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Effects of Biodegradable Film and Polyethylene Film Residues on Soil Moisture and Maize Productivity in Dryland

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Abstract: With the dramatic increased use of agricultural film, the potential environmental risks associated with it have been receiving widespread attention. Biodegradable film (BF) is considered an alternative to conventional polyethylene film (PF), but its feasibility to replace PF needs to be verified. Thus, we conducted a two-year field experiment in the Loess Plateau region of China, exploring the effects of residual biodegradable film and polyethylene film (RBF and RPF) on soil moisture, maize root, and productivity at different residual levels (75 kg ha^{-1}, 150 kg ha^{-1} and 300 kg ha^{-1}). Regardless of the residual film type, soil water content (SWC), root length density (RLD), and root surface area density (RSD) all decreased with increasing residual level; this phenomenon observed significant differences when the residual level exceeded 150 kg ha^{-1}. Different organs (root and shoot) of maize differed in their sensitivity and sensitivity period to residual film. The two-year degradation rate of RBF was 59.24%, which was higher than that of RPF. Compared to the RPF treatments, the SWC, RLD, RSD, biomass, and root–shoot ratio of the RBF treatments were closer to the no residual film treatment in the second maize growing season. After the two-year experiment, compared to the grain yield, water use efficiency, and precipitation use efficiency of the RPF treatments, that of the RBF treatments increased 0.41–6.24%, 0.12–4.44%, and 0.41–06.24%. The application of BF to replace PF is beneficial to sustainable maize production in dryland, but finding efficient methods to recycle the residual film remains a priority.

Keywords: residual film; soil water content; root morphology; maize yield; biodegradable film

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1. Introduction

With abnormal global climate change and continued population growth [1,2], how to ensure food security has become a current focus for mankind [3]. Dryland agriculture, the main source of global food production, accounts for 80% of the total arable land and feeds more than 4 billion people [4]. However, water scarcity has been a constraint to dryland agricultural production. Mulching is widely used in dryland agriculture as an agronomic practice to improve soil hydrothermal environment, suppress weed growth, and increase crop yield, and water and fertilizer use efficiency [5]. Global use of mulch is expected to increase by 59% in 2026 compared to 2018 [6]. China, the world's largest market for agricultural mulch, will reach 2.28 million tons of use in 2025 [7]. This shows that until new agricultural production technologies emerge, mulching is difficult to replace in ensuring dryland crop yield.

About 40% of China's cultivated land is located in the Loess Plateau, and spring maize is one of the main food crops in this region [8–10]. Due to the shortage and uneven distribution of precipitation in the growing period of spring maize, it relies heavily on plastic film mulching. Compared with bare field planting, plastic film mulching can increase maize grain yield by 5.91–44.13% [11]. However, due to the limitations of plastic film recycling, farmers do not have strong recycling intentions, resulting in a large amount of residual plastic film accumulating in the topsoil [12]. The material of plastic film is mostly low-density polyethylene (LDPE), whose chemical structure is very stable and difficult to degrade in a short period, thus, the so-called "white pollution" causes irreversible harm to the agroecosystem [13]. At present, due to the long-term high-strength use of LDPE plastic film, the residual amount of plastic film in China has reached 72–259 kg ha^{-1} [14], which will not be conducive to the sustainable development of dryland agriculture. There has also been a heated debate in the academic community about whether the potential long-term risks to soil health from residual film will obscure the short-term benefits of mulching. For instance, microplastics generated from residual film can be a vector for heavy metals transition, posing a serious threat to human food safety [15].

The residual film changes the soil pore structure, blocking small and medium pores and increasing the proportion of large pores, further changing the hydraulic properties of the soil [16], hindering soil water and nutrients transport, and reducing water and fertilizer uptake by the root system [17], ultimately leading to crop yield reduction and inefficient resource use. The root system, as an important organ for obtaining water and nutrients for crop growth, directly senses the changes in soil environment brought by residual film [5]. Crop root morphological parameters are significantly reduced due to mechanical hindrance produced by residual film [18,19]. At the same time, the residual film changed the spatial-temporal arrangement of soil moisture, thus affecting the root morphological distribution in the soil [5,20], which in turn affected the plant assimilate allocation strategy and reduced the net primary productivity of the crop. The effects of residual film on soil physicochemical properties and crop root growth have been reported by former researchers, but we know little about crop root–shoot relationships and assimilate allocation under residual film stress. Additionally, how to reduce the accumulation of film residues in the process of dryland agriculture is the core problem to be solved urgently.

Starch-based biodegradable film (BF) is considered an alternative to conventional polyethylene film (PF), which can also guarantee the yield of dryland crops and gradually degrade, saving the crop from premature aging caused by high soil temperature in the later stages [21,22]. However, BF will be plowed directly into the soil after use and left to degrade freely. Previous studies have focused on residual PF; the effects of residues generated during BF degradation on the soil–crop system in dryland are not clear, and their feasibility to replace PF still needs to be discussed. The European Commission recently noted that the initial environmental impact of BF before complete degradation needs to be explored to facilitate relevant decision making [23]. Meanwhile, there is an urgent need to determine the residue threshold for the negative impact of BF on crop productivity and the sensitive characteristics of different crops to residual film, and to develop industry standards and reasonable application programs accordingly to achieve a veritable green production. To this end, we conducted a two-year experiment in the Loess Plateau region of China to investigate the effects of residual biodegradable film and polyethylene film (RBF and RPF) on soil moisture, maize root morphology and productivity. The specific objectives of this study were to (1) clarify the effects of RBF and RPF on soil moisture distribution; (2) assess the effects of soil moisture changes caused by two types of residual film on dryland maize root morphology and productivity; (3) elucidate the feedback mechanisms of root–shoot synergy to residual film stress; and (4) evaluate the prospect of a wide application of BF in terms of soil moisture and maize productivity, and provide a theoretical reference for cleaner production of maize in dryland.

2. Materials and Methods

2.1. Experimental Site

A field experiment was conducted during the two spring maize growing seasons (April to September 2020 and April to September 2021) at Changwu Loess Plateau Agroecological Experimental Station (35°59′ N, 107°38′ E, 1220 m ASL), in Changwu, Shaanxi province, China. The climate belongs to a warm temperate semi-humid continental monsoon climate, with an average annual precipitation of 584 mm, an average temperature of 9.1 °C, a frost-free period of 171 days, a groundwater level of 70 m, and no irrigation conditions. It belongs to a typical rain-fed agricultural area. During the maize growth period, the air temperature and precipitation were monitored by an automated weather station at the experimental site (Changwu Experimental Station Meteorological Observatory, WS-STD1, England). The meteorological data for the two growing seasons are shown in Figure 1. According to the USDA textural classification system, the soil properties were measured using the recommended methods. The soil is dark loessial soil with the 0–20 cm soil layer consisting of 11.46 g kg^{-1} soil organic matter, 45.63 mg kg^{-1} available nitrogen, 15.78 mg kg^{-1} available phosphorus, and 135.28 mg kg^{-1} available potassium before the field experiment in 2020.

