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Trait Selection for Yield Improvement in Foxtail Millet (*Setaria italica* Beauv.) under Climate Change in the North China Plain

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Abstract: Weather factors and drought could impact the yield of foxtail millet, and varieties with traits that could alleviate the negative effects of deteriorating weather factors in the future should be developed. A total of 25 foxtail millet varieties were evaluated in experiments from 2016 to 2020 under well-watered (WW) and water-stressed (WS) treatments. Future climate change might favor an increased temperature that impedes grain yield, so varieties with characters that are less sensitive to temperature change are preferred. Varieties with a high panicle dry-weight per plant, thousand grain weight, leaf area and water productivity in deep soil layer usually gave better grain production under both water treatments. Under the WW treatment, low grain abortion rate, optimal chlorophyll and canopy temperature and more roots in the upper soil layer could favor a high yield and drought resistance. Under the WS treatment, varieties with a high harvest index, low rate of water loss and more roots in the upper soil layer usually produced a high yield.

Keywords: foxtail millet; weather factor; yield variation

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1. Introduction

Foxtail millet [*Setaria italica* (L.) P. Beauv.] is one of the earliest cultivated crops in human civilization and plays an important role in food and nutritional security in current society. Foxtail millet ranks as the second millet in the total world production of millets [1,2] in China, 1.74 MT foxtail millet was produced in 2014 and China was the second producer of millets in Asia [3]. Foxtail millet is adaptable to a wide range of soil and climatic conditions, and it is much more tolerant to biotic and abiotic stresses as compared with other major crops, such as maize, wheat and rice (which requires about 30% less water than maize [4]). Foxtail millet has some morphological and anatomical features, including thick cell walls, a dense root structure that grows deeper into the soil profile, and a small leaf area, all of which give it an excellent drought tolerance [5]. The crop is considered as an ideal model crop for plant functional studies and molecular mechanisms of drought tolerance [6,7].

Global climate change has a growing impact on crop production [8,9]. Studies have shown that the average global temperature will increase by roughly 0.2 per decade over the next 30 years [10]. New genomic models that take the multiple traits and multiple environments into consideration [11], along with trait × environment, trait × genotype, and trait × genotype × environment interactions, offer a huge potential for the exploitation of correlations between different variables and for the differentiation between effects [12]. Climate change can potentially influence the cereal yield directly by heat and drought [13].

Under rainfed conditions, drought is expected to continue as one of the main abiotic factors affecting crop yields [14]. Krishna et al. [15] reported drought from earhead emergence to grain filling of finger millet reduced the grain yield by 36.6%. Although foxtail millet is drought resistant compared to other cereal crops, drought is still the most prevalent abiotic constraint that causes yield reduction [16]. Drought-resistant breeding of foxtail millet is an effective measure to achieve higher yield potential under drought conditions. Therefore, the trait-based breeding approach would help to improve yield enhancement. Identifying traits that are related to yield and drought resilience from released varieties would be an appropriate option. Krishna et al. [15] found that the leaf temperature of finger millet was the most important physiological trait under drought stress, and leaf temperature can be used as one of the important selection criteria for drought response; among the agronomic traits, productive tillers and panicle size contributed towards the grain yield under drought conditions.

Canopy temperature has been used to study the genotypic response to drought in wheat. Rashid et al. [17] found a significant correlation between canopy temperature and yield under drought conditions and drought-stress susceptibility index values, which indicated their potential for screening drought-tolerant genotypes. Canopy temperatures also provide an indication for yield performance during drought and could effectively be used as a technique to assess the genotypic response to drought [17]. Reza [18] reported that wheat genotypes with a low canopy temperature can maintain a high transpiration and photosynthetic rate, as well as produce a high yield under water-stressed conditions. There was a significant positive correlation between chlorophyll content and yield in both well-watered and water-stressed environments [18]. The significant correlation between canopy temperature and chlorophyll content with yield under water-stressed conditions indicated the potential for screening wheat genotypes for drought response.

The drought resistance index is closely associated with the panicle harvest index; therefore, it is a trait that is related to a better grain-setting and grain-filling capacity [19]. Roots have a range of functions, including anchorage, mechanical support, nutrient and water uptake, and signaling. Roots are also extremely sensitive to water deficit and high temperatures [20]. Drought has different effects depending on the severity; if a moderate drought occurs, primary root development is increased, while lateral roots are repressed [21].

Foxtail millet is mainly grown in northern China's arid and semi-arid region, where the development of drought seriously influences foxtail millet production. Although there have been about 870 varieties released since 1950 [22], the development of drought resistant varieties is hampered by the lack of effective selection criteria. In this study, 25 foxtail millet varieties that were collected from 2016 to 2020 were used to investigate the influence of weather and soil water conditions on the grain yield and the beneficial traits of foxtail millet varieties for future foxtail millet cultivation and breeding.

2. Materials and Methods

2.1. Experiment Site

The experiment was conducted at Hengshui Dryland Agricultural Experimental Station (37°13′ N, 114°37′ E; 23 m above sea level), Hebei province, Northern China from 2016 to 2020. The experiment location was in a semi-arid area of China and the soil was classified as silt loam with a pH of 8.0 to 8.1. The soil organic matter was 1.0 to 1.3% and the soil bulk density was 1.2 to 1.5 g cm^{-3} for the tillage soil layer.

