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Cover Page Footnote

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Quantifying the impacts of soil water stress on the winter wheat growth in an arid region, Xinjiang

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Abstract: Wheat growth in response to soil water deficit play an important role in yield stability. A field experiment was conducted for winter wheat (*Triticum aestivum* L.) during the period of 2002–2005 to evaluate the effects of limited irrigation on winter wheat growth. 80%, 70%, 60%, 50% and 40% of field capacity was applied at different stages of crop growth. Photosynthetic characteristics of winter wheat, such as photosynthesis rate, transpiration rate, stomatal conductance, photosynthetically active radiation, and soil water content, root and shoot dry mass accumulation were measured, and the root water uptake and water balance in different layer were calculated. Based on the theory of unsaturated dynamic, a one-dimensional numerical model was developed to simulate the effect of soil water movement on winter wheat growth using Hydrus-1 D. The soil water content of stratified soil in the experimental plot was calculated under deficit irrigation. The results showed that, in different growing periods, evapotranspiration, grain yield, biomass, root water uptake, water use efficiency, and photosynthetic characteristics depended on the controlled ranges of soil water content. Grain yield response to irrigation varied considerably due to differences in soil moisture contents and irrigation scheduling between seasons. Evapotranspiration was largest in the high soil moisture treatment, and so was the biomass, but this treatment did not produce the highest grain yield and root water uptake was relatively low. Maximum depth of root water uptake is from the upper 80 cm in soil profile in jointing stage and dropped rapidly upper 40 cm after heading stage, and the velocity of root water uptake in latter stage was less than that in middle stage. The effect of limited irrigation treatment on photosynthesis was complex owing to microclimate. But root water uptake increased linearly with harvest yield and improvement in the latter gave better root water uptake under limited irrigation conditions. Appropriately controlled soil water contents can improve the root water uptake and grain yield. Consistently high values of root water uptake and grain yield were produced under conditions of mild water deficit at the seedling and start of regrowth to stem-elongation stages, in addition to a further soil water depletion at the physiological maturity to harvest stage. We suggest that periods of mild soil water depletion in the early vegetative growth period together with severe soil water depletion in the maturity stage of winter wheat is an optimum for limited irrigation regime in this oasis. Considerable potential for further improvement in agricultural water use efficiency in the arid zone depends on effective conservation of moisture and efficient use of the limited water.

Keywords: soil water, water stress, deficit irrigation, numerical simulation, photosynthesis, arid region

1 Introduction

In many regions across the world, drought is a major factor limiting cereal yield because it reduces the carbon balance of the crop through its limiting effects on light interception and radiation use efficiency (Blum, 1996). This can be explained by the relationship between soil or plant water status and stomated conductance (controlling CO_2 flux density) or leaf area index (providing the energy intercepted by the canopy) (Amir and Sinclair, 1991). Plants are often subjected to periods of soil and atmospheric water deficit during their life cycle. In particular, plant leaf area is affected

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by water deficit: the rate of leaf emergence, the rate of individual leaf expansion and tiller development is quickly reduced when soil water potential decreases (Belaygue, 1996). Plant metabolism is also dependent on leaf water conditions, as measured by relative water content (Sinclair and Ludlow, 1985). At the leaf level, the dissipation of excitation energy through processes other than photosynthetic C-metabolism is an important defence mechanism under conditions of water stress and is accompanied by down-regulation of photochemistry and, in the longer term, of carbon metabolism. Responses of plant growth to water stress are complex, involving deleterious or adaptive changes, and these responses would be impacted by the interference from other stresses in field conditions. Dehydration process can be postponed through osmotic adjustment or through reduced transpiration (Lecoeur, 1992; Schonfeld, 1988, Mao, 2001). Obviously, the reduced transpiration suggests a reduction in stomatal conductance and leaf area which would have a negative effect on carbon balance. However, its influences on leaf growth are still not adequately addressed so far, and associated knowledge are quite limited (Munns, 1988; Davies and Zhang, 1991).

