Asymmetric Ridge–Furrow and Film Cover Improves Plant Morphological Traits and Light Utilization in Rain-Fed Maize

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ABSTRACT

Light is one of the most important natural resources for plant growth. Light interception (LI) and use efficiency (LUE) are often affected by the structure of canopy caused by growing pattern and agronomy managements. Agronomy practices, such as the ridge–furrow system and plastic film cover, might affect the leaf morphology and then light transmission within the canopy, thus change light extinction coefficient (k), and LI and LUE. The objective of this study is to quantify LI and LUE in rain-fed maize (*Zea Mays* L.), a major cropping system in Northeast China, under different combinations of ridge–furrow and film covering ratios. The tested ridge–furrow system (DRF: "double ridges and furrows") was asymmetric and alternated with wide ridge (0.70 m in width and 0.15 m in height), narrow furrow (0.10 m), narrow ridge (0.40 m in width and 0.20 m in height), and narrow furrow (0.10 m). Field experiments were conducted in 2013 and 2014 in Jilin Province, Northeast China. Four treatments were tested: no ridges and plastic film cover (control, NRF), ridges without film cover (DRF_0), ridges with 58% film cover (DRF_{58}), and ridges with 100% film cover (DRF_{100}). DRF_0 significantly increased LI by 9% compared with NRF, while film cover showed a marginal improvement. Specific leaf area in DRF experiments with film cover was significantly lower than in NRF, and leaf angle was 16% higher than in NRF, resulting in a 4% reduction in k. LUE of maize was not increased by DRF_0, but was significantly enhanced by covering film in other DRF experiments, especially by 22% in DRF_{100}. The increase of LUE by film cover was due to a greater biomass production and a lower assimilation portioning to vegetative organs, which caused a higher harvest index. The results could help farmers to optimize maize managements, especially in the region with decreased solar radiation under climate change.

Key words: light interception, light use efficiency, film mulching, plant morphology, ridge and furrow cultivation

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1. Introduction

Maize (*Zea Mays* L.) is a major crop in Northeast China under rain-fed condition. Maize yield in this area is 13% higher than the national average (National statistics yearbook, 1980–2008). However, the yield gap is still large (Liu et al., 2012). The major limiting factors on maize growth and grain yield in Northeast China are frequent droughts in summer and low temperatures in spring. Applying ridge–furrow and plastic film cover has

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been a dominant strategy to alleviate the negative impact of climate variability (Liu Y. et al., 2010; Liu et al., 2014) and increase crop yield (Dong et al., 2017) in dry land agriculture (Zhou et al., 2009; Qin et al., 2014).

The ridge–furrow system combined with film cover is developed and used in North China recently, where the total precipitation and heat resource are not sufficient for growing high yield crops such as maize (Zhou et al., 2009; Eldoma et al., 2016) and potato (Hu et al., 2014). This system increases crop yield by collecting water (Gosar et al., 2010; Wang X. K. et al., 2015) and increasing topsoil temperature (Zhou et al., 2009; Li et al., 2013). Maize in Northeast China often suffers drought (Zhang et al., 2016; Cai et al., 2017) and chilling injury (Li et al., 2012; Fan et al., 2013), especially under extremes of climate change (Piao et al., 2010; Chen et al., 2012). The asymmetric ridge–furrow system, alternating with a wide ridge and a narrow furrow (Eldoma et al., 2016), or a narrow ridge and a narrow furrow, and often covered with plastic film on wide ridges, is helpful practice to offset the negative effects of climate change and further shrink the crop yield gap in Northeast China (Dong et al., 2017).

In a previous study (Dong et al., 2017), we found that maize yield could be increased by 33% in an asymmetric ridge–furrow system with full film cover. The effects of ridge and film on maize growth parameters were significantly different between years. When the water supply was sufficient, the positive effect of film cover and ridge was reduced on rain-fed condition crops in Northeast China. The ridge-furrow with film cover improves soil moisture and temperature (Zhou et al., 2009; Zhao et al., 2012) and therefore increases crop yield. However, we have limited data to answer the questions such as whether this asymmetric ridge–furrow and film cover system could also improve light interception and light use efficiency and thus contribute to yield increase. As we know, higher above-ground biomass in traditional film cover and/or ridge and furrow system commonly increases crops' light use efficiency (Jia et al., 2018).

