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Analysis of the Response of Kiwifruit to Soil Water Deficit

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Abstract: Kiwifruit is one of the most successfully commercially cultivated fruit tree species in China and is grown on a large scale and has a pivotal position in the development of the fruit tree industry in China. Seasonal drought is the main disaster weather in southern kiwifruit cultivation, and timely and accurate access to drought information is essential for southern kiwifruit cultivation. We investigated the effects of soil moisture reduction of the morphological and physiological indicators of kiwifruit by using Xu Xiang soft date red kiwifruit cultivars as materials and set up two moisture treatments with adequate water supply and gradual reduction of soil moisture at the end of flowering period to provide scientific basis for the identification and monitoring of kiwifruit drought. The results showed that the physiological indicators started to be affected one after another after a continuous reduction of soil moisture for 3d, and the morphological characters started to receive stress around 9d. The most sensitive kiwifruit physiological indicators were the CO_2 stomatal conductance of the first apical leaf and the most sensitive of morphological indicators were the ground diameter. The onset of CO_2 stomatal conductance, photosynthetic rate, chlorophyll content, ground diameter and plant height of the first fully expanded leaf of kiwifruit was 3, 4, 7, 9 and 10 d. The water deficits were 8, 11.2, 20.9, 24.1 and 30.6 cm^3, respectively, and the corresponding soil relative moisture was 71.17%, 71.09%, 70.87 %, 70.7% and 70.8%, 70.7% and 70.8%, respectively. This indicates that drought in kiwifruit first manifests itself in changes in physiological characteristics and then in morphological characteristics.

1. Introduction

Kiwifruit is an important fruit tree species whose fruits contain a variety of amino acids and rich vitamins, which are beneficial to human health and have high commercial values [1]. China is a major kiwifruit growing country, with FAO data showing that the national production accounted for 50.60% of the world total in 2020, and the kiwifruit industry plays an important role in poverty alleviation and rural revitalization in China [2-3]. Kiwifruit is water-loving and drought-resistant, and precipitation is one of the main environmental factors affecting its cultivation [4]. Global climate change caused changes in precipitation patterns of China, affecting the degree of soil wetness and dryness. The average annual soil moisture in China tended to decrease over the last 60 years, especially in summer and autumn [5]. Some studies showed that kiwifruit was affected by the combined effects of high temperatures and drought, with a disease garden rate of 50% and a disease fruit rate of 30% or even higher, which seriously affected yield and fruit quality [6]. The Global Climate Status 2020 reports indicated that the frequency and intensity of extreme climate events were increasing and that the negative effects of climate change would persist in decades. Kiwifruit may face serious impacts due to increased seasonal drought in the southern region of China [7], and more attention was paid on the responses to seasonal drought of kiwifruit in the southern region.

Plant physiological and ecological indicators reflected their degrees of drought exposure and could also be used for drought early warning [8]. The indicators usually include both morphological and physiological categories. It was more evident that the slowing or cessation of kiwifruit growth, the gradual yellowing and darkening of leaves until they curl, wither, and the reduction of effective photosynthetic leaf area, thus affected fruit tree yield [9]. Under drought stress, kiwifruit plant height decreased, the ground diameter became thinner, and the photosynthetic rate of leaves also decreased significantly, slowing chlorophyll synthesis [10-12].

Drought was a dynamic developmental process, so dynamic assessments of plant physiological and ecological indicators and soil moisture conditions were required to obtain timely information on the extent of plant drought. Kiwifruit was very sensitive to moisture, and understanding the dynamic process of drought development could more accurately predict the occurrence of drought, which was of practical significance for kiwifruit drought resistance researches [13-14]. In this study, we used Xuxiang kiwifruit as the study material to simulate the gradual decrease of soil moisture and to quantitatively describe the response process of kiwifruit physiological and morphological characteristics to the gradual decrease of soil moisture, so as to provide a basis of understanding the development process of drought in kiwifruit and for early monitoring.

2. Materials and Methods

2.1. Experimental Materials

The potted kiwifruit experiments were conducted in March-October 2020 under a rain shelter at the Irrigation and Drainage Laboratory of Hunan Agricultural University (39°08'N, 115°40'E). The experimental materials were 4-year-old Xuxiang kiwifruit potted young trees. Kiwifruit seedlings were prepared in March 2020 and planted in plastic buckets with an inner diameter of 45 cm and an inner height of 46 cm. The soil type in the bucket was red soil developed from Quaternary red clay with an average soil capacity of 1.37 g/cm^3 and soil field capacity taken as 43.57% [15]. The seedlings were placed in the shed for "training" culture with water, without natural rainfall entering the barrel, and only water was supplied during the culture period to ensure survival. Before the experiments, eight pots of seedlings with similar characteristics of kiwifruit trees in terms of trunk, branches, ground diameter, etc. were selected and the experiments started in May 2020.