Owing to oasis agriculture sustainable development closely depends on limited local water resource in inland arid regions, hence, it is essential to provide irrigation service for oasis agriculture (Shi et al., 1996; Wu et al., 2000; Yang and Luo, 2003). The primary target of groundwater conservation is to develop water-saving agriculture, particularly for winter wheat (Wang et al., 1998; Xu et al., 1996). The objectives of this work were herewith: (1) to simulate the flow process of soil water and identify root water uptake of winter wheat under water stress condition; (2) to optimize irrigation schemes for high wheat product and water use efficiency; and (3) to quantify the effect of water stress on root water uptake, photosynthesis and yield. For this purpose, available soil water content, water use, evapotranspiration and grain yield were recorded, and root water uptake and water use efficiency were estimated.

2 Experiment and method

2.1 Study site and field experiment

The experiment of water stress was carried out at Fukang desert ecological experimental station located in the Fukang Oasis of Xinjiang. The study region is dominated by extreme meteorological conditions, which is cold in winter and very hot in summer. Mean annual precipitation is about 164 mm. The soil here is sandy loam with the bulk density of about 1.4 g·cm^{-3} and field capacity is 25% approximately.

The different irrigation requirements were controlled at 80%, 70%, 60%, 50% and 40% of field capacity, respectively. Field capacity in jointing, grouting and mature stage of winter wheat is 50%. 80% of field capacity in other stages. Ground water was pumped from well to each plot (5 m×5 m) through pipe and gauged with flow meter.

Soil physical parameters, such as soil bulk density, field water retention capacity, saturated hydraulic conductivity and soil hydraulic properties for the model were obtained from experiments studies. Soil water content was measured every ten days with neuron probes calibrated by means of baking at fifteen soil depths from 0 to 150 cm over 171 days, and leachate was collected from the bottom. Meteorological data (i.e. temperature, humidity, wind speed, atmospheric pressure, solar radiation and sunshine hours, pan evaporation and rainfall), were analyzed form the weather station at the experimental site.

2.2 Measurement method of photosynthetic characteristic and yield

Photosynthetic characteristic of winter wheat under different conditions of water stress, such as photosynthetic rate, transpiration rate, stomatal conductance and photosynthetically active radiation were measured by CIRAS-1 portable photosynthesis system in sunny days.

The measurement methods of photosynthesis characteristic include close and open gas system. CO_2, H_2O reference concentration and analysis concentration were measured by four absolute infrared gas analyzing instruments, and then transpiration rate, photosynthesis rate and stomatal conductance were calculated by CO_2 difference between reference and analysis concentrations. The equations are as follow:

$$E = [W \times (e_{out} - e_{in})] / (P - e_{out}), \tag{1}$$

$$A = C_{in} \times W - C_{out} \times (W + E), \tag{2}$$

$$g_s = 1 / r_s, \tag{3}$$

$$r_s = e_{leaf} - e_{out} / E \times P^{-rb}, \quad (4)$$

where E is transpiration rate (mol·m^{-2}·s^{-1}), e_{in}, e_{out} are water vapour pressure of the air entering and leaving the cuvette (bar); W is mass flow of air per unit leaf area entering the cuvette (mol·m^{-2}·s^{-1}); P is atmosphere pressure (bar); A is photosynthesis rate (μmol·m^{-2}·s^{-1}); C_{in}、C_{out} are CO_2 concentration entering, that leaving (μmol·mol^{-1}); g_s is stomatal conductance (mol·m^{-2}·s^{-1}); r_s、r_b are stomatal resistance and boundary layer resistances (m^2·s·mol^{-1}), which is fixed value obtained from calibration in factory and checked from instrument technology manual; e_{leaf} is saturated vapour pressure at leaf temperature (bar). In equations (1) and (2),

$$W = \frac{V_{20}}{1000} \times \frac{1}{22.41} \times \frac{273}{293} \times \frac{1}{1.013} \times \frac{10000}{a}, \quad (5)$$

where V_{20} is the volume flow at 20℃ and 1 bar (cm^3·s^{-1}), a is the projected leaf area (cm^2), which is decided by the chamber used.

Major growth features for winter wheat (e.g. height, density, leaf area index, root length, root-biomass and yield) were also measured in each phase. Leaf area index was estimated from the product of plant density and average green leaf area of individual plant. Root-length and root-biomass can be measured after soaking and washing of the samples.

