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Water requirement pattern for tobacco and its response to water deficit in Guizhou Province

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Abstract

The water requirement pattern for tobacco (Yun 85) was identified based on analysis of data obtained from pot experiments in a canopy at the Xiuwen Irrigation Test Central Station in Guizhou Province, China. The results showed that the tobacco water requirement and the tobacco water requirement intensity throughout the growth period in pot experiments were significantly lower than those in field production. In pot experiments, the tobacco water requirement throughout the growth period ranged from 159.00 to 278.90 mm, with a reduction in the range of 241−441 mm, as compared with that in field production. Also, the average water requirement intensity at the vigorous growing stage was 1.97 mm/d, and the water requirement and water requirement module were 33.80−72.60 mm and 16.39%−33.09%, respectively, at the group stage, almost equal to their values at the vigorous growing stage. The patterns of the tobacco water requirement and water requirement module in pot experiments were different from those in field production. In pot experiments, the tobacco water requirement and water requirement module ranked the highest at the mature stage, followed by those at the group/vigorous growing and rejuvenation stages, while the water requirement intensity ranked the highest at the vigorous growing stage, followed by those at the mature, group, and rejuvenation stages. The pattern of the water requirement intensity in pot experiments was consistent with that in field production. In addition, the response of the tobacco water requirement to water deficit was also analyzed. Serious water deficit at the vigorous growing stage and continuous water stress at the group, vigorous growing, and mature stages can greatly influence the tobacco water requirement. Water deficit led to reductions in the water requirement and water requirement intensity at each growth stage. The vigorous growing stage exhibited the highest sensitivity to water deficit. The lower limit of moderate soil water stress at the vigorous growing stage was 65% of the field capacity. Results of this study can help to establish a reasonable irrigation schedule for tobacco production in Guizhou Province, China.

Keywords: Water requirement; Protected cultivation; Water deficit; Tobacco; Guizhou Province

1. Introduction

Tobacco (Yun 85) originated in South America but has now been cultivated around the world (FAO, 2001). China accounts for about 80% of worldwide total tobacco production and brings in significant income. Irrigation plays an important role in tobacco growth. Identification of the water requirement pattern is essential in water irrigation research (Romeroa et al., 2009). Many studies have been conducted on the water requirement patterns of rice and wheat (Wang et al., 2003; Bodner et al., 2007; Parent and Anctil, 2012), but studies on the tobacco water requirement are rarely reported. Clarification of the tobacco water requirement would be of great significance to water-saving irrigation due to the large amount of agricultural water consumption and low agricultural water use efficiency in karst areas in Guizhou Province.

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Related research on tobacco water requirements, yield, and quality has been performed by Orphanos and Metochis (1985) and Caldwell et al. (2010) in Nepal. Physiological characteristics of tobacco response to water deficit stress were clarified by Muthappa et al. (2010). Effects of different irrigation scheduling programs and water stresses on the maturity and leaf chemistry of Virginia tobacco at different growth stages have been studied in Ataturk soil by Cakir and Cebib (2010) at the Water Resources Research Institute in Kirklareli, Turkey. Effects of irrigation systems and fertilization on the growth, yield, and nicotine content of tobacco leaves have also been discussed by Ju et al. (2008). Cakir and Cebib (2010) concluded that irrigation scheduling programs and water stress at different growth stages could influence the ripening of Virginia tobacco, and severe water stress causes a delay in tobacco ripening. Muthappa et al. (2010) followed a stress imposition protocol that allowed plants to experience an initial gradual acclimation stress and, subsequently, severe stress for a definite period. However, there have been few studies on water requirements and effects of water supply on the growth, dry matter accumulation dynamics, yield of tobacco, and especially, the yield response to water deficit (Cakir and Cebib, 2006, 2009). Soil moisture dynamics, water use efficiency, and the relationship between soil moisture and tobacco transpiration have been examined in Henan, Jiangsu, Hunan, and Guizhou provinces, and a water production function of transpiration has been established (Wang et al., 2007; Hajiakbar et al., 2006; Gao and Gu, 2012). Moderate soil water stress can reduce excessive water consumption, thereby improving water use efficiency and enhancing crop quality and yield.

