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Plastic Film Mulch Performed Better in Improving Heat Conditions and Drip Irrigated Potato Growth in Northwest China than in Eastern China

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Abstract: Plastic film (i.e., transparent and black films) is widely applied in mulching to improve thermal environments and plant growth in China. However, choosing suitable film for potato cultivation in different areas is still a problem. A four-year field experiment was conducted to explore the influences of plastic mulch on heat transfer (soil heat flux, G; soil temperature; and canopy net radiation, R_n) and potato growth in two typical areas of China: Experiment 1 in Northwest China (2014 and 2015) and Experiment 2 in Eastern China (2016 and 2017). Three mulch treatments were designed as follows: (1) transparent film (TF), (2) black film (BF), and (3) no film (NF). Results showed that the R_n and G differences between TF, BF, and NF varied at different areas. However, the R_n in TF was always smaller (average 12.4 W/m^2 in 2014–2017) than in BF in the two study areas. The differences of soil temperature between TF, BF, and NF in Experiment 1 were greater than in Experiment 2. The average soil temperature difference between TF and NF was 1.4 °C higher in Experiment 1 than in Experiment 2. TF had 23% and 19% more jumbo tubers than BF in weight and number on average with no significant difference in 2015–2017. TF and BF significantly had greater potato yield and irrigation water use efficiency than NF on average in Experiment 1, while no significant differences were found in Experiment 2. The transparent film was more beneficial to increase soil temperature and jumbo tubers than the black film. Film mulch functioned better for improving heat conditions and drip-irrigated potato growth in Northwest China than in Eastern China.

Keywords: transparent and black films; heat transfer; drip irrigation; water use efficiency

1. Introduction

The potato (*Solanum tuberosum* L.) is the fourth major crop in the world and it occupies an important part in the human diet [1]. Potatoes can produce more dietary energy with less water, i.e., 5600 kcal dietary energy, which is more than rice (2000 kilocalorie (kcal)), wheat (2300 kcal), and maize (3860 kcal) with 1 m^3 water applied in the crop [2]. Moreover, potatoes have remarkable nutritional value (e.g., carbohydrate, vitamin C, minerals, etc.) and is a source of health-promoting antioxidants (e.g., vitamin C, carotenoids, anthocyanins, etc.) [3,4]. In 2015, China launched a strategy to promote potatoes processed into staple foods such as steamed bread, noodles, and so on. It is estimated that more than 50% of potatoes will be consumed as a staple food in China by 2020. China has the largest potato production quantity and cultivated area in the world, while the potato yield is still low [5]. In 2008–2017, the average potato yield was 16.4 t/hm^2, while it was 46.4 t/hm^2 in America [5]. Drip irrigation combined with film mulching is important and effective to increase water use efficiency and potato yield in China [6,7].

Film mulch is commonly used worldwide to improve field hydrothermal environment. Further, it improves the radiative microclimate [8] which maintains moisture through soil surface evaporation reduction [6,9] and increases soil temperature [10,11]. Film mulch can control microbial activity [12], accelerate plant growth [11,13], and improve yield and water use efficiency [10,14] by regulating field hydrothermal conditions. However, these positive effects are accompanied with some potential negative effects such as decreasing soil organic matter content [15] and resulting in soil pollution because of non-degradable plastic film [16]. The influences of the plastic mulch on the heat transport process and plant growth depend on the film optical properties, the gap distance between film and underlying soil, and climatic environment [17].

Transparent and black films, most commonly used in agriculture, affect the thermal environment and crop growth differently [18]. Transparent film, effective for soil solarization [19], can produce higher soil temperature than black film [20]. However, black film can also produce higher soil temperature because of the contact degree between the film and underlying soil which affects the soil temperature [21]. The transparent film can be better or worse than the black film for increasing plant yield because of different climatic environments [22,23]. Potatoes are a shallow-rooted crop and are sensitive to heat stress [24]. Therefore, transparent and black films affect heat transfer and drip irrigated potato growth in different areas of China, which remains a problem.

This paper explored the effects of transparent and black films on heat transfer and drip irrigated potato growth in two typical areas (Northwest China and Eastern China). The purpose was to determine: (1) how the transparent and black films affect heat transfer (soil temperature, soil heat flux, and canopy net radiation) in potato field in these two areas; (2) influences of transparent and black films on potato development, yield, and irrigation water use efficiency; and (3) whether and which film mulch should be applied in drip irrigated potato cultivation in these two areas.

2. Materials and Methods

2.1. Study Sites

Experiment 1 was conducted at the Shiyanghe Experimental Station of China Agricultural University (37°52′ N, 102°50′ E, altitude 1581 m), Wuwei City, Gansu Province, Northwest China with a typical temperate continental climate in 2014 and 2015. The region had a mean sunshine duration over 3000 h, a mean air temperature of 8 °C, a mean precipitation of 164 mm, and 150 frost-free days. The soil texture was sandy loam with mean soil bulk density 1.53 g/cm^3 (0–1.0 m depth). The detail information of the station was described by Ding et al. [25].

Experiment 2 was carried out at the Special Potato Experimental Station (35°25′ N, 118°59′ E, altitude 131 m), China Agricultural University, Rizhao, Shandong Province in 2016 and 2017. The site had a temperate monsoon climate with a mean sunshine duration of 2533 h, a mean air temperature of 13 °C, a mean precipitation of 897 mm, and 213 frost-free days. The soil texture was sandy loam with a mean bulk density of 1.65 g/cm^3 (0–0.6 m depth).

2.2. Experimental Design

In the field experiments, three mulch treatments were designed: (1) transparent film (TF), (2) black film (BF), and (3) no film (NF). The entire soil surface was mulched with film (thickness 0.008 mm) for mulch treatments. The film edges between the beds were fixed with soil (2 to 5 cm thick). Treatments were arranged in a randomized block design with three replications.

2.3. Agronomic Strategies

2.3.1. Experiment 1

In 2014 and 2015, the seed potatoes (cv. Kexin No.1) were grown every 0.3 m with single row in the center of the beds on 22 April and 15 April, respectively. The potatoes were planted manually by cutting holes through the film. Each plot (5.6 m × 6 m, 33.6 m^2) contained 7 beds (6 m in length, 0.8 m in width, and 0.2 m in height). The fertilizers (N and P_2O_5) were applied before the planting. An additional N and K_2O were applied with the drip irrigation system after the planting. The potatoes were harvested on 21 August 2014 and 20 August 2015, respectively. The specific fertilizer information was previously presented by Zhang et al. [6].

2.3.2. Experiment 2

In 2016, the seed potatoes (cv. Favorita) were grown every 0.2 m with double rows (row spacing 0.4 m) in the middle of beds on 20 March. The potatoes were planted manually by cutting holes through the film. Each plot (9.6 m × 5 m, 48 m^2) contained 8 beds (5 m in length, 1.2 m in width, and 0.2 m in height). The N, P, and K fertilizers were applied according to the local farmer field (169 kg/hm^2 N, 169 kg/hm^2 P_2O_5, and 313 kg/hm^2 K_2O). The potatoes were harvested on 10 June because of the early canopy senesces.

