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Response of dry matter translocation and grain yield of summer maize to biodegradable film in the North China Plain**

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A b s t r a c t. In the North China Plain, it is a matter of urgency to explore the feasibility of using biodegradable film to replace polyethylene film. A field experiment was conducted by covering soils with polyethylene white film, biodegradable white film, biodegradable black film, while the control remained uncovered. This study analysed the effects of using different film types on summer maize dry matter accumulation and transfer, grain yield and yield components during the 2016 and 2017 summer maize growing seasons. Results showed that, for both growing seasons, compared with non-mulching, dry matter translocation, dry matter transfer efficiency of vegetative organs and grain yield for plants following polyethylene white film and biodegradable white film treatments were always lower. However, dry matter accumulation, dry matter translocation, dry matter transfer efficiency, grain yield, and the contribution of dry matter translocation to grain yield before flowering in biodegradable black film treatments significantly increased by 21.0, 33.3, 21.4, 12.6, and 18.5%, respectively. Only the black biodegradable film could increase grain yield as determined by the 1000 kernel mass. Results indicate that black biodegradable films are a viable alternative to polyethylene film in summer maize production in the North China Plain.

K e y w o r d s: polyethylene film, leaf area index, dry matter transfer, yield components, North China Plain

INTRODUCTION

In recent years, the North China Plain has experienced a rare drought, which led to a sharp decline in water resources and a reduction in grain yield. By 2030, drought will reduce food production by 4.1 to 8.6% in eastern China (Xin *et al.*, 2013). In order to increase grain yield to meet the future demand for grain amid fierce competition for limited resources, improving the utilization of precipitation is one of the most effective measures (Gan *et al.*, 2013). A suitable soil moisture and temperature is conducive to the development and growth of crops (Yin *et al.*, 2016), therefore optimizing soil temperature and improving soil moisture content is an effective way to improve grain yield (Yin *et al.*, 2017). Plastic mulching techniques are widely used as a water saving practice in the North China Plain, the techniques can be used to improve both the physical and chemical properties of the soil, reduce evaporative soil water losses (Li *et al.*, 2013; Feng *et al.*, 2014), increase surface soil water storage (Wang *et al.*, 2015), thereby improving crop yields. Therefore, Zhang *et al.* (2017) believe that plastic film mulching is an effective method that can be used to adapt to climate change in the future.

However, due to high summer temperatures, plastic mulch makes plants vulnerable to thermal stress and reduces crop yields (Zhao *et al.*, 2014), some measures may be taken to avoid this situation, such as the use of black plastic film (Liu *et al.*, 2016). Black film has a low light transmittance and thermal radiation. It can absorb solar radiation and increase its temperature quickly, but a lower quantity of heat is transferred to the soil, so that the soil temperature near the ground remains at a suitable temperature conducive to the growth of crops in summer. Studies have shown that black mulch treatment can be used to promote maize biomass accumulation (Ding *et al.*, 2018) and increase grain yield (Zhang *et al.*, 2016).

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Plastic mulching technology has brought about great benefits while, at the same time, producing serious pollution. Large amounts of residual plastic films adversely affect soil and crop growth, thus reducing crop grain yield (Liu *et al.*, 2014). China is the largest producer and user of agricultural plastic film of any country. At present, these films cover an area of over 20 million ha, and the actual consumption of film is about 450 000 t per year, ranking first in the world. A large amount of residual mulch can lead to the unsustainable use of farmland, thus adversely affecting the agricultural environment (Jiang *et al.*, 2017). In this situation, degradable film is considered to be a viable option rather than plastic film. Yin *et al.* (2017) found that biodegradable mulch increased maize grain yield in high-altitude and low-temperature regions. In the semi-arid regions of China, biodegradable mulch can increase maize grain yield by an average of 14.5% (Sun *et al.*, 2011). These results show that the benefits of applying biodegradable mulch may be influenced by regional or climatic conditions and the outcomes are different for different regions. However, the impact of using biodegradable plastic mulch on the North China Plain is as yet unclear.