2.2. Experimental Design and Field Management

During the five growing seasons (2016–2020), a total of 25 recently released varieties (Appendix A, Table A1) collected from different breeders were used. Some of the varieties were replaced by the newly released varieties each season. The inclusion of the newly released varieties each season ensured that their characters were considered. The variety Jigu19 was grown in all five seasons to analyze the weather factors on seasonal yield variation.

The experimental design was a randomized block design with three replicates for each variety. The plot size was 2.0 m ×1.5 m and each plot was surrounded by a 20 cm thick concrete wall to avoid water exchange. The depth of each plot was 3.0 m and contained 2 m of soil layer at the top, and 1m of buffer layer at the bottom. There was a movable shed to prevent rainfall. Foxtail millet plants were grown under two irrigation treatments (ITr) during the growing seasons, i.e., water-stressed (WS)—no irrigation; well-watered (WW)—two irrigations. Irrigation was conducted at the jointing stage and the grain-filling stage. For each irrigation, 900 m^3 ha^{-1} (i.e., 90 mm) of water was applied; the amount of irrigation water was controlled by a water meter. The PVC tube was used to irrigate, and this was moved around the plot to ensure that the water content was uniform.

All field managements were the same for all plots, except for the irrigation. The seeds were sown manually. At the seedling, the plants were thinned to a density of 60 plants/m^2. The sowing date and harvest date are shown in Table A2. The row spacing was set at 20 cm. Before planting, the soil was irrigated to ensure that the soil moisture at the top 1 m of the soil profile was more than 80% of the field capacity to promote successful germination for all the treatments. Base fertilizers of 225 kg ha^{-1} for N, 225 kg ha^{-1} for P_2O_5 and 225 kg ha^{-1} for K_2O in the form of composite chemicals were incorporated into the soil. No other fertilizer was applied during the growing season.

2.3. Measurements

2.3.1. Crop Growth and Production

The time of sowing, harvesting, and the occurrence of the major growth stages were recorded. During the growing seasons, the plants were managed free of pest and disease and weeds were controlled manually. At the harvest, firstly, 100 plants were randomly collected from each plot to measure the panicle dry-weight per plant (PDW/plant). Next, all the plants in each plot were harvested manually and the grain and straw were dried to a constant weight at 80 °C to obtain the grain yield (GY) and straw yield (SY). Thousand grain weight (TGW) was measured manually.

2.3.2. Canopy Temperature and Root Sampling

At shoot emergence, anthesis and the grain-filling stages, the canopy temperature (CanopyT) was measured for each plot at an angle of 30° by radiation thermometer (HIOKI 3460-50, HIOKI E. E. COPPORATION, Nagano, Japan). The measurements were taken at 12:00–14:00 on clear days. The average of four measurements were taken as one replicate.

The roots of control variety Jigu19 were sampled in 2019 and 2020 seasons at maturity for both the WW and WS treatments. Soil cores were taken with a 9 cm inner-diameter stainless-steel soil drill down to 160 cm with increments of 20 cm. Three cores were taken for each treatment. The soil samples from the cores were collected with a mesh bag and washed to obtain the roots. The roots were scanned by the Expression 12000XL scanner, and the root length was measured by WinRHIZO (WinRHIZO Pro 32-bit 2013e). The root-length density (RLD) at different depths was calculated by dividing the root length by the sampled soil volume (cm/cm^3).

2.3.3. Leaf Area, Leaf Chlorophyll Content and Rate of Water Loss

Five plants were selected for the determination of leaf area (LA); all the green leaves of each plant were measured using a measuring tape. The length and width of each leaf were measured and LA was estimated based on the following formula: leaf area = length × width × 0.75, in which the length and width were the maximum length and width [23].

The chlorophyll content (ChlC) was measured by chlorophyll meter (SPAD-502, Minolta Camera Co. Ltd., Osaka, Japan); each flag-leaf SPAD value obtained was the average of 10 readings (5 on each side of leaf at midrib), and 10 plants were measured for each plot from anthesis to the late grain-filling stage.

At 9:00–10:00 local time, three young fully expanded leaves from each plot in the field were sampled randomly and transported to a laboratory within 10 min. the laboratory was at a constant temperature and relative humidity. The leaves were surface dried quickly and weighed; the weight was initial weight (IWt) and the time (t0) was recorded. Then, the leaves were laid flat on the mesh. After 2 h on the mesh, the leaves were weighted; the weight was the final weight (FWt) and the time (t1) was also recorded. Then, the leaves were dried at 80 °C for 48 h to measure the dry weight (DWt).

$$\text{Rate of water loss (RWL)} = (\text{IWt} - \text{FWt})/\text{DWt}/(\text{t1} - \text{t0})$$

2.3.4. Weather Factor Monitoring

Daily meteorological data, including daily maximum temperature (Tmax), daily minimum temperature (Tmin), accumulated temperature (AT), relative humidity (RH), and sunshine duration (Shr) were collected at a national weather station that was close to the experimental site during the study period. The diurnal temperature range (DTR) was calculated by subtracting the daily Tmin from the daily Tmax. The reference evapotranspiration (ET_0) was calculated with the crop-water program that was developed by FAO using the FAO Penman–Monteith equation [24].

