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Effects of Solar Radiation on Dry Matter Distribution and Root Morphology of High Yielding Maize Cultivars

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Abstract: The root system connects the plant with the soil, which is a key factor in determining the utilization of soil resources and plant growth potential. Solar radiation can change maize shoot and root growth and affect grain formation. In this study, the effects of different solar radiation conditions on root morphology of three maize cultivars XY335, ZD958 and DH618 and their quantitative relationships were studied by conducting shading experiments. This study was conducted in maize high yield region of Qitai and Yinchuan, China, in 2018 and 2019. The planting densities were 7.5×10^4 (D1) and 12×10^4 (D2) plants ha^{-1}. The shading levels were natural light (CK), shading 15% (S1), 30% (S2) and 50% (S3). The results showed that maize responded to the decreased solar radiation through the increase in ratio of shoot dry weight (SWR) to whole plant dry weight and the decrease in ratio of root dry weight (RWR) to whole plant dry weight. As the solar radiation decreased, the root length density (RLD), root surface area (RSA), average root diameter (ARD) and root length ratio (RLR) decreased, while the specific root length (SRL) increased. With 100 MJ m^{-2} decrease in solar radiation, the RWR, RLD, RSA and RLR each decreased by 1.47%, 0.5 mm cm^{-3}, 0.4 m m^{-2} and 0.19 m g^{-1}, respectively. Among the cultivars, the changes of DH618 were the fastest followed by XY335 and ZD958 but DH618 maintained the largest root system under any solar radiation condition. After the decrease of solar radiation, RWR, RLD and RLR were significantly positively correlated with the yield. This indicated that large root systems were conducive to the rapid response to decreased solar radiation and important for achieving stable and high yield. Maize cultivars with these type of root systems should be recommended to better adapt low solar radiation induced by regional variation or climate change.

Keywords: solar radiation; maize; yield; shoot; root morphology; cultivar

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1. Introduction

Solar radiation is an important ecological factor that affects crop growth and development and drives photosynthesis [1–4]. Enhancing photosynthesis also contributes to sustainable yield increases [5]. As is typical for C4 crops, maize has a stronger photosynthetic and material production capacity, yet ensuring suitable solar radiation conditions during the growth period of maize is of great importance for achieving a stable and high yield [6,7]. However, the solar radiation in China has decreased in recent years due to climate change and environmental pollution [8–10]. Especially in some maize growing areas, the maize growing season often encounters rainy weather, and the continuous dense cloud cover leads to less solar radiation [11,12]. Researchers have studied the effects of solar radiation on maize growth and development through shading experiments in order to alleviate the negative effects of solar radiation [13–15]. Overall, when solar radiation was decreased, the photosynthetic production capacity likewise decreased, and the accumulation of assimilates was insufficient [16,17]. At the same time, insufficient solar radiation leads to limited ear development, an unbalanced growth of female and male ears, a shortened grain filling period, and a final yield decline [18–20]. The plant growth is weak, and the risk of lodging also increases as solar radiation decreases [21,22].

The maize root system can effectively guarantee a connection between soil and plant, and this connection is important for obtaining soil resources. Roots help provide the necessary nutrients and water for plant vegetative and reproductive growth [23,24]. Good root system architecture contributes to nutrient and water absorption, and is one of the key determinants of plant growth potential [25,26]. The root system architecture includes root growth and spatial distribution, which has a high plasticity. Root growth refers to the comprehensive changes in the size and morphology of the root system. The biomass allocated to the root determines the size of the root and its ability to support the shoot [27]. Root morphology plays an important role in root development and function. The size and morphology of the root system determine the total volume of soil explored by the plant, and the total surface of exchange between roots and soil solution [28]. It is supposed that plants can optimize their root system architecture to adapt to unfavorable growth conditions [29,30]. Manipulating the root system architecture towards a distribution of roots in the soil that optimizes water and nutrient uptake, can both increase plant yield and optimize agricultural land use [31].

The root morphological parameters mainly include root length, average root diameter (ARD), and root surface area (RSA) [32]. Root morphology usually perceives external changes and can produce adaptive mechanisms through self-regulation [33]. When the external solar radiation changes, and the maize aboveground growth and development are limited, the photosynthate distributed to the root system is reduced, which affects root growth and morphological parameters [34]. The effect of solar radiation on maize root dry weight was shown to be greater than that on shoot dry weight. There is also a quantitative relationship between root dry weight and solar radiation [35]. However, whether the responses of maize shoot and root to solar radiation change are consistent remains unknown. It is also not clear whether there is a quantitative relationship between root morphology and solar radiation. As root morphology is more important to reflect the function of root than root dry weight [36,37], further research into the quantitative relationships between root morphology and solar radiation is essential for matching solar radiation to changes in the root system and increased grain yield.

The morphological differences among maize root system determines their absorption and utilization efficiency of water and nutrients and their adaptability to the environment [38]. It is an effective way to improve the utilization of soil resources to shape the appropriate root system, which is of great significance to further realize high yield [39]. With the improvement of cultivars, modern cultivars have a smaller root system than old cultivars, and the root biomass, root length and root surface area have decreased, showing the characteristics of "intra-row contraction and inter-row extension", which has stronger adaptability to high fertilization level and high planting density [40,41]. In addition, the shoot of maize responded to the competition among plants through plant type adjustment. Research suggests that the upper leaves of the ear are more important at high density. When the yield potential increased from 15.0 Mg ha^{-1} to 22.5 Mg ha^{-1}, the number of leaves on the upper ear increases by 0.8–1.1 [42]. The smaller stem–leaf angle is helpful for better light distribution at the bottom of the canopy, which can adapt to a larger population [43–45]. Therefore, modern cultivars have a high grain yield under a high planting density [46]. However, with the increase of planting density, light transmission decreases in the canopy, the aboveground growth is limited determining the less assimilates transported to the root system and results in poor root system [47,48]. However, there is limited research on the root morphology responses of different genotypes to changing solar radiations.

The plasticity of root morphology plays an important role in plant growth under the changing conditions of climate and solar radiation [49]. A few studies have focused on the effects of solar radiation on maize root system morphology by conducting shading experiments [50–52]. However, these studies were mainly conducted in regions of low solar radiation, which allow less flexibility in evaluating multiple solar radiation conditions [53,54]. Therefore, this study mainly analyzed the effects of solar radiation on maize shoot and root growth to make clear whether the effects were consistent and the quantitative relationship between morphology and solar radiation in the region with the highest solar radiation resources in China. The aim of this study is to provide a theoretical reference for high yield maize cultivar selection and breeding under different solar radiation conditions in different regions or induced by climate change.

2. Materials and Methods

2.1. Site Description and Weather Data

The field experiments were carried out in Qitai (Xinjiang Uygur Autonomous Region, China, 43°50′ N, 89°46′ E) and Yinchuan (Ningxia Hui Autonomous Region, China, 38°13′ N, 106°14′ E) in 2018 and 2019. The specific location of the experiment site was shown in Figure 1. Each year it was sown in mid-April and harvested in mid-October. These are two locations among those with the highest solar radiation intensity in China. Qitai's accumulated solar radiation during the maize growth period in 2018 and 2019 were 1702.8 and 1638.8 MJ m^{-2}, and Yinchuan's were 1682.7 and 1616.0 MJ m^{-2}. The accumulated precipitation of Qitai during the maize growth period in 2018 and 2019 were 223.1 and 149.6 mm; and the average temperature were 16.8 and 18.2 °C, respectively. These data of Yinchuan were 181.9 and 132.8 mm; 20.9 and 21.0 °C, respectively (Figure 2).