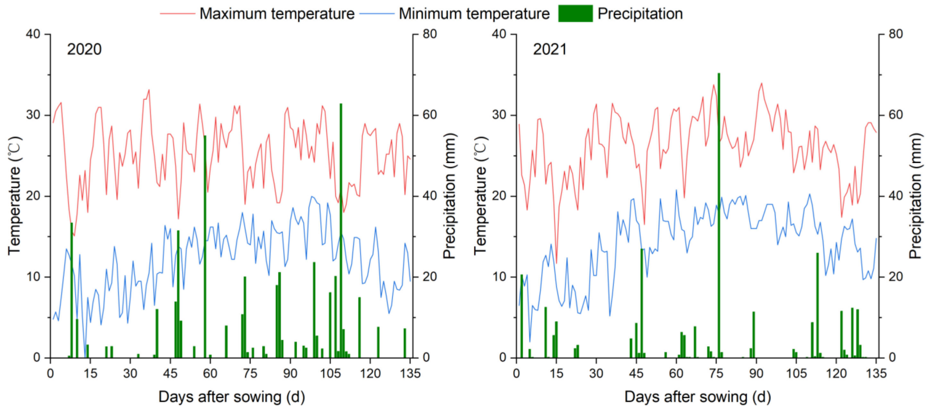

Figure 1. Meteorological data (maximum temperature, minimum temperature, and precipitation) for the 2020 and 2021 spring maize growing seasons.

2.2. Experimental Design and Treatments

In this experiment, two types of residual film were set: residual polyethylene film (RPF) and residual biodegradable film (RBF). Three residual levels were set based on a relationship between the residual film amount and the film mulching years [18,24,25]. Seven treatments were designed as: (1) NRF, no residual film; (2) RPF_{75}, 75 kg ha^{-1} of RPF; (3) RPF_{150}, 150 kg ha^{-1} of RPF; (4) RPF_{300}, 300 kg ha^{-1} of RPF; (5) RBF_{75}, 75 kg ha^{-1} of RBF; (6) RBF_{150}, 150 kg ha^{-1} of RBF and (7) RBF_{300}, 300 kg ha^{-1} of RBF.

The material of the RPF is low-density polyethylene (LDPE), and the material of the RBF is polylactic acid (PLA). The thickness of the two types of films is 0.008 mm, which were obtained from Sichuan Kaiyuanchuangyi Biotechnology Co. Ltd. located in Mianyang, Sichuan province, China. The plastic film was cut into square pieces of 4 cm^2 (2 cm × 2 cm) by scissors, and the amount of residual film required for different treatments was obtained by weighing with an accuracy of 0.001 g using a balance (METTLER TOLEDO, PL203, Switzerland). Before sowing in 2020, the debris was evenly spread on the soil surface of each plot, and mixed with the topsoil (0–20 cm) using a rotary tiller. The field experiment was conducted in a completely randomized design with three replicates, and each plot was 18 m^2 (5 m length × 3.6 m width).

The spring maize variety is Zhengdan 958 (which is widely grown in the local area), which is sown on 30 April 2020 and 2021, and harvested on 13 September 2020 and 15 September 2021 respectively. The planting method is manual sowing, with row spacing of 60 cm, plant spacing of 24.7 cm, and planting density of 67,500 plants ha^{-1}. Cover the soil surface with transparent plastic film and compact the edges of the film with soil. The new plastic film should be covered before sowing every year and removed after the harvest to prevent the generation of new residual film. Before mulching, all treatments were fertilized at the ratio of 225 kg N ha^{-1} (urea) and 120 kg P_2O_5 ha^{-1} (superphosphate). During the study period, irrigation was not used, and all water inputs were from natural rainfall. The precipitation during the maize growing seasons in 2020 and 2021 was 394.2 and 295.2 mm, respectively. Manual ridges were set up around each plot to prevent water from flowing into the plots, and a 1 m protection row was set up. The diseases, pests, and weed management methods are the same as those of local ordinary fields (spraying phoxim and amide herbicides). They are carried out in strict accordance with the experimental requirements.

2.3. Sampling and Measurement

2.3.1. Residual Film Density (RFD) and Degradation Rate (DR)

Before sowing and after harvesting in each growing season, a sampling pit (Figure 2, 100 cm length × 100 cm width × 20 cm depth) was dug in each plot [26]. Using a 2 mm mesh sieve, the residual films in the pit soil were screened out and then brought back to the laboratory. The residual film was cleaned by ultrasonic and weighed after natural drying. The film was weighed with an accuracy of 0.001 g using a balance (METTLER TOLEDO, PL203, Switzerland) and the residual film density (RFD) and degradation rate (DR) were calculated. RFD (kg ha^{-1}) and DR (%) were calculated as follows:

$$\text{RFD} = \text{residual film mass at sampling/sampling area} \quad (1)$$

$$\text{DR} = [(\text{initial residual film density} - \text{residual film density at sampling})/\text{initial residual film density}] \times 100\% \quad (2)$$