The average Tmin, Tmax, Shr, RH and DTR during the vegetative stage, reproductive stage and the whole growing stage; the total AT and ET_0 during the vegetative stage, reproductive stage and the whole growing stage were calculated. The vegetative stage was defined as from sowing to booting, while the reproductive stage was defined as from booting to harvest. The duration for the two periods is shown in Table A2. The date at which more than 50% of the plants reached a particular growth stage (booting) was considered as their booting (growth stage) date.

2.3.5. Calculations

Harvest index is calculated as: Harvest index (HI) = GY/(GY + SY).

Abortive grain rate (AGR) is defined as: 1 − (grain weight per panicle/panicle weight per plant).

Water productivity is defined as grain yield divided by the seasonal evapotranspiration (ET), which was calculated using the following equation: ET = I + P + C + SWD − R − D, where I is irrigation; P is rainfall; C is capillary rise; SWD is soil water depletion (soil water contents at sowing, minus that at harvesting for the 2 m soil profile); R is runoff; and D is drainage from the root-zone profile. Due to the rainfall being prevented by the moveable shelter, no runoff was observed, irrigation did not result in the drainage, and capillary rise was not observed due to the deep groundwater level. P, R, D and C were taken as zero under the conditions of this study. Therefore, ET was calculated as I + SWD.

The drought resistance index (DRI) for each cultivar was calculated using the equation [25]: $\text{DRI} = (\text{GY}^2_{\text{WS}}/\text{GY}_{\text{WW}}) \times (\text{GY}_{\text{CK-WW}}/\text{GY}_{\text{CK-WS}})^2$, where GY_{WS} and $\text{GY}_{\text{CK-WS}}$ are the yield of the newly collected and control variety, respectively, under WS treatment; GY_{WW} and $\text{GY}_{\text{CK-WW}}$ are the yield of the newly collected and control variety, respectively, under WW treatment.

2.4. Data Analysis

The average values from three replicates for each variety were used for the statistical analysis; a one-way ANOVA was performed by SPSS 16.0 and a Pearson correlation analysis was used (SPSS Version 16.0) to assess the correlations between traits. A path analysis was performed by SPSS Version 16.0; linear regression was used to calculate the standardized coefficients (direct effect) and correlation coefficients, grain yield was the dependent variable, and agronomic and physiological traits were the independent variables. The indirect effect was the product of the standardized coefficients and correlation coefficients.

3. Results

3.1. Selecting Traits for Improving Yield under Climate Change

3.1.1. The Effects of Weather and Irrigation on Yield

The changes in yield of all foxtail millet varieties for each season under the two water treatments are shown in Figure 1. A large yield difference was observed between the varieties in each season under both water treatments. Under the WS treatment, the smallest difference (0.36 t/ha) and the largest difference (1.43 t/ha) were observed in 2018 and 2020, respectively. Under the WW treatment, the smallest difference (0.38 t/ha) and the largest difference (1.75 t/ha) were observed in 2019 and 2017, respectively. The results indicated that there was a large variation in the yield performance among different varieties. The yield of most varieties was significantly different from the control variety.

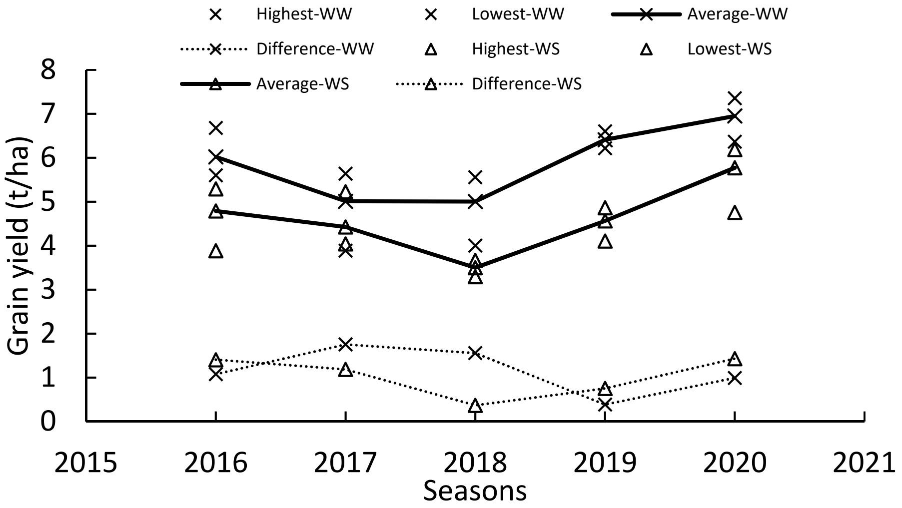

Figure 1. The changes in the highest and the lowest yield among the foxtail millet varieties each season and the average yield of the varieties under well-watered and water-stressed treatments for the five growing seasons (the Difference was defined as the difference between the varieties with the highest and lowest yield).

The average grain yield across varieties in each season varied from 3.50 (in 2018) to 5.77 (in 2020) t/ha under the WS treatment; from 5.01 (in 2017) to 6.95 (in 2020) t/ha under the WW treatment. The average grain yield of all varieties in each season decreased slightly from 2016 to 2017, then increased from 2018 to 2020, which indicated that the yield of millet had the potential to increase.

Compared with no irrigation, the average yield of all varieties in each season increase was around 25.66%, 13.19%, 43.01%, 40.40% and 20.39% irrigation in 2016, 2017, 2018, 2019 and 2020 seasons, respectively. The yield of foxtail millet was greatly improved with irrigation application compared with that without irrigation.