Summer maize is an important food crop in the North China Plain, and the current continuous arid weather has caused a decline in summer maize production. Despite this fact, it remains one of the core areas with potential for increasing national agricultural production in the future (Cao *et al.*, 2012). The results achieved thus far indicate that the effect of using biodegradable plastic mulch on summer maize yields has not been optimal. However, this technology has not been widely used in actual production. Therefore, in order to reduce the impact of drought on grain reserves in the North China Plain and mitigate the adverse impact of "white pollution" on the agricultural environment, it is necessary to study the effect of degradable film on the summer maize yield. The economic crop yield is basically influenced by the balance of assimilate allocation between the vegetative and reproductive organs (Retasánchez and Fowler, 2002). Most studies have consistently shown that crop yield is determined by biomass accumulation and the proportion of the biomass partitioned to reproductive organs (Saleem *et al.*, 2010). Therefore, dry matter accumulation and translocation is the basis of crop yield. According to the analysis mentioned above, we hypothesized that biodegradable black mulch could improve the translocation and transfer efficiency of the dry matter of summer maize and increase the yield in the North China Plain. In this experiment, different plastic films were selected in order to study the effects of plastic films on dry matter translocation and summer maize yield. These experiments were designed to explore whether biodegradable black mulch can increase the accumulation and transfer of dry matter of summer maize and increase yields in the North China Plain.

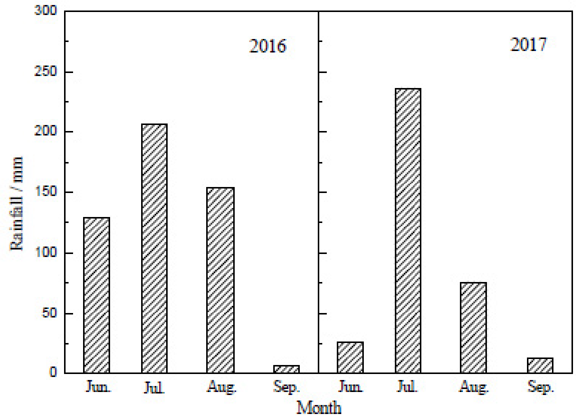

Fig. 1. Rainfall in the 2016 and 2017 summer maize growing seasons. Rainfall in June was the mean monthly rainfall from the sowing day to the end of the month; Rainfall in September was the mean monthly rainfall from the 1st of the month until harvest day.

MATERIALS AND METHODS

In the 2016 and 2017 summer maize growing seasons, this study was conducted at an Experimental Station of Shandong Agricultural University (36°10′19″N, 117°09′ 03″E), which lies in the North China Plain. The region has a temperate continental monsoon climate, the mean annual temperature is 12.9ºC and the mean annual rainfall is 697 mm, mainly concentrated from June to September, which is during the summer maize growing season. Each experimental plot was 3.0 m × 3.0 m × 1.5 m (length × width × depth) in size with concrete slabs placed around the plots to prevent lateral soil water flow. In each experimental plot, the soil was classified as loamy clay, the contents of alkali hydrolysable nitrogen, available potassium, and available phosphorus in 0-20 cm soil profile were 108.1, 92.4, 161.1 mg kg^{-1}, respectively. The pH value of the soil was approximately 6.9, and the organic matter content was 1.4% in weight. In the 2016 and 2017 summer maize growing seasons, rainfall was 494.3 and 350.3 mm, respectively (Fig. 1).

In this study, a single factor randomized block experiment design was adopted. The experiment consisted of four treatments: non-mulching (CK), mulching white polyethylene film (M1), mulching white biodegradable plastic film (M2), and mulching black biodegradable plastic film (M3). The polyethylene film was produced by Shandong Sansu Group Limited Corporation (Ji'nan, Shandong province, China), the white and black degradable films were produced by Shandong Agricultural University (Tai'an, Shandong province, China). The thickness of all the films was 6 μm. The biodegradable mulching films were all made from Poly (butylene adipate-co-terephtalate) (PBAT) and Poly (lactic acid) (PLA), with the exception of the black biodegradable plastic film (M3) which had a small amount of carbon black. The data of the tensile and optical properties are listed in Table 1. The film was mulched on beds in the experimental plots. The height and width of the