2.2. Experimental Design

According to the moisture conditions, the experiments were set up with two treatments, (1) adequate irrigation (A): soil relative moisture was controlled to maintain 75% ± 5% during the test period, and seedlings were irrigated and rehydrated daily during the test period; (2) soil moisture reduction treatment (B): kiwifruit were adequately irrigated before the start of the fast growth period, soil relative moisture was controlled within 75% ± 5%, and no rehydration was done after the start of the fast growth period to simulate the effect of drought on kiwifruit growth. Four replicate of each treatment were used. The water design of the "fully irrigated" treatment was based on the fact that, according to the biological characteristics of kiwifruit, the suitable soil water content for the growth of Xuxiang kiwifruit is between 60% and 80% of the maximum field water holding capacity [16]. Therefore, 75% soil relative moisture was chosen for the adequately irrigated treatment for the experiments. The timing of stopping rehydration in the soil moisture reduction treatment group (B) was selected for the following reasons, based on the net ground diameter growth, Wei Lan [17] divided the kiwifruit growth period into three periods: the pre-growth period (March to mid-April), the rapid growth period (mid-April to mid-September), and the late growth period (mid-September to November). The fast growth period was the key stage of the kiwifruit growth period because it was the longest and the most vigorous, and therefore, the fast growth period was chosen as the main study period.

2.3. Measurement Indicators and Methods

2.3.1. Soil Relative Moisture

The ML3-KIT portable soil moisture quick meter was used to measure the relative moisture of the soil. It was measured in the soil stratification range of 0-30cm, every 10cm, once every 2 days.The irrigation volume (cm^3) was calculated according to the difference between the measured moisture content (volumetric water content θ_v) and the set soil moisture content ($75\%*\theta_f$) of each potted soil, and the irrigation volume was accurately measured with a measuring cylinder according to the formula (1).

$$\Delta Dw = A \cdot \sum (75\% * \theta_f - \theta_v) \cdot h \cdot \rho_b \quad (1)$$

Where ΔD_w is the irrigation volume; A is the irrigated area (cm^2); h is the soil stratification thickness (10 cm was taken as a layer in the experiment); and ρ is the soil bulk density. The cumulative water deficit (D_w) of group B relative to group A can be calculated using equation (2) based on the amount of water ΔD_w per irrigation for treatment A.

$$Dw = \sum \Delta Dw \quad (2)$$

2.3.2. Indicator Measurement

In May 2020, kiwifruit entered the fast-growing stage and the irrigation stopped in the soil moisture reduction treatment group (B). The observed test indicators were recorded as day (d) 0 for the first day, after which physiological and morphological indexes were observed every 2 d. The index measurements and methods are as follows:

(1) Morphological indicators

Plant height was measured with a scale (mm) before, from the soil surface to the highest leaf tip position of the plant; the ground diameter was measured at the soil surface with vernier calipers. Kiwifruit plants to be tested were marked before the start of the experiment. The height and diameter of the seedlings was measured with four replicates, and the indicators were measured every 2 day after the start of the experiment.

(2) Physiological indicators

All physiological indicators were measured on the first unfolded leaf of kiwifruit. CO_2 stomatal conductance and photosynthetic rate were measured using an LCpro T portable photosynthesizer at 8:00 a.m. each day, and the average value was taken for each leaf after three measurements.

Chlorophyll content was measured using an OPTI- CCM 200plus portable chlorophyll meter, which measures chlorophyll content index (CCI) as a relative value without units, and the average of three measurements was taken for each leaf.

2.4. Data Analysis

SPSS 16.0 analysis software was used for data analysis to determine the significance of drought stress on indicators at 0.05 level.

3. Results

3.1. Soil Relative Moisture

The test results show that the soil relative moisture in the adequately irrigated group (A) is controlled within 75% ± 5% during the test period (43.57% of the red soil field water holding capacity observed for many years), and the soil relative moisture in the soil moisture reduction group (B) continues to decrease, eventually to about 38%, with significant differences between the two treatment groups ($P < 0.001$), achieving the intended water control effect, as shown in Figure 1. The relationship between soil relative moisture and duration for the soil moisture reduction group (B) can be fitted by the quadratic equation $y=0.00352x^2 - 0.1094x+71.467$ ($R^2= 0.9838$, $P < 0.01$).