In 2017, the seed potatoes (cv. Favorita) were grown every 0.4 m with double row (row spacing 0.3 m) in the center of the beds on 14 March. Each plot (7.2 m × 6.4 m, 46.08 m^2) contained 8 beds (6.4 m long, 0.9 m wide, and 0.2 m high). The N, P, and K fertilizers (147 kg/hm^2 N, 82 kg/hm^2 P_2O_5, and 385 kg/hm^2 K_2O) were applied on four dates: 10 March (0% of N, 100% of P_2O_5, and 80% of K_2O), 28 April (47% of N, 0% of P_2O_5, and 0% of K_2O), 12 May (24% of N, 0% of P_2O_5, and 10% of K_2O), and 25 May (29% of N, 0% of P_2O_5, and 10% of K_2O). The potatoes were harvested on 9 July.

2.4. Precipitation and Irrigation

The precipitations were insufficient for potato growth in Experiment 1 and Experiment 2 with 176 mm, 124 mm, 66 mm, and 196 mm during the 2014–2017 growth seasons, respectively. The irrigations were essential in both areas. The potato crops were irrigated with surface drip irrigation in Experiment 1 and Experiment 2. The drip irrigation system was controlled by a sluice valve, a pressure gauge, and a water meter. The potato crops were irrigated when the soil matric potential, measured with tensiometers at 0.2 m depth, and reached −25 kPa [7]. The calculation of the irrigation amount have been given by Yang et al. [26]. In 2014–2017, the first irrigation was 15, 19, 18, and 20 mm, and the subsequent irrigations were 17, 23, 18, and 16 mm, respectively. In 2014–2017, the total irrigation amounts were 317, 366, 180, and 276 mm for BF, 277, 392, 144, and 260 mm for NF, and 293, 344, 144, and 276 mm for TF, respectively.

2.5. Plant Height, Yield, Tuber Grade, and IWUE

In each plot the plant heights of ten plants were measured during plant growth stage. Three rows potatoes of each plot were harvested for yield measurement at the end of the growth season. In total, 10 plants in each plot were harvested for potato tuber grade measurement during the maturation stage. Irrigation water use efficiency (IWUE) was calculated from potato yield divided by irrigation water of the whole growth season [27].

2.6. Automatic Measurements

Weather variables including solar radiation, precipitation, and air temperature were obtained from a standard automatic weather station in 2014–2017. At one plot for each treatment, soil temperatures (10, 20, 30, and 50 cm depths), soil heat flux (5 cm depth), and canopy net radiation were measured using soil temperature sensors, soil heat flux plate, and net radiometer, respectively. The data was automatically sampled at 10-s intervals and recorded an average every 10-min. The details of the automatic measurements were described by Zhang et al. [28].

2.7. Statistical Analyses

Differences of plant height, tuber weight and number, potato yield, and IWUE for each growth season were statistically analyzed with a one-way analysis of variance. Duncan's multiple range test was used to analyze mean differences between treatments at $p < 0.05$ level. The SPSS version 20 was used for the statistical analyses.

3. Results

3.1. Solar Radiation and Air Temperature

The average daily solar radiation was 233.2, 233.1, and 212.6 W/m^2 in 2014, 2015, and 2016, respectively (Figure 1). The average daily minimum air temperatures in Experiment 1 (11.1 °C in 2014 and 11.5 °C in 2015) were lower than in Experiment 2 (12.1 °C in 2016 and 13.7 °C in 2017). The average daily maximum air temperatures in Experiment 1 (25.8 °C in 2014 and 26.5 °C in 2015) were higher than in Experiment 2 (23.4 °C in 2016 and 25.4 °C in 2017). It meant that the air temperature amplitude was greater in Experiment 1 than in Experiment 2. During the last 30 days of the growth seasons, the average daily maximum air temperatures in 2017 (31.2 °C) was higher than in 2014 (27.6 °C), 2015 (29.8 °C), and 2016 (25.9 °C).

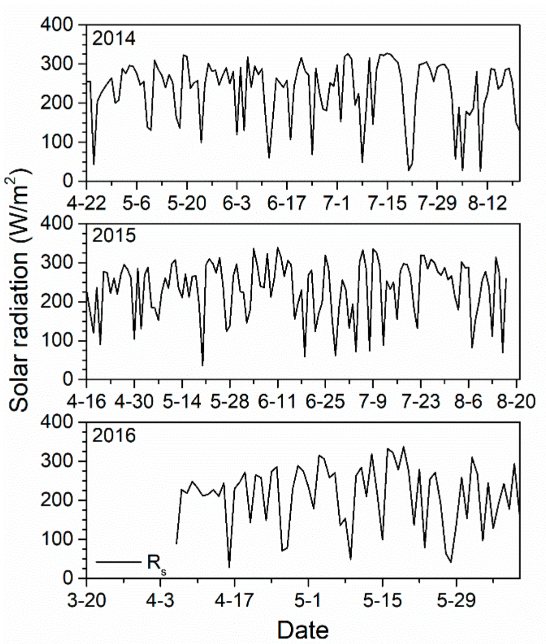

Figure 1. Seasonal variations of the daily average solar radiation (R_s) in 2014–2016. Note: The data of solar radiation in 2017 was missed because of equipment failure.

3.2. Variation of Thermal Conditions

The variations of thermal conditions (canopy net radiation, soil heat flux, and soil temperature) changed with the potato canopy growth (Figures 2–5 and Tables 1–4). As the canopy grew, more film was covered by the canopy. Thus, the thermal conditions differences between the TF, BF, and NF got smaller since the effects of the film on thermal environment decreased. When the canopy senesced, more plastic film was uncovered and the thermal conditions differences between different treatments got greater again. The thermal conditions of different treatments were compared in Figures 2–5 and Tables 1–4 including the daily maximum net radiation ($R_{n\text{-}max}$), average net radiation ($R_{n\text{-}avg}$), and minimum net radiation ($R_{n\text{-}min}$); daily maximum soil heat flux (G_{max}) and average soil heat flux (G_{avg}); and daily maximum soil temperature (T_{max}), average soil temperature (T_{avg}), and minimum soil temperature (T_{min}).

