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Response of Soil Temperature, Moisture, and Spring Maize (*Zea mays* L.) Root/Shoot Growth to Different Mulching Materials in Semi-Arid Areas of Northwest China

Haidong Lu [1,2], Zhenqing Xia [1], Yafang Fu [1], Qi Wang [1], Jiquan Xue [1,2] and Jie Chu [3,*]

1 College of Agronomy, Northwest A&F University, Yangling 712100, China; chujie392111@mwsuaf.edu.cn (H.L.); 17854233612@163.com (Z.X.); f13546632915@163.com (Y.F.); QiWangNwafu@163.com (Q.W.); xjq2934@126.com (J.X.)
2 The Research Center of Maize Engineering and Technology of Shaanxi Province, Northwest A&F University, Yangling 712100, China
3 College of Forestry, Northwest A&F University, Yangling 712100, China
* Correspondence: chujie392111@163.com

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Abstract: Adaptive highly efficient mulching technologies for use on dryland agricultural ecosystems are crucial to improving crop productivity and water-use efficiency (WUE) under climate change. Little information is available on the effect of using different types of mulch on soil water thermal conditions, or on root/shoot trait, leaf area index (LAI), leaf area duration (LAD), yield, and WUE of spring maize. Hence, in this study, white transparent plastic film (WF), black plastic film (BF), and maize straw (MS) was used, and the results were compared with a non-mulched control (CK). The results showed that the mean soil temperature throughout the whole growth period of maize at the 5–15 cm depth under WF and BF was higher than under MS and CK, but under BF, it was 0.6 °C lower than WF. Compared with CK, the average soil water storage (0–200 cm) over the whole growth period of maize was significantly increased under WF, BF, and MS. WF and BF increased the soil water and temperature during the early growth stages of maize and significantly increased root/shoot biomass, root volume, LAI, LAD, and yield compared with MS. Higher soil temperatures under WF obviously reduced the duration of maize reproductive growth and accelerated root and leaf senescence, leading to small root/shoot biomass accumulation post-tasseling and to losses in yield compared with BF

Keywords: spring maize; mulching types; soil temperature; soil moisture; growth and development

1. Introduction

In China, dryland farming is practiced on about one third of the arable land, 56% of which is situated in the northwest [1]. Soil water shortage is the major limiting factor for crop production owing to low rainfall and high potential evaporation in this area [2]. Mulching technologies that improve crop water-use efficiency (WUE) play an important role in sustainable crop production and local food security [3–5]. As one of the most effective mulching measures, the technique of plastic film mulching for maize production is used extensively in semi-arid areas of northwest China [6,7]. The effect of plastic film mulching on soil temperature and water is generally regarded as the most important means by which the use of mulch affects crop yield, and studies have confirmed that plastic film mulching decreases the amount of water loss caused by evaporation [3], enhances soil water infiltration [4], improves crop yields [8], increases WUE [9], and significantly increases topsoil temperature. Recently, global warming has led to an increase in total thermal time [10,11], and although higher soil temperatures under a plastic film mulch could prompt crop growth [8], the additional increase in temperature will have several disadvantages: The growth period of crops will be shortened [12]; plants will be more likely to suffer from heat stress in their late stages of growth [5]; and leaf senescence after the flowering of maize will be accelerated, leading to a decrease in maize productivity [6]. Under global climate change, deferring senescence in the late growth stages of maize and increasing productivity have become critical issues in semi-arid areas of northwest China, and finding an effective mulching material has been the main goal of research investigating how to tackle these problems.

The type of material covering the land has a different impact upon soil moisture and temperature. White transparent plastic film mulch has been found to increase soil temperature by 2 to 6 °C in spring maize in China [13], temperatures in unshaded soil as high as 50 ~ 60 °C have been recorded during high-temperature periods [14]. In contrast, soil temperatures under a straw mulch have been found to be lower compared with white transparent plastic film mulch [3]. Furthermore, straw mulch effectively leads to the retention of soil water and therefore lower water consumption, thereby enhancing crop productivity [15]. However, the effectiveness of straw mulching depends on climatic conditions and soil type [16]. For example, Gao and Li (2005) showed that straw mulching tends to lower the soil surface temperature, which can lead to a reduction in crop yield [17]. Some reports of the effects on soil temperature suggest that the use of black plastic film mulches can lower the maximum temperature experienced by the soil compared with white transparent plastic film [18]; this observation is purely down to the increased penetration of sunlight that occurs when white film is used compared with black film. Black polyethylene film mulches have been reported to be better than transparent polyethylene film mulch for growing groundnuts [19], tomatoes [20], and winter rapeseed [21].

Unlike other crops, very limited work has been done on the use of black film or maize straw mulches for maize, and most studies have focused on use of white transparent plastic film. In arid and semi-arid areas, the benefits of reduced soil evaporation from the use of white transparent plastic film mulches are countered by very high increases in soil temperature, which are likely to have a negative impact on maize growth [6]. Few studies have compared the effects of using these different types of mulch on the soil temperature and maize root/shoot development. Against this background, we conducted a field experiment to examine the effects of different mulching materials on soil water, temperature, and their effects on the root/shoot growth and yield of maize. This field study aimed to (i) assess the impacts of varying mulching treatments on soil water storage and temperature; (ii) investigate the influence of varying mulching treatments on root and volume, shoot weight, leaf area index (LAI), and the ratio of root to shoot of maize; and (iii) determine appropriate mulching materials for maximum WUE and yields of spring maize in the semi-arid areas of northwest China.

2. Materials and Methods

2.1. Description of the Experimental Site

The experiment was conducted from 2013 to 2015 at the Northwest A&F University Arid Maize Research Station (34°59′ N, 107°38′ E; altitude 1220 m) in Changwu County of Shaanxi Province, China. The climate is temperate semi-arid, with a long-term annual average air temperature of 9.1 °C, a mean monthly maximum temperature of 23 °C (July), and a mean monthly minimum temperature of −6.5 °C (January). Average annual meteorological data for the past 30 years were as follows: Precipitation was 584 mm; potential evaporation was 1560 mm; sunshine was 2124 h; frost-free period was 171 days; and 64% rainfall occurred in July, August, and September. Data on the precipitation, high air temperature, ranges and low air temperature ranges during the maize-growing periods in 2013, 2014, and 2015 are given in Table 1. Irrigation was unavailable in this area. The soil at the experimental site was a loess sandy soil with a pH of 8.2. In the 0–20 cm soil layer, the soil organic matter content was 11.56 g kg^{-1}. The available N, P, and K contents were 46.66, 16.94, and 122.35 mg kg^{-1}, respectively.