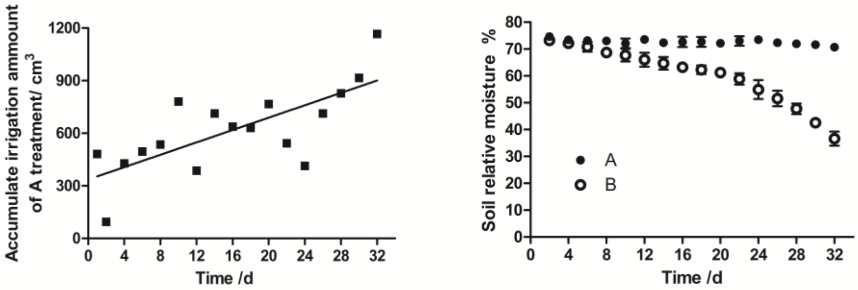

Figure 1: Changes in soil relative moisture and cumulative irrigation water

The cumulative water deficit in the soil moisture reduction treatment group (B) relative to the adequately irrigated group (A) can be calculated from the amount of water (cm^3) irrigated in each time in the adequately irrigated group (A), as shown in Figure 1. The cumulative water deficit shows a linear relationship of water stress time: $y=3.2308x - 1.7048$ ($R^2=0.99$, $P < 0.01$).

3.2. Morphological Characteristics

Figure 2 shows that the ground diameter and plant height of the soil moisture reduction treatment group (B) are higher than those of the adequately irrigated group (A) at the beginning, then gradually begins to be lower than those of group (A) as the moisture stress continues, and the differences between them gradually increase. From the whole experimental period, the differences in ground diameter and plant height between the two groups reach significant levels. The intersection of the fitted curves of the two treatment groups is the point at which soil water stress begins to adversely affect the diameter and height of the plant, i.e., the time when the morphological indicators are firstly stressed by drought (9 and 10 d, respectively), and the difference in water supply between the two groups at this point is the water deficit value (cm^3) at which the morphological characteristics are first affected; the soil relative moisture at this point is the threshold value (%) at which kiwifruit morphology begins to be stressed by reducing soil water. The soil relative moisture at this point is the threshold value (%) at which kiwifruit morphology starts to be stressed by reducing soil moisture. Based on the time of stress onset and the equations for cumulative water deficit and soil relative moisture obtained in Figure 1, the cumulative water deficit and the soil relative moisture at which the kiwifruit form is initially affected are calculated to be

30.6, 24.1 cm^3 and 70.7% and 70.8%, respectively, as shown in Table 1. The sensitivity of kiwifruit morphological indicators to soil moisture reduction is ranked as ground diameter > plant height, based on the time of initial impact, cumulative moisture deficit and soil relative moisture values.

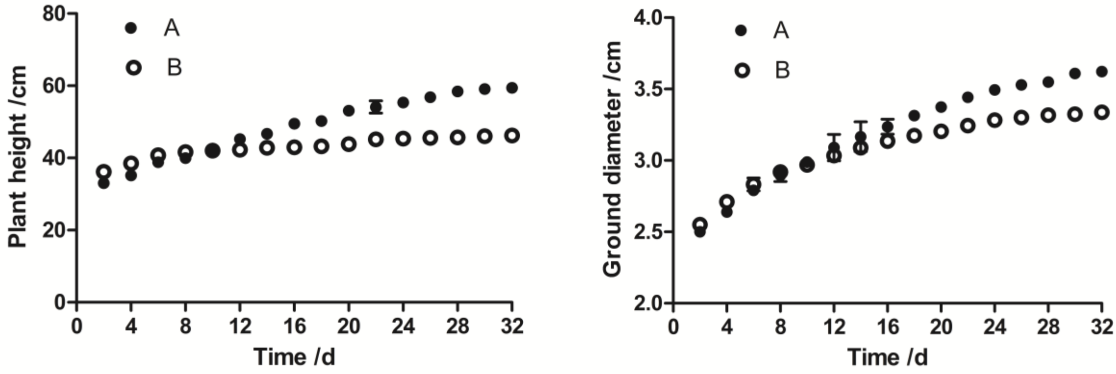

Figure 2: Effect of soil moisture reduction on morphological indicators of kiwifruit