This study was based on experimental tobacco cultivation data from the Xiuwen Irrigation Test Central Station in Guizhou Province. The tobacco water requirement pattern and its response to water deficit were analyzed. The results can provide a scientific basis for the establishment of a proper irrigation schedule for tobacco and improvement of irrigation water use efficiency.

2. Materials and methods

2.1. Experimental site

Pot experiments were conducted in a canopy at the Xiuwen Irrigation Test Central Station (26°45′ to 27°12′N, and 106°22′ to 106°53′E) in Guizhou Province in southwest China. Guizhou Province is a region with typical karst landforms consisting of relatively low mountains and hills. The study area has a subtropical monsoon humid climate, with an average annual air temperature of 14.6°C and annual precipitation of 1 235 mm. The mean annual relative humidity is 77%, the annual sunlight is 1 021.5 h, and the frost-free growing season is 270 d per year. The experiments were performed on a plowed soil layer consisting of loess soil with an organic matter content of 33.69 g/kg, total nitrogen of 2.2 g/kg, total phosphorus of 0.3 g/kg, total potassium of 24.87 g/kg, dry density of 1.38 g/cm, and pH value of 7.0. The field capacities were 37.3%, 35.7%, and 33.6% for different soil layers at depths of 0–10 cm, 10–20 cm, and 20–40 cm, respectively.

2.2. Experimental design

Pot experiments were conducted in 2006 and 2007 to investigate the tobacco water requirement and the effect of water deficit on tobacco yield. To avoid the effect of precipitation, experiments were carried out in a canopy with two open ends. The canopy was 30 m long, 10 m wide, and 4 m high. To facilitate the experiment, tobacco was planted in plastic pots with a height of 40 cm and a diameter of 35 cm.

Tobacco seeds (Yun 85), the most popular cultivar in the region, were transplanted on April 25, 2006 with five various treatments (treatments 1 through 5) and on May 1, 2007 with nine various treatments (treatments 6 through 14). Treatment 5 was considered the conventional treatment. A randomized complete block experimental design with all the treatments described above and 15 repetitions for each treatment were adopted.

In contrast to the common classification of tobacco growth stages, including the elongation, vigorous growing, and mature stages, the whole growth period was classified into four growth stages in the experiments, including the rejuvenation, group, vigorous growing, and mature stages. In order to investigate the water requirement under various water stress levels, lower limits of soil water content at different growth stages were set for the 14 treatments involved in this study (Table 1).

2.3. Observation and calculation methods

Daily climatic parameters, mainly including precipitation, wind speed, temperature (maximum, minimum, and average), sunshine duration, relative humidity, and pressure, were measured at the Xiuwen Weather Station adjacent to the experimental site. Soil moisture was monitored at 8:00 am every day with a time-domain reflectometer (TDR; soil moisture meter, USA). The TDR was installed at different flow depths: 0–10 cm at the rejuvenation stage, 10–20 cm at the group and vigorous stages, and 20–40 cm at the mature stage. In pot experiments, water was discharged into pots through point-source irrigation until the soil moisture reached the lower limits of soil water content determined in Table 1. In this study, the water requirement intensity was defined as the ratio of the water requirement to the corresponding duration of time, and the water requirement module was defined as the ratio of the water requirement of a certain period of time to the water requirement throughout the growth period.

The tobacco water requirement (ET_t) at each growth stage was calculated with the field water balance equation:

$$ET_t = W_{0t} - W_t + P_t + I_t - S_t + K_t \tag{1}$$

where the subscript t means the growth stage t; W_{0t} and W_t are the water contents in the soil profile at the beginning and end of stage t, respectively; P_t is the precipitation; I_t is the amount of irrigation water; S_t is the percolation; and K_t is the

Table 1
Lower limits of soil water content at different growth stages for different treatments in pot experiments.