The ridge–furrow system affects potential leaf expansion (Salah and Tardieu, 1997), leaf area index, and leaf morphology (e.g., angle and thickness) (Liu F. D. et al., 2010). The plant morphological plasticity can be affected by the spatial arrangements, such as row space (Mattera et al., 2013) and so on. Leaf morphological changes, i.e., specific leaf area (SLA) and leaf angle (Hirose and Werger, 1995; Valladares et al., 2002), would pose an impact on light extinction coefficient and its distribution within the canopy. Light interception (LI) of crop is determined by leaf area index and light extinction coefficient (k) (Monsi and Saeki, 1953). Biomass production depends on the interception of incoming photosynthetic active radiation (PAR) and the conversion efficiency into dry matter, i.e., the light use efficiency (LUE) (Sinclair and Horie, 1989; Willey, 1990; Idinoba et al., 2002). However, light distribution and use efficiency of crop by the ridge and film cultivation were seldom reported, especially in relation to plant morphological plasticity.

The slope of the regression between crop biomass and LI is well known as LUE (Dreccer et al., 2000; Yang et al., 2004), which is strongly affected by the biomass allocation to the organs, harvest index (Tadesse et al., 2001), water availability (Bajgain et al., 2015), and row spacing (Mattera et al., 2013). Ridges and film cover improved crop growth rate (Dong et al., 2017) and increased soil temperature and soil water content (Zhou et al., 2009) by reducing evaporation loss, collecting rainfall into the place of growing crop, and enhancing the harmony of crop growth and natural resources (rainfall and heat). We hypothesize that leaf morphology might be changed by the asymmetric ridges and film cover, which further impacts on LI and LUE.

The objectives of this study are to (i) quantify LI in relation to the plant morphological traits under the asymmetric ridge–furrow and film cover system, and (ii) quantify LUE of maize under different combinations of ridges/furrows and film cover ratios in response to biomass partitioning.

2. Material and methods

2.1 *Experimental site*

Field experiments were conducted in 2013 and 2014 at Shuangyang (43°33′N, 125°38′E; 219.5 m in altitude), Jilin Province, Northeast China. The soil was loam, with a pH of 5.6, a bulk density of 1.43 g cm^{-3}, and a total N content of 1.15 g kg^{-1} on average of 0–100 cm soil depth. The annual mean air temperature was 5.8 ± 0.13°C and 620 ± 27 mm for precipitation from 1980 to 2010. The average non-frost period was 149 days. The average annual pan evaporation was 1408 mm. Total rainfall from April to September (the crop growing season) was 737 mm in 2013, much higher than that in 2014 (365 mm). Annual mean air temperature during the maize growing period was 17.4°C in 2013 and 17.9°C in 2014. The climate data (Table 1) were obtained from Shuangyang Meteorological Experimental Station, 2 km away from the experimental field.

Table 1. Monthly mean maximum (T_{max}) and minimum (T_{min}) air temperatures, total rainfall, and sunshine hours in 2013 and 2014 at Shuangyang, Jilin Province, China

Month	T_{max} (°C)		T_{min} (°C)		Rainfall (mm)		Sunshine hours (h)	
	2013	2014	2013	2014	2013	2014	2013	2014
April	8.6	17.9	–0.5	10.6	48.7	5.7	205	255
May	24.1	20.8	11.6	15.0	38.8	96.6	265	192
June	26.6	27.4	16.3	21.8	159.1	80.0	225	237
July	27.5	28.1	19.1	22.8	288.3	105.1	211	236
August	26.9	28.2	18.3	21.8	142.1	32.6	206	251
September	22.7	22.6	9.3	14.8	59.6	44.9	243	243
Average/Total	22.7	24.2	12.4	17.8	736.6	364.9	1356	1414

2.2 *Experiment design*

An asymmetric ridge–furrow system (DRF, "double ridges and furrows") in the experiments was alternated with a wide ridge (0.70 m in width, 0.15 m in height), a narrow furrow (0.10 m), a narrow ridge (0.40 m in width, 0.20 m in height), and a narrow furrow (0.10 m). Maize was planted in furrows (Fig. 1). Four treatments were tested in this study, including (1) no ridge and plastic film cover as a control (NRF); (2) DRF without plastic film cover (DRF_0); (3) DRF with wide ridge covered by plastic film, i.e., 58% of the ground was covered by film (DRF_{58}); and (4) DRF with plastic film covering full ground (DRF_{100}). The experiments were replicated four times in a complete randomized block design. The size of the experiment plot was 6 m in width and 10 m in length. Plastic film was white and transparent with a thickness of 0.008 mm.