Table 1. Data of tensile and optical properties of film for different treatments

Treatments	Optical (%)	Tensile strengh (MPa)	Elongation at break (%)
M1	89	23	460
M2	91	30	600
M3	31	35	580

beds were 15 and 40 cm, the distances between the two beds were 20 cm. Each treatment was repeated three times and there were a total of twelve experimental plots (Four treatments × Repeated three times) in this study. In both growing seasons, summer maize was planted on June 13 and harvested on October 1. Before planting, 2.5 g m^{-2} of urea, 22.5 g m^{-2} of diammonium phosphate, and 16.9 g m^{-2} of potassium chloride was applied as a base fertilizer, then 0.5 m^3 water was applied on every plot. The summer maize variety used for the experiment was 'Zhengdan 958', which is widely planted in the North China Plain. In this experiment, the summer maize was sown artificially. Row spacing and plant distance was 60.0 and 21.0 cm, respectively. The different films were covered artificially after sowing.

For each plot, samples of three plants were selected randomly at the flowering, milking, and maturity stages. A sickle was used to cut them from the base. In the laboratory, samples were divided into vegetative organs (including leaves, stems, leaf sheaths, cobs, and bracts) and ears, and their mass noted after first exposing the samples to 105°C for 0.5 h and thereafter to 85°C until constant mass was achieved. After obtaining the dry matter (DM) accumulation data at the flowering and maturity stages, various parameters related to dry matter measurements were calculated using the following formula (Liu *et al.*, 2016):

$$DMR = DMA - DMA^*, \quad (1)$$

where: *DMR* is the *DM* translocation of the vegetative organ (g m^{-2}); DMA is the *DM* accumulation of the vegetative organs at the flowering stage (g m^{-2}); *DMA** is the *DM* accumulation of vegetative organs at the maturity stage (g m^{-2}); Respiration and root *DM* translocation were not taken into account in Eq. (1):

$$DMA^1 = DMA^2 - DMA^3, \quad (2)$$

where: DMA^1 is the accumulation of *DM* after the flowering stage (g m^{-2}); DMA^2 is the *DM* accumulation at the maturity stage (g m^{-2}); DMA^3 is the *DM* accumulation at the flowering stage (g m^{-2}):

$$DMRE = (DMR/DMA)\ 100\%, \quad (3)$$

where: *DMRE* is the *DM* transfer efficiency of vegetative organs (%).

$$CDMRG = (DMR/GY)\ 100\%, \quad (4)$$

where: *CDMRG* – contribution of post-flowering *DM* translocation to grain yield (%); *GY* – grain yield (g m^{-2}).

When measuring summer maize *DM* accumulation, the leaf area index (LAI) was measured and calculated before transferring the leaves into the envelopes. The LAI was calculated using the following formula:

$$LAI = [\ L\ B\ 0.75\ N^1 \times N^2] \div S, \quad (5)$$

where: *L* is the length of the leaf (cm); *B* is the maximum width of the leaf (cm); 0.75 is the conversion coefficient; N^1 is the number of single leaves and N^2 is the number of plants per unit area; *S* is the area of land (m^2).

Before harvesting, the number of ears in each plot was recorded and the number of ears per m^2 was calculated. At the maturity stage, two central lines in each plot were harvested by hand, to determine the number of ears per row, kernels number per row, 1000-kernel mass, and air-dried mass.

The experimental results were presented in the form of means and standard deviations. Data processing and statistical analyses were conducted using Microsoft Excel 2013 (Data processing, Microsoft, Redmond, Washington, USA), Origin 8.5.1 (Mapping software, OriginLab Corporation, Northampton, Massachusetts, USA) and IBM SPSS Statistics 19 (Statistical analysis, International Business Machines Corporation, Armonk, New York, USA). Multiple comparisons were made using the least significant difference test at alpha = 0.05.

RESULTS

In the 2016 summer maize growing season, at the flowering stage, LAI under M1 and M2 treatment was lower by 9.5 and 3.1%, and the same parameter under M3 treatment was decreased by 18.5% when compared to the CK treatment (Fig. 2); At the milking stage, LAI under M1, M2, and M3 treatment was lower by 28.0, 20.5 and 1.1% respectively compared to that of the CK treatment. At the maturity stage, LAI under M1 and M2 treatment was lower by 11.9 and 5.0%, and the same parameter under M3 treatment was higher by 13.8% than that under CK treatment. In the 2017 growing season, at the flowering stage, LAI under the M1, M2, and M3 treatment was lower by 12.1, 19.6, and 10.6% respectively than that under CK treatment. At the milking stage, the M1 and M2 treatment decreased LAI by 6.1% in both cases, while the M3 treatment resulted in an increase by 7.5% compared to the CK treatment. At the maturity stage, compared with the CK treatment, LAI under M2 treatment decreased by 6.0%, and the same parameter under M1 and M3 treatment was higher by 10.8 and 5.1%, respectively.