Treatment	Lower limit of soil water content (%)				Treatment	Lower limit of soil water content (%)			
	Rejuvenation stage	Group stage	Vigorous growing stage	Mature stage		Rejuvenation stage	Group stage	Vigorous growing stage	Mature stage
1	80	75	45	60	8	80	65	75	65
2	80	75	50	60	9	80	55	70	65
3	80	75	70	45	10	80	60	75	55
4	80	75	70	50	11	80	65	65	60
5	80	75	70	60	12	80	55	75	60
6	80	55	65	55	13	80	60	65	65
7	80	60	70	60	14	80	65	70	55

Note: Values represent percentages of the field capacity.

groundwater recharge. Since the experiments were conducted in a canopy, the values of precipitation, percolation, and groundwater recharge were set as zeros.

3. Results and discussion

3.1. Variation of tobacco water requirement

The tobacco water requirement throughout the growth period in pot experiments ranged from 159.00 to 278.90 mm (Table 2), while it ranged from 400 to 600 mm in field production (Chen et al., 1995; Gao, 2006; Li et al., 2008), much higher than in pot experiments. He (2004) demonstrated that the tobacco water requirement was 45 mm at the elongation stage in a pot experiment, while it was 58 mm in field production. In pot experiments, the tobacco water requirement ranked the highest at the mature stage, followed by those at the group/vigorous growing and rejuvenation stages, while it ranked the highest at the group stage in field production, followed by the tobacco water requirement at the vigorous growing stage (Wang et al., 2007; Chen et al., 1995).

A small portion of the tobacco water requirement at the rejuvenation stage sustained plant growth, whereas the remaining portion was lost through soil surface evaporation. Weak soil evaporation was observed in pot experiments in the canopy. Thus, the tobacco water requirement at the rejuvenation stage was relatively low, ranging from 5.90 to 8.10 mm. With growth and development, tobacco evapotranspiration increased constantly, leading to an increase in the tobacco water requirement. Although the water requirement intensity at the group stage was lower than it was at the vigorous growing stage, the duration of the group stage was twice that of the vigorous growing stage. Thus, water requirements at the group and vigorous growing stages were almost the same. The average tobacco water requirements at the group and vigorous growing stages were 53.50 mm and 49.50 mm, respectively. The tobacco water requirement reached the maximum value at the mature stage, ranging from 61.60 to 152.10 mm.

3.2. Variation of tobacco water requirement intensity

Crop water requirement intensity can be affected by the water requirement, growth stage, and metabolism. The average water requirement intensity of tobacco throughout the growth period in pot experiments was 1.39 mm/d, which was lower than the value of 2.93 mm/d in field production (Li et al., 2008; Jiang et al., 2011). The water requirement intensity ranked the highest at the vigorous growing stage in pot experiments, followed by those at the mature, group, and rejuvenation stages. These results were consistent with those in field production.

The tobacco water requirement intensity at each growth stage in field production was higher than in pot experiments. The minimum water requirement intensity of tobacco occurred at the rejuvenation stage in pot experiments, ranging from 0.77 to 1.16 mm/d, with an average of 0.92 mm/d (Table 3). The

Table 2
Tobacco water requirements at different growth stages for different treatments in pot experiments.

Treatment	Water requirement (mm)					Treatment	Water requirement (mm)				
	Rejuvenation stage	Group stage	Vigorous growing stage	Mature stage	Whole growth period		Rejuvenation stage	Group stage	Vigorous growing stage	Mature stage	Whole growth period
1	7.04	53.73	39.99	61.60	162.36	8	5.90	52.70	66.50	144.60	269.70
2	7.44	56.27	41.39	104.49	209.59	9	8.10	39.30	47.80	144.60	239.80
3	6.54	57.37	60.21	125.51	249.63	10	7.60	52.20	62.20	85.00	207.00
4	6.14	54.73	61.09	142.84	264.80	11	6.20	62.60	36.50	111.60	216.90
5	6.34	60.07	60.39	152.10	278.90	12	7.90	58.90	36.20	138.60	241.60
6	6.10	33.80	23.30	95.80	159.00	13	5.90	72.60	44.50	116.60	239.60
7	6.50	41.30	50.00	115.60	213.40	14	6.70	53.40	62.40	124.40	246.90

Table 3
Water requirement intensities of tobacco at different growth stages for different treatments in pot experiments.