3.3. Physiological Characteristics

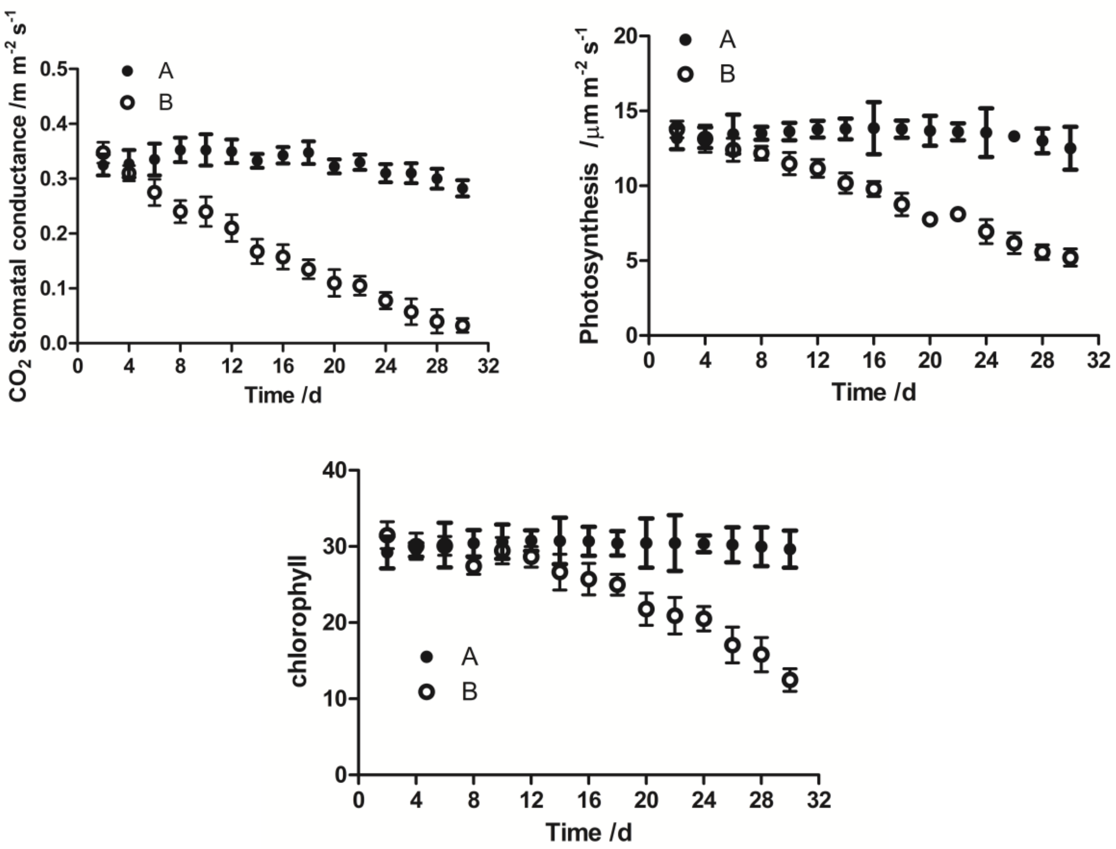

Figure 3: Response of kiwifruit physiological indicators to soil moisture reduction

Figure 3 shows that the photosynthetic rate and stomatal conductance of the first fully expanded leaf at the tip of the soil water reduction group (B) are significantly lower than those of the fully irrigated group (A), and chlorophyll content is also significantly lower. Similar to the morphological indicators, the intersection of the fitted curves of the two treatment groups for each physiological indicator is the point at which drought stress begins to adversely affect kiwifruit, i.e., the point at which the physiological condition of kiwifruit is gradually reduced by soil water, and the corresponding cumulative water deficit and soil relative moisture are the threshold values at which each indicator began to be adversely affected by drought. The onset of soil water stress on physiological indicators is as follows, with apical first leaf CO_2 stomatal conductance, photosynthetic rate and chlorophyll content at 3, 4 and 7 d, respectively. The onset of soil water stress on physiological indicators is as follows, with apical first leaf CO_2 stomatal conductance, photosynthetic rate and chlorophyll content at 3, 4 and 7 d, respectively. The corresponding water deficit values are as follows, with apical first leaf CO_2 stomatal conductance, photosynthetic rate and chlorophyll content of 8, 11.2 and 20.9 cm^3, respectively. The corresponding soil relative moisture values are as follows, and the CO_2 stomatal conductance, photosynthetic rate, and chlorophyll content of the apical first leaf are 70.09%, 71.17%, and 70.87%, respectively, as shown in Table 1. The sensitivity of kiwifruit physiological characteristics to soil moisture reduction is ranked as follows: CO_2 stomatal conductance > photosynthetic rate > chlorophyll content of the first apical leaf, based on the sequence of the onset of drought stress, the cumulative water deficit and the soil relative moisture of each indicator.