At the flowering, milking, and maturity stages in 2016, compared with the CK treatment, dry matter accumulation in the M1 treatment was reduced by 25.7, 2.5, and 6.3%, in the M2 treatment it was reduced by 28.0, 4.4, and 7.2%, respectively; however, dry matter accumulation under

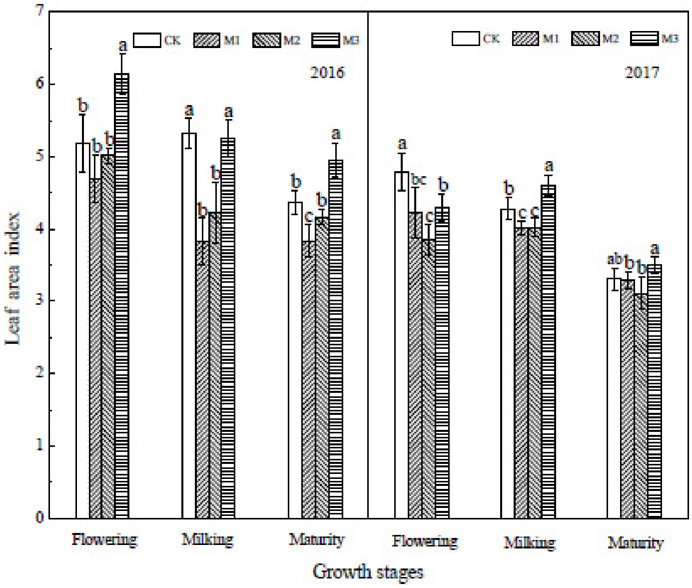

Fig. 2. LAI of summer maize at the flowering, milking, and maturity stages in the 2016 and 2017 growing seasons. Bars are ± standard errors of means (n = 3). Other explanations as in Table 2.

Table 2. Summer maize dry matter translocation in the 2016 and 2017 growing seasons

Year	Treatment	DMA[1]	DMA[2]	DMA[3]	DMR	DMRE	CDMRG
		(g m^{-2})				(%)	
2016	CK	954.8d	2290.3b	1335.4a	217.8b	20.3ab	18.0b
	M1	1025.8c	2083.4c	1057.6b	183.6c	18.8b	18.9b
	M2	1164.8b	2126.4c	961.6 b	187.6c	20.0ab	17.1b
	M3	1731.9a	3167.7a	1435.8a	296.8a	23.3a	21.4a
2017	CK	944.4b	2456.1b	1511.7a	129.7b	11.9b	10.1b
	M1	1160.3a	2464.8b	1304.5a	84.7 d	7.7 c	7.4d
	M2	1075.5a	2217.6c	1142.1b	109.7c	11.9b	9.1c
	M3	1140.3a	2546.0a	1405.7a	169.0a	15.3a	11.9a

DMA is the dry matter accumulation: [1]after the flowering stage (g m^{-2}), [2]at the maturity stage (g m^{-2}), [3]at the flowering stage (g m^{-2}). DMR is the dry matter translocation in the vegetative organ (g m^{-2}). DMRE is the dry matter transfer efficiency of vegetative organs (%). CDMRG is the contribution of dry matter translocation to grain yield before flowering (%). CK represents non-mulching, M represents mulching using: 1 – polyethylene film, 2 – white biodegradable film, and 3 – black biodegradable film. In each growing season, different letters indicate significant differences between means ($p < 0.05$).

the M3 treatment was enhanced by 6.0, 28.4, and 38.3%, respectively (Fig. 3). In the 2017 growing season, at the flowering stage, dry matter accumulation under the M1, M2, and M3 treatment was lower than in the CK treatment by 9.0, 24.5, and 7.0%, respectively. At the milking and maturity stages, compared with the CK treatment, the M1 and M2 treatment didn't promote summer maize dry matter accumulation, however, dry matter accumulation in the M3 treatment was increased by 2.0 and 3.7%, respectively.