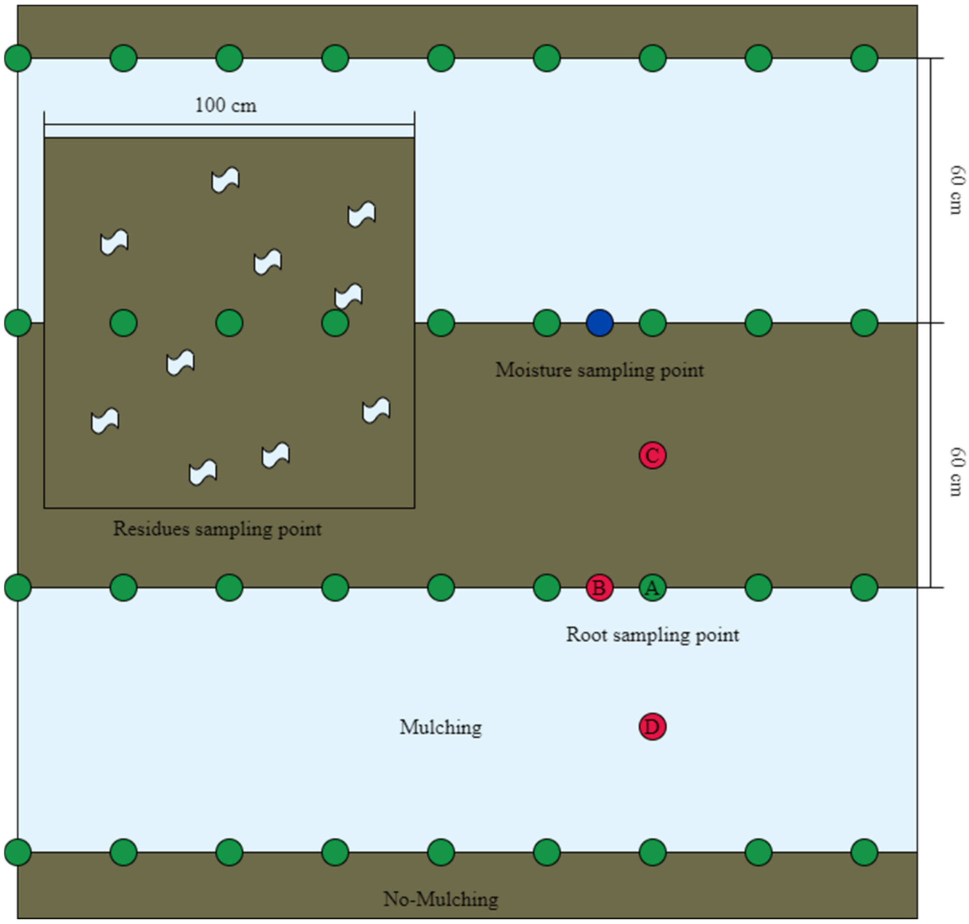

Figure 2. Schematic diagram of sampling point. Planting with 60 cm equal row spacing. A, planting spots; B, intra-plants' spots; C and D, intra-rows' spots.

The experimental site was selected in a plot with no residual film. Therefore, the initial residual film density is the amount of residual level applied.

2.3.2. Soil Moisture

Soil samples were collected at 20 cm intervals in 0−100 cm soil layers at the six-leaf (V6), tasseling (VT), filling (R3), and physiological maturity (R6) stages. The soil samples (Figure 2) were manually obtained from each plot by using a 70 mm diameter portable auger in the middle between two maize plants [27]. Soil samples were placed into aluminum boxes, weighed immediately, and then returned to the laboratory to dry at 105 °C until a constant weight was obtained, and weighed again. Soil water content (SWC, %) was calculated as follows:

$$\text{SWC} = [(\text{fresh soil weight} - \text{dry soil weight})/\text{dry soil weight}] \times 100\% \quad (3)$$

Soil water storage (SWS) is the product of SWC, the average soil bulk density in each layer, and the depth of the soil layer. The SWS in the 0–100 cm soil layer was the sum of the average values in all soil layers.

2.3.3. Root Morphology, Plant Biomass, and Root–Shoot Ratio (RSR)

Five evenly growing maize plants from the inner rows of each plot were sampled to determine root morphology and plant biomass at the V6, VT, R3, and R6 stages in 2020 and 2021. Soil–root columns were excavated using a 100 mm diameter portable auger at four separate locations [28], including planting spots, intra-plants' spots, and intra-rows' spots (Figure 2). Each core was undisturbedly obtained at 20 cm intervals in 0–100 cm depth of the soil column: 0–20, 20–40, 40–60, 60–80, and 80–100 cm. The soil–root mixture is put into a nylon net bag and brought back to the laboratory. After being soaked for 12 h, it is washed with slow-flowing water. The root samples from the nylon net bag are carefully screened with tweezers, then the samples are wiped with absorbent paper, and put into the self-sealing bag for scanning. Roots in different soil layers were scanned using a root scanner (Epson, V700, Atlanta, GA, USA). Root morphological parameters were measured such as length (cm) and surface area (cm^2) through the WinRHIZO (Version 5.0, Regent Instruments Inc., Boul Wilfrid-Hamel, QC, Canada). Root length density (RLD, cm cm^{-3}) and root surface area density (RSD, cm^2 cm^{-3}) were calculated as follows:

$$\text{RLD} = \text{root length in different soil layer/soil volume} \quad (4)$$

$$\text{RSD} = \text{root surface area in different soil layer/soil volume} \quad (5)$$

where the soil volume of each layer was 6280 cm^3 (3.14 × 5 cm × 5 cm × 20 cm × 4). The shoot of the sampled plants and the samples subjected to root morphology evaluation were dried to investigate plant biomass. The root and shoot dry weight were measured by drying the samples at 105 °C for 30 min to deactivate their enzymes and dried at 75 °C to constant weight. Root–shoot ratio (RSR) refers to the ratio of the dry weight of the root part and the shoot part of a plant.

2.3.4. Grain Yield, Water Use Efficiency (WUE) and Precipitation Use Efficiency (PUE)

At R6 stage, plants in the middle two rows of each plot were sampled, and the ears were harvested, shelled, and air-dried to determine the grain yield (the moisture content of the kernel after being air-dried was approximately 14%). Plants from border rows were excluded from the harvest. Ten ears were randomly selected from each plot to determine the kernel number per ear, and the 100-grain dry weight.

There is no irrigation at the experimental site, the water table is 70 m, and the water input is only from precipitation. No drainage or runoff occurred at the experimental site during the maize growth period. Thus, evapotranspiration (ET, mm) was calculated by the soil water balance equation [29,30] as follows:

$$\text{ET} = \text{P} + \Delta\text{W} \quad (6)$$

where P is the precipitation (mm) during the growth period, and ΔW is the change value (mm) of SWS in 0–100 cm before sowing to harvest. Water use efficiency (WUE) refers to the ratio of grain yield per unit area to the ET in the growing season [31]. Precipitation use efficiency is the ratio of grain yield to precipitation in the growing season [32]. WUE (kg ha^{-1} mm^{-1}), and PUE (kg ha^{-1} mm^{-1}) were calculated as follows:

$$WUE = \text{grain yield}/ET \quad (7)$$

$$PUE = \text{grain yield}/P \quad (8)$$

2.4. Statistical Analysis

Calculation of mean, standard deviation (SD), standard error (SE), and analysis of variance (ANOVA) was carried out by using SPSS (Version 21.0, IBM, Armonk, NY, USA). The LSD was used to determine differences between means when a significant treatment effect was observed at $p < 0.05$. Data figures were created by OriginPro (Version 8.5, OriginLab, Northampton, MA, USA).

3. Results

3.1. Degradation Process of Different Types of Residual Film

The residual film density (RFD) and degradation rate (DR) of different types of residual film differed significantly. After two years of experiment, the RPF showed almost no degradation and the RFD was maintained at the initial application amount. However, the RFD of RBF_{75}, RBF_{150}, and RBF_{300} was 30.32 kg ha^{-1}, 59.73 kg ha^{-1}, and 126.13 kg ha^{-1}, respectively, significantly lower than that of RPF under the same application level (Figure 3a). The two-year DR of RPF was only 0.69%, and the DR of RBF reached a considerable 59.24% (Figure 3b). Although the RBF was not completely degraded, its DR was obviously higher than that of RPF.

3.2. Effect of Residual Film on Soil Moisture

Soil water content (SWC) in the 0–100 cm soil layer of all treatments decreased and then increased with soil depth (Figure 4). SWC in the soil layer which is the main maize root distribution (0–40 cm) decreased with increasing residual levels. The highest SWC was found in the NRF, but it was not significantly different from the low residual level treatments, it was significantly different from the medium and high residual level treatments. In comparison with NRF, the SWC in the 0–40 cm of RPF_{150}, RPF_{300}, RBF_{150}, and RBF_{300} were reduced by 10.87%, 18.29%, 10.34%, and 19.28%, respectively, in 2020; 8.05%, 13.31%, 4.19%, and 8.71%, respectively, in 2021. Comparison between different types of residual film also showed differences in 2021, with significantly higher SWC for RBF_{150}, and RBF_{300} than for RPF_{150}, and RPF_{300}. It indicated that the reduction of RBF contributes to soil moisture retention. However, SWC in the 0–20 cm soil layer at the VT stage in 2021 showed an increase with residual level, which may be due to the high precipitation events that occurred at that growth stage.