Table 1. Rainfall, high air temperature, and low air temperature during the growth period of maize during the study period.

Year	Rainfall (mm)	High Air Temperature (°C)	Low Air Temperature (°C)
2013	413.3	24–35	10–22
2014	454.6	21–36	11–23
2015	438.5	22–36	11–23

2.2. Experimental Design and Field Management

For the field experiment, we used a completely randomized block design with four treatments and three replicates. The four treatments were: (i) Non-mulched control (CK); (ii) mulch with white transparent polyethylene film (0.008 mm thick; 0.7 m wide) (WF); (iii) mulch with black polyethylene film (0.01 mm thick; 0.7 m wide) (BF); and (iv) mulch with maize straw (cut into 30 cm-long segments and uniformly applied at a rate of 5000 kg ha^{-1} similar to the film mulch mode) (MS) (Figure 1).

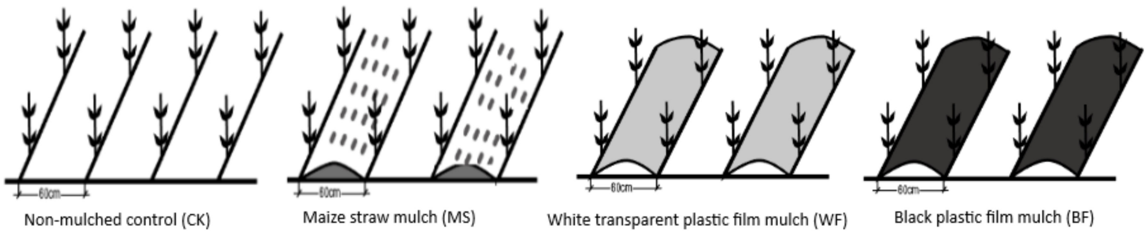

Figure 1. Field planting pattern pictures of different treatments.

We used the maize cultivar Shaandan 609, which most commonly planted in the area. Before sowing, medium-sized machinery for ploughing and land preparation was used, with a working depth of 20 cm. The maize was sown on 21 April 2013, 26 April 2014, and 25 April 2015, and harvested on 28 September 2013, 27 September 2014, and 28 September 2015. The planting density was 6.00×10^4 plants ha^{-1}, and the plot size was 19.5 m^2 (3.0 m × 6.5 m). The maize was fertilized with urea (225 kg N ha^{-1}) and superphosphate (120 kg P_2O_5 ha^{-1}). Both P and 40% N were applied as base fertilizers, and the remaining N was applied at the jointing stage of the sixth extended leaf (30%) and during the grain-filling stage (30%), the latter being 10 days after tasseling. The seeding rate was the same among all the treatments, each yielding 320 grains. No irrigation was performed during the entire growing season. Diseases, pests, and weeds in each treatment were kept under tight control by field staff. After the maize harvest, all plastic film and maize straw were removed by farmers.

2.3. Sampling and Measurement

The dates of sowing, emergence, the 6th leaf stage (V6), 12th leaf stage (V12), tasseling stage (VT), milking stage (R3), and physiological maturity stage (R6) were recorded. One set of mercury-in-glass geothermometers with bent stems (Hongxing Thermal Instruments, Hebei Province, China) were sunk into the ground between the maize rows in every treatment plot at depths of 5, 10, and 15 cm. The soil temperature of every treatment was recorded daily, every two hours between 08:00 and 20:00 h at the V6, V12, VT, R3, and R6 stages of growth in the BF treatment. The daily mean soil temperature was calculated as the average of seven intra-day readings.

The progress of maize growth was recorded over 2013–2015. At the stages of V6, V12, VT, R3, and R6 in the BF treatment, five separate plants of each treatment were cut at ground level. The green leaf area was measured and recorded for each plant. Leaf area was determined using the coefficient method according to Equation (1):

$$\text{Leaf area} = \text{midrib length (cm)} \times \text{maximum leaf width (cm)} \times 0.75. \quad (1)$$

To determine the shoot biomass per unit area, the maize plants were chopped up and oven-dried at 105 °C for 30 min, and then at 80 °C until a constant mass was achieved. The leaf area index (LAI) for each plant was represented by the ratio of leaf area to the average land area occupied (0.17 m^2 $plant^{-1}$). Leaf area duration (LAD) was calculated using Equation (2):

$$\text{LAD}\ (\text{m}^2\ \text{m}^{-2}\ \text{d}) = 1/2\ (\text{LA}_1 + \text{LA}_2) \times (t_2 - t_1), \quad (2)$$

where LA_1 and LA_2 are the first and second measurements of leaf area (m^2 m^{-2}), respectively, and t_1 and t_2 are the times (d) of the first and second measurements, respectively.

Root samples of every treatment were collected at V6, V12, VT, R3, and R6 stages of growth in the BF treatment using a soil drill of depth 90 cm. The aboveground plant parts were removed. and the soil surface was cleaned of unwanted plant material. At each sampling date, soil-root columns were sectioned every 30 cm along the depth of the soil column. Roots were cleaned of soil by placing them on nylon mesh (400 holes cm^{-2}) and washing them with swirling water. Root volumes in different soil layers were determined by the drainage method: The root dry mass was measured by drying the samples at 105 °C for 30 min, and then at 80 °C to constant dry mass.

The soil water content of every treatment was measured in 20-cm increments to a depth of 200 cm with a soil auger at sowing and then at V6, V12, VT, R3, and R6 stages of growth in the BF treatment. The water content in the samples was determined gravimetrically. Soil moisture was determined in volumetric units (mm) by using the measured soil bulk densities in Table 2. Daily weather data (rainfall, air temperature) were obtained from a meteorology station located about 1000 m from the plot area. Soil water balance and crop water consumption (CWC) during the crop growth period were calculated for all treatments. CWC was calculated by using the formula CWC = P + SWS, where P (mm) is the total rainfall during the growing season and SWS (mm) is the difference in soil water storage (0–200 cm) between the beginning and the end of each growing season. WUE was calculated as the total grain yield divided by the total CWC.

Table 2. Soil bulk densities from depths of 0–200 cm in 2013–2015 (g cm^{-3}).

