)</td>
<td>(24/7)</td>
</tr>
</tbody>
</table>

Inner Mongolia, from March to October 1999. With a temperate-semiarid climate, annual mean precipitation is 143 mm, but evaporation is almost 2377 mm; annual mean wind speed is 3 m s\(^{-1}\); annual mean air temperature is 7.6–7.8 °C. The accumulated temperature of ≥10 °C is 3222–3489 °C; frost-free period is 144 days.

The soil along root zone was divided into three different layers: fine sand (0–30 cm), loamy clay (30–90 cm) and sand (90–150 cm).

2.2. Methods

Zhunger alfalfa was drilled on 23 April 1999, at 3 cm in depth, 25 cm in width and 22.5 kg ha\(^{-1}\) in sowing quantity. Urea (150 kg ha\(^{-1}\)) and calcium super phosphate (600 kg ha\(^{-1}\)) were applied to each treatment before sowing. The experiment has carried out during the steady growth of seedlings: water treatment divided in three parts and every treatment was repeated at three areas. The size of each area was 10 m \(\times\) 8 m, total size of each treatment was 240 m\(^2\) (10 m \(\times\) 24 m), with a 0.5 m isolation barrier between two plots. In order to irrigate and determine soil water content, the areas were designed with a statistical ordered method. The details can be found in Table 1.

In each treatment area, a random selection of five (25 cm \(\times\) 25 cm) small samples were taken, the above-ground parts were cut first, then the root was dug out at each 10 cm layer. The samples were the brought to laboratory, washed with clear water, dried at 65 °C in an oven and weighed. This was done every 15 days.

Time-domain-reflectometry (TDR) probes were fixed in each treatment and at different soil layers (0–6, 0–15, 0–30, 15–30, 30–60, 60–90, 90–120 cm) to measure soil moisture content every seven days with five replications. Measure times could be increased after irrigation or rain.

Undisturbed soil was sampled using a cutting ring at every soil layer and measured using a pressure membrane meter in the laboratory. The number of samples were more than five in every soil layer. The soil moisture characteristic curve was given as (Van Genuchten, 1980)

\[
\theta = \theta_s + \frac{\theta_s - \theta_r}{1 + (\alpha |h|)^n}^{1-(1/n)}
\]

where \(\theta\) is the volumetric water content \((\text{cm}^3 \text{ cm}^{-3})\); \(\theta_s\) the saturated moisture content, determined from laboratory experiments of the soil samples; \(\theta_r\) the residual moisture content \((\text{cm}^3 \text{ cm}^{-3})\), determined from calculated; \(h\) the soil matrix potential (cm); and \(\alpha\) and \(n\) are optimized coefficients.
Saturated and unsaturated hydraulic conductivity \((K_s \text{ and } K(h))\) were measured in situ by using Guelph’s permeameter in the field. The hydraulic conductivity results and soil moisture characteristic curve are summarized in Table 2.

2.3. Modeling water uptake by roots

2.3.1. Calculated methods of water uptake by roots

Under the condition of crop growing, ignoring the effect of lateral run-off, the one-dimensional soil water flow equation under unsaturated conditions is

\[
C(h) \frac{\partial h}{\partial t} = \frac{\partial}{\partial z} \left[ K(h) \frac{\partial h}{\partial z} \right] - \frac{\partial K(h)}{\partial z} - S(z, t)
\]  

(2)

The initial and boundary conditions are expressed by

\[
\begin{align*}
    h(z, t) &= h_0(z) & 0 \leq z \leq L, \ t = 0 \\
    -K(h) \frac{\partial h}{\partial z} + K(h) &= \begin{cases} 
        -E(t) & z = 0, \ t > 0 \\
        Q(t) & z = L, \ t > 0 
    \end{cases}
\end{align*}
\]

(3)

where \(h\) is soil matrix potential (cm); \(t\) the time (h); \(z\) the depth from soil surface to positional downward (cm); \(C(h)\) the specific water capacity (cm \(^{-1}\)), \(C(h) = d\theta/dh\); \(K(h)\) the unsaturated hydraulic conductivity (cm h \(^{-1}\)); \(S(z, t)\) the water uptake rate by roots (h \(^{-1}\)); \(Q(t)\) and \(E(t)\) either the net rainfall intensity or the actual soil surface evaporation rate (cm h \(^{-1}\)); \(h_0(z)\) the initial distribution of matrix potential in the profile; \(f(t)\) the known function or discrete node; and \(L\) is the vertical distance (cm).