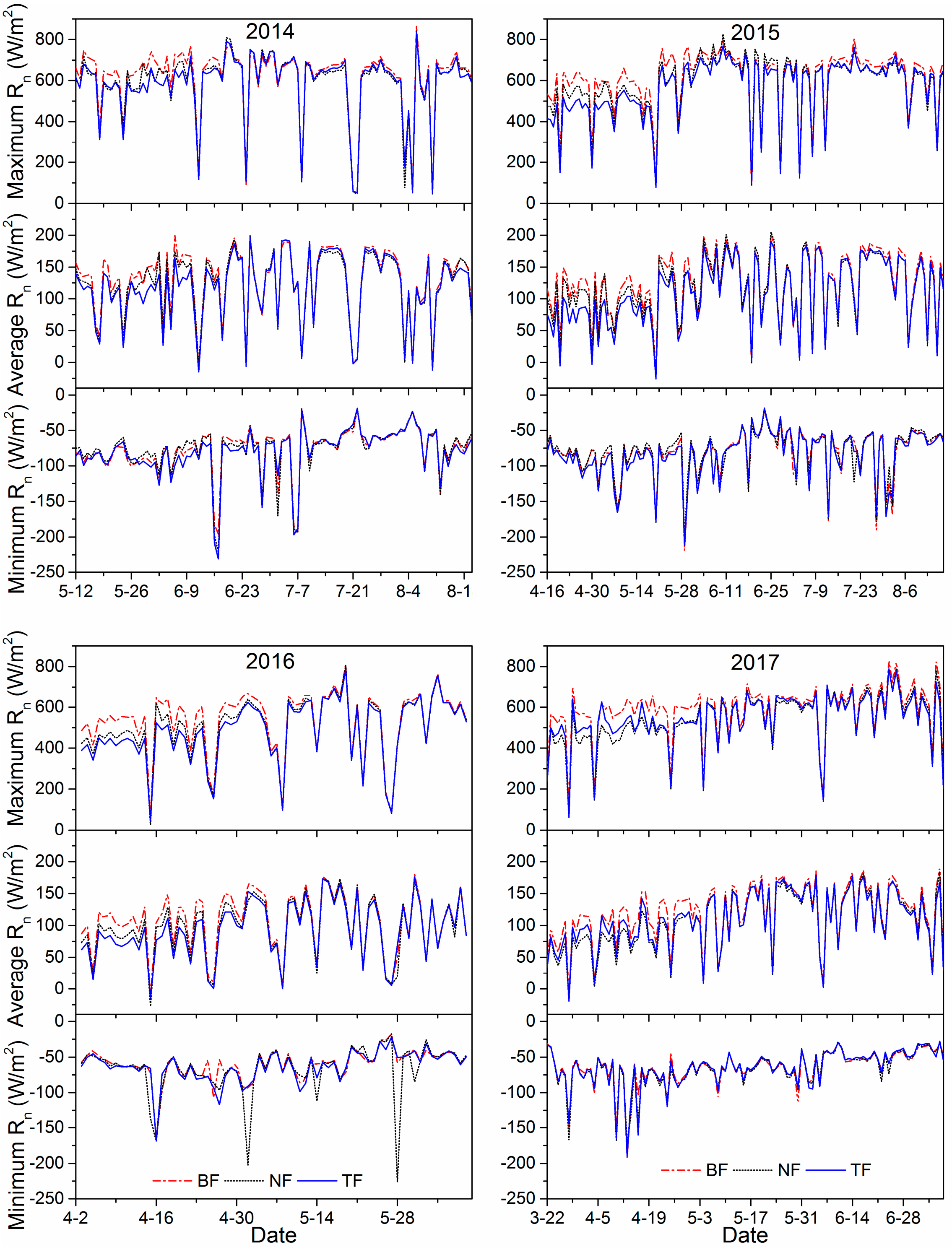

Figure 2. Seasonal variations of the daily maximum net radiation (R_n), daily average net radiation (R_n), and daily minimum net radiation (R_n) for different mulch treatments: black film (BF), no film (NF), and transparent film (TF) in 2014–2017.

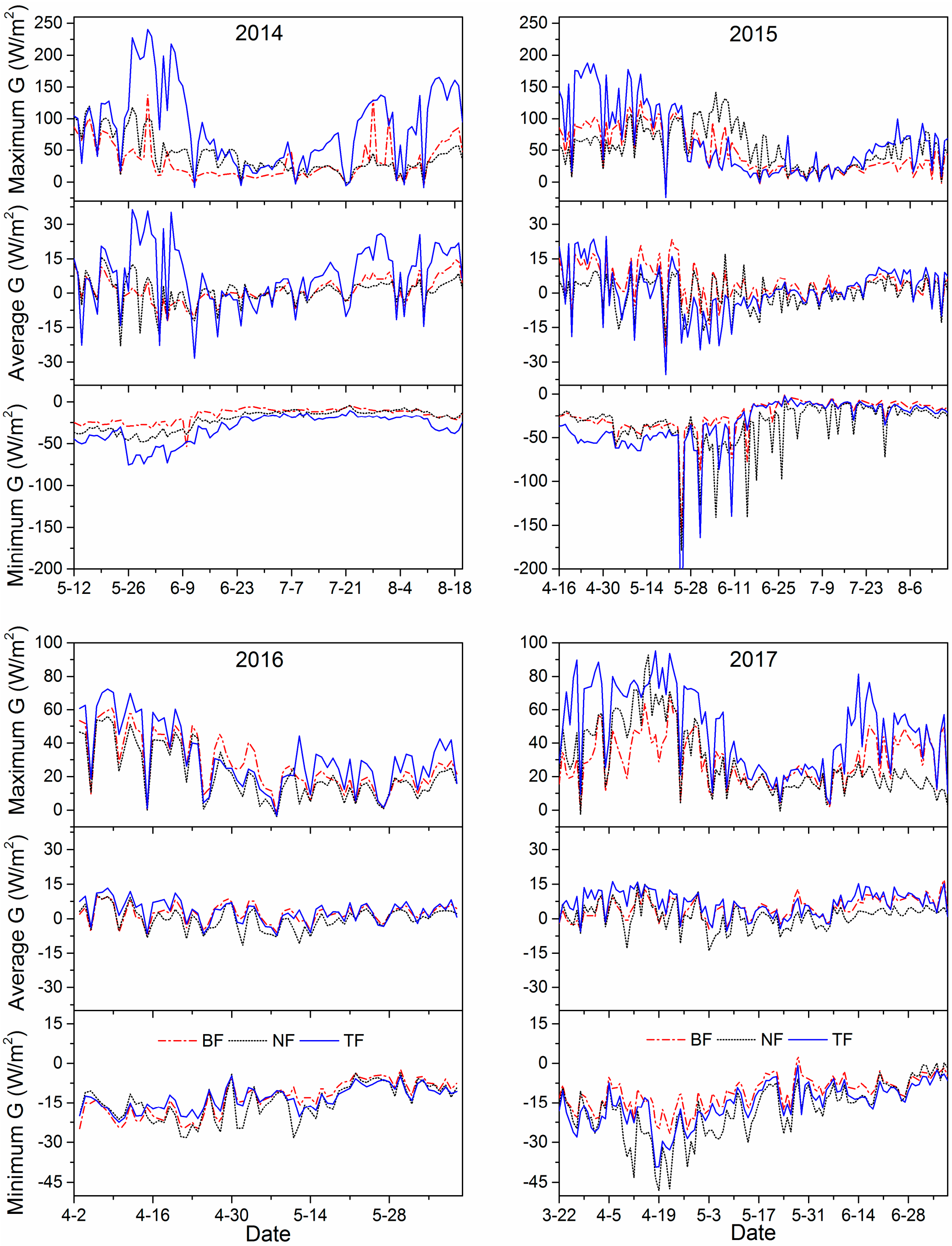

Figure 3. Seasonal variations of the daily maximum soil heat flux (G_{max}), daily average soil heat flux (G_{avg}), and daily minimum soil heat flux (G_{min}) at 5 cm depth in the top of the beds for different mulch treatments: black film (BF), no film (NF), and transparent film (TF) in 2014–2017.