Year	Soil Layer (cm)									
	0–20	20–40	40–60	60–80	80–100	100–120	120–140	140–160	160–180	180–200
2013	1.11	1.19	1.27	1.31	1.36	1.43	1.45	1.49	1.51	1.52
2014	1.11	1.20	1.26	1.32	1.37	1.44	1.44	1.48	1.53	1.51
2015	1.10	1.19	1.26	1.31	1.37	1.44	1.46	1.47	1.52	1.50

At the end of the growing season, all plants in each plot were harvested by hand to obtain the grain yield. Yield components, including ears per unit area, kernel number per ear consisting of kernel rows and kernels per row, and kernel weight, were measured on 20 plants randomly selected from each plot. The ear length and ear density (ear number per unit area) were also determined.

2.4. Statistical Methods

Data were subjected to ANOVA by using SPSS package (SPSS Version 11.0, SPSS Inc., USA). Means were separated by the least significant difference (LSD) test at the probability level of 0.05%. Given that there were significant differences among the treatments by year, the effects of each treatment were discussed by year.

3. Results

3.1. Soil Temperature and Moisture

The mean soil temperatures observed at 5-, 10-, and 15-cm depths during different growth periods of maize and for the different mulches are presented in Table 3. Data obtained from this three-year study showed that the soil temperature increased as each growth period of maize advanced, up to the flare-opening stage, but thereafter gradually decreased until maturity. Among the different mulches evaluated, the soil temperature was significantly higher under white transparent polyethylene film mulch (WF), followed by black polyethylene film (BF), non-mulched control (CK), and maize straw mulch (MS). WF led to higher thermal benefits than BF, MS, or CK, with the mean soil temperature during the whole growth period at the 5–15 cm depth in WF being 0.6 °C higher than in BF, and 1.5 °C and 1.2 °C higher than in MS and CK, respectively.

Normal variations in the temperature, evapotranspiration, and CWC led to a clear difference in soil water storage (0–200 cm) during the growing seasons and for the different mulches and CK (Figure 2). The soil water storage with WF was similar to BF, whereas it was significantly higher than CK. WF and BF led to significantly higher soil water storage compared with MS during the pre-tasseling stage. However, between the stages of tasseling to maturity, MS led to significantly higher soil water storage compared with WF and BF. Compared with CK, the average soil water storage (0–200 cm) over the whole growth period was significantly increased with WF, BF, and MS by 13.6, 14.1, and 14.0 mm in 2013; by 15.8, 16.4, and 13.9 mm in 2014; and by 15.2, 15.7, and 14.2 mm in 2015, respectively.

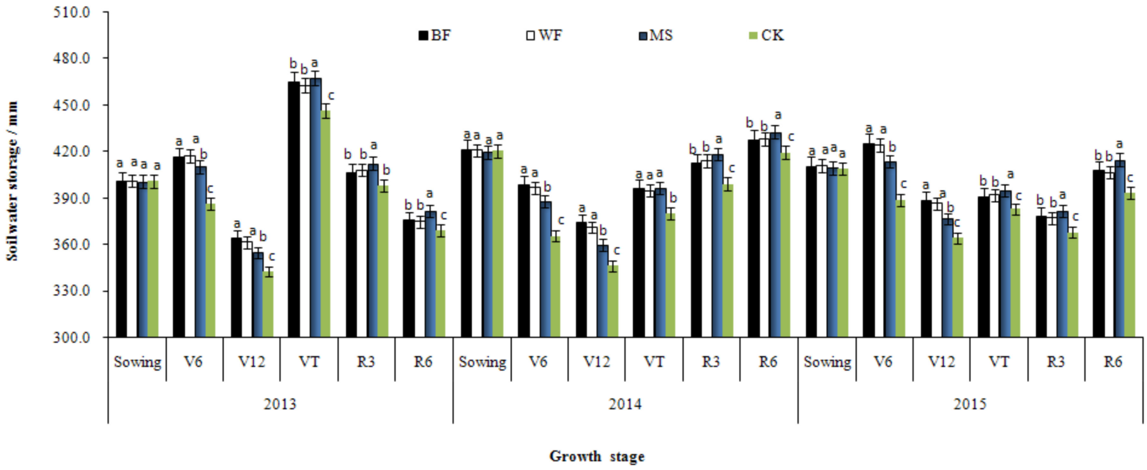

Figure 2. Soil water content dynamics in 0–200 cm layers for different treatments at six maize-growing stages during 2013–2015. The error bars are the standard errors. Different lowercase letters indicate significant differences at the 0.05 ($p < 0.05$) level among different mulching treatments within the same growth stage.

3.2. Growth Duration, LAI, and LAD

The seeds under both film-mulching treatments, i.e., WF and BF, germinated one day earlier than CK and under MS (Table 4). The tasseling date of the WF-treated plants was significant earlier than that under BF, MS, and CK by 2, 6, and 4 days in 2013; by 2, 6, and 5 days in 2014; and by 2, 5, and 4 days in 2015, respectively. However, the maturity date of the WF-treated plants was earlier than that of BF, MS, and CK by 3, 6, and 4 days in 2013; by 4, 8, and 6 days in 2014; and 6, 8, and 6 days in 2015, respectively, indicating that under BF, plants had a longer period of reproductive growth compared with WF, MS, and CK, and the average grain-filling process over the three experimental seasons was longer by 2.3, 1.7, and 2 days, respectively.

Table 3. Effects of different mulching materials on soil temperatures (°C) at different growth periods of maize.