3 Soil water dynamic model

Based on Darcy's law and the principle of mass conservation, one-dimensional soil water dynamic model can be described as

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} + \cos\alpha\right)\right] - S, \quad (6)$$

where θ is the volumetric water content (cm^3·cm^{-3}), h is the matric potential head (cm), given here as a function of the dimensionless water content, t is time (d), x is the vertical coordinate (positive downward) (cm), K is the unsaturated soil hydraulic conductivity function (cm·d^{-1}), α is the angle between the flow direction and the vertical axis (i.e., α =0° for vertical flow, 90° for horizontal flow, and 0°<α<90° for inclined flow), and S is the sink term representing the root water uptake (cm^3·cm^{-3}·d^{-1}). When soil depth is deeper than the effective depth of root zone (L_r) (cm), S in Eq. (6) is 0.

3.1 Initial and boundary conditions

The solution of Eq. (6) requires knowledge of the initial distribution of the pressure head with the flow domain:

$$h(x,t) = h_i(x) \; t{=}t_0, \quad (7)$$

where h_i (x) is the initial distribution of the pressure head with different depth of the soil profile and can be obtained from observation or estimated from soil water content with the soil water retention curve, and t_0 is the time when the simulation begins.

One of the following boundary conditions must be specified at the soil surface (x=L) or at the bottom of the soil profile (x=0):

$$-K\left(\frac{\partial h}{\partial x} + \cos\alpha\right) = q_0(t) \quad x{=}0 \quad \text{or} \quad x{=}L \quad (8)$$

where q_0 (cm·d^{-1}) is the soil water flux at the boundary, L is the distance from soil surface to lower boundary.

Potential transpiration and evaporation were calculated from meteorologic data for this region. Penman-Monteith equation recommended by FAO was used to determine referenced evapotranspiration. Then potential transpiration can be estimated from referenced evapotranspiration and crop coefficient. Finally the actual transpiration and evaporation can be obtained from the leaf area index of winter wheat at each stage.

3.2 Unsaturated soil hydraulic properties

The unsaturated soil hydraulic properties, $\theta(h)$ and $K(h)$, in Eq. (6) are in highly nonlinear functions of the pressure head. The model implements the soil-hydraulic functions of Van Genuchten (1980) who used the statistical proe-size distribution model by Mualem (1976) to obtain a predictive equation for the unsaturated hydraulic conductivity function in term of soil water retention parameters. The expressions by Van Genuchten (1980) are given by

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} & h < 0 \\ \theta_s & h \geqslant 0, \end{cases} \quad (9)$$

$$K(h) = K_s \cdot S_e^l [1 - (1 - S_e^{1/m})^m]^2, \quad (10)$$

where S_e is the effective water content,

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}, \quad (11)$$

in which θ_r and θ_s are the residual and saturated water contents ($cm^3 \cdot cm^{-3}$), K_s is the saturated soil hydraulic conductivity ($cm \cdot d^{-1}$), α is the inverse of the air-entry value, n and m are empirical shape parameters with $n > 1$ and m=1−1/n, and the pore-connectivity parameter l in the hydraulic conductivity function was estimated (Mualem, 1976) to be about 0.5 as an average for many soils. In this study the above hydraulic parameters were obtained from soil water retention curve $\theta(h)$ measured through pressure membrane.

3.3 Root-water uptake

The sink term, S, is defined as the volume of water removed from a unit volume of soil per unit time due to plant water uptake. Feddes et al. (1978) defined S as

$$S(h) = \alpha(h) \times S_P, \tag{12}$$

where the root-water uptake water stress response function $\alpha(h)$ is a prescribed dimensionless function of the soil water pressure head ($0 \leqslant \alpha \leqslant 1$), and S_P the potential water uptake rate (d^{-1}). Water uptake is assumed to be zero close to saturation (i.e., wetter than some arbitrary "anaerobiosis point", h_1). For $h < h_4$ (the wilting point pressure head), water uptake is also assumed to be zero. Water uptake is considered optimal between pressure head h_2 and h_3, whereas for pressure head between h_3 and h_4 (or h_1 and h_2), water uptake decreases (or increases) linearly with h. The variable S_P in (12) is equal to water uptake rate during period of no water stress when $\alpha(h)$=1. When the potential water uptake rate is equally distributed over the root zone, S_P becomes