The actual evaporation from the surface soil layer is evaluated from the potential evaporation rate calculated by using the Penman–Monteith equation (Smith, 1991) and the water content at soil surface; these are the upper boundary and lower boundary is at 180 cm, i.e. ground water level. Water uptake rate \(S(z, t)\) by roots of alfalfa was simulated using the approach introduced by Zuo et al. (1998). Under the condition of crop growing, the supposed moisture content of the profile is \(\theta(z, t_0)\) at \(t_0\); after \(\delta t\), water moisture content changed into \(\theta(z, t_0 + \delta t)\), because of water movement and water uptake by roots. If \(\theta(z, t_0)\) is the initial condition, when we do not consider water uptake by roots, we obtain soil moisture content distributed in the soil profile at \(t_0 + \delta t\) under the same conditions through simulation. A discrepancy still exists between observed \(\theta(z, t_0 + \delta t)\) and simulated \(\theta_m(z, t_0 + \delta t)\), because

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>(\theta_s) (cm (^3) cm (^{-3}))</th>
<th>(\theta_i) (cm (^3) cm (^{-3}))</th>
<th>(\sigma) (cm (^{-1}))</th>
<th>(n)</th>
<th>(K_s) (cm per day)</th>
<th>(K(h)) (cm per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–30</td>
<td>0.434</td>
<td>0.039</td>
<td>0.01233</td>
<td>2.88</td>
<td>149.6</td>
<td>1158.4</td>
</tr>
<tr>
<td>30–90</td>
<td>0.575</td>
<td>0.280</td>
<td>0.15766</td>
<td>1.24</td>
<td>7.7</td>
<td>2333.6</td>
</tr>
<tr>
<td>90–150</td>
<td>0.500</td>
<td>0.052</td>
<td>0.01219</td>
<td>1.75</td>
<td>18.3</td>
<td>34.7</td>
</tr>
</tbody>
</table>
this process does not considered water uptake by roots. In the time period $\delta t$, water uptake rate of roots is approximated by the following function:

$$S(z, t_0 \rightarrow t_0 + \delta t) \approx \frac{\theta(m(z, t_0 + \delta t) - \theta(z, t_0 + \delta t))}{\delta t}$$

(4)

where $\delta t$ is 7 days, measured for time interval and corresponding soil moisture content.

2.3.2. Numerical methods

The solution uses the implicit difference method (Eqs. (2) and (3): let $S(z, t) = 0$). Step size of space $\Delta z$ is 2.5 cm, step size of time $\Delta t$ is 2 min, and the number of nodes is 73. The differential of Eq. (2) is by the following function ($i = 2, 3, \ldots, 72$):

$$a_i h_{j-1}^{i+1} + b_i h_i^{i+1} + c_i h_{i+1}^{i+1} = d_i$$

(5)

$$a_i = -K_j^{i+1}$$

$$b_i = K_{i-1}(1/2) + K_j^{i+1} + \frac{C_j^{i+1}}{r}$$

$$c_i = -K_{i+1}(1/2)$$

$$d_i = \frac{C_j^{i+1}}{r}h_i^j - \Delta z(K_j^{i+1} - K_j^{i+1})$$

$$r = \Delta t/\Delta z^2$$

where $i$ is number of space nodes and $j$ is number of time nodes.

Eq. (5) was composed of 71 equations, and combining upper and lower boundary, they formed a tridiagonal equation group of the 73rd order. The solution used the speedup method through an iterative channel; the relative error of control iterative numbers ($\varepsilon$) is 0.001.

$$\max_i \left| \frac{h_{i}^{j+1(p)} - h_{i}^{j+1(p-1)}}{h_{i}^{j+1(p-1)}} \right| < \varepsilon = 0.001 \quad (i = 1, 2, \ldots, 73)$$

where $p - 1$ and $p$ are in the last and next nodes of iterative numbers, respectively.

3. Results

3.1. Root water uptake

Simulated $S(z, t)$ distribution curves for three treatments at every growing stage are plotted in Fig. 1 and the observed soil moisture content profiles in Fig. 2. In treatment W1, $S(z, t)$ increased with alfalfa growth and its peak mainly appeared in the 0–30 cm soil layer because of the sufficient water supply. The value of $S(z, t)$ reduced with increased depth of soil. In treatment W2, the main water uptake zone was also concentrated in the 0–30 cm layer, and water requirement increased quickly after flowering stage. Soil moisture content
Fig. 1. Simulated $S(z, t)$ distribution curves in different water supply.
Fig. 2. Measured soil moisture content profiles in different water supply.
in the surface soil layer could not meet the need of the plant, so the water uptake peak moved downwards and the second peak of water uptake by roots came between 40 and 80 cm. The value of $S(z, t)$ in W3 was the lowest among the three treatment because it received the least irrigation water. Accordingly, the main water uptake zone moved down to the 30–90 cm soil layer. In general, roots of local alfalfa could extract water mainly from the soil in the upper root zone if the water content was appropriate. Otherwise, the peak of $S(z, t)$ would move, usually down, to other places where moisture content was higher. Simulated $S(z, t)$ results from all the treatments also showed that the strongest transpiration period of local alfalfa was at flowering and productive stages (Fig. 1).