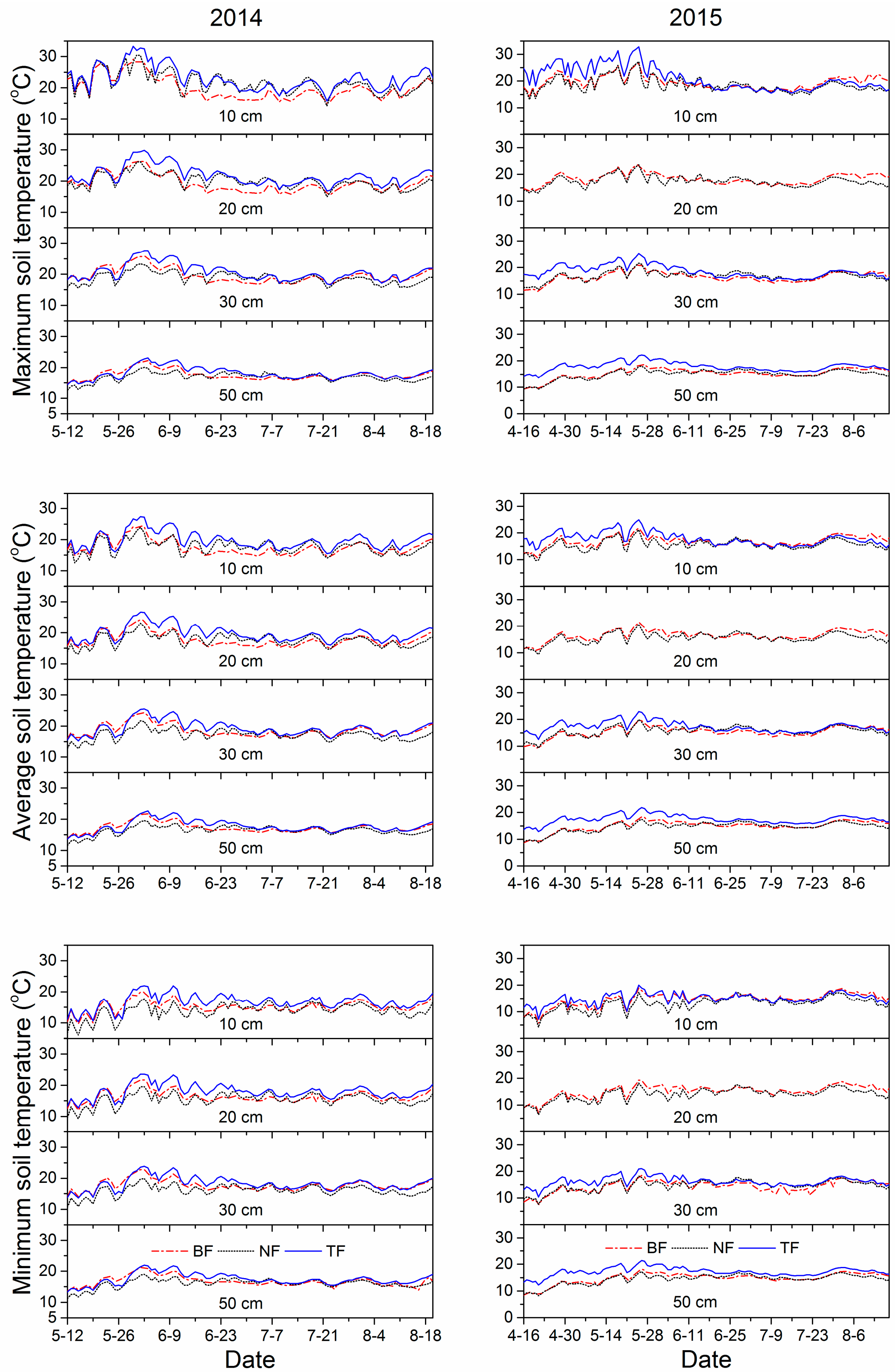

Figure 4. Seasonal variations of the daily maximum soil temperature, daily average soil temperature, and daily minimum soil temperature at 10–50 cm soil depths for different mulch treatments: black film (BF), no film (NF), and transparent film (TF) in 2014 and 2015.The soil temperature at 20 cm soil depth in 2015 was not shown because of data anomalies.

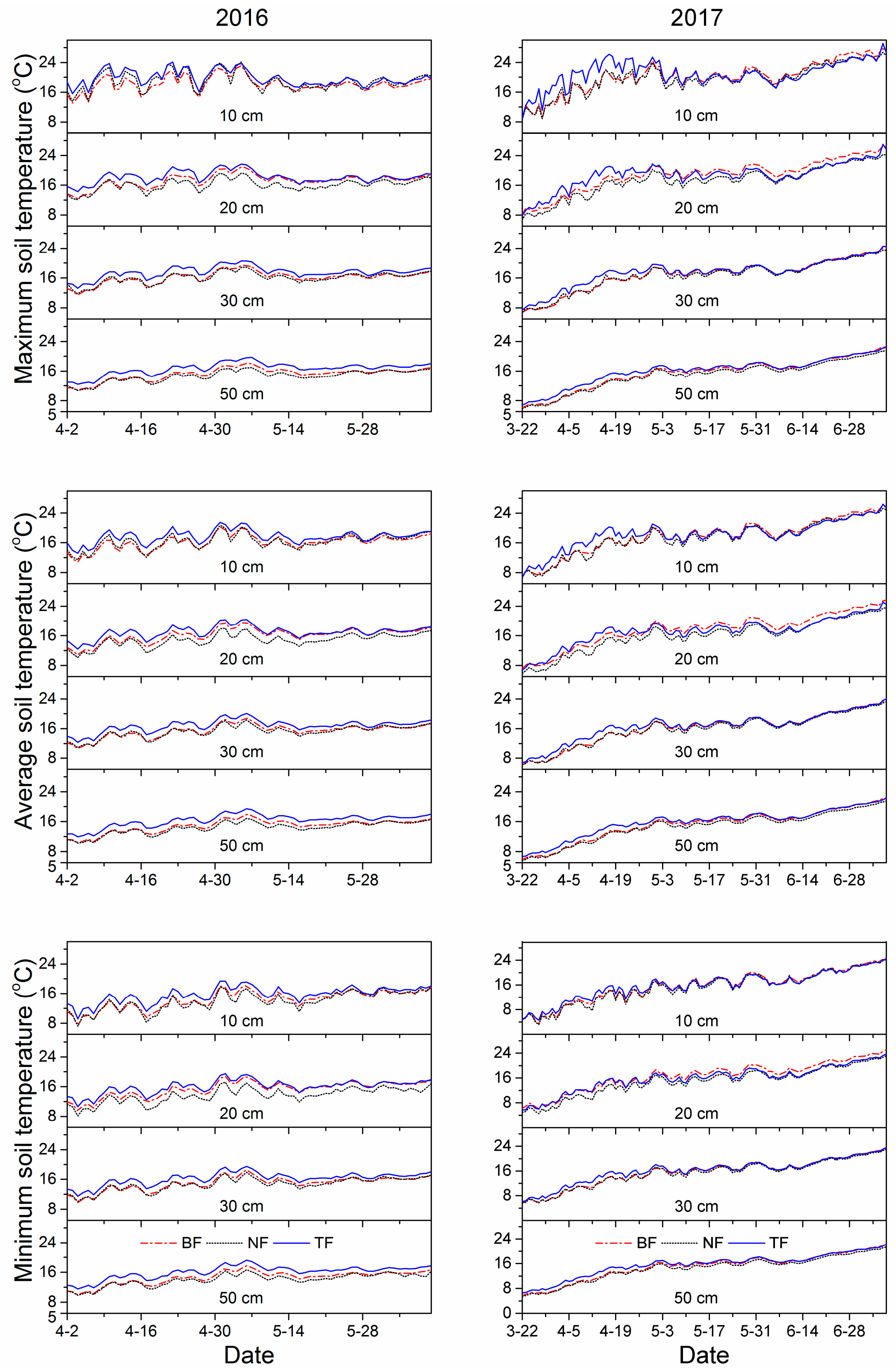

Figure 5. Seasonal variations of the daily maximum soil temperature, daily average soil temperature, and daily minimum soil temperature at 10–50 cm soil depths for different mulch treatments: black film (BF), no film (NF), and transparent film (TF) in 2016 and 2017.

Table 1. The net radiation (R_n) (daily maximum R_n, daily average R_n, and daily minimum R_n) differences between different treatments: black film (BF), no film (NF), and transparent film (TF) in the whole growth season and the early 30 days after potato growing in 2014–2017.