3.1.2. Weather Factors Related to Yield

The correlation of the yield with different weather factors during the vegetative, reproductive and the whole growth durations for variety Jigu19 that was grown from 2011 to 2020 was analysed (Table 1). Among the different weather factors, only temperature significantly affected GY under the WW treatment. High accumulated temperature and daily Tmax during the whole growth period had significant negative effects on GY, and high accumulated temperature and daily Tmax and daily Tmin during the vegetative growth period also had significant negative effects on GY under the WW treatment. Other weather factors did not significantly affect the GY of Jigu19. The results indicated that temperature was the main weather factor that influenced millet production; high temperature could impede high grain yield.

Table 1. Correlation analysis of grain yield of foxtail millet under water-stressed and well-watered conditions with weather factors during vegetative, reproductive and whole growing stages for variety Jigu19.

Weather Factors	**GY (Well-Watered)**			**GY (Water-Stressed)**		
	WhS	**VS**	**RS**	**WhS**	**VS**	**RS**
AT	−0.697 *	−0.843 **	−0.212	−0.471	−0.109	−0.499
Tmin	−0.609	−0.809 **	−0.273	−0.468	−0.279	−0.457
Tmax	−0.637 *	−0.774 **	−0.152	−0.366	−0.029	−0.492
DTR	−0.225	−0.434	0.103	0.008	0.231	−0.229
ET_0	−0.434	−0.517	−0.258	−0.294	−0.084	−0.411
Shr	−0.157	−0.219	−0.075	−0.183	0.035	−0.264
RH	0.608	0.532	0.513	−0.008	−0.279	0.277

Note: AT: accumulated temperature; DTR: diurnal temperature range; Tmin: minimum temperature; Tmax: maximum temperature; ET_0: reference evapotranspiration; Shr: sunshine duration; RH: relative humidity; WhS: the whole stage; VS: vegetative stage; RS: reproductive stage. * and **: significant at $p < 0.05$ and $p < 0.01$, respectively.

3.1.3. Climate Change and Trait Selection

The changes in the main weather factors in the past 15 years (from 2006 to 2020) at the experimental site are shown in Figure 2. There were large variations in the main weather factors. DTR, sunshine duration and temperature were in a slight increase trend and ET_0 also showed a positive increase trend, while the RH showed a negative decreasing trend. The increased ET_0 was related to the increased temperature and decreased relative humidity. The correlation analysis of yield with the main weather factors (Table 1) showed that decreased temperature favored yield formation, especially under well-watered conditions. The increasing temperature trend would negatively influence foxtail millet production in sufficient water supply conditions.

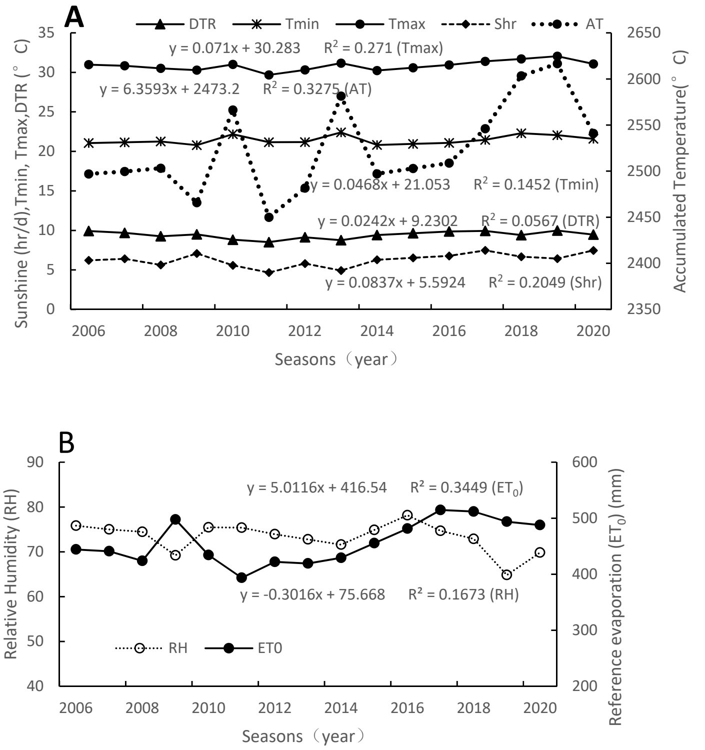

Figure 2. Changes in weather factors during the 5 growing seasons of foxtail millet and the recent 15 years from 2006 to 2020 (Sunshine: sunshine duration; Tmax: maximum temperature; Tmin: minimum temperature; accumulated temperature; DTR: average daily diurnal temperature range; (**A**). RH: relative humidity; ET_0: reference evaporation (**B**)).

Grain yield in 2018 was the lowest, compared to the grain yield in other years (Figure 1), Table A3 showed that the Tmin in 2018 was the highest among the five seasons, especially during the vegetative stage. The AT and Tmax were not the highest, but they were relatively high. The high temperature could reduce the GY. Figure 2 shows the daily Tmin, daily Tmax and AT increase trends which indicate the possible negative effects of temperature on GY.

3.2. Traits Related to the Yield Improvement of Foxtail Millet under Different Water Supply Conditions

Table 2 lists the correlations of GY and DRI with the physiological and agronomic parameters of those varieties that were tested in 2016–2020. DRI is an important parameter for drought resistant estimation. Table 2 shows that the correlation between GY and DRI was stronger under the WS treatment than under the WW treatment; although the correlations were not statistically significant, DRI improvement could be beneficial to a high grain yield under water stress.