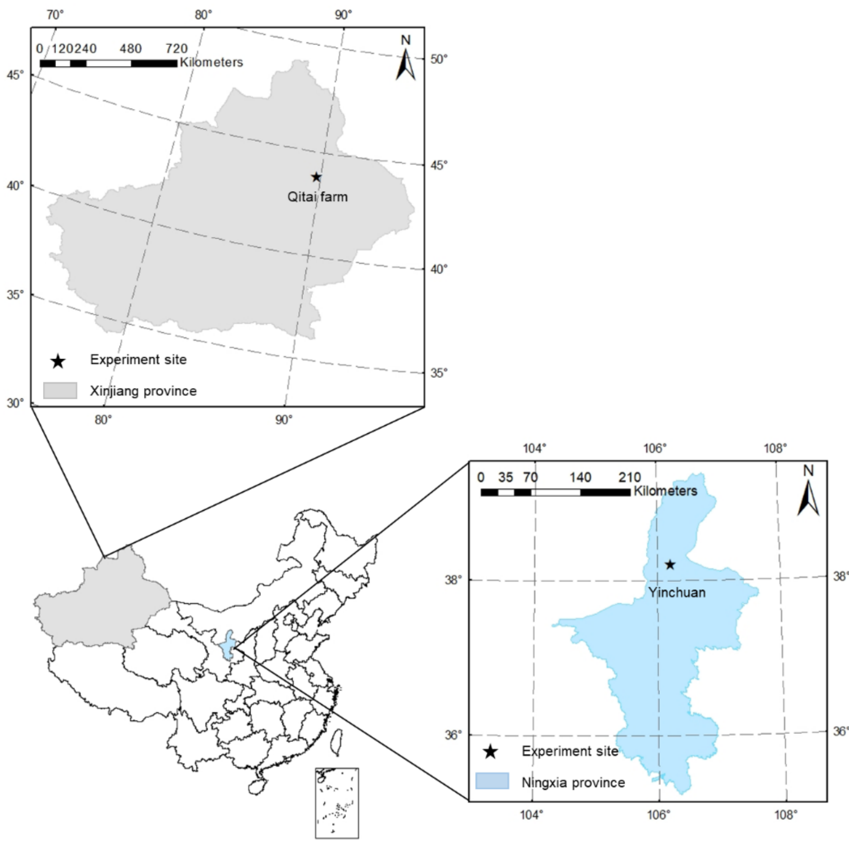

Figure 1. The positions of two experimental sites.

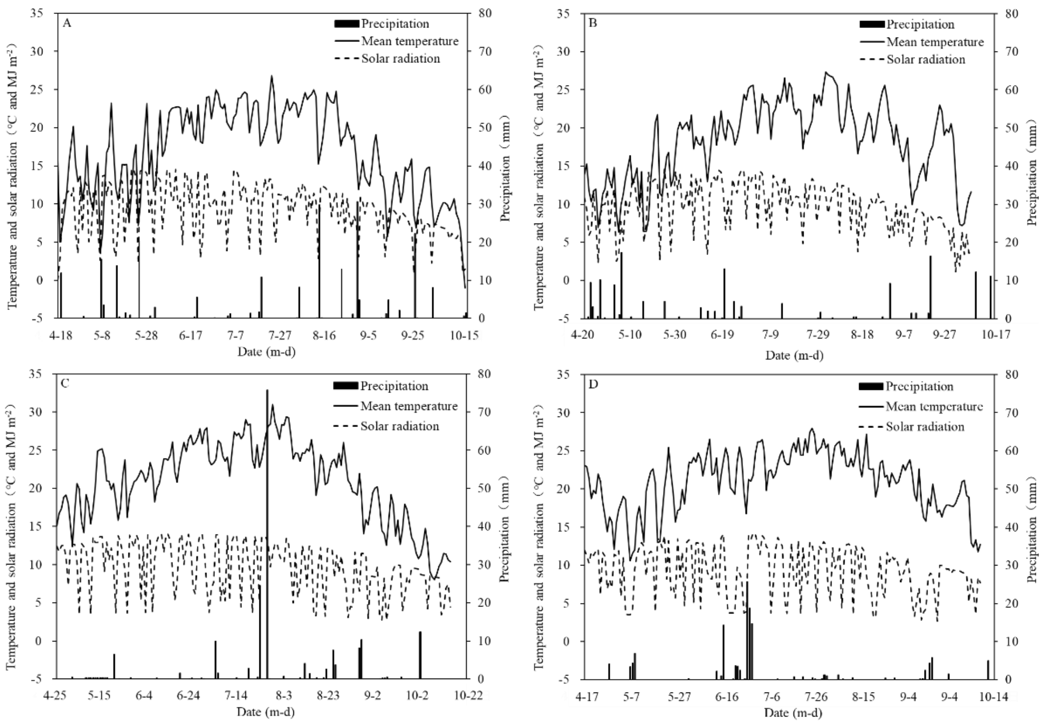

Figure 2. Weather data of the site from 2018 to 2019. (**A**) 2018 Qitai, (**B**) 2019 Qitai, (**C**) 2018 Yinchuan, (**D**) 2019 Yinchuan.

The soil types of Qitai and Yinchuan are sandy soils. Soil total organic matter concentrations were 14.1 and 13.3 g kg^{-1}, and alkaline-N were 87.6 and 64.5 mg kg^{-1}, olsen-P were 53.8 and 19.9 mg kg^{-1}, alkaline-K were 108.6 and 137.0 mg kg^{-1} in Qitai and Yinchuan, respectively [35].

2.2. Experiment Design

The experiment included 16 treatments (two cultivars, two densities and four shading levels) in both sites in 2018, 24 treatments (three cultivars, two densities and four shading levels) in Qitai, and 16 treatments in Yinchuan in 2019. The plot area was 110 m^2, which includes 22 experimental rows of 10 m length and 0.55 m width, with a 1 m walkway between the plots. The shading period began when the plants were at the three-leaf stage and continued to the mature stage. Shading was achieved by building shade nets suitable for the required shading level at 1.5 m away from the maize canopy. The experiment adopted a split-plot design with three cultivars Xianyu 335 (XY335), Zhengdan 958 (ZD958), and Denghai 618 (DH618) as the main factor, two planting densities of 7.5×10^4 plants ha^{-1} (D1) and 12×10^4 plants ha^{-1} (D2) as subplot factors, and four shading levels of natural light as a control (CK), 15% shading (S1), 30% shading (S2), and 50% shading (S3) of natural light as the secondary subplot factor. All treatments were arranged completely randomly and replicated three times.