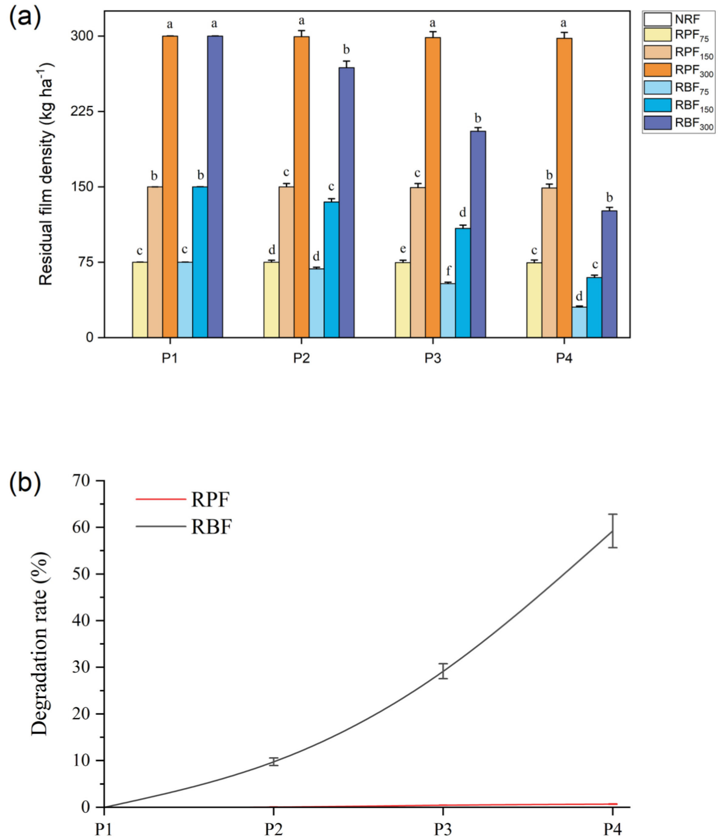

Figure 3. Dynamic changes of residual film density under different treatments (**a**), and degradation rate of different types residues (**b**) during the two-year experiment (P1: before sowing in 2020, P2: after the harvest in 2020, P3: before sowing in 2021, and P4: after the harvest in 2021). Vertical bars represent the standard error of the mean. Different lowercase letters indicate significant ($p < 0.05$) differences based on the LSD test. (NRF, no residual film; RPF_{75}, 75 kg ha^{-1} of residual plastic film (RPF); RPF_{150}, 150 kg ha^{-1} of RPF; RPF_{300}, 300 kg ha^{-1} of RPF; RBF_{75}, 75 kg ha^{-1} of residual biodegradable film (RBF); RBF_{150}, 150 kg ha^{-1} of RBF and RBF_{300}, 300 kg ha^{-1} of RBF.)

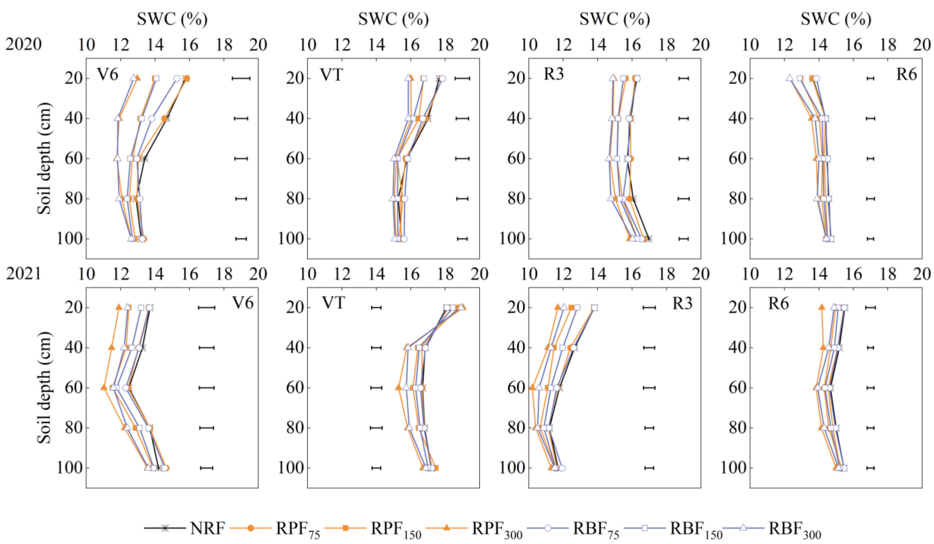

Figure 4. Dynamics of soil water content (SWC) in the 0–100 soil layer under different treatments during the spring maize growing seasons in 2020 and 2021. Horizontal bars stand for LSD at 0.05 levels. Sixth leaf stage (V6), tasseling stage (VT), filling stage (R3), and physiological maturity stage (R6).

3.3. Effect of Residual Film on Maize Root Morphology

The root system of maize is concentrated in the 0–40 cm soil layer, and this part is also most affected by the residual film in this study. With the residual level increased, the root length density (RLD) and root surface area density (RSD) of maize decreased (Figure 5). In both growing seasons, RLD and RSD without residual film were significantly higher than the medium and high residual level treatments. This indicated that residual film amounts above 150 kg ha^{-1} inhibit maize root growth. Compared to NRF, RLD and RSD in the 0–40 cm decreased by 9.69–15.29% and 10.02–19.23% for RPF_{150}, RPF_{300}, RBF_{150}, and RBF_{300} in 2020, by 2.74–14.10% and 6.67–17.63% in 2021. Comparison of different types of residual film also showed differences in 2021, with 0.55–7.65% and 1.15–8.21% increase in RLD and RSD for RBF compared to RPF (Figure 6). This indicated that the root morphological parameters were better in the RBF treatments, which facilitated water and nutrient uptake and utilization by maize.