Treatment	Water requirement intensity (mm/d)					Treatment	Water requirement intensity (mm/d)				
	Rejuvenation stage	Group stage	Vigorous growing stage	Mature stage	Whole growth period		Rejuvenation stage	Group stage	Vigorous growing stage	Mature stage	Whole growth period
1	0.88	1.12	1.67	0.76	1.01	8	0.84	1.08	2.56	1.79	1.62
2	0.93	1.17	1.72	1.29	1.30	9	1.16	0.80	1.84	1.79	1.44
3	0.82	1.20	2.51	1.55	1.55	10	1.09	1.07	2.39	1.05	1.25
4	0.77	1.14	2.55	1.76	1.64	11	0.89	1.28	1.40	1.38	1.31
5	0.79	1.25	2.52	1.88	1.73	12	1.13	1.20	1.39	1.71	1.46
6	0.87	0.69	0.97	1.18	0.96	13	0.84	1.48	1.71	1.44	1.44
7	0.93	0.84	1.92	1.43	1.29	14	0.96	1.09	2.40	1.54	1.48

low water requirement intensity was attributed to the small size of plants at the rejuvenation stage. As tobacco plants grew, the water requirement intensity at the group stage increased, ranging from 0.69 to 1.48 mm/d. The vigorous growing stage was a period of quick growth, at which the water requirement intensity reached the highest level, ranging from 0.97 to 2.56 mm/d. This finding was consistent with Wang et al. (2007) and Hajiakbar et al. (2006). Physiological-metabolic activity decreased at the mature stage, at which tobacco leaves were picked. Thus, the water requirement intensity declined, ranging from 0.76 to 1.88 mm/d. However, the average water requirement at the rejuvenation and group stages were more than 1.5 mm/d in field production, and the values were greater than 4.0 mm/d and 2.0 mm/d, respectively, at the vigorous growing and mature stages (Chen et al., 1995; Hajiakbar et al., 2006).

3.3. Variation of tobacco water requirement module

The water requirement module of tobacco at the mature stage in pot experiments ranked the highest under protected cultivation, followed by those at the group/vigorous growing and rejuvenation stages. The water requirement module at the group stage in pot experiments was close to that at the vigorous growing stage (Table 4). However, the tobacco water requirement module at the vigorous growing stage ranked the highest in field production, followed by those at the mature and elongation stages. Sun et al. (2000) found that the tobacco water requirement modules at the elongation, vigorous growing, and mature stages were 20.0%, 50.0%, and 30.0%, respectively. Gao (2006) found that these values were 16.6%, 50.0%, and 33.4%, respectively. Cai et al. (2005) also found that these values ranged from 17.3% to 22.3%, 42.7% to 46.1%, and 35.0% to 36.8%, respectively. Hajiakbar et al. (2006) measured these values as well, obtaining ranges of 16.0%–20.0%, 44.0%–44.6%, and 34.8%–37.0%, respectively.

For pot experiments in the canopy, the tobacco water requirement module at the rejuvenation stage ranged from 2.19% to 4.34%. This narrow value range was attributed to the small size of plants and short duration of the rejuvenation stage. The water requirement modules at the group and vigorous growing stages ranged from 16.39% to 33.09% and 14.65% to 30.05%, respectively. The mature stage lasted for 81 d, which was approximately three times longer than the vigorous growing stage. In general, the water requirement module at the mature stage, ranging from 37.94% to 60.30%, was higher than those at other stages.

3.4. Effects of water deficit on tobacco water requirement

Water deficit at the group, vigorous growing, and mature stages affected the tobacco water requirement to different extents. Compared with the conventional treatment, the water requirements throughout the growth period with water deficit occurring at the group stage decreased by 37.3 mm and 39.1 mm under treatments 12 and 9, respectively; the values

Table 4
Water requirement modules of tobacco at different growth stages for different treatments in pot experiments.