The sowing dates were 8 May 2013 and 23 April 2014. The harvest dates were 26 September of both years. Maize cultivars were Fuyou 968 in 2013 and Tunyu 98 in 2014, which were cultivars used by local farmers with similar genetic traits. The compound fertilizer (N 25%, P_2O_5 10%, and K_2O 12%) of 500 kg ha^{-1} was applied once in the furrow at sowing time in 2013, and 450 kg ha^{-1} in 2014. There was no irrigation given in both years. Other managements were practiced according to local farmers.

2.3 *Measurements*

2.3.1 *Yield and dry matter*

To measure maize grain yield (g m^{-2}), the ear density (number of ears per m^2 ground area), kernel number per ear, and 1000-kernel weight were determined at harvesting time in a sampling area of 4.4 m wide × 1 m long (row) in each plot. The final maize grain yield was calculated as the product of yield components, i.e., ear density, kernel number per ear, and kernel weight in each plot, and standardized to 14% water content.

To measure maize dry matter (g m^{-2}) and partitioning of dry matter (e.g., ratio of vegetative organs over total dry matter), three plants in a sub-sampling area were randomly sampled in each plot at each sampling dates: 5 times on 31 May, 7 July, 1 August, 27 August, and 26 September (harvesting) 2013 and 6 times on 28 May, 21 June, 15 July, 5 August, 29 August, and 26 September (harvesting) 2014. The sub-sampling area was 1 m^2 each and at least 0.5 m away from the plot edges and previous sub-sampling area to avoid subsequent sampling effects. Samples were subdivided into leaf, stem, and reproductive organ, and then oven-dried at 105°C for 1 h, then at 80°C for 48 h to obtain a constant weight.

Harvest index (HI), the ratio of the grain yield to above-ground dry matter, was calculated by grain yield and final dry matter.

2.3.2 *Leaf area index*

Leaf area of maize was measured by the product of

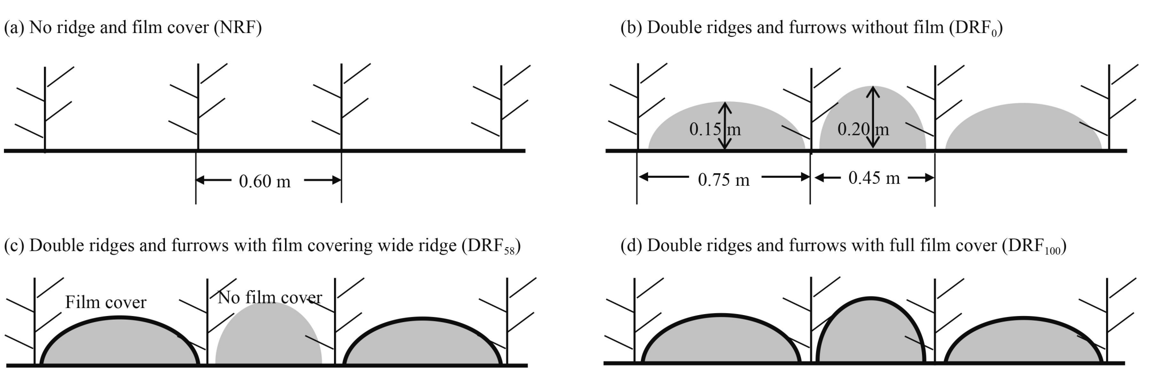

Fig. 1. Layout of the asymmetric ridge–furrow system and film cover. Black curve indicates the place where plastic film is covered.

leaf length, maximal width, and an empirical shape factor 0.75 (McKee, 1964). The sampling dates and number of plants were the same as dry matter samplings. Leaf area index (LAI) was calculated by multiplying total leaf area per plant and plant density.

2.3.3 *Morphological traits*

Leaf angle as the insertion angle between stem and a leaf was measured on 15 July (flowering stage) and 29 August (grain filling stage) 2014 by using a transparent plastic protractor with an accuracy of 0.1°, when the leaves were fully expanded. Leaf thickness presented as specific leaf area (SLA; m^2 g^{-1}), the ratio of the area to the mass for an individual leaf, was measured on 5 August 2014. For both leaf angle and SLA, all leaves in three randomly selected plants in the sub-sampling area per plot were measured. The plant samples were the same as those used in measuring dry matter.

2.3.4 *Light intensity within canopy*

To measure the light intensity within the canopy, the PAR sensors were placed across the rows for each plot with a LI-191 Line Quantum Sensor (Li-Cor Co. Ltd, Lincoln, Nebraska, USA) within the canopy and a LI-250A Light Meter (Li-Cor) at the top of the canopy. The measurement was carried out during 1000 to 1400 local time on 5 August 2014 (a sunny day, canopy fully closed the field). Eight canopy layers were measured, i.e., 0 cm (soil surface), 100, 160, 190, 220, 250, 280, and 360 cm (top of the canopy).