Summer maize dry matter translocation in the 2016 and 2017 growing seasons are presented in Table 2. In the 2016 summer maize growing season, DMR was significantly lower for M1 and M2 than for CK by 15.7 and 13.9%; however, for M3 the same parameter was significantly increased by 36.3%. As for DMRE, no significant difference was found between M1, M2, and CK, while it was significantly increased for the M3 treatment. CDMRG was significantly higher in M3 than in CK by 18.6%. In the 2017 growing season, DMR was significantly lower in M1 and M2 than in CK by 34.7 and 15.4%, while for M3 this parameter was significantly increased by 30.3%. Under M1 treatment, DMRE was significantly reduced by 35.3% compared with CK, while under M3 treatment, this parameter increased significantly by 29.0% compared with CK.

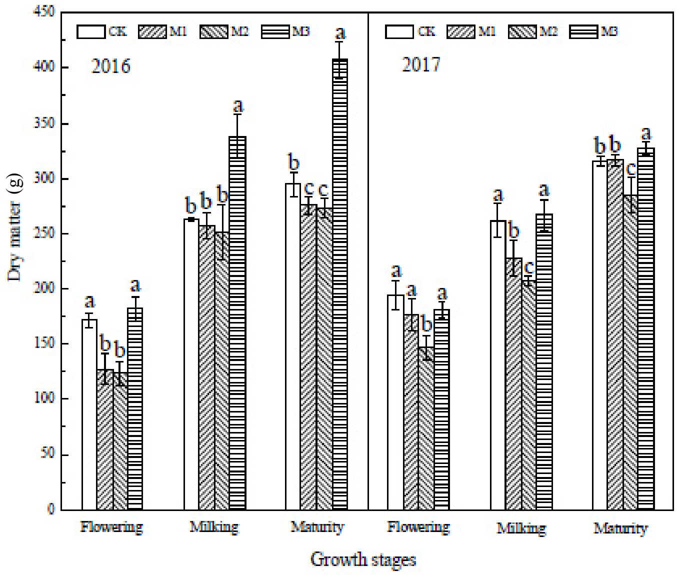

Fig. 3. Dry matter accumulation of summer maize at the flowering, milking, and maturity stages in the 2016 and 2017 growing seasons. Bars are ± standard errors of means (n = 3). Other explanations as in Table 2.

Table 3. Grain yield and yield compositions in the 2016 and 2017 summer maize growing seasons

Treatments	Ears number (ears m^{-2})	Rows number per ear (rows/ear)	Kernels number per row (kernels/row)	1000-kernel mass (g)	Grain yield (g m^{-2})
			2016		
CK	7.1b	15.1a	35.2a	338.7b	1210.2b
M1	7.3ab	14.3a	36.0a	305.8c	971.3 d
M2	7.7a	14.8a	36.4a	310.0c	1095.7c
M3	7.7a	14.9a	36.7a	368.7a	1389.9a
			2017		
CK	7.5a	15.7a	34.6ab	339.3b	1287.4b
M1	7.2a	15.3a	32.2b	303.7d	1142.5d
M2	7.4a	14.9a	32.1b	330.4c	1202.2c
M3	7.3a	15.3a	35.9a	347.9a	1418.4a

Explanations as in Table 2.

CDMRG was significantly lower in M1 and M2 compared with CK, by 26.5 and 9.4% respectively, while it was 18.3% higher in M3 compared to CK, a significant increase.

Grain yield and compositions in the 2016 and 2017 summer maize growing seasons are presented in Table 3. In both growing seasons, the highest grain yield was found in M3, which was significantly higher than in CK; however, grain yield was significantly lower in M1 and M2 than in CK. In both growing seasons, the highest 1000-kernel mass was found in M3, followed by CK and M2, and the lowest was found in M1. In the 2016 summer maize growing season, the number of ears was 8.5% higher in M3 than in CK (a significant increase). However, the different treatments did not have a significant effect on the number of ears per row and kernel number per row. In the 2017 growing season, the kernel number per row was significantly higher in M3 than in M1 and M2; however, different treatments had no significant effect on the number of ears and the number of ears per row. Therefore, for both growing seasons, the differences in grain yield were mainly determined by the 1000-kernel mass.