Growth Stage	Treatment	2013				2014				2015			
		5 cm	10 cm	15 cm	Average	5 cm	10 cm	15 cm	Average	5 cm	10 cm	15 cm	Average
V6	WF	21.8 a	21.2 a	20.7 a	21.2 a	22.3 a	21.6 a	21.3 a	21.7 a	22.0 a	21.6 a	21.0 a	21.5 a
	BF	21.0 b	20.6 b	20.3 b	20.6 b	21.6 b	21.0 b	20.8 b	21.1 b	21.1 b	20.8 b	20.4 b	20.8 b
	MS	20.1 d	19.7 d	19.4 d	19.7 d	20.2 d	19.8 d	19.7 d	19.9 d	20.2 d	19.6 d	19.3 d	19.7 d
	CK	20.4 c	20.0 c	19.6 c	20.1 c	20.8 c	20.6 c	20.4 c	20.6 c	20.5 c	20.1 c	19.7 c	20.1 c
V12	WF	23.8 a	23.5 a	22.7 a	23.3 a	24.2 a	24.0 a	23.7 a	24.0 a	24.5 a	24.2 a	23.8 a	24.2 a
	BF	22.8 b	22.6 b	22.2 b	22.5 b	23.6 b	23.4 b	23.2 b	23.4 b	23.6 b	23.4 b	23.0 b	23.3 b
	MS	21.5 d	21.3 d	20.9 d	21.2 d	22.4 d	22.1 d	21.8 d	22.1 d	22.4 d	22.1 d	21.7 d	22.1 d
	CK	21.9 c	21.8 c	21.4 c	21.7 c	22.8 c	22.7 c	22.3 c	22.6 c	22.9 c	22.7 c	22.1 c	22.6 c
VT	WF	20.2 a	20.1 a	19.5 a	20.0 a	19.8 a	19.5 a	19.3 a	19.5 a	21.0 a	20.6 a	20.3 a	20.6 a
	BF	19.8 b	19.7 b	19.4 a	19.6 b	19.5 b	19.3 b	19.2 a	19.3 b	20.7 b	20.2 b	20.0 b	20.3 b
	MS	19.3 c	19.3 c	18.9 b	19.2 c	18.9 c	18.8 c	18.6 b	18.8 c	19.8 d	19.4 d	19.2 c	19.5 c
	CK	19.4 c	19.3 c	19.0 b	19.2 c	19.0 c	19. 0c	18.7 b	18.9 c	20.0 c	19.6 c	19.3 c	19.6 c
R3	WF	19.5 a	19.1 a	18.6 a	19.1 a	19.6 a	19.1 a	18.8 a	19.2 a	18.7 a	18.4 a	18.0 a	18.4 a
	BF	19.1 b	18.8 b	18.2 b	18.7 b	19.0 b	18.5 b	18.3 b	18.6 b	18.0 b	17.8 b	17.6 b	17.8 b
	MS	17.8 d	17.4 d	17.3 d	17.5 d	18.3 d	17.6 c	17.6 c	17.8 c	17.4 c	17.1 c	16.9 c	17.1 c
	CK	18.6 c	18.1 c	17.9 c	18.2 c	18.8 c	17.9 c	17.8 c	18.2 c	17.5 c	17.3 c	17.1 c	17.3 c
R6	WF	18.8 a	18.5 a	18.1 a	18.5 a	17.5 a	17.2 a	16.8 a	17.2 a	17.6 a	17.4 a	17.0 a	17.3 a
	BF	18.1 b	17.8 b	17.4 b	17.8 b	16.9 b	16.7 b	16.4 b	16.7 b	17.0 b	16.9 b	16.6 b	16.8 b
	MS	16.8 d	16.6 c	16.3 d	16.6 c	16.1 c	16.0 c	15.6 c	15.9 c	16.3 c	16.1 c	15.8 c	16.1 c
	CK	17.2 c	16.7 c	16.5 c	16.8 c	16.2 c	16.0 c	15.7 c	16.0 c	16.3 c	16.2 c	15.9 c	16.1 c

LSD, different lowercase letters indicate significant at the 5% level. Columns with different small letters indicate significantly different of among different mulching treatments within the same growth stage.

Table 4. Growth duration (days) of different growing stages of maize treated with different mulches (white transparent polyethylene film (WF), black polyethylene film (BF), and maize straw (MS)) and the non-mulched control (CK) in the 2013, 2014, and 2015 growing seasons.

Treatment	2013			2014			2015		
	Emergence	Tasseling	Maturity	Emergence	Tasseling	Maturity	Emergence	Tasseling	Maturity
WF	13 b	92 d	154 c	12 c	90 c	153 d	12 b	91 d	152 c
BF	13 b	94 c	157 b	12 c	92 b	157 c	12 b	93 c	158 b
MS	14 a	98 a	160 a	14 a	98 a	161 a	13 a	97 a	160 a
CK	14 a	96 b	158 b	13 b	97 a	159 b	13 a	95 b	158 b

LSD, different lowercase letters indicate significant at 5% level. Columns with different small letters indicate significant differences among different mulching treatments.

LAI increased throughout the growing season of each year, peaked in the tasseling stage, and then decreased because of leaf losses (Figure 3). Compared with CK, all three mulching treatments significantly increased LAI. However, the type of mulch had a significant ($p < 0.05$) effect on LAI: LAI values of both film mulches (WF and BF) were higher than MS. Compared to WF, BF gave a similar LAI pre-tasseling but led to a significantly higher LAI post-tasseling.

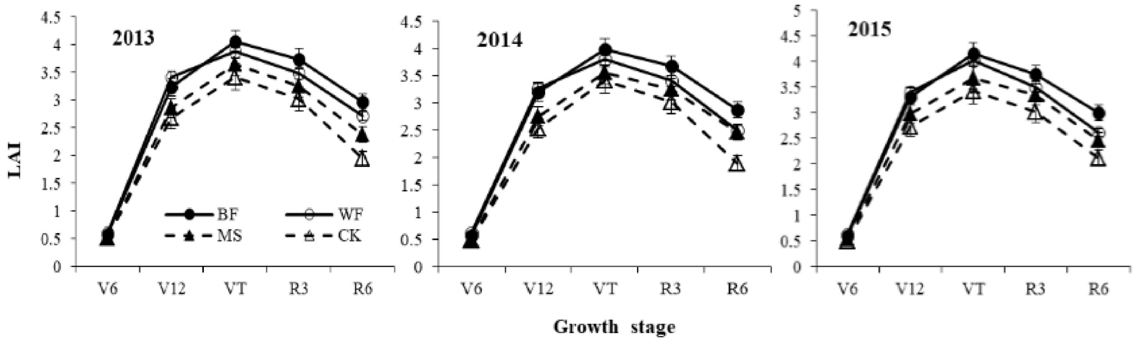

Figure 3. LAI of maize at different growth stages under different treatments in 2013, 2014, and 2015.

LAD was also affected by the three mulching materials (Table 5). LAD at the pre-tasseling stage was significantly higher under both film mulches (BF and WF) than under straw (MS) and the control (CK); the LAD under MS was significantly higher than CK, but there was no significant difference between the LAD of the WF and BF treatments pre-tasseling. However, LAD post-tasseling was significantly higher under BF, followed by WF, MS, and CK. Total LAD under BF was highest, and that of CK was lowest. On average, the LADs under BF, WF, and MS were 41.8%, 26.7%, and 10.9% higher than that of CK, respectively.