$$S_P = \frac{1}{L_R} T_P, \tag{13}$$

where T_P is the potential transpiration rate (mm.day^{-1}), L_R is the region occupied by the root zone (cm), h is soil pressure head, $\alpha(h)$ is the root-water uptake water stress response function. Water uptake is assumed to be zero close to saturation (h_1). Root water uptake is also zero for pressure heads less than the wilting point (h_4). Water uptake is considered optimal between pressure heads h_2 and h_3, whereas for pressure heads between h_1 and h_2 (or h_3 and h_4) water uptake decreases (or increases) linearly with pressure head. A database of suggested values for different plants provided by the model was consulted in this study.

3.4 Model performance and calibration

The simulation period was the main crop water requirements stage from jointing stage to mature stage of winter wheat. Simulations on the variation of soil moisture and irrigation scheduling were carried out to eight irrigation treatments described above. The model was calibrated with the experimental results of several plots in the growing period of winter wheat from 2002 to 2003, and validated with other experimental results from 2002 to 2004. The results of verification show clearly that the variety trends of soil water content with time of simulated value were consistent with experimental results. So the results of simulation can be applied to discussing the effects of water stress on the soil water movement and consumption of winter wheat.

4 Results and discussion

4.1 Impact of water stress on evaporation and transpiration

As can be seen from the measured daily precipitation (including irrigation amount) and estimated daily crop transpiration and evaporation of soil when which field capacity was 80% (Fig. 1), crop transpiration was obviously more than soil evaporation. The transpiration was very high in jointing stage of winter wheat, and then decreased with decreasing leaf area index, and the difference between transpiration and evaporation decreased gradually. Moreover, soil evaporation increased with precipitation and irrigation, and decreased gradually to zero.

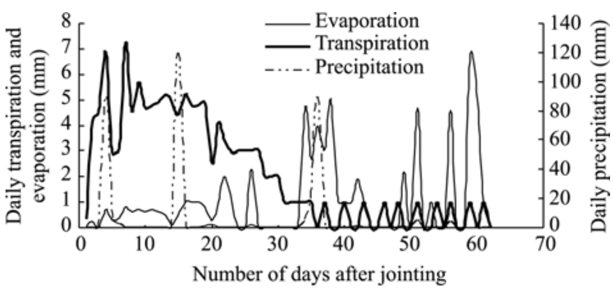

Fig. 1 Daily precipitation, transpiration and evaporation

Cumulative transpiration increased rapidly after jointing stage and tend to be a constant subsequently. The cumulative evaporation increased slower than cumulative transpiration, though cumulative evaporation amount had a sharp variation with irrigation. The result indicated that irrigation was one of the important factors. Cumulative amount of bottom flux increased slowly in prophase of winter wheat and rapidly in latter phase due to decrease of water use rate of winter wheat.

4.2 Impact of water stress on field water balance

The water distribution status of winter wheat from jointing to mature stage with water stress treatments was showed (Table 2 and Fig. 2). The results indicated that the transpiration was almost equal which was due to the same leaf area index used to estimate actual transpiration. Then bottom flux, evaporation and evapotranspiration increased with the increasing irrigation amount. The water use efficiency of winter wheat in grouting stage is higher than mature stage, but the evaporation amount of the former was small relatively. This result further showed that soil water content rather than the crop factor usually affected evaporation.