Stage	Year	TF-NF			BF-NF			TF-BF		
		Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.
Whole growth season	2014	−4.7	−4.4	−3.4	23.8	5.5	−0.2	−28.5	−9.9	−3.3
	2015	−20.1	−8.4	−4.2	31.1	6.4	−0.9	−51.2	−14.8	−3.3
	2016	−17.2	−4.6	3.5	33.7	9.2	6.4	−50.9	−13.8	−2.9
	2017	8.7	3.0	1.3	53.1	14.0	1.7	−44.5	−11.0	−0.5
Early 30 days	2014	−19.1	−12.8	−8.3	51.0	10.3	−5.2	−70.1	−23.0	−3.1
	2015	−50.9	−22.0	−9.0	53.9	11.3	−1.3	−104.8	−33.3	−7.7
	2016	−32.4	−10.2	0.2	60.0	15.2	4.5	−92.5	−25.5	−4.3
	2017	39.0	11.1	1.6	103.1	26.7	5.1	−64.2	−15.6	−3.5

Table 2. The soil heat flux (G) (daily maximum G, daily average G, and daily minimum G) differences between different treatments: black film (BF), no film (NF), and transparent film (TF) at 10 cm soil depth in the whole growth season and the early 30 days after potato growing in 2014–2017.

Stage	Year	TF-NF			BF-NF			TF-BF		
		Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.
Whole growth season	2014	45.9	6.5	−10.4	−8.5	0.3	5.5	54.4	6.2	−15.9
	2015	9.7	1.4	0.9	−7.4	4.1	10.9	17.1	−2.8	−10.0
	2016	9.8	3.2	1.4	5.6	2.3	1.4	4.2	0.9	−0.1
	2017	19.1	5.4	2.2	1.0	3.4	6.4	18.1	2.0	−4.2
Early 30 days	2014	62.7	10.7	−14.6	−23.4	−1.5	11.1	86.1	12.2	−25.7
	2015	69.7	5.8	−18.3	21.0	7.8	−0.7	48.6	−1.9	−17.6
	2016	10.4	3.8	2.0	6.1	1.5	−0.5	4.3	2.3	2.5
	2017	18.8	5.9	2.5	−15.5	−0.1	8.3	34.3	6.0	−5.8

Table 3. The soil temperature (T) (daily maximum T, daily average T, and daily minimum T) differences between different treatments: black film (BF), no film (NF), and transparent film (TF) at 10–50 cm soil depths in the whole growth season in 2014–2017.

Year	Maximum (TF-NF)				Average (TF-NF)				Minimum (TF-NF)			
	10 cm	20 cm	30 cm	50 cm	10 cm	20 cm	30 cm	50 cm	10 cm	20 cm	30 cm	50 cm
2014	1.4	1.8	1.9	1.2	2.1	2.1	2.0	1.3	2.8	2.5	2.1	1.3
2015	2.5	-	1.6	2.9	2.2	-	1.6	2.9	2.0	-	1.5	2.8
2016	0.8	2.1	1.5	2.0	1.3	2.2	1.5	2.0	1.8	2.3	1.5	2.0
2017	1.4	1.5	0.8	1.1	0.9	1.2	0.8	1.1	0.6	1.0	0.8	1.1
Average	1.5	1.8	1.4	1.8	1.6	1.8	1.5	1.8	1.8	1.9	1.5	1.8
	Maximum (BF-NF)				Average (BF-NF)				Minimum (BF-NF)			
	10 cm	20 cm	30 cm	50 cm	10 cm	20 cm	30 cm	50 cm	10 cm	20 cm	30 cm	50 cm
2014	−1.7	−0.7	0.8	0.7	−0.1	0.2	1.3	0.8	1.3	0.9	1.6	0.7
2015	0.9	0.9	−0.5	0.3	1.3	1.0	−0.3	0.3	1.6	1.2	−0.4	0.4
2016	−0.8	1.1	0.1	0.5	−0.2	1.3	0.2	0.5	0.3	1.6	0.2	0.6
2017	0.5	1.6	0.2	0.5	0.5	1.7	0.2	0.5	0.4	1.7	0.2	0.5
Average	−0.3	0.7	0.1	0.5	0.4	1.0	0.3	0.5	0.9	1.4	0.4	0.5
	Maximum (TF-BF)				Average (TF-BF)				Minimum (TF-BF)			
	10 cm	20 cm	30 cm	50 cm	10 cm	20 cm	30 cm	50 cm	10 cm	20 cm	30 cm	50 cm
2014	3.1	2.4	1.1	0.5	2.2	2.0	0.7	0.5	1.5	1.6	0.5	0.6
2015	1.6	-	2.1	2.6	0.9	-	1.9	2.5	0.4	-	1.9	2.5
2016	1.6	1.0	1.4	1.5	1.5	0.8	1.4	1.5	1.4	0.7	1.3	1.5
2017	0.9	−0.1	0.7	0.6	0.4	−0.4	0.6	0.6	0.2	−0.7	0.6	0.6
Average	1.8	1.1	1.3	1.3	1.3	0.8	1.2	1.3	0.9	0.5	1.1	1.3

Table 4. The soil temperature (T) (daily maximum T, daily average T, and daily minimum T) differences between different treatments: black film (BF), no film (NF), and transparent film (TF) at 10 cm soil depth during the early 30 days after potato growth in 2014–2017.

Year	Maximum (TF-NF)				Average (TF-NF)				Minimum (TF-NF)			
	10 cm	20 cm	30 cm	50 cm	10 cm	20 cm	30 cm	50 cm	10 cm	20 cm	30 cm	50 cm
2014	1.9	2.6	2.8	1.9	2.9	3.0	2.9	1.9	3.9	3.4	2.9	2.0
2015	6.0	-	4.0	4.6	4.4	-	3.5	4.5	3.2	-	3.2	4.4
2016	1.2	2.5	1.7	2.0	1.7	2.5	1.8	2.1	2.2	2.6	1.7	2.1
2017	3.7	3.0	1.6	1.6	2.4	2.3	1.5	1.6	1.5	1.8	1.4	1.6
Average	3.2	2.7	2.5	2.5	2.8	2.6	2.4	2.5	2.7	2.6	2.3	2.5
	Maximum (BF-NF)				**Average (BF-NF)**				**Minimum (BF-NF)**			
	10 cm	20 cm	30 cm	50 cm	10 cm	20 cm	30 cm	50 cm	10 cm	20 cm	30 cm	50 cm
2014	−0.5	0.8	2.3	2.0	1.3	1.6	2.7	2.1	2.8	2.3	3.0	2.2
2015	0.9	0.9	−0.5	0.3	1.1	0.9	−0.4	0.3	1.2	1.0	−0.3	0.3
2016	−1.2	0.7	−0.1	0.4	−0.4	1.0	0.0	0.4	0.2	1.4	0.1	0.4
2017	−0.1	1.2	−0.2	0.3	0.2	1.4	0.0	0.3	0.4	1.5	0.0	0.3
Average	−0.2	0.9	0.4	0.8	0.5	1.2	0.6	0.8	1.2	1.6	0.7	0.8
	Maximum (TF-BF)				**Average (TF-BF)**				**Minimum (TF-BF)**			
	10 cm	20 cm	30 cm	50 cm	10 cm	20 cm	30 cm	50 cm	10 cm	20 cm	30 cm	50 cm
2014	2.4	1.8	0.5	−0.1	1.6	1.4	0.1	−0.2	1.0	1.1	0.0	−0.2
2015	5.2	-	4.5	4.3	3.3	-	3.9	4.2	1.9	-	3.5	4.1
2016	2.4	1.8	1.8	1.6	2.1	1.5	1.7	1.7	2.0	1.2	1.7	1.6
2017	3.8	1.8	1.8	1.3	2.2	0.9	1.5	1.3	1.1	0.2	1.4	1.3
Average	3.4	1.8	2.1	1.8	2.3	1.3	1.8	1.7	1.5	0.8	1.6	1.7

3.2.1. Canopy Net Radiation (R_n)

Differences of R_n between TF, BF, and NF varied in Experiment 1 and Experiment 2 (Figure 2 and Table 1). For example, the $R_{n\text{-}min}$ in the TF and BF was smaller than in the NF in Experiment 1, while it was greater than in the NF in Experiment 2. In Experiment 2, the $R_{n\text{-}max}$ and $R_{n\text{-}avg}$ in the TF could be smaller (in 2016) or greater (in 2017) than in the NF.