2.3. Field Management

In this study, irrigation was used in Qitai and Yinchuan, and the irrigation amount was about 540 mm to prevent water stress in the growing season. To ensure uniform emergence, all experimental plots were irrigated (15 mm) on the first day after sowing. Irrigation was applied every 9–10 days after 60 days of sowing [55]. The use of fertilizer followed that of Yang et al. [22] The specific fertilization scheme was shown in Table 1. Total fertilizer used in Yinchuan and Qitai, respectively, were 375 and 450 kg ha^{-1} N as urea, 188 and 225 kg ha^{-1} P_2O_5 (super phosphate), and 53 and 75 kg ha^{-1} K_2O (potassium sulfate) to prevent nutrient stress. The diseases, pests and weeds of the test site were well controlled.

Table 1. Fertilizer application in maize growing season in Qitai and Yinchuan in 2018 and 2019.

	Base Fertilizers			Topdressing
	N	**P_2O_5**	**K_2O**	**N**
	Kg ha^{-1}	**Kg ha^{-1}**	**Kg ha^{-1}**	**Kg ha^{-1}**
Qitai	150	225	75	300
Yinchuan	75	188	53	300

2.3.1. Total Intercepted Photosynthetically Active Radiation

From elongation to silking, the amount of photosynthetically active radiation reaching the top and bottom of the canopy was measured every 10 days with six replications by using a line quantum sensor (Sunscan, Delta-T Devices, Ltd.; Burwell, UK). The total intercepted photosynthetically active radiation (TIPAR) was calculated according to the method of Yang et al. [2]

2.3.2. Root Sampling

In 2018 and 2019, samples were taken at the silking stage. In each plot, the above ground parts of the three plants in the same row were cut manually, and then the roots were excavated layer by layer according to the soil profile method with the roots as the center (Figure 3A,B). The total depth of root excavation was 60 cm, which was divided into three layers: 0–20 cm, 21–40 cm and 41–60 cm [56]. For each layer, the excavation area of D1 and D2 was 0.24 × 0.55 m and 0.15 × 0.55 m respectively, and the total soil volume were 0.08 m^3 and 0.05 m^3 respectively. The soil of each layer was placed in a separate nylon bag, and then all roots were manually picked and cleaned with water until all the roots observed were white (Figure 3C). Take photos and record the cleaned main root system of 0–20 cm (Figure 4A,B). Then the roots cleaned of each soil layer were floated evenly and non-superposed in the water storage glass tank (length × width × height = 25 × 20 × 2 cm^3), scan the clean roots with a scanner (Indo-nesia Epson V800) (Figure 4C), and store them in JPG format (Figure 4D,E). Finally, we used an analysis program (WinRhizo Pro Vision5.0, Canada) to analyze the scanned image to obtain root length, root surface area and root diameter. The scanned roots were dried at 85 °C to a constant weight to determine the root dry weight and the corresponding aboveground were dried together to determine the shoot dry weight. The specific introduction of root morphological parameters were shown in Table 2.

Figure 3. Maize roots were collected in the field. This method will be adopted in both Qitai and Yinchuan in 2018 and 2019. (**A**) Plant selection and shoot cutting; (**B**) Excavating fixed soil layer by layer; (**C**) Root system cleaning.

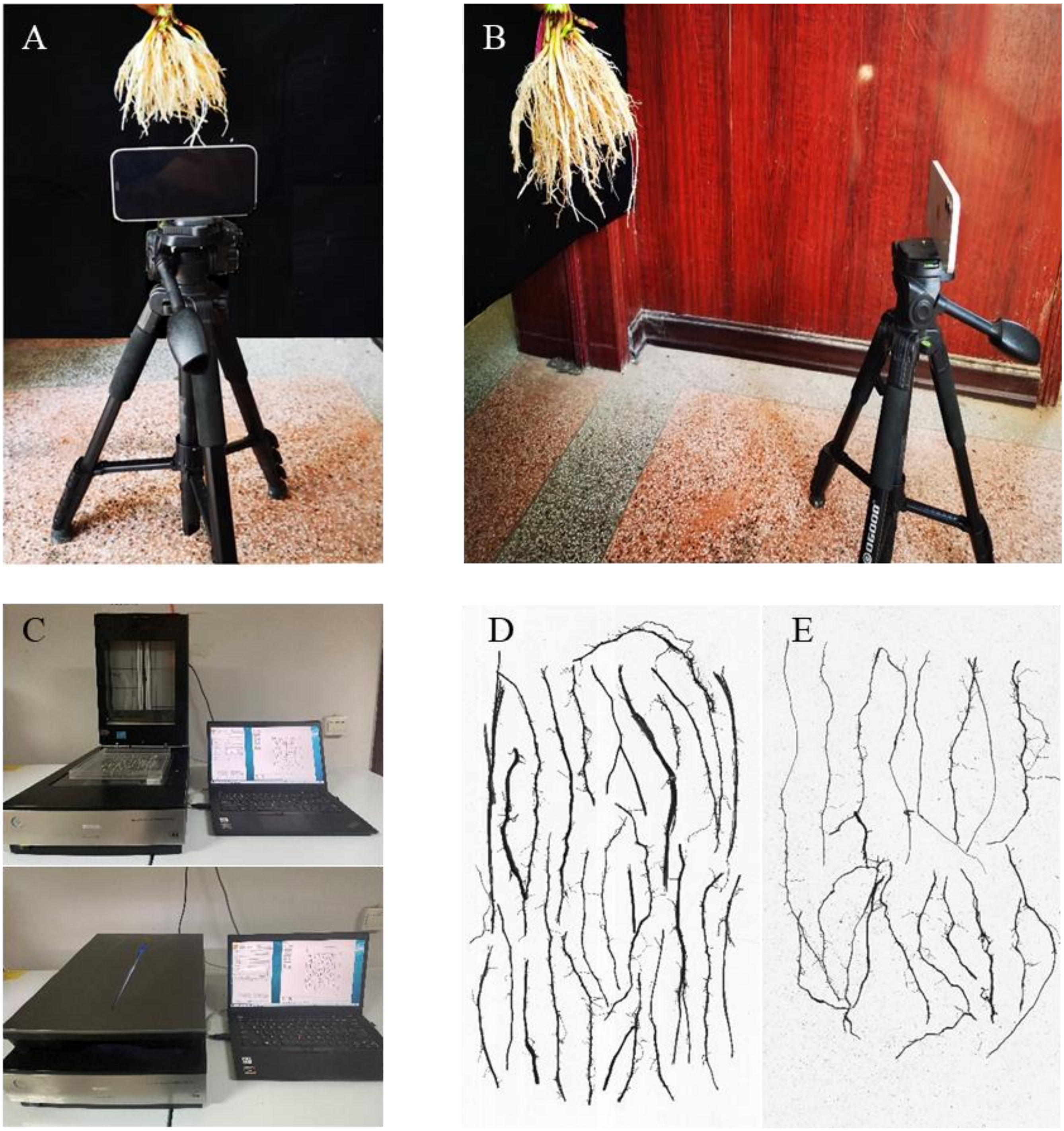

Figure 4. The whole picture of maize root system and root system scan pictures. (**A**,**B**) was the shooting method of the main maize root system. The maize roots of different treatments were fixed on the black background cloth, and the camera was fixed on the tripod 50 cm away from the roots system for shooting; (**C**) is the instrument for root scanning; (**D**,**E**) was a partial image of a clean root scanned and it selected from thou-sands of images. All the treatments roots were scanned in this way.

Table 2. Root traits and their functional characteristics.