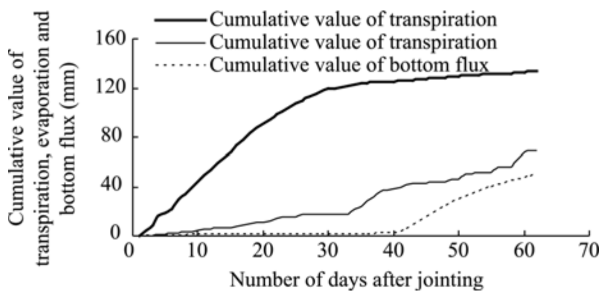

Fig. 2 Cumulative transpiration, evaporation and bottom flux

4.3 Impact of water stress on root water uptake

The potential of absorbing water is determined by the temporal and spatial growing process of root in growing stage. More dry matter need distribute to root, as a result of water stress, to accelerate the growth of root and absorbing the water of deep soil layer (Bai et al., 2001). Root water uptake from deep soil layer increased with the increasing root depth (Fig. 3). Maximum water uptake is from the 80 cm of soil in jointing stage and dropped rapidly upper 40 cm after heading stage, and that water uptake velocity increased gradually as a result of growing neonatal root below 1 m. Furthermore, water uptake velocity of winter wheat in later stage was less than middle stage because the premature root system can not bear water stress.

In this study the winter wheat root was obtained to investigate from upper 60 cm in soil profile. Dry weight of different winter wheat growth stages and their corresponding water stress are shown in Figure 4 and Figure 5. The root growth in heading stage decreased with the increasing water stress. The root growth was activated when water stress satisfy the water demand of growth of overground plant, which was due to impact of water stress throughout the mature stage, and dry weight of root with the heaviest water stress was the maximum. However the root grew fast at prophase and slowly in latter stage, this indicated that winter wheat root growth had good self-regulation ability under moderate water stress and promoted to a certain extent under water stress. While water stress occurred at some growing period, the im-

Table 1 Parameters for the model of soil hydraulic properties

Depth of profile (cm)	θ_r (cm^3·cm^{-3})	θ_s (cm^3·cm^{-3})	α (cm^{-1})	n	m	l	Ks (cm·d^{-1})
0−30	0.035	0.308	0.0955	1.3607	0.2651	0.5	14.11
30−150	0.057	0.416	0.0562	1.3310	0.2487	0.5	18.66

Table 2 The balance of water volume in 1.5 m soil layer with different irrigation treatment

Plan	Precipitation (mm)	Irrigation (mm)	Transpiration of crop (mm)	Evaporation of soil surface (mm)	Bottom flux (mm)	Soil pondage (mm)
1	66.70	300.00	134.00	68.70	49.90	113.00
2	66.70	262.52	134.00	72.22	4.05	117.00
3	66.70	225.04	134.00	71.74	0.91	83.00
4	66.70	187.48	134.00	74.18	1.13	45.00
5	66.70	150.00	131.00	68.70	1.32	16.00
6	66.70	266.24	133.00	67.94	20.70	110.00
7	66.70	255.00	134.00	67.70	5.36	114.00
8	66.70	266.24	134.00	71.94	28.20	98.00

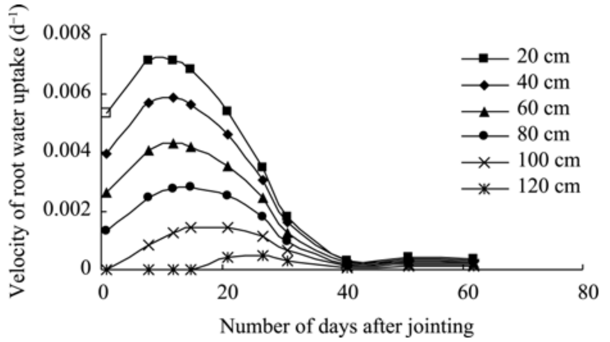

Fig. 3 The average velocity of root water uptake at different depth of soil profile