The $R_{n\text{-}max}$ and $R_{n\text{-}avg}$ in the BF were greater than in the TF and NF in both areas. The $R_{n\text{-}max}$ and $R_{n\text{-}avg}$ in the BF were 35.4 and 8.8 W/m^2 greater than in the NF on average during the whole growth season in 2014–2017, respectively. The $R_{n\text{-}max}$ and $R_{n\text{-}avg}$ in the BF were averagely 43.8 and 12.4 W/m^2 greater than in the TF during the whole growth season (82.9 and 24.3 W/m^2 during the early 30 days after potato growing) in 2014–2017, respectively. The $R_{n\text{-}min}$ in the BF was also greater than in the TF.

3.2.2. Soil Heat Flux (G)

Differences of G between TF, BF, and NF varied with the area and growth stage (Table 2 and Figure 3). For example, the G_{max} in the BF was smaller than in the NF in Experiment 1, while it was greater than NF in Experiment 2 on average during the whole growth season. The G_{max} in the TF were on average 21.1 W/m^2 greater than in the NF during the whole growth season in 2014–2017, while it was smaller than in the NF in the middle growth stage when more plastic film mulch was covered by plant canopy such as from 20 June to 2 July in 2014 and from 27 May to 27 June in 2015.

The G_{max} in the TF was on average 23.5 W/m^2 greater than in the BF, while the G_{min} in the TF was on average 7.5 W/m^2 smaller than in the BF during the whole growth season in 2014–2017. The G_{avg} in the TF was greater than in the BF in average in 2014, 2015, and 2016.

Film mulch changed the G more in Experiment 1 than in Experiment 2. For example, the average difference of G_{max} between TF and NF was 66.2 W/m^2 in Experiment 1, while it was on aeverage greater than the NF in Experiment 1, while it was 14.6 W/m^2 in Experiment 2.

3.2.3. Soil Temperature (T)

The T_{max}, T_{avg}, and T_{min} in the TF were greater than in the NF in average during the whole growth season in 2014–2017 (Table 3). The T_{max}, T_{avg}, and T_{min} in the TF were 1.6, 1.7, and 1.8 °C greater during the whole growth season, and 2.7, 2.6, and 2.5 °C greater during the early 30 days of potato growth than in the NF in average, respectively (Tables 3 and 4). The soil temperature differences between the TF and NF decreased as the plant canopy enlarged (Figures 4 and 5). The TF had even lower soil temperature than the NF at some growth stage. For example, the TF had averagely 0.7 °C lower soil temperature in 10 cm depth than the NF from 20 June to 11 July in 2015 and 0.5 °C lower than the NF from 29 May to 6 July in 2017.

Generally, the T_{max}, T_{avg}, and T_{min} in the BF were greater than in the NF in average during the whole growth season in 2014–2017. The differences of T_{max}, T_{avg}, and T_{min} between the BF and NF were smaller than between the TF and NF. The T_{max}, T_{avg}, and T_{min} in the BF were 0.3, 0.6, and 0.8 °C greater during the whole growth season, and 0.5, 0.8, and 1.1 °C greater during the early 30 days after potato growth than in the NF on average, respectively. However, the BF had a lower soil temperature than the NF at some soil depths. For example, the T_{max} at 10 cm soil depth in the BF was averagely 1.7 °C and 0.8 °C lower than in the NF in 2014 and 2016 during the whole growth season, respectively.

Generally, the T_{max}, T_{avg}, and T_{min} in the TF were 1.4, 1.1, and 1.0 °C greater during the whole growth season, and 2.3, 1.8, and 1.4 °C greater during the early 30 days after potato growing than in the BF on average, respectively (Tables 3 and 4). The T_{max}, T_{avg}, and T_{min} in the TF were smaller than in the BF in 2015 and 2017 in the late growth stage (from 29 June to 18 August 2015 and from 12 May to 9 July 2017) (Figures 3 and 4).

Moreover, the differences of T_{max}, T_{avg}, and T_{min} between the TF, BF, and NF in Experiment 1 were greater than in Experiment 2. For example, the differences of T_{max}, T_{avg}, and T_{min} between TF and NF were 3.6, 3.4, and 3.3 °C in Experiment 1, and 2.2, 2.0, and 1.9 °C in Experiment 2 in average during the early 30 days after potato growing, respectively.

3.3. Plant Height

Generally, the plant heights in the TF and BF were significantly greater than in the NF in Experiment 1 (except during the late growth stage), with the maximum plant heights differences of 20 and 18 cm between TF and NF, and 28 and 23 cm between BF and NF in 2014 and 2015, respectively (Figure 6). However, the plant heights in the TF and BF did not differ markedly from that in the NF in Experiment 2. The plant heights in the BF were significantly greater than in the TF in Experiment 1 from 1 June to 3 July in 2014 and from 28 May to 17 June in 2015, while no significant differences were observed in Experiment 2 in 2016 and 2017.

3.4. Tuber Grade

In Experiment 1, the jumbo tubers (W ≥ 300 g) in the TF and BF were more (on average 40% and 50% in weight, and 41% and 49% in number, respectively) than in the NF with significant differences in weight and number in 2014 and in number in 2015 (Tables 5 and 6). In Experiment 2, the jumbo tubers in the TF and BF were more (on average 58% and 21% in weight, and 49% and 17% in number, respectively) than in the NF, although the differences were not significant. The jumbo tubers in the TF were 22% and 18% significantly lower than in the BF in weight and number in 2014. However, the jumbo tubers in the TF were on average 23% and 19% more than in the BF in weight and number in 2015–2017, although no significant differences were observed.

In Experiment 1, the small tubers (W < 100 g) in the BF and TF were less (on average 33% and 25% in weight, and 40% and 20% in number, respectively) than in the NF with significant differences in number in 2014. In Experiment 2, the small tubers in the BF and TF were less (on average 7% and 36% in weight, and 6% and 30% in number, respectively) than in the NF with significant differences in weight and number in 2016.