Table 2. Correlation analysis of agronomic and physiological traits with the grain yield and drought resistance for foxtail millet varieties grown under two irrigation treatments for five seasons.

ITr		GY	PDW/Plant	TGW	AGR	HI	LA	ChlC	CanopyT	RWL
WW	GY		0.405 *	0.745 **	−0.729 **	0.054	0.563 **	0.374 *	0.365 *	−0.311
	DRI	−0.151	0.008	−0.194	0.309	0.320	−0.316	0.198	−0.366 **	0.095
WS	GY		0.495 **	0.629 **	0.171	0.430 *	0.530 **	−0.006	−0.029	−0.505 **
	DRI	0.354	0.347	−0.038	0.074	0.552 **	−0.233	0.085	−0.365 *	−0.059

Note: ITr: irrigation treatment; WW: well-watered; WS: water-stressed; GY: grain yield; DRI: drought resistance index; PDW/plant: panicle dry weight/plant; TGW: thousand grain weight; HI: harvest index; AGR: abortive grain rate; LA: leaf area; ChlC: chlorophyll content; CanopyT: average canopy temperature; RWL: rate of water loss. * and **: significant at $p < 0.05$ and $p < 0.01$, respectively.

GY significantly positively correlated with PDW/plant, TGW, and LA under both WW and WS treatments, which indicated that high PDW/plant, TGW, and LA played a vital role in improving GY independent of the water conditions. Under the WW treatment, significant positive correlations between GY, ChlC, and CanopyT were found, while significant negative correlations were found between GY and AGR. Thus, high ChlC and CanopyT and low AGR were more important under sufficient water-supply conditions. However, under the WS treatment, there were significant positive correlations between GY and HI, and significant negative correlations between GY and RWL.

In order to obtain a clear picture of the interrelationships between different traits, the direct and indirect effects of different traits were worked out using a path analysis in respect of grain yield (Table 3). Under the WW treatment, the direct effect of TGW, PDW/plant and HI on grain yield were positive, and the direct effect of AGR on grain yield were negative. The indirect effects of TGW on AGR had the greatest positive influence on grain yield. Under the WS treatment, the direct effect of PDW/plant, LA and DRI on grain yield were positive, and the direct effect of ChlC on grain yield were negative. The indirect effects of ChlC on PDW/plant and LA had the greatest positive and negative influence on grain yield, respectively. The indirect effects of DRI on PDW/plant had a great positive influence on grain yield. The indirect effects of LA on PDW/plant and PDW/plant on LA had great negative influences on grain yield.

Table 3. Direct and indirect effects of factors influencing grain yield in foxtail millet under two irrigation treatments for five seasons.

ITr	Trait	Direct Effect	Indirect Effect through			
			TGW	AGR	PDW/Plant	HI
WW	TGW	0.274	-	0.403	0.073	−0.021
	AGR	−0.632	−0.175	-	0.081	−0.005
	PDW/plant	0.535	0.037	−0.096	-	0.058
	HI	0.221	−0.006	0.013	−0.174	-
			PDW/Plant	LA	DRI	ChlC
WS	PDW/plant	0.725	-	−0.213	0.096	−0.113
	LA	0.696	−0.222	-	−0.064	0.120
	DRI	0.276	0.252	−0.162	-	−0.012
	ChlC	−0.228	0.360	−0.368	0.108	-

Note: ITr: irrigation treatment; WW: well-watered; WS: water-stressed; GY: grain yield; DRI: drought resistance index; PDW/plant: panicle dry weight/plant; TGW: thousand grain weight; HI: harvest index; AGR: abortive grain rate; LA: leaf area; ChlC: chlorophyll content.

DRI significantly positively correlated with HI under the WS treatment, which could contribute to a high yield of foxtail millet under water stress conditions. However, DRI significantly negatively affected CanopyT under both WW and WS treatments. Low CanopyT could be beneficial to DRI improvement.

Root distribution in the soil profile is an important factor for efficient soil water utilization, especially under limited irrigations. Most roots occurred in the 0–40 cm soil layer. Under the WS treatment, the roots in the 0–40 cm soil layer accounted for 37.4% and 58.4% in 2019 and 2020, respectively (Figure 3). Under the WW treatment, this accounted for 57.6% and 83.8% in 2019 and 2020, respectively. In the 0–60 cm soil layer, root density was higher under WW than that under the WS treatment, while in the deeper soil layer, root density was higher under WS than under the WW treatment.