3.2. Root biomass

The systematic measurements of root biomass of alfalfa were taken from March to September 1999. The results at each treatment are shown in Fig. 3. Root biomass increased with alfalfa growth in three treatments and reached to maximum after the productive phase. In three treatments, the order of total dry weight of root was W3 $>$ W1 and W2 after the productive phase. The results of variance analysis showed that: root biomass was significant different after the productive phase in three treatments ($F = 39.157, P < 0.0001$), the order of dry weight of root was W3 $>$ W2 $>$ W1 and their values were 516.86, 445.25 and 301.57 g m$^{-2}$, respectively. In view of this, insufficient water supply could stimulate development of roots. Because soil texture was of the heavier-textured type in the 30–90 cm layer in each treatment, the percent of root dry weight in total dry weight was $>$60% in the 0–30 cm soil layer at every growth stage. So under local soil conditions, most of the roots developed in the 0–30 cm soil layer in the three treatments.

3.3. Shoot biomass

Different water supply showed significant effects on shoot biomass of alfalfa in the sandy region. Shoot biomass of W2 was higher than that of W1 and W3 in the flowering stage ($F = 9.833, P < 0.0030$). There was a significant different in shoot biomass between W2 and W3 at the productive stage ($F = 5.153, P < 0.0242$). The differences between the
treatments were also significant after the productive stage ($F = 29.532, P < 0.0001$). The order of maximum value of shoot biomass was $W_2 > W_1 > W_3$ in three treatments in the dry sandy region and their values were 702.08, 571.20 and 402.88 g m$^{-2}$, respectively (Fig. 4). Because of the integration of shoot biomass with a regular pattern of water uptake by roots, though irrigation quota was approach between the $W_1$ and $W_2$, we came to the conclusion that water uptake rate and total quantity of $W_2$ were lower than that of $W_1$. When compared with flooding irrigation, the sprinkler method had more shoot biomass of alfalfa although its water consumption were lower than that of flooding method.

4. Discussion and conclusions

Soil moisture content not only significantly affects water uptake by roots but also affects root growth of alfalfa (Wu et al., 1999). Irrigation methods and quota affected water uptake by root of alfalfa and the effect is mainly from the soil moisture content. When soil moisture content was higher in surface soil layer, the main water uptake zone was concentrated in the soil surface; the main water uptake zone moved downwards with reduction of soil moisture in surface soil layer. So the water uptake by roots often moved to the place where soil moisture was appropriate. $S(z, t)$ increased along with the growth of alfalfa and reached a maximum value at the flowering and productive stages (Fig. 1). These experimental results were similar to the Zuo et al. (1998) study on all annual winter wheat crop; water uptake characteristics by roots were related to biological rhythm. There was no report until now on water uptake by root of alfalfa, so further research remain to be done to extend out knowledge of root water uptake in alfalfa.

Almost all alfalfa roots developed in the 0–30 cm soil layer in the three treatments. However, irrigation methods and stages showed significant effects on root growth; these results implied that insufficient water supply could stimulate root development and elongation (Salter et al., 1984; Matthias and Smith, 1997). These observations are supported in the present study. Roots in $W_2$ and $W_3$ of the sprinkler method elongated more than that of $W_1$. Roots biomass of $W_3$ was largest after productive stage and its irrigation quota was lowest.
At present, the most important problems are the relationship between yield and water utilization of alfalfa. Grimes et al. (1992) reported that casual irrigation affected yield of alfalfa and water content of the plant, and advanced the theory that there is positive linear relationship between the yield and transpiration capacity. Another reports that yield of alfalfa were notably reduced, density of plants was also reduced and even all plants died when the time of irrigation termination was above 12 weeks in sand soil (Ottman et al., 1996).

Irrigation methods showed significant effects on shoot biomass of alfalfa in the particular environment conditions of the Wulanbuhe sandy region. The sprinkler method resulted in more biomass and used less water than flooding irrigation. So the sprinkler method would be suitable to extend the growing of alfalfa in this region.

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