Treatment	Water requirement module (%)				Treatment	Water requirement module (%)			
	Rejuvenation stage	Group stage	Vigorous growing stage	Mature stage		Rejuvenation stage	Group stage	Vigorous growing stage	Mature stage
1	4.34	33.09	24.63	37.94	8	2.19	19.54	24.66	53.62
2	3.55	26.85	19.75	49.85	9	3.38	16.39	19.93	60.30
3	2.62	22.98	24.12	50.28	10	3.67	25.22	30.05	41.06
4	2.32	20.67	23.07	53.94	11	2.86	28.86	16.83	51.45
5	2.27	21.54	21.65	54.54	12	3.27	24.38	14.98	57.37
6	3.84	21.26	14.65	60.25	13	2.46	30.30	18.57	48.66
7	3.05	19.35	23.43	54.17	14	2.71	21.63	25.27	50.38

with water deficit occurring at the vigorous growing stage decreased by 39.3 mm and 62.0 mm under treatments 13 and 11, respectively; and the values with water deficit occurring at the mature stage decreased by 14.10 mm and 29.27 mm under treatments 4 and 3, respectively. The corresponding water requirement intensities throughout the growth period decreased by 0.27 mm/d and 0.29 mm/d under treatments 12 and 9, by 0.29 mm/d and 0.42 mm/d under treatments 13 and 11, and by 0.09 mm/d and 0.18 mm/d under treatments 4 and 3, respectively. The influence of soil water stress at the vigorous growing stage on the water requirement and water requirement intensity of tobacco was the most significant, followed by that of soil water stress at the group and the mature stages.

Serious water deficit at the vigorous growing stage induced an aftereffect on the tobacco water requirement. The water requirements throughout the growth period with serious water deficit occurring at the vigorous growing stage decreased by 116.54 mm and 69.31 mm under treatments 1 and 2, respectively, as compared with that under the conventional treatment. The significant aftereffect of this water deficit lasted for the recovery of soil water content at the mature stage. With severe water stress under treatments 1 and 2, the water requirements at the mature stage were 61.6 mm and 104.49 mm, and decreased by 90.5 mm and 47.6 mm, respectively, as compared with that under the conventional treatment. The water requirement intensities at the mature stage were 0.76 mm/d and 1.29 mm/d under treatments 1 and 2, showing reductions of 1.12 mm/d and 0.59 mm/d, respectively, as compared with that under the conventional treatment. Moreover, the water requirement modules at the mature stage were 37.94% and 49.85% under treatments 1 and 2, indicating reductions of 16.60% and 4.69%, respectively, as compared with that under the conventional treatment. In general, when serious water deficit occurred at the vigorous growing stage, it caused significant aftereffects on the water requirement, water requirement intensity, and water requirement module.

Continuous water stress can significantly influence the tobacco water requirement. The tobacco water requirement and water requirement intensity throughout the growth period were 159.0 mm and 0.96 mm/d, respectively, when severe water stress occurred at three continuous growth stages under treatment 6, indicating reductions of 119.9 mm of the water requirement and 0.77 mm/d of the water requirement intensity, as compared with those under the conventional treatment. The values were 213.4 mm and 1.29 mm/d, respectively, when moderate water stress occurred at three continuous growth stages under treatment 7, indicating reductions of 62.0 mm of the water requirement and 0.42 mm/d of the water requirement intensity, as compared with those under the conventional treatment. Meanwhile, the values were 216.90 mm and 1.31 mm/d, respectively, when moderate water stress occurred at three continuous growth stages under treatment 11, indicating reductions of 65.5 mm of the water requirement and 0.44 mm/d of the water requirement intensity, as compared with those under the conventional treatment. The values were 239.8 mm and 1.44 mm/d, respectively, when water stress occurred at the group and vigorous growing stages under treatment 9, indicating reductions of 39.1 mm of the water requirement and 0.29 mm/d of the water requirement intensity, as compared with those under the conventional treatment. Therefore, the effects of severe water stress occurring at the early growth stages on the tobacco water requirement were slight, as compared with those of water stress occurring at three continuous growth stages. The most significant effect was observed when severe water stress occurred at three continuous growth stages, followed by those with moderate water stress occurring at three continuous growth stages and at the early growth stages.