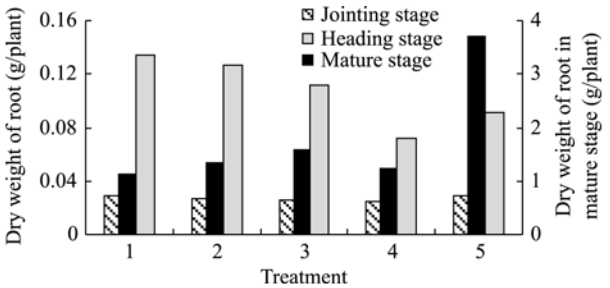

Fig. 4 Effects of different degree of water stress on the growth of root

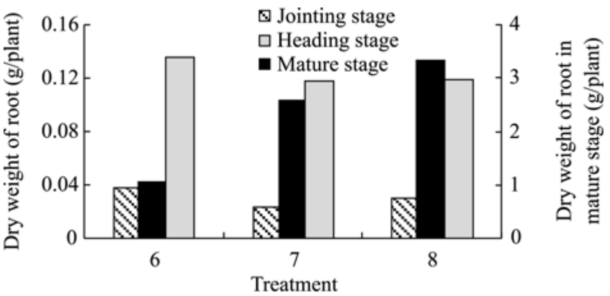

Fig. 5 Effects of different stage of water stress on the growth of root

pacts of water stress on root growth existed permanently. For instance, root weight of the treatments with water stress at jointing and grouting stage were more than other plans in mature stage.

4.4 Impact of water stress on photosynthetic characteristics

Grouting stage is critical to fast-growing winter wheat. When winter wheat suffer from water stress in grouting stage, transpiration and photosynthesis will be affected strongly. The experiment commenced at 10 O'clock of the 5 th June under the condition of air temperature at 30℃ and photosynthetically active radiation at about 1400 μmol·m^{-2}·s^{-1}. The results indicated that photosynthetic rate, transpiration rate and stoma- tal conductance of flag leaves depressed with the increasing water stress (Table 3.). But for the different treatment during growing period, the impacts of water stress on photosynthesis are different, in jointing stage permanent and in grouting stage moderate, respectively.

4.5 Impact of water stress on winter wheat height, biomass and yield

4.5.1 Impacts of water stress on winter wheat height

The increasing trend of plant height from jointing to heading period and from heading to mature period was presented in Figure 6. The increasing trend of plant height during jointing and heading stage was lower than with the increasing water stress, and the increment of plant height of 2nd—5th plan reduced 41.9%, 15.4%, 31.5%, 38.6% compared with the 1st plan, respectively. Similarly, the increment of plant height of

Table 3 Photosynthetic rate，transpiration rate and stomatal conductance of flag leaves with different water stress treatment in the grouting stage

Plant	Photosynthetic active radiation (μmol·m^{-2}·s^{-1})	Transpiration rate (mmol·m^{-2}·s^{-1})	Stomatal conductance (mmol·m^{-2}·s^{-1})	Photosynthetic rate (μmol·m^{-2}·s^{-1})
1	1148	6.12	415.67	25.37
2	1207	4.97	235.67	17.53
3	1593	8.22	528.00	26.07
4	1601	6.09	258.33	20.70
5	1465	4.61	168.67	14.23
6	1702	5.86	225.33	18.47
7	1297	7.57	416.33	25.40
8	1623	8.44	471.67	26.23

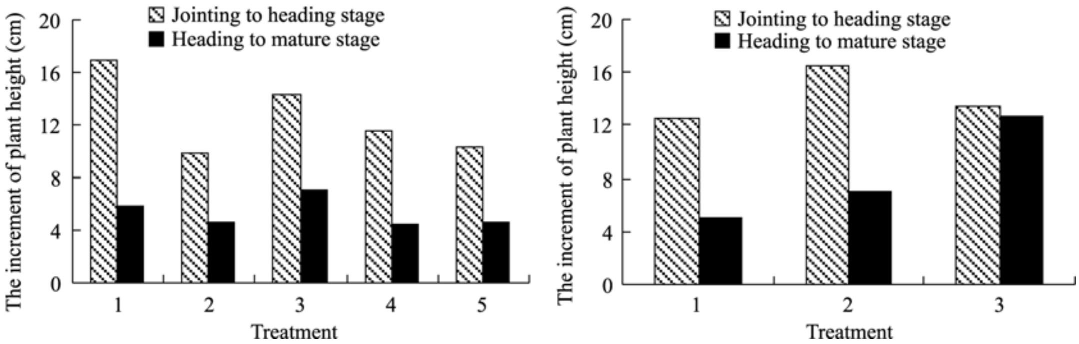

Fig. 6 Effects of different water stress degree and period on winter wheat height

the 2nd, 4th and 5th plan reduced 22.7%, 23.9%, 21.5% during heading to mature period. The variations between plans were obvious in early stage. However, the difference between plans was small in late period, which was possibly due to the change of structure of plant by self-regulating processes to provide conditions. For different treatment during jointing and heading stage, the stem growth of wheat in the 6th plan suffered from water stress in jointing stage, and the light impact on the stem growth in other plans. During the heading and mature stage, the stem growth was affected by water stress and not resumed natural growth after rewatering. The increase of stem height in 8th plan was more than other plans because the impact of water stress on stem growth was not important in later stage. The influence of water stress on the wheat height in jointing stage was more serious, and the effect of water stress on cumulative biomass was more slight than in grouting and mature stage.