Table 1: Values of time T, Water reduction W and Relative soil water content when kiwifruit are influenced by soil water

Indicators	Treatment	Equations	R^2	P	Threshold		
					T/d	W/cm^3	SC/%
Morphological characteristics							
Plant height	A	$y=0.0157x^2 + 1.4421x + 29.898$	0.9968	<0.01	10	30.6	70.7
	B	$y= 0.0091x^2 + 0.5883x + 36.416$	0.9462	<0.01			
Ground diameter	A	$y= -0.001x^2 + 0.0691x + 2.3881$	0.9987	<0.01	9	24.1	70.8
	B	$y= 0.0009x^2 + 0.0543x + 2.5031$	0.9905	<0.01			
Physiological characteristics							
CO_2 Stomatal conductance	A	$y= -0.0002x^2 + 0.0054x + 0.3117$	0.8831	<0.01	3	8	71.17
	B	$y= 0.0001x^2 - 0.0145x + 0.3601$	0.993	<0.01			
Photosynthetic rate	A	$y= -0.0045x^2 + 0.1292x + 12.883$	0.9255	<0.01	4	11.2	71.09
	B	$y= -0.0009x^2 - 0.2863x + 14.389$	0.9935	<0.01			
Chlorophyll	A	$y= -0.0075x^2 + 0.2549x + 28.63$	0.9006	<0.01	7	20.9	70.87
	B	$y= -0.0167x^2 - 0.1083x + 31.521$	0.979	<0.01			

A: adequate irrigation; B: continuous reduction of soil moisture

4. Discussion

There is a critical value response of the crop to soil moisture reduction, i.e., when soil moisture falls below a specific value before it significantly affects its physiological-ecological indicators. Differences in the response of each physiological-ecological indicator to soil water stress result in different critical values, leading to inconsistent timing of the appearance of drought symptoms [4]. The reduction in soil water causes a series of physiological changes in kiwifruit, firstly leaf photosynthesis is affected, when no significant changes in plant morphology occur, and as the degree of water deficit increases, chlorophyll synthesis is hindered and leaf color changes, which in turn reduces photosynthetic rate and eventually affects the morphological structure of the plant [18].

Soil moisture is a commonly used indicator for drought characterization, and the cumulative water deficit can reflect the dynamic process of gradual drought development [19-20]. In this experiment, we investigated the threshold values of water stress for each indicator of kiwifruit plants during the fast-growing period in terms of the onset of water reduction, water deficit and soil relative moisture. After 4 d of water reduction, the cumulative soil water deficit is 11.2 cm^3 and the soil relative moisture decreases to 71.09%, and the physiological indicators are affected successively. 9 d later, the cumulative soil water deficit reaches 24.1 cm^3 and the soil relative moisture decreased to 70.8%, and affects plant morphological indicators such as ground diameter and plant height.

5. Conclusion

In this study, we simulated the effect of soil moisture reduction on kiwifruit in two treatment groups: fully irrigated (soil relative moisture controlled at 75% ± 5% during the experiment) and reduced soil moisture (fully irrigated before the fast-growing period, with the same soil moisture control as in the fully irrigated group, but no water supply after the start of the fast-growing period). The experiment observed the changes in morphological indicators such as height and diameter of kiwifruit plants, and physiological indicators such as CO_2 stomatal conductance, photosynthetic rate and chlorophyll content with the gradual reduction of soil moisture, and analysed the onset of soil moisture stress and the amount of water deficit in the physiological and ecological indicators of kiwifruit. The results show that under drought stress, the physiological indicators of kiwifruit began to be affected 3 d after the beginning of the fast growth period and the morphological indicators begin to be affected 9 d later. The sensitivity of kiwifruit physiological and ecological indicators to soil water stress is ranked as follows: physiological characteristics: CO_2 stomatal conductance > photosynthetic rate > chlorophyll content of the first apical leaf, with onset times of 3, 4 and 7 d, water deficits of 8, 11.2 and 20.9 cm3, and relative soil moisture of 71.17%, 70.09% and 70.87%, respectively; morphological characteristics: ground diameter > plant height The time thresholds were 9 and 10 d, respectively, with water deficits of 24.1 and 30.6 cm^3 and soil relative moisture of 70.8% and 70.7%. The growth of kiwifruit underwent multiple changes after soil water stress, firstly in the physiological characteristics and then in the morphological structure of the plant.

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