Table 5. LAD (m^2 m^{-2} d) of maize at different growth stages under different treatments in 2013, 2014, and 2015.

Treatment	2013			2014			2015		
	Pre-Tasseling	Post-Tasseling	Total LAD	Pre-Tasseling	Post-Tasseling	Total LAD	Pre-Tasseling	Post-Tasseling	Total LAD
WF	149.5 a	155.6 b	305.1 b	156.3 a	160.2 b	316.5 b	155.2 a	167.1 b	322.3 b
BF	153.6 a	182.2 a	335.8 a	158.9 a	197.4 a	356.3 a	150.8 a	213.2 a	364.0 a
MS	132.2 b	133.3 c	265.5 c	130.1 c	144.3 c	274.4 c	135.4 b	150.2 c	285.6 c
CK	121.4 c	120.8 d	240.2 d	123.2 d	134.2 d	257.4 d	119.8 c	127.3 d	247.1 d

LSD, different lowercase letters indicate significance at the 5% level. Columns with different small letters indicate significant differences among different mulching treatments.

3.3. Root Volume and Biomass, and Shoot Biomass

The effects of the mulches were significant for shoot biomass and for root parameters over 0–90 cm (but particularly up to 60 cm) (Table 6). Data obtained from our three-year study showed that root volume and biomass decreased significantly with soil depth, with volume and biomass in the 0–30 cm layer accounting for 72%–78% of the respective totals. Root volume and biomass for WF-treated plants were significantly higher than those under BF, MS, and CK in the 0–30 cm soil layer pre-tasseling; no significant differences in these parameters were found between MS and CK pre-tasseling. However, post-tasseling, root volume and biomass accelerated under BF and MS compared with WF and CK. Root volume and biomass in the 0–30 cm layer in the case of BF was significantly higher than those of WF, MS, and CK; and those of MS were significantly higher than those of CK. There was no significant difference between root biomass at a depth of 60–90 cm under WF compared with BF during the whole growing season in any of the three years of the experiment.

Table 6. Root volume (cm^3 $plant^{-1}$) and root biomass (g $plant^{-1}$) in the 0–90 cm soil profile, and shoot biomass (g $plant^{-1}$) for the different growth stages under different treatments.

Year	Growth Stage	Treatment	Root Volume			Root Biomass			Shoot Biomass
			0–30 cm	30–60 cm	60–90 cm	0–30 cm	30–60 cm	60–90 cm	
2013	V6	WF	11.72 a	3.08 a	1.03 a	4.96 a	1.53 a	0.25 a	64.89 a
		BF	10.69 b	2.88 b	0.91 b	4.38 b	1.48 a	0.23 a	60.07 b
		MS	9.03 c	2.14 c	0.77 c	3.89 c	1.24 b	0.21 a	49.04 c
		CK	9.34 c	2.11 c	0.82 c	3.94 c	1.19 c	0.20 a	51.93 c
	V12	WF	86.35 a	24.22 a	4.51 a	16.05 a	5.15 a	0.81 a	101.14 a
		BF	81.14 b	20.30 b	4.51 a	15.53 b	5.13 a	0.83 a	96.37 b
		MS	72.06 c	15.61 c	3.23 b	13.65 c	4.54 b	0.79 a	80.65 c
		CK	70.50 c	16.02 c	3.22 b	12.57 d	3.93 c	0.78 a	79.68 c
	VT	WF	124.87 a	33.84 a	6.35 a	22.51 a	6.85 b	1.03 a	194.78 a
		BF	123.13 a	34.69 a	6.44 a	22.69 a	7.28 a	1.02 a	197.29 a
		MS	110.85 b	28.64 b	5.37 b	19.35 b	6.00 c	0.99 a	185.64 b
		CK	100.52 c	21.97 c	4.78 c	17.38 c	5.08 d	0.98 a	171.16 c
	R3	WF	133.29 b	34.23 b	6.36 a	24.68 b	7.97 b	1.01 a	250.47 b
		BF	141.16 a	35.47 a	6.34 a	25.38 a	8.52 a	1.16 a	274.50 a
		MS	118.78 c	30.99 c	5.81 b	20.00 c	6.21 c	1.03 a	232.61 c
		CK	107.33 d	24.64 d	5.09 c	18.77 d	5.87 d	0.98 a	208.14 d
	R6	WF	101.32 b	26.42 b	5.01 b	19.71 b	6.11 b	1.01 a	384.96 b
		BF	120.04 a	29.67 a	5.98 a	21.58 a	7.21 a	1.06 a	413.09 a
		MS	102.54 b	25.57 b	4.86 b	19.61 b	6.53 c	0.98 a	369.02 c
		CK	85.35 c	20.66 c	4.46 c	18.02 c	5.97 d	0.97 a	339.76 d
2014	V6	WF	12.26 a	3.35 a	1.08 a	5.26 a	1.75 a	0.26 a	72.20 a
		BF	11.54 b	3.01 b	0.95 b	4.87 b	1.60 b	0.22 a	66.82 b
		MS	9.84 c	2.45 c	0.81 c	4.01 c	1.46 c	0.22 a	53.87 c
		CK	9.95 c	2.51 c	0.80 c	4.08 c	1.48 c	0.21 a	54.11 c
	V12	WF	90.11 a	28.72 a	4.86 a	17.09 a	5.41 a	0.85 a	110.38 a
		BF	85.36 b	24.73 b	4.81 a	16.62 b	5.34 a	0.82 a	105.26 b
		MS	75.12 c	16.56 c	3.40 b	14.06 c	4.57 b	0.81 a	92.45 c
		CK	71.25 d	16.42 c	3.42 b	13.08 d	4.23 c	0.80 a	86.33 d
	VT	WF	130.00 a	34.24 a	6.60 a	23.65 a	6.52 b	1.19 a	216.47 a
		BF	128.35 a	33.98 a	6.61 a	23.12 a	6.87 a	1.20 a	212.61 b
		MS	118.06 b	29.86 b	5.77 b	20.43 b	6.11 c	1.06 b	191.35 c
		CK	106.12 c	22.39 c	4.90 c	18.35 c	5.82 d	1.12 b	177.36 d
	R3	WF	140.78 b	34.85 b	6.35 a	25.85 b	7.06 b	1.23 a	261.33 b
		BF	149.66 a	35.94 a	6.37 a	27.74 a	7.55 a	1.26 a	283.79 a
		MS	125.96 c	32.02 c	5.98 b	22.17 c	6.88 c	1.14 b	241.06 c
		CK	109.61 d	25.36 d	5.12 c	19.04 d	6.03 d	1.09 b	211.68 d
	R6	WF	108.54 b	27.24 b	5.11 b	20.12 b	6.34 b	1.06 a	396.48 b
		BF	127.30 a	30.79 a	6.12 a	22.95 a	7.57 a	1.13 a	436.25 a
		MS	106.57 b	26.05 b	4.98 c	20.77 b	5.65 c	1.07 a	378.38 c
		CK	90.65 c	21.56 c	4.60 d	18.90 c	5.07 d	1.05 a	345.13 d
2015	V6	WF	12.17 a	3.21 a	1.15 a	5.49 a	1.73 a	0.27 a	71.03 a
		BF	11.05 b	3.02 b	0.99 b	4.68 b	1.58 a	0.25 a	67.79 b
		MS	9.77 c	2.14 c	0.77 d	4.03 c	1.30 c	0.22 a	50.45 c
		CK	9.88 c	2.15 c	0.84 c	3.96 c	1.35 c	0.23 a	53.01 c
	V12	WF	92.65 a	29.47 a	4.91 a	18.01 a	5.82 a	0.85 a	114.13 a
		BF	85.15 b	25.30 b	4.80 a	17.13 b	5.79 a	0.85 a	104.87 b
		MS	76.02 c	16.55 c	3.38 b	14.53 c	4.54 b	0.81 a	93.53 c
		CK	72.05 d	16.14 c	3.36 b	13.17 d	4.05 c	0.82 a	87.89 d
	VT	WF	132.74 a	35.13 a	6.36 a	23.31 a	6.78 b	1.22 a	221.79 a
		BF	128.39 b	35.06 a	6.34 a	22.97 a	7.03 a	1.25 a	219.33 a
		MS	118.85 c	30.65 b	5.87 b	20.55 b	6.46 c	1.05 b	195.46 b
		CK	107.35 d	23.09 c	4.88 c	18.61 c	6.18 d	1.03 b	181.06 c
	R3	WF	142.12 b	36.02 a	6.43 a	25.16 b	7.98 b	1.28 a	268.57 b
		BF	151.16 a	36.13 a	6.44 a	27.95 a	8.52 a	1.29 a	287.74 a
		MS	128.27 c	32.89 b	6.01 b	22.90 c	6.92 c	1.13 b	243.86 c
		CK	108.97 d	25.24 c	5.03 c	18.81 d	6.07 d	1.19 b	209.84 d
	R6	WF	110.52 b	27.46 b	5.13 b	21.17 b	6.38 b	1.07 a	408.39 b
		BF	129.05 a	31.36 a	6.19 a	23.01 a	7.92 a	1.10 a	443.09 a
		MS	107.25 b	26.15 b	4.96 b	20.98 b	5.73 c	0.97 a	384.02 c
		CK	87.57 c	20.63 c	4.40 c	18.39 c	4.60 d	0.94 a	339.76 d