Root Trait	Functional Characteristics
Total root length/surface area (RSA)/root weight ratio (RWR)	The total system size: the size of contact with soil (major determinant of water and nutrient uptake as an entire root system)
Root length density (RLD)	Rate of water and nutrient uptake
Root diameter	Potential for penetration ability, branching, hydraulic conductivity
Specific root length (SRL)	Degree of branching, density of root materials, porosity due to aerenchyma development

Source: reference [32].

2.4. Statistical Analysis

Calculations were performed using Microsoft Excel 2010 software. The SPSS 21.0 software (IBM, Armonk, NY, USA) was used for variance analysis and correlation analysis to test for differences among treatments. RLD, RSA, ARD, SLR and RLR were firstly analyzed by one-way ANOVA followed by the Duncan's test to compare the mean values among the treatments at $p < 0.05$. The formula calculated from the tested indicators are as follows [57]:

$$\text{Shoot weight ratio (SWR)} = (\text{Shoot dry weight}/\text{whole plant dry weight}) \times 100\% \quad (1)$$

$$\text{Root weight ratio (RWR)} = (\text{Root dry weight}/\text{whole plant dry weight}) \times 100\% \quad (2)$$

$$\text{Root length density (RLD)} = \text{Root length}/\text{Soil volume } (\text{mm cm}^{-3}) \quad (3)$$

$$\text{Specific root length (SRL)} = \text{Root length}/\text{Root dry weight } (\text{m g}^{-1}) \quad (4)$$

$$\text{Root length ratio (RLR)} = \text{Root weight ratio} \times \text{Specific root length } (\text{m g}^{-1}) \quad (5)$$

3. Results

3.1. Effects of Different Shading Levels on Maize Dry Matter Distribution

The distributions of plant dry matter to shoot and root were significantly affected by site, year, cultivar, planting density and shading levels, among which cultivars and shading levels had the greatest influence (Figure 5). For the aboveground, the SWR of XY335, ZD958 and DH618 control treatments were 91.2–93.3%, 92.6–93.8% and 83.3%, respectively. With the decrease of solar radiation, the SWR increased, and the increase degree was S3 > S2 > S1. The average SWR of shading treatment for XY335, ZD958 and DH618 were 94.1–95.3%, 95.4–96.0% and 92.9%, respectively. Compared with the control, the SWR of XY335, ZD958 and DH618 increased by 2.9%, 2.7% and 11.5% respectively with the decrease of solar radiation. For the underground, the RWR of XY335, ZD958 and DH618 control treatments were 6.7–8.9%, 6.2–7.4% and 16.7%, respectively. With the decrease of solar radiation, the RWR decreased, and the decrease degree was S3 > S2 > S1. The average RWR of shading treatment for XY335, ZD958 and DH618 were 4.7–5.9%, 4.0–4.6% and 7.1%, respectively. Compared with the control, the RWR of XY335, ZD958 and DH618 decreased by 33.1%, 37.2% and 57.3% respectively with the decrease of solar radiation (Figure 6). In summary, the increase in the SWR of XY335 and ZD958 and the decrease in the RWR after the decrease of solar radiation were both smaller than that of DH618. Under any solar radiation level, the shoot dry weights of XY335 and ZD958 were significantly higher than DH618, while the root dry weights were significantly lower than that of DH618. The shoot dry weight of XY335, ZD958 and DH618 decreased with radiation by 25.1, 23.1 and 17.4%, respectively; root dry weight decreased by 44.5, 43.9 and 53.7%, respectively (Figure 7).

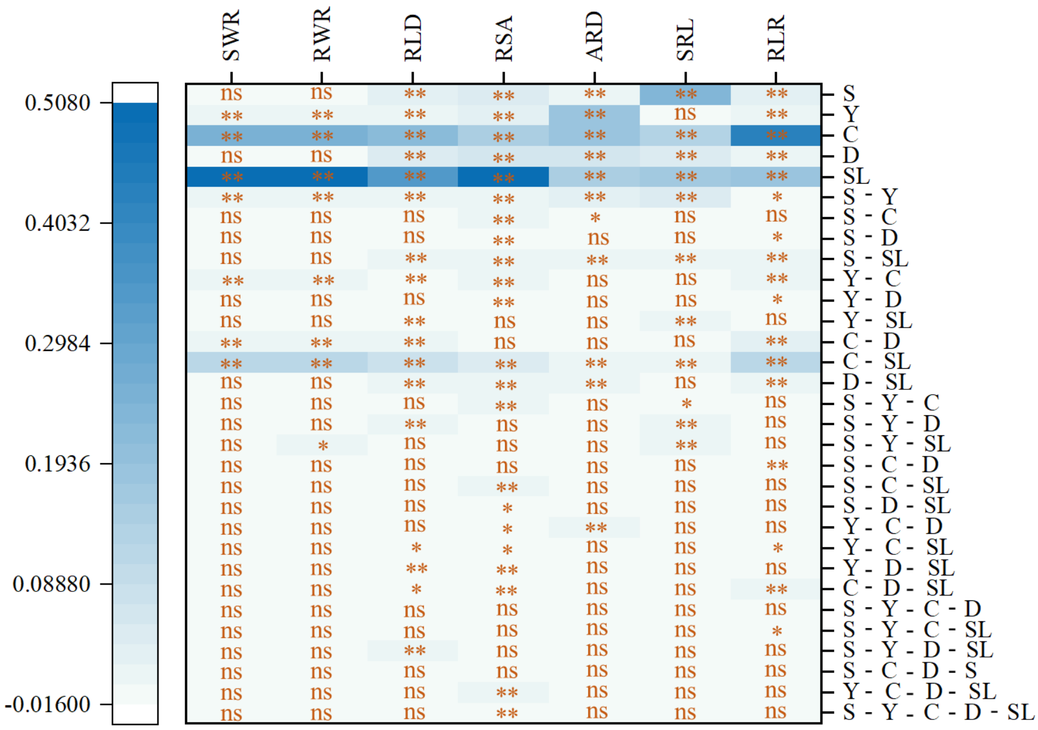

Figure 5. ANOVA results for shoot weight ratio (SWR, %), root weight ratio (RWR, %), root length density (RLD, mm cm^{-3}), root surface area (RSA, m^2), average root diameter (ARD, mm), specific root length (SRL, m g^{-1}) and root length ratio (RLR, m g^{-1}). S: site; Y: year; C: cultivar; D: planting densities; SL: shading level. *, ** significant differences at $p < 0.05$ and $p < 0.01$, respectively. ns represents no significant differences.