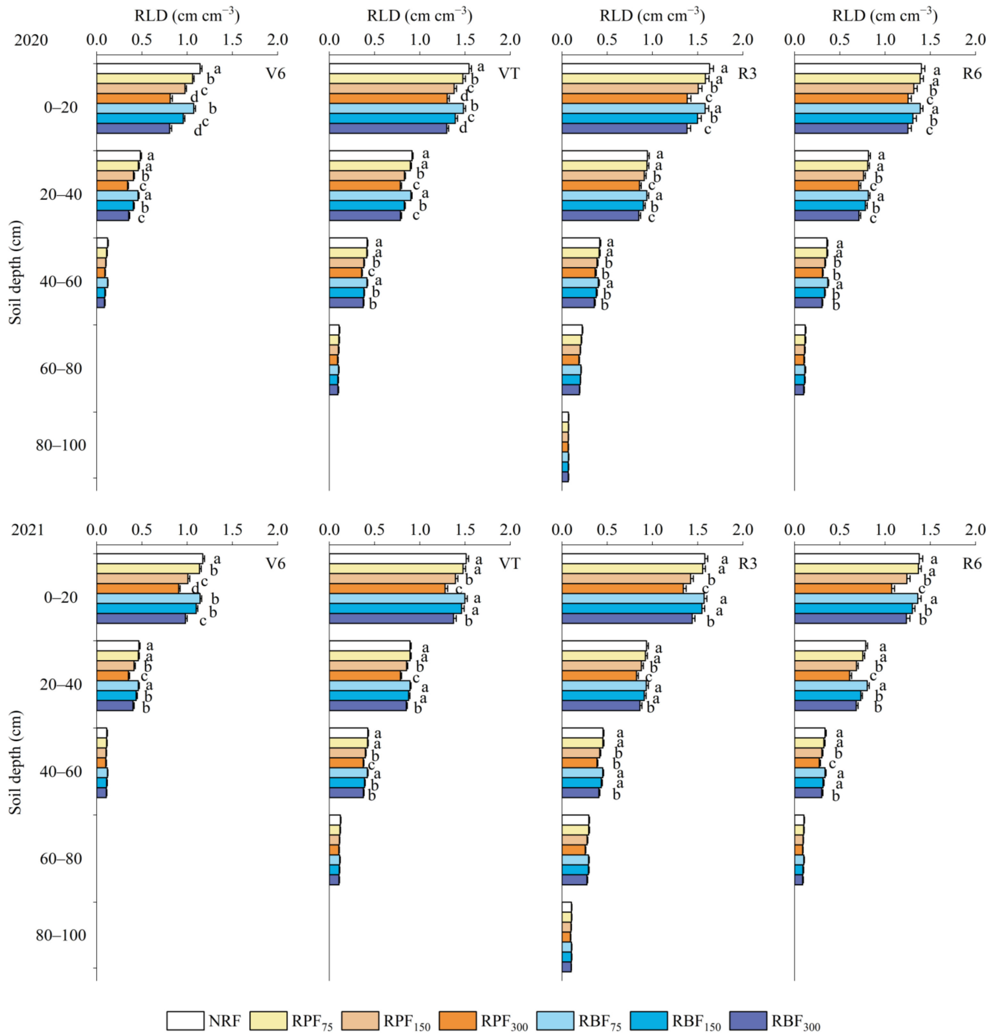

Figure 5. Root length density (RLD) in different soil layers in 2020 and 2021 spring maize growing seasons. Horizontal bars represent the standard error of the mean. Different lowercase letters indicate significant (p < 0.05) differences based on the LSD test.

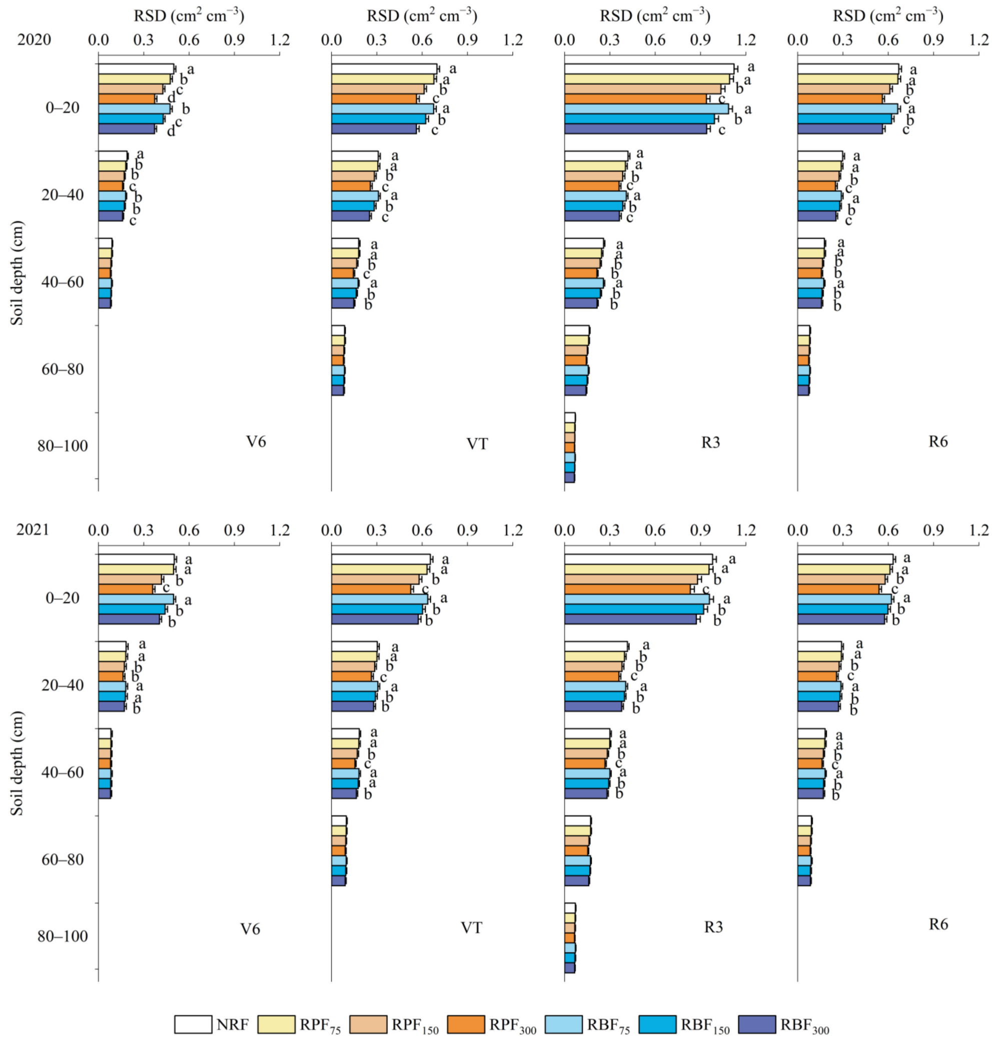

Figure 6. Root surface area density (RSD) in different soil layers in 2020 and 2021 spring maize growing seasons. Horizontal bars represent the standard error of the mean. Different lowercase letters indicate significant ($p < 0.05$) differences based on the LSD test.