LSD, different lowercase letters indicate significance at the 5% level. Columns with different small letters indicate significant differences among different mulching treatments within the same growth stage.

The crops continuously accumulated dry biomass until the maize was mature. Shoot biomass under WF and BF was significantly higher than under MS and CK, and it accumulated faster under WF than under the other treatments during the early stages of maize development; in contrast, during the later stages, shoot biomass accumulated faster under BF than under WF.

3.4. Maize Yield and Water-Use Efficiency (WUE)

The mulching practices significantly affected grain yield, water consumption, and WUE during the experiment (Table 7). BF, WF, and MS significantly increased maize yields during each of the experimental seasons, with the highest yields being recorded in 2015. Compared with CK, maize yields under BF, WF, and MS were increased by 15.2%, 3.7%, and 1.2% in 2013; by 22.0%, 11.1%, and 3.8% in 2014; and by 23.2%, 13.1%, and 5.2% in 2015, respectively. Moreover, a higher grain yield was obtained when maize was mulched with BF compared with the other mulches.

Table 7. Yield, water consumption, and water-use efficiency (WUE) under different treatments.

Treatment	Yield (kg ha^{-1})			Water Consumption (mm)			WUE (g mm^{-1})		
	2013	2014	2015	2013	2014	2015	2013	2014	2015
WF	10188.40 b	11070.65 b	11249.40 b	439.62 b	447.18 b	445.01 b	2.32 b	2.48 b	2.54 b
BF	11320.65 a	12153.70 a	12307.58 a	438.18 b	448.06 b	445.38 b	2.58 a	2.71 a	2.79 a
MS	9943.42 c	10343.40 c	10507.74 c	429.65 c	433.62 c	432.69 c	2.31 b	2.38 c	2.42 b
CK	9825.68 d	9962.80 d	9987.03 d	447.06 a	454.21 a	453.41 a	2.20 c	2.19 d	2.20 c

LSD, different lowercase letters indicate significance at the 5% level. Columns with different small letters indicate significant differences among different mulching treatments.

CWC and WUE were two critical physiological parameters used to assess the effectiveness and contribution of different mulches. CWC of CK was significantly higher than under MS, WF, and BF across the three seasons due to the high evaporation rates in this area (Table 7). There were no significant differences in CWC between WF and BF, but both treatments led to significantly higher CWC than MS. All three mulches significantly increased WUE compared with CK (Table 6). On average, WUE under BF, WF, and MS was 23.1%, 11.9%, and 7.9% higher than CK, respectively; among the mulches, the WUE under BF was significantly higher than under WF and MS.

3.5. Correlations between Grain Yield and Root/Shoot Systems

Regardless of the type of treatment, significant correlations were found during both pre-tasseling and post-tasseling stages among grain yield, root dry mass, root volume, and shoot dry mass, and the correlations became highly significant post-tasseling (Tables 8 and 9). In particular, positive and highly significant correlations were found between (1) root dry mass and root volume and (2) aboveground parts' dry mass and root dry mass. The root dry mass, root volume, and shoot dry mass of all growth stages have significant effects on maize yield, especially post-tasseling, and there is a close relationship between the roots and aboveground parts, and yield.