To maintain a stable yield, the water-saving irrigation of tobacco should be conducted under moderate water stress. The water stress cannot be less than the lower limits of soil water moisture. In addition, tobacco should not undergo severe water stress at three continuous growth stages. As seen in Table 5, continuous severe water stress occurring at the vigorous growing and mature stages under treatment 1 and three-stage continuous severe water stress under treatment 6 greatly affected the growth, yield, and leaf quality of tobacco. The water production functions (WPFs) were 0.38 kg/m^3 and 0.36 kg/m^3, respectively, under treatments 1 and 6, which significantly decreased as compared with that under the conventional treatment. Under these two conditions, tobacco water requirements throughout the growth period were 162.36 mm and 159.01 mm, respectively, with reductions of 116.54 mm and 119.89 mm, as compared with those under the conventional treatment. Meanwhile, the water requirement intensities throughout the growth period were 1.01 mm/d and 0.96 mm/d under the two treatments, respectively, showing reductions of 0.72 mm/d and 0.77 mm/d, as compared with those under the conventional treatment. A similar result was obtained under treatment 2, when serious water deficit occurred at the vigorous growing and mature stages: the WPF decreased by 0.08 kg/m^3 as compared with that under the conventional treatment. Consequently, the lower limits of soil water content in pot experiments at the vigorous growing stage should be 65% of the field capacity. Otherwise, the water requirement pattern and leaf quality of tobacco will be severely affected.

As for physiological characteristics, previous studies suggested that the low limits of soil water content at the elongation, vigorous growing, and mature stages should be 60%−70%, 75%−85%, and 70%−80% of the field capacity,

Table 5
Yield of tobacco and water production function (WPF) of growth for different treatments in pot experiments.

Treatment	Yield (kg/hm^2)	WPF (kg/m^3)	Treatment	Yield (kg/hm^2)	WPF (kg/m^3)
1	1 560	0.38	8	1 806	0.44
2	1 765	0.43	9	1 888	0.46
3	1 929	0.47	10	1 724	0.42
4	2 176	0.53	11	1 888	0.46
5	2 094	0.51	12	2 094	0.51
6	1 478	0.36	13	2 053	0.50
7	1 847	0.45	14	1 847	0.45

respectively, which can improve stomata conductance and net photosynthetic rate of tobacco (Sun et al., 2000; Gao, 2006).

4. Conclusions

(1) The tobacco water requirement throughout the growth period in pot experiments ranged from 159.00 to 278.90 mm, a range lower than that in field production. The tobacco water requirements at the rejuvenation, group, vigorous, and mature stages ranged from 5.90 to 7.60 mm, 33.80 to 72.60 mm, 23.30 to 66.50 mm, and 36.20 to 142.84 mm, respectively. The tobacco water requirement and water requirement module at the group stage were almost equal to those at the vigorous growing stage in pot experiments. At these two stages, the tobacco water requirement, water requirement intensity, and water requirement module ranged from 23.3 to 72.6 mm, 0.69 to 2.55 mm/d, and 14.65% to 33.09%, respectively.

(2) The tobacco water requirement intensity in pot experiments showed the same pattern as that in field production. The water requirement intensity at the vigorous growing stage under protected cultivation ranked the highest, followed by those at the mature, group, and rejuvenation stages. However, the average tobacco water requirement intensity was 1.97 mm/d at the vigorous growing stage in pot experiments, with an obvious reduction of 2.04 mm/d as compared with that in field production.

(3) The tobacco water requirement at the vigorous growing stage was the most sensitive to water stress in pot experiments at the study site. Serious water deficit at the vigorous growing stage can cause a significant aftereffect on the tobacco water requirement. Tobacco in pot experiments should not undergo severe water stress at the vigorous growing stage and at three continuous growth stages. Results showed that the lower limit of moderate soil water stress at the vigorous growing stage was 65% of the field capacity.

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