DISCUSSION

Film mulching can improve the stomatal behaviour and heat absorption of maize (Gong *et al.*, 2015); thereby increasing the summer maize grain yield (Liu *et al.*, 2017). Related studies showed that with mulching, the maize grain yield was increased by 44-83% (Luo *et al.*, 2015). However, the present study showed that only M3 improved the summer maize grain yield significantly, whereas both M1 and M2 reduced the summer maize grain yield. However, the grain yield of M2 was greater than that of the M1 treatment. Abebe *et al.* (2016) and Ren *et al.* (2017) indicated that excessive soil temperatures have a negative effect on crop grain yield. Mulch technology can change the soil temperature, and the soil temperature produced by polyethylene film mulching is always higher than that in biodegradable mulch, because biodegradable mulch permits an increase in gas exchange with the open air as a result of their higher permeability (Moreno and Moreno, 2008). Soil temperature in white mulch is higher than that in black mulch (Li *et al.*, 2013). A high temperature accelerates the development of maize, thus shortening the nutrition and reproduction stage and affecting the growth and development of the maize (Lizaso *et al.*, 2018). Higher soil temperatures also enhance soil respiration (Liu *et al.*, 2013). This is equivalent to increasing the respiration rate of the root system, which is not conducive to the accumulation of organic matter, this may be the reason why grain yield was lower for M1 and M2 than it was for CK. Also, grain yield reduction in M1 and M2 may be due to a combination of higher soil temperatures and increased soil moisture content (Liu *et al.*, 2016). However, all of these theories require further study.

Dry matter accumulation and distribution is a necessary condition for high grain yield, and the dry matter accumulation and distribution of crop nutrients and reproductive organs can affect the resource utilization of the crop (Echarte and Andrade, 2003). Grain yield was positively correlated with the total biomass accumulation of the crops (Dai *et al.*, 2015). In this study, dry matter accumulation and grain yield under M3 treatment was greater than that under M2 treatment, but these parameters under M2 treatment were lower than those under CK treatment at maturity. Dry matter production is always positively correlated with light interception (Zhang *et al.*, 2016). In the growing canopy, leaf traits, such as LAI are important factors associated with the ability of leaves to collect light and photosynthesize (Yang *et al.*, 2017). Different plastic mulching techniques also had an effect on summer maize LAI, and both LAI and grain yield had the same trend in 2016. M3 had a higher LAI, which increased the ability of the leaves to collect light and photosynthesize and also increased the accumulation of organic matter, thus increasing the grain yield. DMR and DMRE were highest under the M3 treatment, and these parameters under M1 and M2 were lower than those under CK. The shortening of the vegetative and reproductive stages greatly reduced the amount of dry matter transfer and transfer efficiency in summer maize. Assimilation can recombine nutrients to form organic matter and store energy at post-anthesis (Álvaro *et al.*, 2008). DMR and DMRE can reflect the amount of organic matter formed by post-anthesis assimilation. During the growth and development of summer maize, post-anthesis assimilation is a very important process, it can enhance and stabilize crop yield (Feng *et al.*, 2017). The data presented herein shows that DMR and DMRE had the same effect on grain yield. This result showed that the augmentation of DMR and DMRE could increase the yield of summer maize. This experiment indicates that dry matter transfer could better be a better indicator of summer maize grain yield.

CONCLUSIONS

1. Although the summer maize yield of mulching white film decreased, the yield of mulching white biodegradable film was higher than that of mulching white polyethylene film in the North China Plain.

2. The summer maize yield of mulching black biodegradable film was higher than that of mulching white biodegradable film and non-mulching treatment in the North China Plain.

3. In the North China Plain, black biodegradable film improved dry matter accumulation and translocation in summer maize; therefore, the summer maize grain yield was significantly enhanced.

4. Mulching using black biodegradable film can increase the summer maize yield without damaging the ecological environment, and it could be used as a feasible measure for the sustainable development of agriculture in the North China Plain.

Conflict of interest: The Authors declare that they have no conflict of interest.

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