Table 8. Pearson correlation coefficients between grain yield and root/shoot systems (pre-tasseling).

	Root Dry Mass	Root Volume	Shoot Dry Mass	Yield
Root dry mass of population	1	0.9827 **	0.9085 **	0.7464 *
Root volume of population		1	0.9027 **	0.7325 *
Shoot dry mass of population			1	0.8104 *
Yield				1

* indicate correlation significances were tested at $p = 0.05$ ($p < 0.05$) (1-tailed). ** indicate correlation significances were tested at $p < 0.01$ (2-tailed).

Table 9. Pearson correlation coefficients between grain yield and root/shoot systems (post-tasseling).

	Root Dry Mass	Root Volume	Shoot Dry Mass	Yield
Root dry mass of population	1	0.9538 **	0.9206 **	0.9053 **
Root volume of population		1	0.9105 **	0.8937 **
Shoot dry mass of population			1	0.9311 **
Yield				1

** indicate correlation significances were tested at $p < 0.01$ (2-tailed).

4. Discussion

4.1. Soil Moisture and Temperature and Maize Growth Responses to Different Mulching Materials

Water stress is the main limiting factor for maize production in semi-arid areas of northwest China [22]. Mulching is seen as an effective way of improving the efficient use of rainwater for crops grown in these dry regions [5]; specifically, mulching has been found to affect the topsoil temperature during the various growth stages of maize [4]. In this study, we showed that three types of mulch (two plastic film, one straw) significantly increased average soil water storage (0–200 cm) over the whole growth period of maize compared with an unmulched control (CK) (Figure 2), and our findings are consistent with other studies [1,5,13]. Wu et al. (2017) showed that a plastic film mulch was superior to straw for suppressing evaporation; hence, the use of a plastic mulch should lead to better water retention in soil during the fallow period in semi-arid areas prone to drought [13]. We found that compared with a straw mulch (MS), soil water storage was significantly higher with plastic film mulch (black film, BF; and white, WF) during the pre-tasseling stage but significantly lower post-tasseling (Figure 2). This result might be due to the fact that in the early growth stages (pre-tasseling), when maize plants were smaller and their water demands were relatively low, the loss of water from the soil was mainly via evaporation, and in this situation, the plastic film mulches BF and WF would be expected to be better than MS simply because they would be more efficient at suppressing evaporation, and indeed film mulch-treated soil had significantly higher soil water storage compared with MS. Later (post-tasseling), when maize growth was more vigorous and there was greater consumption of water due to higher crop transpiration, MS-treated plants grew more slowly and consumed less water than those with the plastic mulches, so the plots treated with MS showed higher soil water storage than those under BF and WF [3]. At the same time, it may also be related to the amount and mode of straw mulching.

The soil temperature distribution at different soil depths depends on radiation absorption, reflection, and permeation, and Chen et al. (2013) noted that mulches, and their type, affect the amount of radiation received by a soil surface [23]. In our study, both BF and WF significantly increased the soil temperature during all the stages of maize growth, and MS significantly decreased it, compared with CK (Table 3); our results agree with those obtained by Wu et al. (2017) and Li et al. (2013) [3,13]. However, the soil temperature under BF was lower than that under WF throughout the growth period due to the low rate of light transmittance under the black plastic compared with the white.

Temperature and light are the main ecological factors affecting the length of crop growth [24]. In our study, there was faster growth and earlier development of maize under WF and BF compared with CK (Table 4). With WF and BF, the emergence and tasseling stages were advanced by 1 and 2–7 days, respectively, compared with CK, while the growth stage was reduced by 1–6 days. In contrast, MS delayed these two stages by 0–1 and 1–2 days, respectively, compared with CK, while the maturity stage was delayed by 2 days. Compared with the WF treatment, the vegetative period with BF was delayed by 2 days, although the duration of reproductive growth was prolonged by 1–4 days. This result might be because the black film was not as effective in raising the soil temperatures compare with the white [21], and the soil temperature alters not only the rate of development in maize but also the general pattern of vegetative and reproductive growth [25]. In addition, the soil temperature changed the physical and chemical properties of soil, and the high soil temperature under WF may have led to an insufficient nutrient supply at the later stage of maize growth. We will pay attention to the changes of soil nutrients under different mulching materials.

4.2. Photosynthetic Characteristics under Different Mulching Materials

Increased photosynthetic capacity is one of the most important factors for improving grain yield [26]. LAI plays an important role in the capture of light energy, and therefore of photosynthesis, by crops. In our study, we found that mulching significantly increased the LAI compared with CK simply because mulches help retain soil water, although the two film mulches were more effective than MS (Figure 3). Compared with WF, BF had a similar LAI pre-tasseling, but a significantly higher LAI post-tasseling, indicating that a black film mulch could greatly enhance the LAI after the tasseling of maize, and this finding is important for maize grown in semi-arid areas of northwest China. This difference between the use of BF and WF might have been due to the higher soil temperature under WF leading to heat stress, which would have promoted maize root and leaf senescence during the late growing season [9,22].

Kumar and Singh (2001) argued that the leaf area duration (LAD) is an important component for determining dry matter accumulation and grain yield in maize [27]. Fakorede and Mock (1980) reported that high-yielding maize varieties demonstrated longer LADs after anthesis than those of lower yield [28]. In our study, the LADs under WF and BF treatments were not significantly different from one another pre-tasseling but were significantly higher than under MS or CK, and the LAD of BF was significant higher than under WF, MS, and CK post-tasseling (Table 5). The difference in LAD under the different mulches is attributed to changes in the green leaf area of the plants pre- and post-silking (Figure 3). Compared with WF, MS, and CK, the BF treatment led to a longer LAD during all stages of maize growth (Table 5), and this longer duration of the green leaf area would have improved maize yields [29].