2.4 *Data analyses*

2.4.1 *Light interception and use efficiency*

Daily incoming solar radiation was calculated by using Angström–Prescott formula (Almorox and Hontoria, 2004).

$$H = H_0 \times \left(a + b \times \frac{S}{S_L}\right), \tag{1}$$

where H and H_0 are daily solar radiation (MJ m^{-2} day^{-1}) and extraterrestrial solar irradiance (MJ m^{-2} day^{-1}), respectively; S is actual daily sunshine hours (h), S_L is day length (the maximum possible sunshine hours, h); a and b are empirically determined regression constants, 0.25 for a and 0.50 for b (Almorox and Hontoria, 2004). Incoming PAR was calculated by an empirical equation (Zhu et al., 2010) as follows,

$$\text{PAR} = \mu \times H, \tag{2}$$

$$\mu = c + d \times \ln\frac{H}{H_0}, \tag{3}$$

where μ is the photosynthetic effective coefficient; c and d are empirical coefficients, 0.3549 for c and –0.0491 for d in the situation of Northeast China (Zhu et al., 2010).

Daily light interception of crop canopy (LI; MJ m^{-2} day^{-1}) for all plots in 2013 and 2014 was computed by Eq. (4). Total LI was the sum of daily LI during the growing period.

$$\text{LI} = \text{PAR} \times [1 - \exp(-k \times \text{LAI})]. \tag{4}$$

Light use efficiency (g MJ PAR^{-1}) for yield (LUE_Y) was calculated by final yield divided by total LI during the whole growing season. LUE for biomass (LUE_DM; g MJ^{-1}) was computed as the slope of the regression between dry matter and light interception during each crop growing period (Monteith, 1977).

2.4.2 *Light extinction coefficient*

Light extinction coefficient (k) was derived by an exponential relationship between light transmission within a canopy layer i (I_i/I_0) and the leaf area index of this layer (LAI_i) measured for each plot in August 2014 when crop fully covered the field,

$$I_i = I_0 \times \exp(-k \times \text{LAI}_i), \tag{5}$$

where I_0 is the PAR that reaches the top of crop canopy while I_i is the PAR that reaches the ith canopy layer.

2.4.3 *Statistical analyses*

The effects of LUE, LI, leaf angle, LAI, and SLA were analyzed by General Linear Model Univariate in SPSS 17.0. The least significant difference (LSD) test was used to compare the differences in mean values at $\alpha = 0.05$ between those treatments.

3. Results

3.1 *Leaf area index*

Film cover significantly ($P < 0.05$) increased LAI, across two years and two film treatments (DRF_{58} and DRF_{100}), by 90% at 60 days after sowing (DAS) comparedwith NRF. At the time of canopy closure (85 DAS), LAI in DRF_{100} was 7% higher than that in NRF and 16% higher than that in DRF_0 across two years (Fig. 2). Ridge–furrow without film cover (DRF_0) increased LAI at 60 DAS in 2013 but not in 2014 compared with NRF.

3.2 *Morphological traits and light extinction coefficient*

Leaf angle was significantly ($P < 0.05$) increased by 16% in DRF experiments compared with NRF. Film cover treatments did not affect leaf angle compared with DRF_0 (Fig. 3).

SLA within the 0–100 cm canopy layer (below ear position) in DRF_{100} was 0.01 m^2 g^{-1}, 46% lower than in NRF and 35% lower than in DRF_0, but similar to that in DRF_{58} (Fig. 4). The effect of film cover on SLA reduced in the upper canopy layer (above 160 cm). Without film cover, ridge and furrow treatment (DRF_0) also decreased SLA of maize.