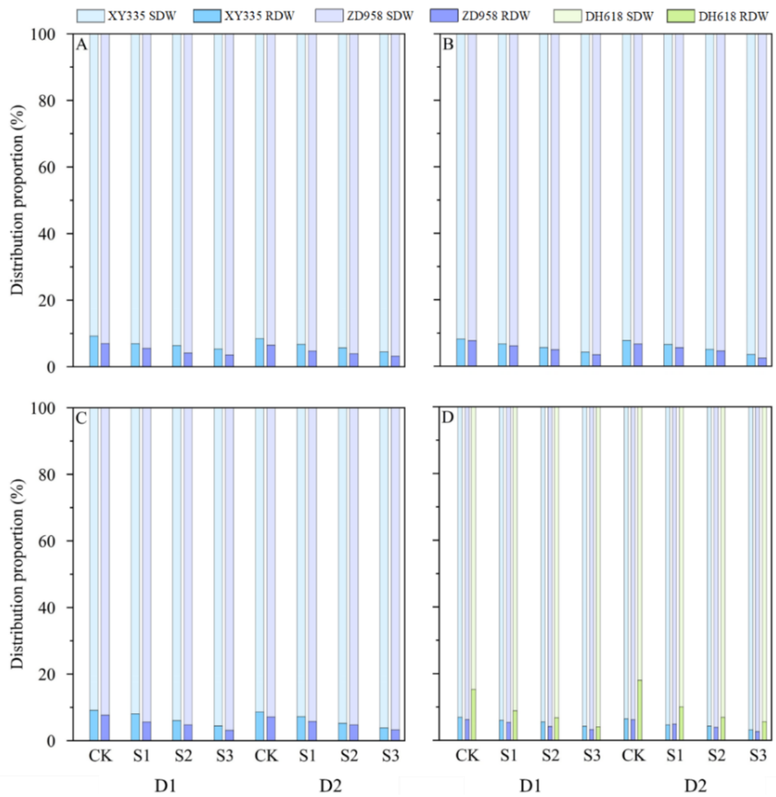

Figure 6. Distribution ratio of aboveground and underground biomass under different shading levels and planting densities. (**A**) 2018 Yinchuan; (**B**) 2019 Yinchuan; (**C**) 2018 Qitai; (**D**) 2019 Qitai.

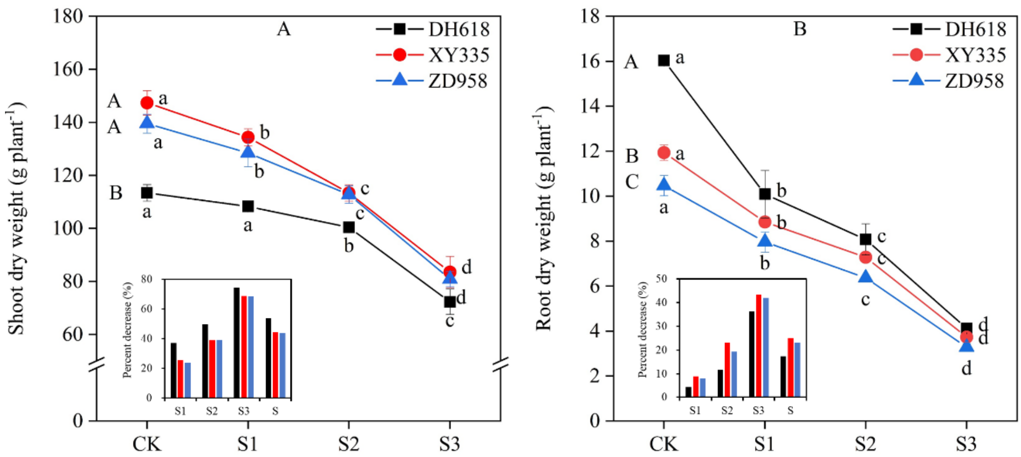

Figure 7. Maize shoot dry weight and root dry weight of different cultivars under different shading levels by averaging two densities. (**A**): Shoot dry weight; (**B**): Root dry weight. The bars represented the error standard ($n = 24$). Analysis of variance was used to compare the differences of CK, S1, S2 and S3 among different cultivars. No shared lowercase letters indicate significant differences between treatments at $p < 0.05$.

3.2. Effects of Different Shading Levels on Maize Root Morphology

Different levels of solar radiation had obvious effects on the maize root system. As solar radiation decreased, the root system became smaller (Figure 8). Through Figure 9 we can further analyze the changes in root morphological parameters. The RLD of D2 density was significantly higher than D1 density, while the RSA and ARD were significantly lower than D1 density. The RLD and RSA of DH618 were significantly higher than those of XY335 and ZD958, and the ARD was significantly lower than that of ZD958 and XY335. With the decrease of solar radiation, RLD, RSA and ARD all decreased, the degree of decrease was S3 > S2 > S1. The RLD of DH618, XY335 and ZD958 under the control treatment were 4.6, 1.6 and 1.4 mm cm^{-3}, respectively, which decreased with the decrease of solar radiation and the average decrease rate were 55.4%, 39.2% and 36.4%. The RSA of DH618, XY335 and ZD958 under the control treatment were 0.3, 0.2 and 0.2 m^2, respectively, with the average decrease rate of 53.7%, 41.3% and 38.7% after solar radiation decrease. The ARD of DH618, XY335 and ZD958 under the control treatment were 0.3, 0.5 and 0.6 mm, respectively, with the average decrease rate of 21.1%, 19.2% and 13.8% after solar radiation decrease.

Figure 8. Maize root of DH618 under different shading level (CK: natural light control; S1: 15% shading; S2: 30% shading; S3: 50% shading) at D2 (12×10^4 plants ha^{-1}) planting densities at the silking stage.