3.4. Effect of Residual Film on Root–Shoot Synergy

During the two-year experiment, shoot biomass of maize gradually increased with the growing process. However, the increasing trend of root biomass peaked at R3 stage and then decreased. Both shoot biomass and root biomass decreased with increasing residual levels (Figure 7). Compared to NRF, shoot biomass and root biomass decreased by 3.85–24.32% and 3.12–15.90% under the residual film treatments in 2020, by 1.24–20.48% and 1.39–15.57% in 2021. Significant differences were observed in 2021 when comparing different types of residual film. Compared to RPF, the shoot biomass and root biomass of RBF increased by 0.90–10.26% and 0.71–6.22%. This indicated that the rapid degradation of the RBF mitigated the negative effects on maize growth. Interestingly, different organs of maize differed in the period of sensitivity to residual film, with the greatest difference in shoot biomass around the R3 stage and the greatest difference in root biomass at the V6 stage. Regression analysis showed that the shoot biomass was positively correlated with the root biomass under different treatments (Figure S1).

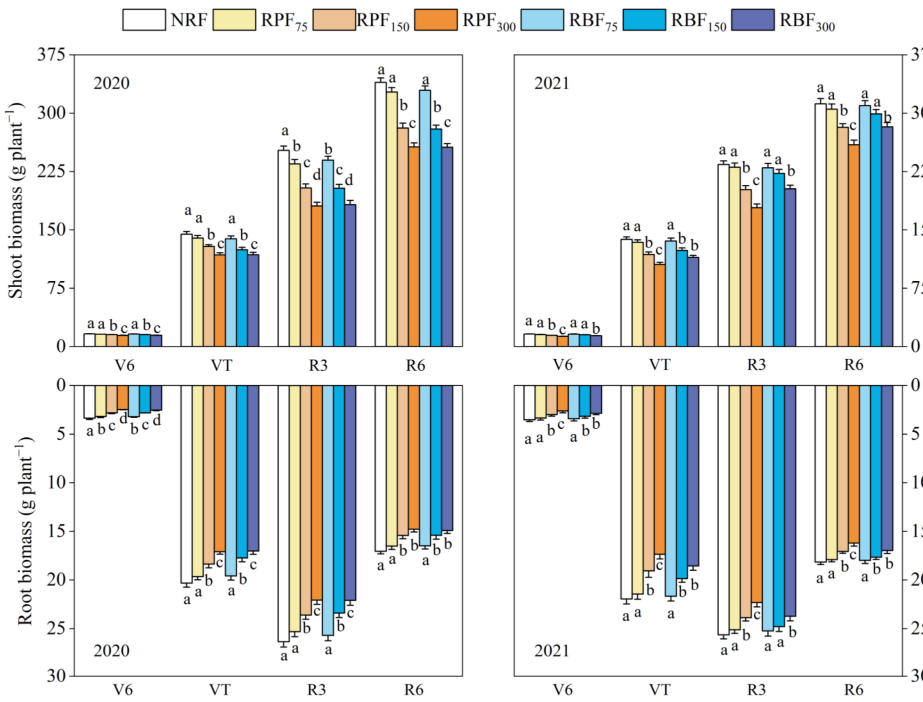

Figure 7. Dynamics of shoot and root biomass in response to the different treatments in 2020 and 2021 spring maize growing seasons. Vertical bars represent the standard error of the mean. The different lowercase letters are significantly different at $p < 0.05$.

Root–shoot ratio (RSR) reflects the correlation between the root and shoot of the crop. RSR reached the maximum value at the early growth stage and then gradually decreased with the growing process, reaching the minimum value at the R6 stage. The differences in RSR were mainly concentrated at the V6 and R3 stages, and there was no significant difference among all treatments during the VT stage (Figure 8). The presence of residual film reduced the RSR of maize at the V6 stage; however, at the R3 stage, RSR increased with increasing residual levels. Significant differences between different types of residual film under the same residual level appeared in 2021, with higher RSR in the RBF treatments than in the RPF treatments 0.61–3.13% at the V6 stage, and lower RSR in the RBF treatments than in the RPF treatments 5.92–6.40% at the R3 stage.

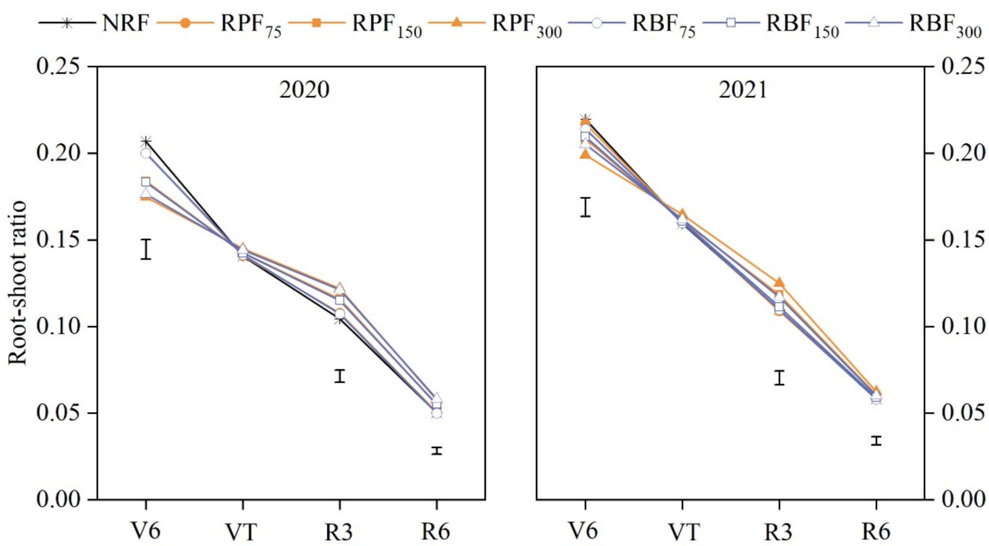

Figure 8. Effects of different treatments on spring maize root–shoot ratio in 2020 and 2021 growing seasons. Vertical bars stand for LSD at 0.05 levels.

3.5. Effect of Residual Film on Maize Productivity

The kernel number per ear and 100-grain weight of maize decreased with increasing residual level, resulting in lower grain yield (Table 1). Compared to the NRF, the kernel number per ear and 100-grain weight in 2020 decreased by 1.09–11.29% and 1.91–8.92% in the residual treatments, and the grain yield decreased by 3.61–18.92%. In 2021, the kernel number per ear and 100-grain weight in the residual treatments decreased by 0.34–8.30% and 1.66–9.27%, and the grain yield decreased by 2.98–16.81%. There was no significant difference between the NRF and low residual level treatments, indicating that residual amounts below 75 kg ha^{-1} were not sufficient to cause an obvious reduction in maize yield. Comparing the different types of residual film, there was no significant difference in grain yield and yield components at the same residual level in 2020. However, in 2021, the RBF treatments were 0.41–6.24% higher than the RPF treatments, especially under medium and high residual levels where the differences were significant.

Table 1. Differences of yield components, grain yield, evapotranspiration (ET), water use efficiency (WUE), precipitation, and precipitation use efficiency (PUE) under different treatments in 2020 and 2021.