4.5.2 Impact of water stress on biomass

The distribution of winter wheat photosynthetic product was obviously affected by soil water conditions, photosynthetic product was enhanced with low soil water condition, and the overground plant benefited from high soil water condition (Wu et al., 2000). Overground dry weight of single plant decreased at each stage, the increment of biomass reduced under the intensifying water stress. Furthermore, the cumulative biomass in later stage was more than the earlier stage (Table 4.). The increment of biomass of the 2th to 5th plan in later stage reduced by 41.9%, 15.4%, 31.5%, 38.6% compared with the first plan, respectively, which indicated that spike growth was affected seriously by water stress. The cumulative biomass of overground plant affected by water stress in jointing stage was more than the plans at grouting and mature stage. Therefore, winter wheat should avoid high water stress at grouting and mature stage, which was regarded as sensitive to moisture.

4.5.3 Impact of water stress on winter wheat yield

The result showed that winter wheat yield reduced under water stress in most growing stages (Table 5.). The yield in moderate condition of water stress plan (the 1st plan) was 70.3%, moreover, the high product of that was only 49.9% of which reduction of product was more than half.

Table 4 Overground matter dry weight of winter wheat under water stress condition

Plan	Jointing stage (g/plant)	Heading stage (g/plant)	Mature Stage (g/plant)	Jointing to heading stage (g/plant)	The percent of decrease in comparison with control (%)	Heading to mature stage (g/plant)	Decreasing percentage of in comparison with control (%)
1	0.15	0.72	2.84	0.57	1	2.12	—
2	0.14	0.57	1.64	0.43	24.84	1.07	49.51
3	0.16	0.62	1.64	0.45	21.00	1.02	51.74
4	0.13	0.44	1.21	0.31	45.59	0.77	63.60
5	0.14	0.58	1.10	0.44	23.68	0.52	75.40
6	0.21	0.57	2.08	0.36	36.36	1.51	28.73
7	0.12	0.53	1.53	0.41	28.75	1.00	52.63
8	0.13	0.56	1.63	0.43	24.65	1.07	49.48

Table 5 Effects of water stress on winter wheat yield

Plan	Spike number (units per 25 m^2)	Kernel number (units per kernel)	The percent of kernel number in comparison with control (%)	The weight of 1000 kernel (g)	The percent of kernel weight in comparison with control (%)	Yield (kg/hm^2)	The percent of yield in comparison with control (%)
1	80	42.4		38.1		5169	
2	81	32.8	77.36	34.2	89.76	3635	70.31
3	66	23.0	54.25	25.3	66.40	1536	29.72
4	83	20.0	47.17	27	70.87	1793	34.68
5	77	29.2	68.87	28.7	75.33	2582	49.94
6	113	36.8	86.79	36.6	96.06	6089	117.79
7	108	32.0	75.47	32	83.99	4424	85.58
8	84	27.2	64.15	32.1	84.25	2934	56.76

Many studies were conducted on the impact of water deficit at different growing periods for winter wheat yield, whereas, the conclusions were not quite uniform (Day, 1970; Fischer, 1973; Li, 1991; Luellen, 1980; Rab and Mogensen, 1984; Shi, 1996). For winter wheat, the grouting stage is widely considered the most fastly growing stage with plenty of water consumption. It was verified by the results of this study: The kernel number and weight reduced obviously under water stress in grouting stage. Compared with the yield factors under moderate water stress, the main factor of reduction of yield with high water stress was reduction of kernel number, and that the kernel weight was slightly higher than the former treatment. The yield decreased obviously with high water stress in later stage, whereas, the yield of treatment with light water stress in jointing stage was more than the treatments at grouting and mature stage. Therefore, water stress should be avoided for winter wheat in grouting stage, which can lead to reduction of yield, and light water stress in jointing stage can endure. Further improvement in agricultural water use efficiency in the arid zone depends on effective conservation of moisture.