4.3. Root/Shoot Growth under Different Mulching Materials

Agronomic practices can affect firstly the growth and distribution of roots, and secondly the aboveground parts and crop yield [30]. Fan et al. (1997) studied the use of plastic film mulches for winter wheat in arid fields; they showed that plastic film mulch could improve the root weight and extend the range of the root distribution [31]. In our study, we found that by using the plastic film mulches, the root volume of maize in the 0–90 cm layer of soil was 28.6%–32.5% and 12.8%–16.2% higher, and the root biomass was 24.8%–29.4% and 12.9%–17.1% higher, compared with CK and MS, respectively (Table 6). Root biomass at a depth of 60–90 cm under WF and BF showed no significant difference from CK or MS, although the root biomass and root volume in the 0–60 cm soil layer under BF were 3.8% and 3.0% higher, respectively, than those under WF. Post-tasseling, root volume, and root biomass accelerated under BF more than under WF. This was probably because the black plastic film reduced soil temperatures compared with WF, which would have led to thermal conditions more conducive to root growth post-tasseling, and to slower root senescence as the growing season progressed. Although WF had a warming effect that would have benefited maize root growth during early growth stages (in the relatively cool growing season), during late growth stages (in the relatively warm growing season), it would have decreased root dry matter accumulation and the root volume of maize, and accelerated root senescence, which would have led to a lack of nutrients post-tasseling, i.e., when the maize grains had started to form. We found that root volume and root biomass decreased significantly with soil depth, with the 0–30 cm layer of soil accounting for 72%–78% of the total values of either parameter (Table 6).

The root system is fundamental to the absorption of water and nutrients, and therefore for the growth of a maize crop [30]. In our study, the plastic mulches BF and WF significantly increased shoot biomass compared with MS and CK (Table 6). Shoot biomass accumulated faster under WF than under the other treatments during the early stages of maize development. However, during the later stages, shoot biomass accumulated faster under BF than under WF. These results were similar to the previous results for maize root, in which the root biomass under WF accumulated rapidly pre-tasseling, then subsequently decreased post-tasseling. The total shoot biomass under BF was 8.6%, 14.2%, and 26.1% higher than under WF, MS, and CK, respectively (Table 6). Ren et al. (2016) showed that the negative effects of water logging on root growth and development led to abnormal development of aboveground biomass, resulting in significant reductions in dry matter and yield [32]. We found that positive and highly significant correlations were observed between the root dry mass and shoot dry mass of a population of plants, and significant correlations were obtained among the grain yield, root dry mass, root volume, and shoot dry mass at pre-tasseling (Table 8), with the correlation becoming highly significant post-tasseling (Table 9). This may further indicate that the root dry mass and shoot dry mass post-tasseling are more important for grain yield contribution than those of pre-tasseling [32].

4.4. Grain Yield and WUE under Different Mulching Materials

Previous studies indicate that by increasing soil moisture for maize, plastic film mulches can provide favorable conditions for grain formation and yield [3,5,6,11]. In our study, treatments under plastic film mulches (BF and WF) and straw mulch (MS) significantly increased maize yield and WUE compared with the non-mulched control (CF) (Table 7). The maize yields under BF were significantly higher than under WF or MS (Table 7). We deduce that the increased grain yield under BF was a result of overall improvements in various factors that affect maize yield, in particular root/shoot growth, population photosynthetic characteristics, and plant dry matter accumulation. Previous studies have also indicated that the maize grain yield was positively and significantly correlated with dry matter accumulation [6,11,22]. Our results demonstrate that dry matter accumulation under BF and WF was better than under MS (Table 6) during all growth stages. In the early stages, the effect of WF was similar to or better than that of BF, but the effect was significantly lower in late stages of growth. This finding could be attributed to a combined effect of soil temperature and water. In semi-arid areas, the soil temperature and moisture are equally important for maize growth and development [6,13]. In our study, we found that soil temperature was most marked when WF was used, while BF was not as effective in raising soil temperatures (Table 3). Hence, when air temperatures during the maize-growing season were warm, the improvement in soil temperature under WF reduced the duration of maize reproductive growth and accelerated root and leaf senescence, which led to a lack of nutrients and less accumulation of biomass post-tasseling. However, the lower soil temperatures under BF led to better thermal conditions for maize root/shoot growth during the relatively warm maize-growing season and ensured a longer duration of reproductive growth; the higher LAI and LAD would have improved photosynthetic assimilation post-tasseling, and therefore increased dry matter accumulation and grain yield. BF, WF, and MS reduced the total water consumption compared with CK (Table 7) and increased soil water storage (0–200 cm) over the whole growth period of maize (Figure 2), but those mulches led to lower soil temperatures and therefore poorer thermal conditions, which would have delayed growth during early growth stages (Table 4). Our results are consistent with many other studies [3,8,33]. Over the three years of our study, soil water storage under WF and BF was significantly higher than under MS pre-tasseling (Figure 2), thereby encouraging maize growth, as observed through significant increases in the dry matter of roots and shoots (Table 6).

Variations in WUE depend on rainfall, soil evaporation, and CWC for growth and crop yield. Improving WUE is the main objective of researchers and farmers in semi-arid areas of northwest China [3,6]. During our study, water consumption under CK was significantly higher than under any of the mulches; there was no significant difference between the WF and BF treatments, but both led to significantly higher consumption than under MS. However, the WUE of BF was significantly higher than under WF and MS because BF led to the greater yield (Table 7). We suggest that the reason for this difference is that BF not only significantly decreased water consumption but also significantly increased the yield compared with CK (Table 7). Therefore, improvements in maize yield in semi-arid areas can best be achieved by optimizing the conditions of soil water thermal resources and by the reduction of CWC through reducing soil evaporation; compared with WF and MS, we demonstrated the superior effect of BF on the soil water thermal conditions for root growth in maize. In this area, it may be possible to increase yields by replacing the ordinary white plastic film with black plastic film for plastic film mulched maize.

5. Conclusions

In the semi-arid areas of northwest China, drought and the uneven distribution of precipitation are the primary factors that limit maize production. In our study, we showed that use of both plastic film and straw as mulches for maize can increase soil moisture, and thereby provide better conditions for grain formation and yield. Compared with straw mulches, plastic film mulches provided favorable soil water thermal conditions during the early stages of maize growth, resulting in good vegetative growth. Plastic film mulches also significantly increased the root/shoot biomass, root volume, LAI, LAD, and yield of maize. The significantly decreased soil temperature and soil water storage at the pre-tasseling stage under straw mulching led to decreases in LAI, LAD, and root/shoot biomass, thereby causing losses in yield. Compared with white transparent plastic mulching, black plastic mulching caused lower soil temperatures, which created thermal conditions that were more conducive to maize root/shoot growth post-tasseling, and to prolonging the duration of reproductive growth, thereby increasing the yield and WUE. We therefore conclude that the use of black plastic film as a mulch material for maize grown in a semi-arid area that experiences intense light and heat will lead to higher grain yields.

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