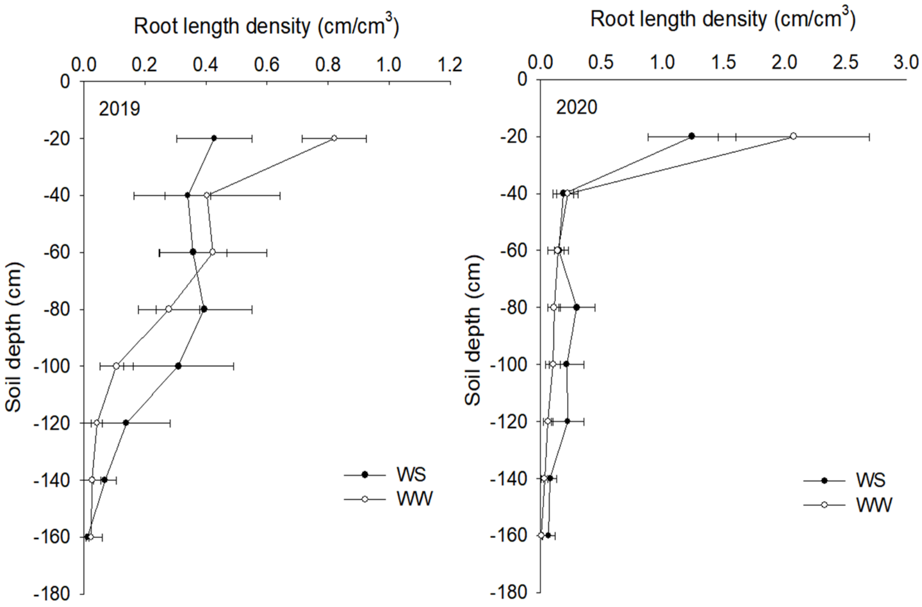

Figure 3. The distribution of the total root length (TRL) along the soil profile in 2019 for four varieties and 2020 for six varieties under well-watered (WW) and water-stressed (WS) treatments. (Bars represent the range of the RLD among the cultivars sampled).

The correlations of root density in the upper (0–40 cm), middle (40–100 cm) and deep (100–160 cm) soil layers with water productivity of different varieties in 2019 and 2020 are shown in Table 4. There was a significant negative correlation between root density and water productivity in upper layer soil under both the WW and WS treatments. For root density in the middle and deep soil layers, no significant correlations were found between them and water productivity under both the WW and WS treatments. The results indicated that water productivity of foxtail millet closely related to the root system in the upper soil layer.

Table 4. Correlation analysis of root density with water productivity and grain yield for foxtail millet varieties grown under two treatments in 2019 and 2020.

Treatment			**Water Productivity**			**Grain Yield**	**Drought Resistance Index**
			Upper Soil	**Middle Soil**	**Deep Soil**		
Water-stressed	Root density	upper soil	−0.804 **			0.633 *	0.218
		middle soil		0.350		−0.454	−0.348
		deep soil			0.430	0.288	0.128
	Grain yield		−0.826 **	−0.799 **	0.745 *		
	Drought resistance index		−0.440	−0.499	0.398		
Well-watered	Root density	upper soil	−0.722 *			0.519	0.271
		middle soil		0.096		−0.512	−0.211
		deep soil			−0.003	−0.160	0.553
	Grain yield		−0.592	−0.006	0.789 **		
	Drought resistance index		0.234	−0.097	0.380		

* and **: significant at $p < 0.05$ and $p < 0.01$, respectively.

For GY, the root density in the upper soil layer significantly correlated with GY under the WS treatment, but it did not significantly correlate with GY under the WW treatment. There were no significant correlations between root density in the middle and deep soil and GY under both the WS and WW treatments. Under the WS treatment, water productivity in the deep soil significantly positively correlated with GY, but water productivity in the upper and middle soil significantly negatively correlated with GY. Under the WW treatment, water productivity in the deep soil significantly positively correlated with GY. High root density in deep soil would contribute to a high grain yield.

In terms of DRI, there were no significant correlations between root density and water productivity in the upper, middle and deep soil and DRI under both the WS and WW treatments. Thus, root density and water productivity did not significantly influence DRI.

4. Discussion

In this study, large seasonal variation in grain yield was observed under both irrigation and non-irrigation treatments (Figure 1), and there was a large variation in the yield of some varieties (Figure 2, Table A4). Selecting a better variety could alleviate some of the negative effects of water deficit and weather factors on foxtail millet production. A better understanding of how climate factors and water stress influence grain yield is important for developing measures to eliminate the negative impacts.

Previous studies have indicated that weather factors significantly affect millet production [26–28]. There was a strong negative effect of both rainfall and temperature on millet yield, suggesting that there was variation in the climatic requirement, there is no doubt that farmers increasingly need detailed maps of this kind to plan crop-planting schemes and monitor the rate of yield (smart agriculture) [28]. In this study, the main weather factor that influenced the grain yield of foxtail millet Jigu19 was identified as being temperature only under the WW treatment, and the influence of other weather factors was small. Low temperature was beneficial for grain yield, but future climate change might favor an increased temperature that impedes grain yield in water-sufficient conditions. The weather factors in this study did not significantly impact grain yield in water-deficient conditions. Therefore, weather factors were not the main factors that influence the grain yield of foxtail millet varieties, which is similar to Jigu19 in a dry place without irrigation.

Djanaguiraman et al. [29] found that high temperature stress ($\geq$36/26 °C) imposed at different stages and durations caused a decrease in the number of seeds, individual seed weight and seed yield. Two periods (10–12 days and 2–0 days before anthesis) were identified as the most sensitive to short episodes of stress, causing maximum decreases in the pollen germination percentage and seed numbers of pearl millet. In this study, the grain yield of Jigu19 was more sensitive to the temperature during the vegetative stage than to the temperature during the reproductive stage under the WW treatment. High AT, Tmax and Tmin during the vegetative stage could decrease the grain yield of Jigu19. Therefore, millet varieties with characters that are less sensitive to temperature change during the vegetative stage would be preferred for the regions with sufficient water supply. However, trait × environment, trait × genotype, and trait × genotype × environment interactions are complicated, so further research at different experiment sites is needed.