5 Conclusions

(1) Soil evaporation increased sharply with precipitation and irrigation, then decreased gradually to zero. Maximum root water uptake of winter wheat is from the upper 80 cm of soil in earlier and middle stage, and water uptake amount in deep layer increased gradually as a result of increasing neonatal root in later stage. The results based on field experiment showed that root growth was slow with water stress in middle stage due to premature senility of root after rewatering in later stage. After resuming irrigation the influence of moderate water stress after effect on root was heavy than high water stress. The dry weight of root with irrigation amount controlled at 40% of field capacity was more than other plans, for water stress can facilitate the development of new root that makes root system adequately take up water in mid-down layer soil for sake of water saving.

(2) The influence of water stress on the height and photosynthesis of winter wheat in jointing stage is more serious, and the effect of water stress on cumulative biomass was more slight than in grouting and mature stage. The wheat product decreased obviously under high water stress in later stage, whereas, the yield under slight water stress in jointing stage was more than other plans. Hence in jointing stage low degree of water stress, yield will decrease under water stress in grouting stage, and the great irrigation must avoid in mature stage because leakage of water will lead to the waste of water resource and soil salinity. Further improvement in agricultural water use efficiency in the arid zone depends on effective conservation of moisture.

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References

Bai W M, Zuo Q, Huang Y F, et al. Effect of water supply on root growth and water uptake of Alfalfa in Wulanbuhe sand region. Acta Phytoecologica Sinica, 2001, 25(1): 35–41.

Day A D, Intalap S. Some effect of soil moisture stress on the growth of wheat (*Triticum aestivum* L. em Thell.). Agronomy Journal, 1970, (62): 27–29.

Feddes R A, Kowalik P J, Zaradny H. Simulation of field water use and crop yield. New York: John Wiley and Sons. 1978.

Fischer R A. Plant response to climatic factors. UNESCO, In Slatyer, RO Ed, Paris. 1973. 233–241.

Li J G. Study on drought tolerance of winter wheat in three different stages. Agricultural Research in the Arid Areas, 1991, 4: 53–59.

Luellen W R. Soil and water. Crop and soils, 1980, 32(4): 23–25.

Mao X M, Shang S H, Lei Z D, et al. Research of evapotranspiration of winter wheat by using SPAC model. Journal of hydraulic engineering, 2001, 8: 7–11.

Mualem Y. A new model for predicting the hydraulic conductivity of unsaturated porous media, Water resources research, 1976, 12(3): 513–522.

Rab A, Jensen H E, Mogensen V O . Dry matter production of spring wheat subjected to water tress at various growth stages. Cereal Research Communication, 1984, 12(1~2): 19–25.

Shi Y. Impacts of soil water stress on photosynthesis and yield of winter wheat. Acta Agriculturae Boreali-Sinica, 1996, 11(4): 80–85.

van Genuchten M Th. A closed-form equation for predicting the hydraulic conductivity of unsaturated soil, Soil Science Society of American Journal, 1980, 44: 892–898.

Wang D W, Zhou D M, Zhang J P, et al. A research on soil moisture dynamics and production effect of water-fertilizer coupling in dryland in Taihangshan Mountain area. Agricultural Research in the Arid Areas, 1998, 16(2): 32–40.

Wu H Q, Duan A W, Yang C C. Physiological and morphological responses of winter wheat to soil moisture. Acta Agriculturae Boreali-Sinica, 2000, 15(1): 92–96.

Xu Z Z, Yu Z W, Dong Q Y. The variety law of soil moisture of cornfield with different planting condition. Agricultural Research in the Arid Areas, 1996, 14(3): 20–24.

Yang G Y, Luo Y P. Effect of different soil water conditions on growth of root and shoot of winter wheat. Agricultural Research in the Arid Areas, 2003, 21(3): 104–109.