Year	Treatments	Kernel Number Per Ear	100-Grain Weight (g)	Grain Yield (kg ha^{-1})	ET (mm)	WUE (kg ha^{-1} mm^{-1})	Precipitation (mm)	PUE (kg ha^{-1} mm^{-1})	Decrease in Yield (%)	Decrease in WUE (%)	Decrease in PUE (%)
2020	NRF	458 ± 10 a	31.4 ± 0.5 a	9707 ± 270 a	494.7 ± 8.8 a	19.62 ± 0.56 a	394.2	24.63 ± 0.68 a			
	RPF_{75}	448 ± 11 a	30.8 ± 0.3 a	9316 ± 320 a	490.7 ± 7.5 a	18.98 ± 0.50 a	394.2	23.63 ± 0.81 a	4.03	3.25	4.03
	RPF_{150}	425 ± 8 b	29.7 ± 0.5 b	8524 ± 303 b	483.2 ± 8.2 a	17.64 ± 0.43 b	394.2	21.62 ± 0.76 b	12.19	10.10	12.19
	RPF_{300}	408 ± 5 c	28.6 ± 0.6 b	7876 ± 243 c	478.9 ± 8.0 a	16.45 ± 0.52 c	394.2	19.98 ± 0.61 c	18.86	16.18	18.86
	RBF_{75}	453 ± 8 a	30.6 ± 0.4 a	9357 ± 289 a	492.1 ± 8.7 a	19.02 ± 0.56 a	394.2	23.74 ± 0.73 a	3.61	3.10	3.61
	RBF_{150}	427 ± 10 b	29.7 ± 0.5 b	8550 ± 258 b	485.7 ± 6.9 a	17.61 ± 0.58 b	394.2	21.69 ± 0.65 b	11.92	10.29	11.92
	RBF_{300}	406 ± 5 c	28.7 ± 0.5 b	7871 ± 241 c	480.0 ± 7.8 a	16.40 ± 0.48 c	394.2	19.97 ± 0.61 c	18.92	16.44	18.92
2021	NRF	440 ± 7 a	30.2 ± 0.4 a	8959 ± 359 a	417.2 ± 7.3 a	21.47 ± 0.48 a	295.2	30.35 ± 1.21 a			
	RPF_{75}	432 ± 7 a	29.7 ± 0.4 a	8657 ± 252 a	411.0 ± 7.3 a	21.06 ± 0.50 a	295.2	29.32 ± 0.85 a	3.38	1.91	3.38
	RPF_{150}	418 ± 6 b	28.3 ± 0.5 b	7985 ± 254 b	408.0 ± 6.8 a	19.57 ± 0.48 b	295.2	27.05 ± 0.86 b	10.88	8.86	10.88
	RPF_{300}	403 ± 6 c	27.4 ± 0.5 b	7453 ± 244 c	402.5 ± 7.1 a	18.52 ± 0.50 c	295.2	25.25 ± 0.82 c	16.81	13.76	16.81
	RBF_{75}	438 ± 5 a	29.4 ± 0.5 a	8692 ± 245 a	412.0 ± 7.6 a	21.10 ± 0.51 a	295.2	29.44 ± 0.83 a	2.98	1.75	2.98
	RBF_{150}	427 ± 7 ab	29.2 ± 0.6 a	8406 ± 198 a	409.4 ± 7.0 a	20.53 ± 0.53 a	295.2	28.48 ± 0.67 a	6.17	4.38	6.17
	RBF_{300}	416 ± 5 b	28.2 ± 0.4 b	7919 ± 207 b	403.2 ± 7.7 a	19.64 ± 0.56 b	295.2	26.82 ± 0.70 b	11.62	8.54	11.62

Mean values followed by the different lowercase letters indicate significant differences at $p < 0.05$ based on the LSD test. (NRF, no residual film; RPF_{75}, 75 kg ha^{-1} of residual plastic film (RPF); RPF_{150}, 150 kg ha^{-1} of RPF; RPF_{300}, 300 kg ha^{-1} of RPF; RBF_{75}, 75 kg ha^{-1} of residual biodegradable film (RBF); RBF_{150}, 150 kg ha^{-1} of RBF and RBF_{300}, 300 kg ha^{-1} of RBF.)

Evapotranspiration (ET) decreased with the increasing residual level in both growing seasons, but there was no significant difference in ET among all treatments. Residual levels had a significant effect on the water use efficiency (WUE) and precipitation use efficiency (PUE) of maize (Table 1). Compared with NRF, WUE and PUE decreased by 3.10–16.44% and 3.61–18.92% in 2020, and 1.75–13.76% and 2.98–16.81% in 2021 under residual treatments, respectively. Although there was no significant difference between NRF and low residual level treatments, the presence of residual film resulted in a reduction in WUE and PUE. In the same trend as that shown for grain yield, a significant difference between the different types of residual film at the same residual level was observed in 2021.

It is noteworthy that the higher the initial residual level, the greater the difference between the different residual films. Compared to RPF, RBF has 0.12–4.44% and 0.41–6.24% higher WUE and PUE. In addition, the WUE and PUE of all treatments were higher in 2021 than that in 2020, which may be due to 99.0 mm lower precipitation in 2021 than in 2020, resulting in significantly lower evapotranspiration in 2021, thus promoting water productivity.

4. Discussion

4.1. Effect of Residual Film on Soil Moisture

Previous studies have demonstrated the effect of residual film on soil hydraulic properties, where soil water migration pathways are blocked and soil water holding capacity decreases as residual film increases in the soil [33,34]. It has also been shown that soil water storage increases with the amount of residual film [9]. In this study, it was found that SWC in the soil layer of maize main root distribution decreased with increasing residual level, and the difference with NRF was significant at medium and high residual levels, indicating that 150 kg ha^{-1} may be the threshold value for the residual film to affect soil moisture conditions in dryland. The film mulching constituted an internal circulation of water from under the film to the soil, it changed the open movement of soil moisture without mulching, significantly reducing ineffective evaporation of water and ensuring SWC of the cultivated soil [35]. However, the soil physical properties that determine soil moisture movement and distribution are affected by the residual film, resulting in the formation of the moisture barrier in the topsoil layer (0–20 cm) [25]. The presence of the moisture barrier hinders vertical infiltration and lateral diffusion of rainfall, resulting in uneven soil moisture distribution, and water being easily lost by evaporation through no mulching areas. The excellent dry–wet alternation created by mulching is disrupted and the positive benefits of mulching are offset by the residual film. In this study, the degradation rate of RBF was significantly higher than that of RPF, and its spatio-temporal distribution of SWC was closer to that of the NRF, which would favor the water supply of maize roots under the RBF treatments. This is consistent with the results of Koskei et al. (2021)'s study. Better soil moisture dynamics also contributed to soil nutrient cycling and microbial metabolism under the RBF treatments [22,36]. In addition, precipitation is closely related to SWC in dryland agriculture, which will determine the growth and development of crops [37]. Film residues significantly amplified the stress caused by the lack of rainfall during the 2021 R3 stage, while the RBF treatments effectively mitigated this negative effect and secured water productivity.