The correlation analysis between grain yield and drought resistance index with physiological factors and agronomic traits could be used to select new varieties with traits under different water supply conditions, which could reduce the negative effects of water deficiency. Sanjana Reddy et al. [30] pointed out that the interaction between variety and environment was highly significant for the grain yield of pearl millet. In India, from the early 1950s to 2010, the development and diffusion of improved varieties along with suitable agronomic practices facilitated productivity, which increased grain yield from 430 kg ha^{-1} to 1079 kg ha^{-1} over a period of four decades [31]. In this study, the panicle dry weight per plant, thousand grain weight, leaf area and grain yield of different varieties of foxtail millet in five seasons had strong positive relationships under both the WW and WS treatments. High panicle dry weight per plant, thousand grain weight and leaf area could improve grain yield. However, abortive grain rate negatively affected grain yield and chlorophyll concentration positively affected grain yield only under the WW treatment; less abortive grains and high chlorophyll concentration could contribute to high grain yield, especially with sufficient water supply. Chlorophyll is a crucial component of crop photosynthesis machinery; high chlorophyll concentration could cause more photosynthate, which causes a low abortive grain rate.. Reza [18] also found a significant positive correlation between chlorophyll concentration and grain yield in both WW and WS conditions in wheat. However, Gu et al. [32] reported that a relatively low chlorophyll content increased photosynthesis and photosynthetic nitrogen-use efficiency. They also reported that it would avoid excessive light absorption, increase PSII efficiency, and result in a higher electron transport rate, and lowering chlorophyll content would not only benefit leaf photosynthesis, but also improve the light distribution in the canopy. Therefore, optimum chlorophyll concentration is better than too much or too little chlorophyll concentration in good water supply conditions.

In this study, CanopyT significantly positively affected grain yield under the WW treatment, while CanopyT significantly negatively affected the drought resistance index under the WW and WS treatment. In wheat, it is considered that wheat genotypes with a low canopy temperature can maintain a high transpiration and photosynthetic rate, as well as produce a high yield under water-stressed conditions [18]. Thus, optimal canopy temperature is preferred for a relatively high yield and drought resistance in sufficient water supply conditions. In addition, under the WS treatment, harvest index significantly positively affected grain yield and drought resistance index, while the rate of water loss significantly negatively affected grain yield. High harvest index and low rate-of-water-loss varieties selection could be considered for high grain yield, and a high harvest index is also beneficial to a high drought resistance index. Therefore, in dry areas, harvest index improvement and rate-of-water-loss reduction are very important for drought-resistant millet breeding or drought-resistant mechanism research.

Root development and distribution in the soil profile are of great importance for the water and nutrients uptake of foxtail millet. In the upper soil layer (0–40 cm), more roots were grown under WW than under the WS treatments, while in the deeper soil layer, more roots were grown under WS than under the WW treatments, because foxtail millet reorients its root growth toward deeper soil layers that retain more water in drought conditions [33]. The enhancement of water productivity in agriculture is very important to achieve efficient crop production [34]. In this study, grain yield significantly positively correlated with water productivity in deep soil layers under both the WS and WW treatments. However, grain yield significantly negatively correlated with water productivity in the upper and middle soil layers under only the WS treatment; grain yield significantly positively correlated with root density in the upper soil layer under only the WS treatment, which indicated that root density and water-use efficiency were more important than weather factors to millet production under water deficient condition, and high root density in the upper soil layer, high water productivity in the deep soil layer and low water productivity in the upper and middle soil layers could improve grain yield. However, in this study, the drought resistance index did not significantly correlate with root density and water productivity. Probably, for millet, root density and water productivity change could not influence drought resistance.

5. Conclusions

A large difference in yield among some varieties was observed, indicating the possibility of selecting better varieties to mitigate the negative effects of fluctuations in weather factors. For foxtail millet that was grown without water stress, temperature was the main weather factor influencing the grain yield of Jigu19; varieties with characters that are less sensitive to temperature change would be preferred.

The high panicle dry weight per plant, thousand grain weight and leaf area would improve the grain yield of foxtail millet under both irrigation treatments. Low abortion grain rate and optimal chlorophyll and canopy temperature could favor high grain yield and drought resistance under good water supply conditions. A high harvest index and low rate of water loss could favor high grain yield under limited water supply conditions.

The varieties with more roots in the upper soil layer could be beneficial to high grain yield, especially under water stress conditions. High water productivity in the deep soil layer was beneficial to high grain yield under good water supply and water stress conditions.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. The information of 25 varieties.