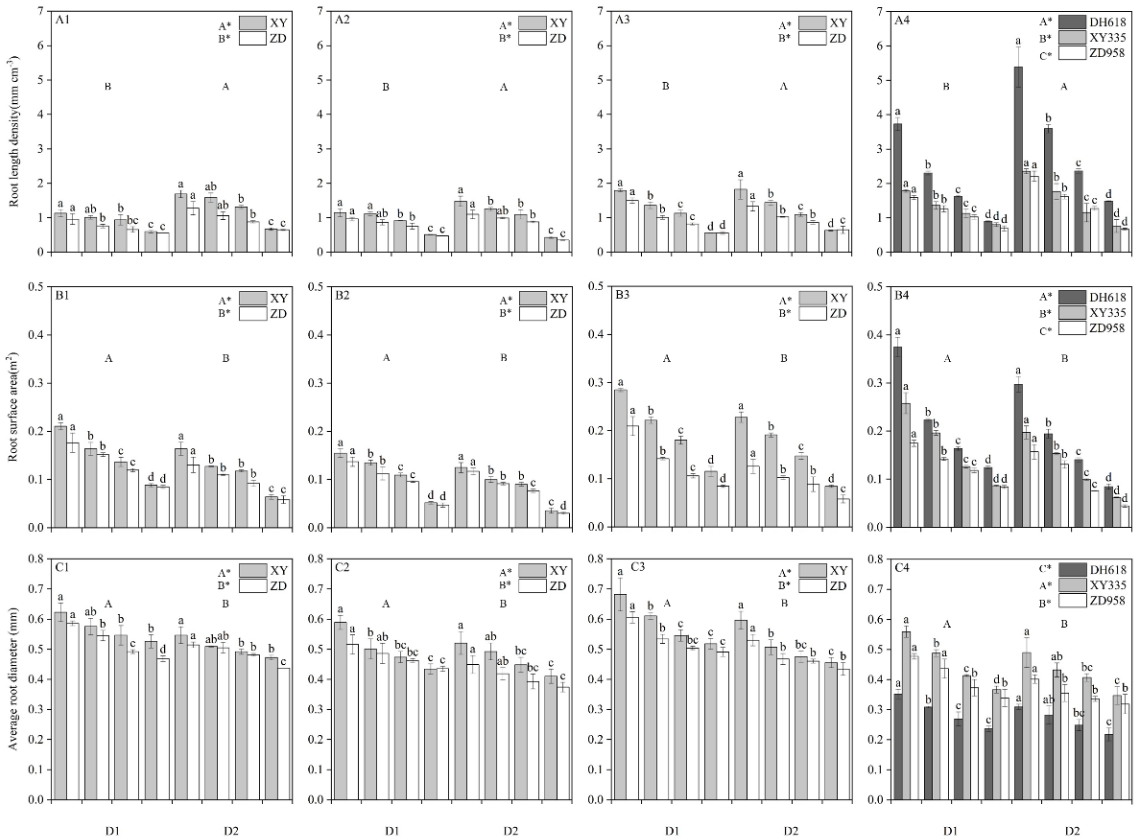

Figure 9. Maize root length density (RLD, mm cm^{-3}), root surface area (RSA, m^2) and average root diameter (ARD, mm) under different shading levels and planting densities. The bars represented the error standard (n = 3). Analysis of variance was used to compare the differences of CK, S1, S2 and S3 among different cultivars under D1 or D2 density. No shared lowercase letters indicate significant differences between shading levels at $p < 0.05$. No shared capital letters indicate significant differences between planting densities at $p < 0.05$. No shared capital letters and * indicate significant differences between planting cultivars at $p < 0.05$. (**A1**,**B1**,**C1**): 2018 Yinchuan; (**A2**,**B2**,**C2**): 2019 Yinchuan; (**A3**,**B3**,**C3**): 2018 Qitai; (**A4**,**B4**,**C4**): 2019 Qitai.

3.3. Effects of Different Shading Levels on the Acquisition Ability of Root

Root size and root morphology are important factors that determine the ability of roots to obtain underground resources. The RLR is closely related to the component reflecting the quantity of biomass allocated to the roots (RWR) and the pattern of investment of this biomass (SRL). From Figure 10(A1–A4), it was shown that the SRL increased after the solar radiation decrease, indicating that the root system became thinner under weak solar radiation. The SRL of DH618, XY335 and ZD958 under the control treatment were 14.7, 9.5 and 9.1 mg^{-1}, respectively, and the average increase rate was 18.0%, 22.9% and 21.7% with the decrease of solar radiation. With the decrease of solar radiation, the RLR decreased significantly, and the degree of decrease was S3 > S2 > S1. Under natural light, the RLR of DH618, XY335, and ZD958 are 2.5, 0.7 and 0.6 m g^{-1}, respectively. After shading, the RLR were 1.2, 0.6 and 0.5 m g^{-1} on average, with decrease rate of 50.2%, 21.1% and 20.4%, respectively (Figure 10(B1–B4)). The SRL of D2 density was significantly higher than D1 density, while the difference in RLR was not significant. The SRL and RLR of DH618 were significantly higher than those of XY335 and ZD958 (Figure 10).

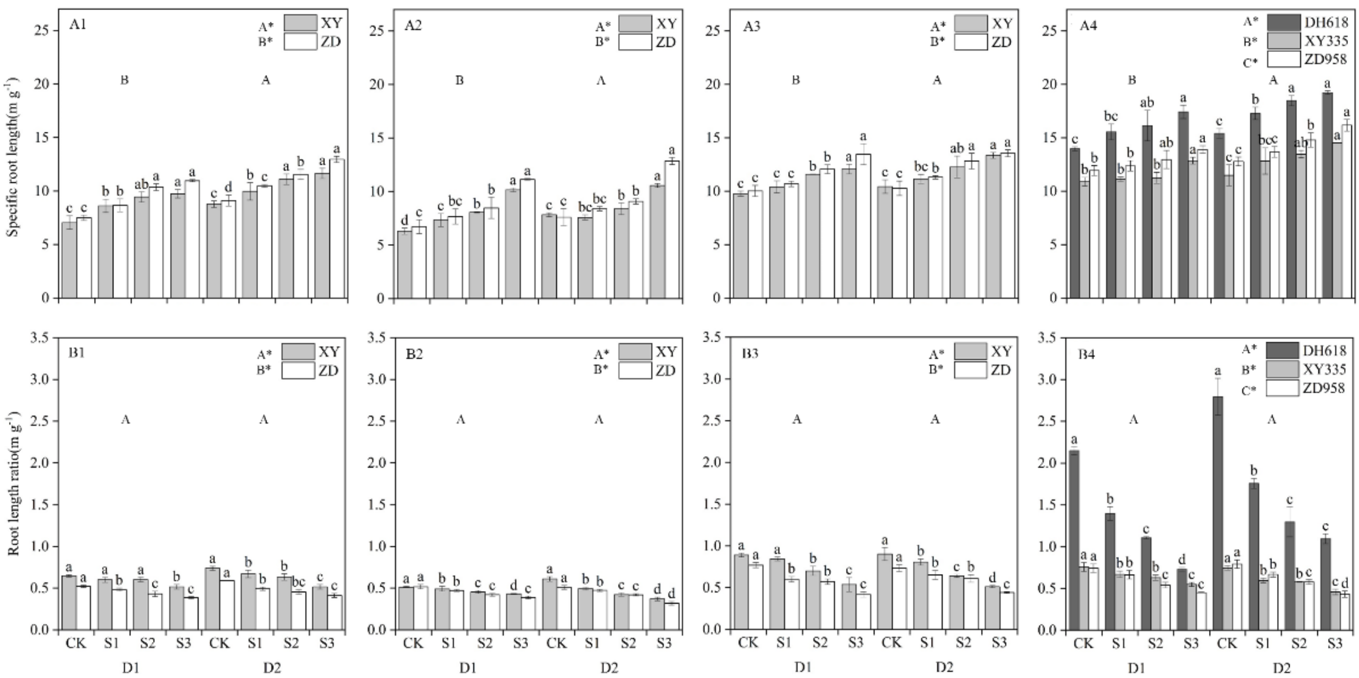

Figure 10. Acquisition ability of maize roots to underground resources. The bars represented the error standard ($n = 3$). Analysis of variance was used to compare the differences of CK, S1, S2 and S3 among different cultivars under D1 or D2 density. No shared lowercase letters indicate significant differences between treatments at $p < 0.05$. No shared capital letters indicate significant differences between planting densities at $p < 0.05$. No shared capital letters and * indicate significant differences between planting cultivars at $p < 0.05$. (**A1**,**B1**): 2018 Yinchuan; (**A2**,**B2**): 2019 Yinchuan; (**A3**,**B3**): 2018 Qitai; (**A4**,**B4**): 2019 Qitai.

3.4. Quantitative Relationships between TIPAR and Root Morphology

The analysis of TIPAR from the elongation stage to the silking stage and root morphology at silking showed that there were quantitative relationships between RWR, RLD, RSA, RLR, and TIPAR. With 100 MJ m^{-2} decrease of TIPAR, the RWR of DH618, XY335, and ZD958 decreased by 3.01, 0.76 and 0.63%, respectively. Similarly, the RLD decreased by 0.92, 0.31 and 0.27 mm cm^{-3}, respectively, the RSA decreased by 0.59, 0.38 and 0.24 m^2 m^{-2}, respectively, and the RLR decreased by 0.41, 0.08 and 0.08 m g^{-1}, respectively. Overall, as the TIPAR decreased by 1 MJ m^{-2}, the RWR, RLD, RSA and RLR each decreased by 1.47%, 0.5 mm cm^{-3}, 0.4 m m^{-2} and 0.19 m g^{-1}, respectively (Figure 11).