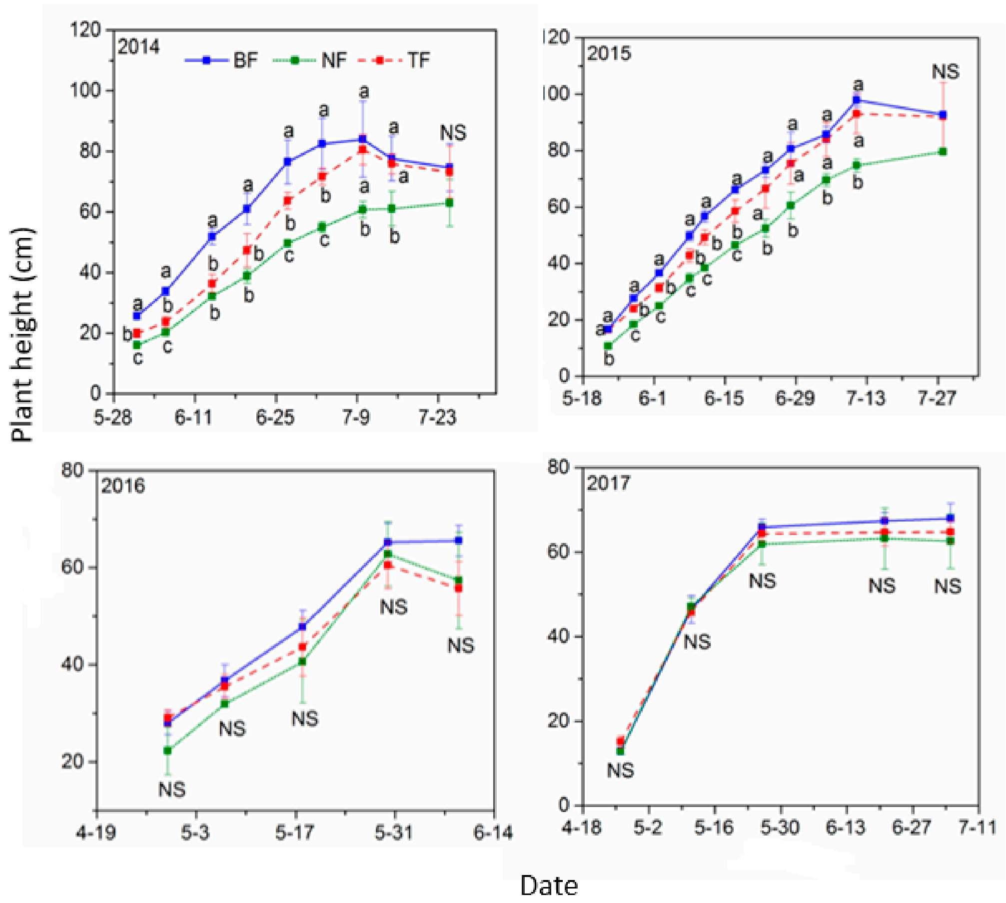

Figure 6. Plant height of potatoes grown with black film (BF), no film (NF), and transparent film (TF) in 2014–2017. (Graphs of plant heights in 2014 and 2015 were according to Zhang et al., 2017b). Note: "NS" meant values of different treatments were not significantly different by F-test ($p > 0.05$).

Table 5. Potato tuber fresh weight of 10 plants sampled from black film (BF), no film (NF), and transparent film (TF) treatment in 2014–2017.

Treatment	W ≥ 300 g			300 g > W ≥ 100 g			W < 100 g			Total		
2014												
BF	7241	(465)	a *	8061	(924)	a *	1061	(217)	a *	16362	(620)	a *
NF	5142	(808)	b	6510	(1157)	a	1447	(188)	a	13099	(1629)	a
TF	5646	(766)	b	7764	(1930)	a	1658	(288)	a	15069	(1931)	a
2015												
BF	10789	(2343)	a *	8807	(1212)	a *	1081	(418)	a *	20677	(981)	a *
NF	6759	(1640)	a	6702	(540)	a	1804	(636)	a	15266	(1650)	a
TF	12050	(2508)	a	7775	(807)	a	637	(340)	a	20462	(2950)	a
2016												
BF	5239	(865)	a *	6223	(1830)	a *	854	(135)	a *	12316	(1285)	a *
NF	3392	(2764)	a	5850	(1068)	a	811	(72)	a	10053	(2090)	a
TF	7015	(1678)	a	5022	(1376)	a	433	(229)	b	12470	(514)	a
2017												
BF	15451	(699)	a *	15552	(375)	a *	2123	(577)	a *	33125	(1482)	a *
NF	17510	(5329)	a	14110	(2797)	a	2615	(592)	a	34235	(3088)	a
TF	19051	(2479)	a	13014	(2760)	a	1943	(561)	a	34007	(1094)	a

W: Weight per tuber. Values of standard deviations were in the parentheses. * Values in a column with different letters were statistically different by Duncan's multiple range test ($p < 0.05$). Values in a column with the same letter were statistically similar by Duncan's multiple range test ($p > 0.05$).

Table 6. Potato tuber number of 10 plants sampled from black film (BF), no film (NF), and transparent film (TF) treatment in 2014–2017.

Treatment	W ≥ 300 g			300 g > W ≥ 100 g			W < 100 g			Total		
2014												
BF	17	(2)	a *	41	(3)	a *	19	(4)	b *	78	(4)	b *
NF	13	(2)	b	36	(5)	a	28	(6)	a	77	(2)	b
TF	14	(1)	b	45	(8)	a	35	(3)	a	93	(6)	a
2015												
BF	25	(4)	a *	45	(7)	a *	19	(8)	a *	90	(10)	a *
NF	15	(3)	b	38	(1)	a	37	(14)	a	90	(11)	a
TF	26	(6)	a	40	(7)	a	13	(8)	a	79	(18)	a
2016												
BF	13	(3)	a *	32	(8)	a *	14	(2)	a *	59	(3)	a *
NF	9	(7)	a	30	(6)	a	13	(1)	a	51	(4)	a
TF	17	(4)	a	26	(7)	a	7	(3)	b	50	(7)	a
2017												
BF	38	(1)	a *	78	(3)	a *	48	(18)	a *	163	(21)	a *
NF	42	(15)	a	74	(15)	a	60	(12)	a	176	(8)	a
TF	46	(5)	a	68	(13)	a	52	(14)	a	166	(12)	a

W: Weight per tuber. Values of standard deviations were in parentheses. * Values in a column with different letters were statistically different by Duncan's multiple range test ($p < 0.05$). Values in a column with the same letter were statistically similar by Duncan's multiple range test ($p > 0.05$).

In Experiment 1, the total tubers in the BF and TF were on average 30% and 25% more than in the NF in weight, respectively. In experiment 2, the total tubers of the TF and BF were 24% and 23% more than that of the NF in weight in 2016, while it was a little less than that of the NF in 2017. The total tubers of the TF were similar with that of the BF.

3.5. Yields and IWUE

In Experiment 1, yields in the TF and BF were significantly greater (23% and 22% in 2014 and 32% and 33% in 2015, respectively) than in the NF (Table 7). The yield in the TF did not differ markedly from that of the BF. Compared with the NF, the yields in the TF and BF were greater in 2016 and smaller in 2017 in Experiment 2 with no significant differences.

Table 7. Potato tuber yield, irrigation, and irrigation water use efficiency (IWUE) of black film (BF), no film (NF), and transparent film (TF) treatment in 2014–2017.

Treatment	Yield (kg/hm^2)		Irrigation (mm)	IWUE ($kg/hm^2/mm$)	
2014					
BF	62,353	a *	317	197	ab *
NF	51,206	b	277	185	b
TF	63,031	a	293	215	a
2015					
BF	82,704	a *	366	226	a *
NF	62,191	b	392	159	b
TF	81,968	a	344	238	a
2016					
BF	51,317	a *	180	285	a *
NF	41,888	a	144	291	a
TF	51,957	a	144	361	a
2017					
BF	59,426	a *	276	215	a *
NF	61,913	a	260	238	a
TF	59,389	a	276	215	a

* Values in a column with different letters were statistically different by Duncan's multiple range test ($p < 0.05$). Values in a column with the same letter were statistically similar by Duncan's multiple range test ($p > 0.05$).