Variety	Pedigree	Regions of Adaption	Year of Release	Year Grown	Yield (t/ha)	Thousand Grain Weight (g)
Canggu9	Heng968 × K492	Hebei	2018	2018	5.30	2.77
Heng1475	(Henggu12 × Yugu18) × kn2009-2	Hebei	2019	2017	5.22	2.60
Heng2011-2	Jigu17 × Henggu15	Hebei, Jilin	2018	2017	5.08	2049
Henggu13	Yugu15 × Jigu31	Hebei, Shandong, Henan, Liaoning, Jilin	2018	2016, 2019	6.50	2.91
Henggu15	Not clear	Henan, Liaoning, Jilin	2018	2016	7.53	2.88
Henggu16	Shagu × K721-1	Henan, Liaoning, Jilin	2018	2017	5.40	2.68
Henggu17	Shagu × K720-3	Henan, Liaoning, Jilin	2018	2017	5.62	2.69
Henggu18	Not clear	Henan, Liaoning, Jilin		2017	3.88	2.57
Henggu2018-1	Henggu11 × Ji0506	Hebei	2018	2018	5.51	2.32
Henggu2018-2	Henggu11 × (Hengyan5 × SR3522)	Hebei	2019	2018	5.56	2.32
Henggu2018-3	(Hengyan5 × SR3522) × M1508	Hebei	2019	2018	4.49	2.68
Hengsi1	Not clear	Hebei	2018	2016	7.62	2.86
Jigu22	Yugu9 × Jigu25	Hebei, Shandong, Henan	not clear	2020	7.08	2.81
Jigu168	Yugu18 × 1310-2	Hebei, Liaoning, Neimongol, Shaanxi	2020	2020	6.37	2.99
Jigu19	Ai88 × Qingfenggu	Shanxi, Shandong, Henan, Shaanxi	2004	2016–2020	5.48	2.49
Jigu34	Not clear	Shanxi, Shandong, Henan, Shaanxi	2013	2016	8.59	2.94
Jigu37	Not clear	Shanxi, Shandong, Henan, Shaanxi		2016	8.91	3.13
Jigu39	An09-8525 × [An4585 × (Jigu24 × 2010-M1445)]	Hebei, Henan, Shandong, Shanxi, Xinjiang, Beijing, Liaoning, Jilin	2018	2019, 2020	7.11	3.10
Jigu42	An4585 × (Shi98622 × 1310-2)	Hebei, Henan, Shandong, Xinjiang, Liaoning, Jilin, Neimongol, Shanxi, Shaanxi, Heilongjiang	2018	2018	4.00	2.48
Lvmi16	Not clear	Not clear	Not clear	2016	7.47	3.27
Zhonggu10	Zhonggu2 × Chuang877	Beijing, Tianjin, Hebei, Shanxi, Neimongol	2020	2020	6.92	3.05
Zhonggu2	Yugu1 × Ai88	Beijing, Tianjin, Hebei, Shanxi, Neimongol	2015	2017–2020	6.00	2.72
Zhonggu7	Not clear	Beijing, Hebei, Henan, Shandong	2020	2017	4.26	2.31
Zhonggu8	Jigu20 × Q31	Beijing, Hebei, Henan, Shandong	2020	2017	5.64	2.51
Zhonggu18	Not clear	Beijing, Hebei, Henan, Shandong	2018	2018–2020	6.07	2.44

Table A2. The recorded dates of sowing, booting and harvest.

Year	Sowing Date	Booting Date	Harvest Date
2016	21 June	4 August	27 September
2017	19 June	5 August	25 September
2018	18 June	3 August	23 September
2019	16 June	4 August	25 September
2020	23 June	6 August	29 September

Table A3. The major weather factors during the five seasons at different growing stages of foxtail millet.

Weather Factors	Seasons	Whole Stage	Vegetative Stage	Reproductive Stage
Accumulated temperature (°C)	2016	2508.80	1314.70	1194.10
	2017	2546.00	1350.00	1196.00
	2018	2603.40	1396.10	1207.30
	2019	2616.60	1408.40	1208.20
	2020	2541.00	1312.90	1228.10
Minimum temperature (°C)	2016	21.07	22.31	19.83
	2017	21.46	22.77	20.20
	2018	22.30	23.92	20.69
	2019	22.06	23.70	20.41
	2020	21.60	22.16	21.03
Maximum temperature (°C)	2016	30.94	32.03	29.86
	2017	31.40	32.90	29.94
	2018	31.70	33.81	29.66
	2019	32.04	34.50	29.58
	2020	31.07	31.80	30.34
Diurnal temperature range (°C)	2016	9.87	9.72	10.02
	2017	9.94	10.13	9.74
	2018	9.41	9.85	8.97
	2019	9.99	10.80	9.17
	2020	9.47	9.64	9.31
Reference evaporation (mm)	2016	481.38	263.91	217.47
	2017	514.67	292.71	221.95
	2018	511.89	296.15	215.74
	2019	493.78	288.57	205.21
	2020	487.74	281.94	205.80
Sunshine duration (hr/d)	2016	6.77	6.27	7.27
	2017	7.47	7.08	7.87
	2018	6.67	7.33	6.02
	2019	6.43	6.92	5.93
	2020	7.46	8.50	6.43
Relatively humidity (%)	2016	78.15	75.67	80.63
	2017	74.68	70.12	79.24
	2018	72.88	70.06	75.69
	2019	64.82	60.14	69.49
	2020	69.82	66.22	73.41

Table A4. The maximum, minimum, mean and coefficient of variation of grain yield of different varieties in five seasons.

Treatment	Year	Maximum	Minimum	Mean	Coefficient of Variation (%)
WW	2016	6.68	5.60	6.02	8.07
	2017	5.64	3.89	5.01	13.06
	2018	5.56	4.00	5.01	12.49
	2019	6.60	6.22	6.41	2.89
	2020	7.36	6.37	6.95	5.23
WS	2016	5.29	3.89	4.79	12.97
	2017	5.23	4.04	4.43	11.78
	2018	3.67	3.30	3.50	4.26
	2019	4.86	4.11	4.57	7.75
	2020	6.19	4.76	5.77	9.50

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