4.2. Effect of Residual Film on Maize Root Morphology

Root morphology is critical for crop water and nutrient uptake, which will directly affect the growth of aboveground parts and grain yield [11,38]. Previous studies found that root characteristic parameters were significantly lower in wheat and cotton under residual film treatment compared to no residual film [17,24]. However, it has also been shown that residual film can stimulate root growth in cotton [39]. In this study, we found that residual film obviously hindered the root growth of maize, and the root biomass of maize significantly decreased under medium and high residual level treatments compared to NRF. The reason for the different findings may be due to the different experimental conditions; our experiment was conducted in non-irrigation conditions, while Li et al. (2008)'s study was conducted under film drip irrigation conditions. The SWC of the residual film layer (0–40 cm) was higher than that of the deeper soil, and root growth tended to be in the water-rich zone, resulting in the cotton root area, RLD, and root dry weight in the 0–40 cm layer increasing with the residual level.

RLD and RSD are root characteristic parameters that provide a good indication of crop utilization of soil resources [28]. In this study, we found that the presence of residual films significantly reduced the RLD and RSD of maize in the 0–40 cm soil layer, especially when the residual level exceeded 150 kg ha^{-1}. The RLD and RSD of RBF treatments were significantly higher than those of RPF treatments. This may be related to the difference in water availability in the soil under different types of residual films [40]. As a fibrous root system crop, the root distribution of maize is concentrated in the shallow soil layer. The shallow soil environment under RBF treatments is significantly better than that of RPF treatments, and maize has better root morphology to ensure water and fertilizer uptake and utilization. In the early growth stage, the presence of residual film creates entanglement and pulling on root growth, while the RBF degrades faster and effectively avoids mechanical hindrance to the maize root. In the middle and late stages, even if the root has increased its undergrowth, the uneven distribution of soil moisture due to changes in soil physical structure caused by residual film significantly inhibits the elongation activity of the maize root. The deteriorated soil hydrothermal environment hinders soil nutrient cycling and microbial activity [10], resulting in the inefficient use of maize resources. Meanwhile, the decrease in root characteristic parameters will reduce the ability of maize to withstand extreme weather, while the RBF treatments have better root morphology and are more risk resistant than the RPF treatments.

4.3. Effect of Residual Film on Maize Productivity

The shoot growth of the crop is closely related to root growth. The root system supplies the shoot growth by absorbing water and nutrients from the soil, and in turn, the assimilates produced by photosynthesis in the shoot provide a boost to the root activities [41]. In rainfed drylands with limited water resources, the presence of residual film will be detrimental to this positive feedback process. The assimilate partitioning ratio between the root and the shoot has a key influence on the final grain yield. In late maize growth, a smaller RSR means that the assimilate allocation favors the aboveground, which is more conducive to shoot biomass accumulation and grain yield [42]. Previous studies showed that residual film significantly reduced maize RSR [5]. In the present study, residual film hindered the accumulation of maize biomass, but the root showed a stronger adaptation ability to adversity compared to the shoot. The residual film changes the moisture status of the topsoil, the root needs more assimilates and energy to obtain water and nutrients, and the shoot receives correspondingly fewer resources, leading to an increase in RSR. The RSR was smaller in the RBF treatments compared to the RPF treatments in the reproductive growth stage, indicating that the assimilate allocation strategy of maize under the RBF treatments was more favorable to the shoot and more conducive to the efficient use of resources by maize compared to the RPF treatments. In the two-year experiment, RBF was gradually degraded and its negative effect on maize root development was significantly diminished, and good root growth conditions contributed to root–shoot synergy.

Grain yield is the economic portion of the crop used for human and animal consumption and it reflects soil productivity [11,38]. Related studies have shown that as residual film increases, the number of harvested plants, boll number per plant, and single boll quality decrease, resulting in a lower economic yield of cotton [43,44]. Similar results were obtained in this study, with the increasing residual level, blocking soil pore continuity, reducing SWC, and inhibiting root respiration and water uptake behavior. This resulted in weaker maize assimilation and reduced biomass accumulation. When the residual level exceeded 150 kg ha^{-1}, the kernel number per ear and 100-grain weight of maize were significantly reduced, and the grain yield was significantly lower. Improving WUE is a key objective for sustainable agroecosystems [45]. In rainfed dryland, precipitation plays an important role in crop water requirements [46]. However, film residues reduce crop WUE (Mo [47] et al., 2017; Zhang et al., 2022b). In this study, the WUE and PUE of maize decreased as the residual level increased. It comes down to that the residual film reduced the rate of rainfall infiltration into the soil and increased the inefficient evaporation of soil moisture [34]. The residual biodegradable film (RBF) has a much lower impact on the soil environment due to its ability to degrade effectively. [36]. In our study, RBF treatments significantly increased the WUE and PUE of maize compared to the RPF treatments, indicating that RBF treatments can effectively utilize precipitation resources. After the two-year experiment, RBF was heavily degraded, with little soil environmental stress, good soil moisture status and effective use of precipitation for maize growth. In contrast, RPF was almost not degraded and a large amount of water was ineffectively dissipated, resulting in lower WUE and PUE.

In our experiments, 4 cm^2 (2 cm × 2 cm) of residual film was buried in the topsoil, but later in the experiment, we found that the residual film degraded into smaller sizes. Therefore, the effects of microplastics (plastic debris and particles < 5 mm in diameter) on agroecosystems need further exploration. In addition, only BF made of polylactic acid (PLA) was used as the material in this experiment. However, different materials of BF have different degradation efficiency, production, and use costs. Future environmental risk experiments can be conducted on different types of BF (i.e., petroleum-based biodegradable plastics and biological-based biodegradable plastics) to find the best solution for application. Although BF can mitigate the negative effects of film residues on soil moisture and maize productivity, it requires a process to degrade and the RBF produced in the short term is also detrimental to maize production. The ecological impact of the BF degradation process is also yet to be investigated [48]. Therefore, we suggest that in addition to the use of BF in agricultural production, film recycling programs should be optimized to ensure sustainable development [49]. Meanwhile, it is also imperative to strengthen awareness of green production.

5. Conclusions

In this two-year study, the SWC, maize root morphological parameters, and grain yield showed a significant downward trend with the increasing residual film amount, especially when the residual level exceeded the threshold of 150 kg ha^{-1}. Compared with RPF, the two-year degradation rate of RBF was higher and the impact on soil moisture, RLD, and RSD was lower. The RBF treatments had more plant biomass accumulation, and their root–shoot ratio was closer to the NRF, thus guaranteeing the grain yield, WUE, and PUE. Different organs of maize differed in their sensitivity and sensitivity period to residual film. Root and shoot were more sensitive at the V6 and R3 stages, respectively, and root also showed greater adaptation to residual film.

Based on the results of this study, BF is an effective substitute for PF in the short term. In the long run, the effective recycling of plastic film and awareness of cleaner production are still very necessary.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture13020332/s1, Figure S1: The relationship between root biomass and shoot biomass of spring maize under different treatments. The data of the 2021 growing seasons were included in the analysis, and data for generating regression models were the treatment means (n = 3).

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