The IWUE in the TF was 16% and 50% significantly greater than in the NF in Experiment 1 in 2014 and 2015, respectively. The IWUE in the BF was 42% significantly greater than in the NF in Experiment 1 in 2015. The IWUE in the TF and BF did not differ markedly from that of the NF in Experiment 2 in 2016 and 2017. No significant differences were found in IWUE between the TF and BF in Experiment 1 and Experiment 2.

4. Discussion

4.1. Different Effects of Transparent and Black Films on Heat Conditions

Previous studies have shown that the transparent film causes smaller net radiation (R_n) above the crop canopy and the black film results greater R_n than the no film [28–30]. In our research, the result of average R_n was consistent with the previous study, while the TF could also produce greater R_n and the BF could result in smaller R_n than the no film (Figure 1 and Table 1). On the one hand, the optical properties of soil depend on soil texture and soil moisture [21,31,32], which caused different R_n in the no film in different areas or even in different years of the same area. On the other hand, different canopy growth (Figure 5) in Experiment 1 and Experiment 2 could also cause the different R_n. That was why the results of R_n between TF and NF, and BF and NF were different in different experiments. The BF resulted in greater R_n than the TF because of the high shortwave absorptance of the BF, which was consistent with Bonachela et al. [8].

Researches indicated that the TF produced greater soil heat flux (G) in the daytime than the NF [29,30]. Generally, the TF produced greater G than the NF in daytime during early and late growth stages, while it produced lower G than the NF in middle growth stage in this study. Yuan et al. [33] also reported lower daytime G in the drip irrigated field with transparent film. This lower G in the TF might be caused by the greater canopy growth in the middle growth stage as shown in Figure 5. The daytime G in the BF was similar with that in the NF by modeling [34], while it was smaller or greater than in the NF in this study. Bonachela et al. [8] also found the G in the BF was greater than in the NF. The different results between the BF and NF might be caused by the different contact degrees between the BF and underlying soil [21]. The daytime G in the TF was greater than in the BF in average, while the nighttime G in the TF was smaller than in the BF, which was consistent with Bonachela et al. [8]. This result meant more heat was stored during daytime and more heat released from the soil in the TF than the BF. It was because the transparent plastic film had greater shortwave and longwave transmittances than the black plastic film [21].

Previous studies have found that both the TF and BF increase soil temperature [10,14]. In this study, the film improved night soil temperature more that daytime soil temperature (0.2 °C for the TF and 0.5 °C for the BF in average). Thus, daily soil temperature amplitude was decreased, which was in accord with Zhang et al. [14]. However, during the middle growth stage, the soil temperature in the BF and TF was even lower than in the NF because of the greater canopy growth in the mulched as shown in Figure 5. This result was in accord with Fan et al. [29] who observed lower soil temperature during plant canopy growth than the no film treatment. Soil temperatures in the TF and BF were averagely greater than the NF during the whole growth stage. The TF had 1.8 °C higher soil temperature than the BF. Ham and Kluitenberg [34] found clear film had 1.2 °C higher soil temperature than black film at 10 cm soil depth, while Bonachela et al. [8] observed clear film had 1.0 °C lower soil temperature than black film at 25 cm soil depth. The contrary results might be caused by different air gaps among the film and underlying soil, which affect heat conduction. Film mulching was more effective on soil temperature increase in Experiment 1 than in Experiment 2.

4.2. Different Effects of Transparent and Black Films on Plant Growth

Researches indicated that film mulching could increase plant heights [20]. In our study, film mulching significantly increased plant heights in Experiment 1, while no significant differences were found in Experiment 2. The plant heights grown with black film was greater than transparent film in early growth stage in Experiment 1, which was consistent with Decoteau et al. [35], while no significant differences were found in Experiment 2 which was consistent with Anikwe et al. [20]. This might be because the thermal effects of plastic film mulch in Experiment 2 were less than in Experiment 1.

Previous researches have showed that high soil temperature can promote tuberization and increase tuber number and yield [36–38], soil temperature above 27 °C or 29 °C is harmful for tuber production and decrease tuber yield [38,39]. In our research, higher soil temperature (lower than 27 °C) during tuber growth stage in the film mulch treatments caused considerably greater jumbo tubers in weight and number than the no-mulched in both experiments. The higher soil temperature in the TF caused the average 23% and 19% more jumbo tubers than in the BF in weight and number in 2015–2017. Moreover, film mulching produced greater yield and IWUE than the no film except in 2017. The smaller yield and IWUE in the TF and BF in 2017 might be caused by more precipitation in 2017 than in 2014, 2015, and 2016. This was consistent with Jia et al. [18], who observed film mulching did not affect potato yield in water sufficient season. The higher soil temperature in potato maturation stage in 2017 might be another reason that caused the lower yield in the plastic film mulch treatment. Thus, film should be removed at the late growth stage because of the negative effects on potato yield caused by high soil temperature [7,40].

4.3. How to Choose the Plastic Film Mulch for the Drip Irrigated Potato

Since plastic film mulch has positive and negative effects on potato growth, it does not always increase potato yield and water use efficiency [17,18,41]. The film need for plant production should be chosen according to climate conditions and the crop [17]. Transparent film is more suitable for increased soil temperature and potato jumbo tubers production than the black film for both areas. In Experiment 1, both the transparent and black film can significantly increase the potato yield and IWUE. In Experiment 2, the effects of film mulching on potato plant height, potato yield, and IWUE was not significant. The plastic film performed better in improving the heat conditions and drip-irrigated potato growth in Northwest China (Experiment 1) than in Eastern China (Experiment 2).

5. Conclusions

The R_n and G differences between the TF, BF, and NF were different at different areas in different growth seasons. The R_n and G in the BF and TF can be greater or smaller than in the NF. However, the R_n in the TF was always smaller (averagely 12.4 W/m^2 in 2014–2017) than in the BF in the two study areas. The daily G_{max} in the TF was greater (averagely 23.5 W/m^2 in 2014–2017) and the daily G_{min} was smaller (on average 7.5 W/m^2 in 2014–2017) than in the BF in both areas. The soil temperature in the TF and BF was 1.7 °C and 0.6 °C higher than in the NF on average at 10–50 cm soil depths in 2014–2017, respectively, although it might be a little bit smaller than in the NF in the middle growth stage. The average temperature difference between the TF and NF was 1.4 °C higher in Experiment 1 than in Experiment 2.

The plant heights in the TF and BF were significantly higher (maximum differences 19 and 26 cm on average, respectively) than in the no film in Experiment 1, while it did not differ markedly in Experiment 2. Both the TF and BF increased the jumbo tubers and decreased the small tubers in weight and number in Experiment 1 and Experiment 2. The TF had 23% and 19% more jumbo tubers than the BF in weight and number on average with no significant difference in 2015–2017. The TF and BF had 28% significantly greater potato yield than the NF on average in Experiment 1, while it did not differ markedly in Experiment 2. The TF and BF had 16% and 50% significantly greater irrigation water use efficiency than in the NF in Experiment 1, respectively, while no significant differences were found in Experiment 2.

In conclusion, the transparent film was more suitable to increase soil temperature and jumbo tubers than the black film. The plastic film mulch functioned better for improving heat conditions and drip-irrigated potato growth in Northwest China than in Eastern China.

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