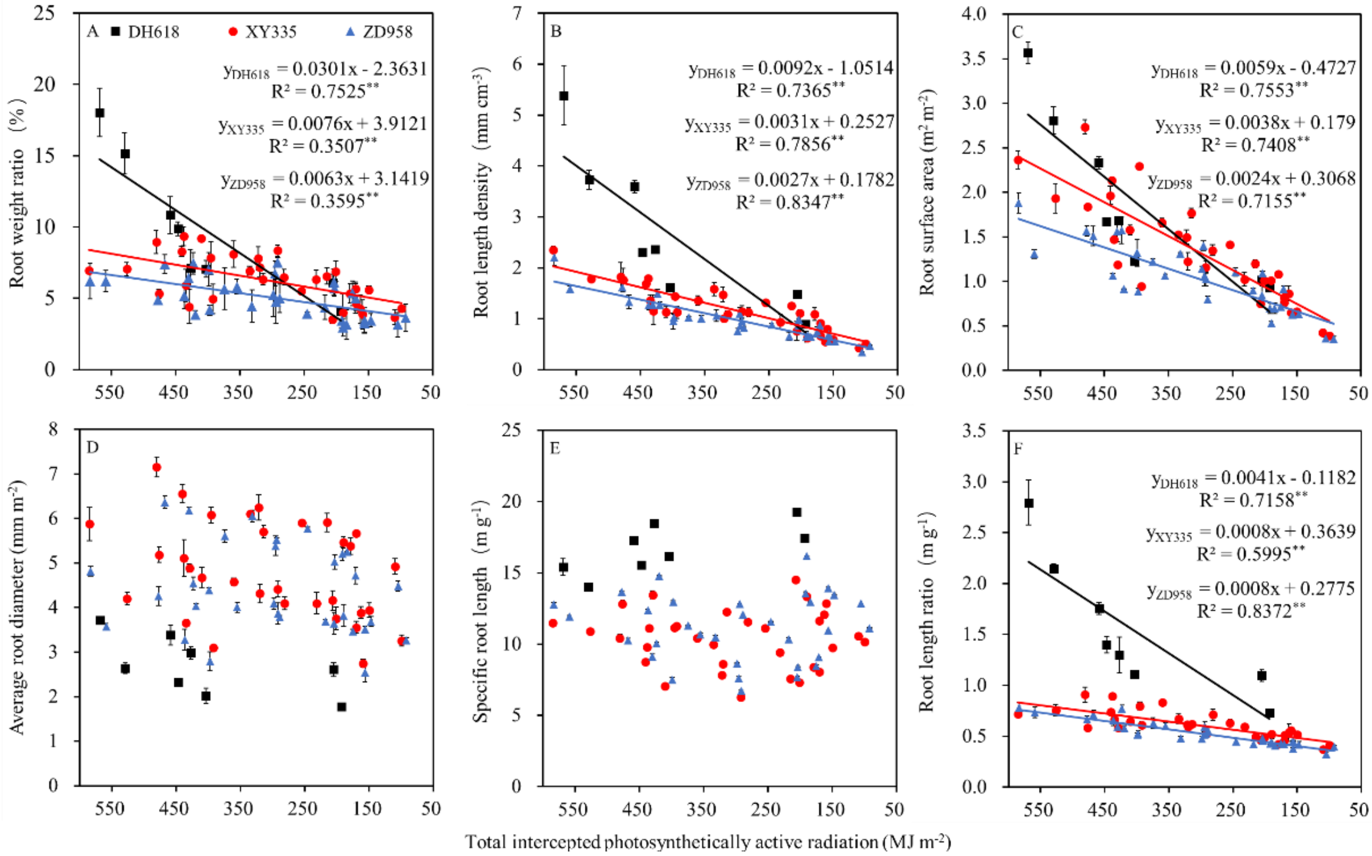

Figure 11. Quantitative relationships between TIPAR and root weight ratio (RWR, %) (**A**), root length density (RLD, mm cm^{-3}) (**B**), root surface area (RSA, m^2 m^{-2}) (**C**), average root diameter (ARD, mm m^{-2}) (**D**), specific root length (SRL, m g^{-1}) (**E**) and root length ratio (RLR, m g^{-1}) (**F**). The bars represented the error standard (n = 24). ** significant differences at $p < 0.05$ and $p < 0.01$, respectively.

3.5. Effects of Different Root Morphology on Maize Yield

The acquisition of soil resources by roots is conducive to the growth of aboveground, which in turn affects the yield. Under natural light, there were no significant positive correlations between RWR, RLD, RLR and yield, whereas under S1, S2 and S3 treatment there were significant positive correlations between RWR, RLD, RLR and yield except for RWR of S1. Under natural light and shading treatments, there were not significant positive correlations between RSA and yield. It showed that root size and root length under low solar radiation had a greater impact on yield than the normal environment (Figure 12).

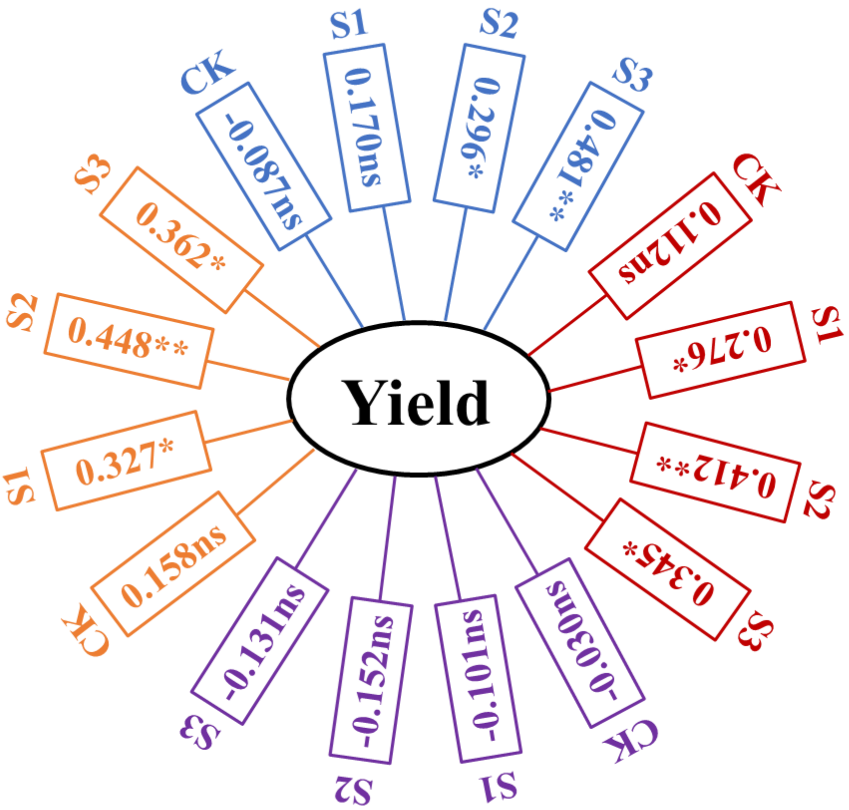

Figure 12. The correlation between root weight ratio (RWR, %), root length density (RLD, mm cm^{-3}), root surface area (RSA, m^2 m^{-2}), root length ratio (RLR, m g^{-1}) and yield of maize. *, ** significant differences at $p < 0.05$ and $p < 0.01$, respectively. ns represents no significant differences. Blue: RWR. Red: RLR. Purple: RSA. Orange: RLD.

4. Discussion

4.1. Effect of Solar Radiation on Maize Root and Shoot

Root systems are the main route for soil resources, not only by transportation but also by uptake, and their functions are closely related to root size and root morphology [58–60]. The root system obtains photoassimilates, which is helpful for the plant to overcome poor growing environments [61]. When the solar radiation condition is limited, photosynthetic products are preferentially distributed to the aboveground organs, and root growth is blocked [62,63]. In previous studies, it was found that the whole plant became smaller, and the aboveground and root biomass decreased after shading [16,64]. However, in this study, we found when the solar radiation decreased, the root weight ratio decreased while the shoot weight ratio increased (Figure 6). This indicated that the responses aboveground and underground to changes in solar radiation were not consistent. Changes in biomass allocation will affect the balance between root and shoot growth [65]. Several studies have shown that, for different maize cultivars, higher biomass allocations to shoots and less allocations to root biomass lead to a higher yield [66]. We also found similar results. Compared with XY335 and ZD958, DH618 responded more quickly to solar radiation, so it had a more coordinated relationship between shoot and root and it always maintained a higher root/shoot ratio. In addition to the rapid response of the root system, the larger root system helps to provide sufficient nutrients and water for the aboveground growth [67]. The larger root system mainly depends on the larger root dry weight. The root dry weight of DH618 was the largest under any solar radiation conditions, which might be conducive to its supply aboveground to ensure a high yield (Figure 7).

The change of root morphology is affected by root system size. It is generally considered that root length, root surface area and root fineness are the key morphological parameters affecting nutrient and water absorption [68,69]. Root length and root surface area are important factors that determine the degree of root system contacting with soil. Root length can be expressed by root length density, and root fineness reflects the size of the root diameter [54]. After the decrease in solar radiation, the decline of root dry weight will lead to the decline of root morphological parameters [34]. Root length density, root absorption area and active absorption area under low solar radiation were lower than those under high solar radiation [63]. Our results showed that the RLD, RSA and ARD decreased after the decrease of solar radiation (Figure 9). In our results, the decrease of RLD was 38.7–53.7%, which was lower than the experimental results of Gao et al. (53–66%) [54]. This may be due to cultivar differences. Under the same environmental conditions, the root system of different genotypes are significantly different [36]. Studies have shown that the total root length and root diameter of XY335 are less than those of ZD958 [70]. This is inconsistent with our results. In this study, under natural light conditions, the RLD and RSA showed the decreasing trend of DH618 > XY335 > ZD958 and the ARD showed the decreasing trend of XY335 > ZD958 > DH618. This may be due to the different environmental and soil conditions. The root system of DH618 was the most sensitive to solar radiation changes, followed by XY335 and ZD958. However, DH618 always maintained the largest root length density and root surface area to achieve more resources in the soil.

The ability to acquire underground resources can be reflected by RLD, which can be decomposed into RWR and SRL [71]. A large RWR means that more biomass is distributed to the root system, which is conducive to the root system to obtain a larger root length. Generally, large roots can improve the efficiency of root nitrogen absorption [72]. The distribution of root biomass in root length, which in SRL determines its efficiency in obtaining resources and a higher SRL is more efficient [73]. In this study, we found that the SRL increased after the solar radiation decreased (Figure 10), which was actually the root thinning. The RLR decreased with the decrease of solar radiation, which might be closely related to the decrease in RWR (Figures 6 and 10). For the three cultivars, the SRL and RLR change of DH618 were the fastest in response to solar radiation. Compared with the other two cultivars, its RWR and SRL were larger, and the RLR was larger, which resulted in a stronger ability to acquire underground resources.

Although some studies reported the effects of solar radiation on maize root morphology by conducting shading experiments [50–52], the quantitative effects of solar radiation on root morphology were reported. In this study, the quantitative relationships between RWR, RLD, RSA, RLR and TIPAR during plant growth stages were established. The results showed that with every 100 MJ m^{-2} decline in TIPAR, the RWR, RLD, RSA and RLR each decreased by 1.47%, 0.5 mm cm^{-3}, 0.4 m m^{-2} and 0.19 m g^{-1}, respectively (Figure 11). The cultivars of ZD958, XY335 and DH618 showed different quantitative relationships. This can provide a theoretical reference for maize cultivar selection and breeding under different solar radiation conditions in different regions, or those induced by climate change.

4.2. Effect of Root Morphology on Yield

In the absence of other factors, there is a simple linear relationship between yield and photosynthetically active radiation [74–76]. At the same time, too-high planting density results in a low solar radiation in the group, which will intensify the contradiction between individuals and groups, which is not conducive to the increase of the yield [77,78]. In addition to the aboveground regulation of grain formation, the root system also plays an important role [79,80]. The plant's root system provides sufficient nutrients and moisture for development, which is conducive to a higher crop yield [67]. It has been found that, in most cases, crop yield is highly correlated and nearly linear with crop root mass [81]. In this study, we found that there was no significant correlation between RWR, RLD, RLR and yield under natural light, but there were significant positive correlations between RWR, RLD, RLR and yield after the decrease of solar radiation (Figure 12). This meant that root growth was more important for crop growth and yield after solar radiation decrease. This is similar to some studies in the Huang-Huai-Hai region of China where there are also significant positive correlations between root morphology and yield due to the lower solar radiation in that region [52,54].

Under the same environmental conditions, the root morphology of different genotypes are significantly different and preferable root morphology contributes to an increased yield of cultivars [36]. RWR is very important for root morphology. The larger the RWR, the larger the root system, which means that the root length in contact with the soil will be more and it is more conducive to extending into the deeper soil to efficiently acquire sufficient water and nutrient supply for grain formation [82]. In this study, the highest yield of DH618 might be due to its higher RWR, RLD and RLR than the other two cultivars under any solar radiation conditions, and its root system was finer, which was conducive to the acquisition of deep soil resources [83]. Cultivars with this kind of root morphology should be recommended to better adapt to a low solar radiation environment in different regions or those induced by climate change.

5. Conclusions

This study showed contrary effects of solar radiation on the dry matter distribution of maize shoot and root growth. As solar radiation decreased, SWR increased and RWR decreased. There were quantitative relationships between the root morphology parameters (RWR, RLD, RSA and RLD) of different cultivars and TIPAR. The root size, length and surface area were more responsive to solar radiation. Compared with the other two cultivars, DH618 had the largest root weight ratio, longer and finer roots under each treatment, and it changed rapidly with the decrease in solar radiation. This was conducive to the acquisition of soil resources. There was a positive correlation between RWR, RLD, RLR and yield under shading treatments, indicating that root size and root length had a greater effect on yield under low light conditions. Therefore, the selection of large root cultivars with the longer root length is beneficial to cope with low light stress.

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