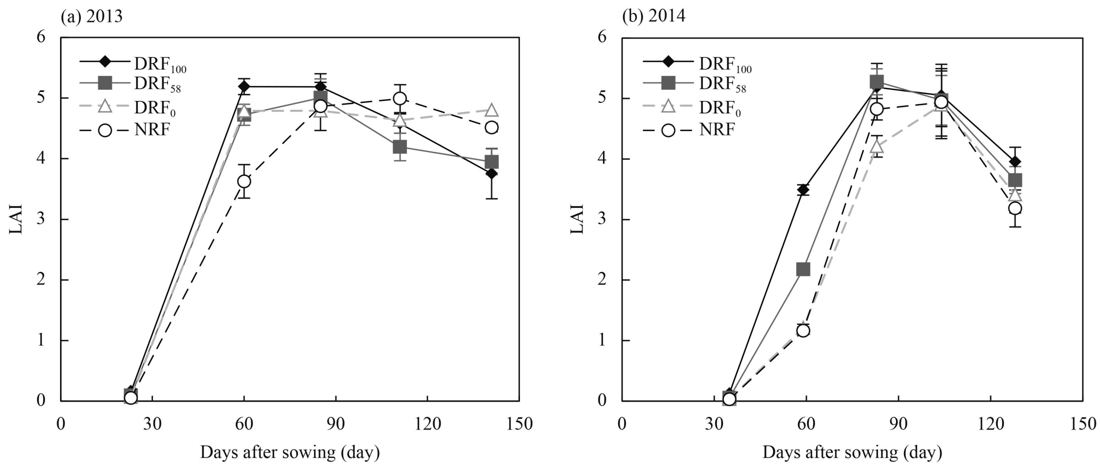

Fig. 2. Leaf area index (LAI) under ridge and film cover treatments in (a) 2013 and (b) 2014. Error bar indicates the standard error for replicates.

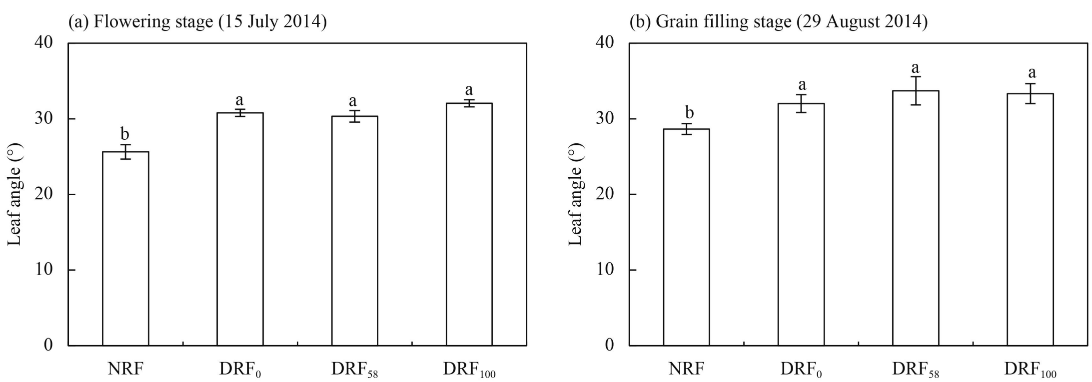

Fig. 3. Leaf angles of maize under ridge and film treatments at (a) flowering and (b) grain filling stages measured on 15 July and 29 August 2014, respectively. Leaf angle was averaged for all leaves. Error bar indicates the standard error for replicates. Same small letters (a or b) indicate no significant difference between treatments.

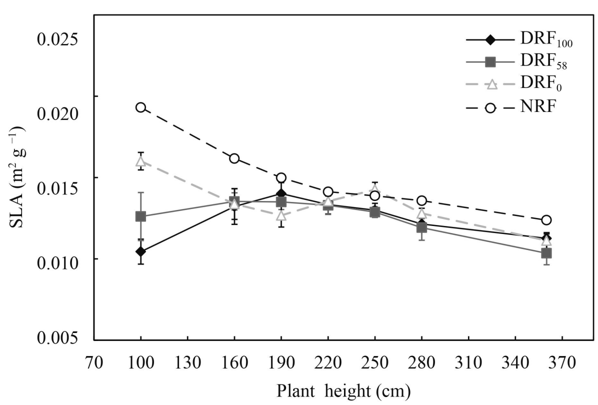

Fig. 4. Specific leaf area (SLA) within maize canopy under ridge and film treatments at grain filling stage measured on 5 August 2014. Error bar indicates the standard error for replicates.

Light extinction coefficient (k) derived from exponential regression between I/I_0 and LAI ranged from 0.42 to 0.52 in all treatments (Fig. 5). Compared with NRF, ridges (DRF_0) increased k by 16%; however, film cover decreased k by 4%, as indicated by the two film treatments.

3.3 *Light interception and use efficiency*

LI was significantly (P = 0.002) affected by DRF treatments (Table 2). LI in DRF_0 was 9% higher than in NRF in 2013/14, but not further increased by film cover.

LUE_Y was significantly (P = 0.01) increased by film cover. LUE_Y of DRF_{100} ranged from 2.06 to 2.59 g MJ PAR^{-1} in 2013 and 2014, 27% higher than that of NRF. LUE_{DM} ranged from 3.69 to 4.95 g MJ^{-1} in all treatments (Fig. 6). Similar to LUE_Y, LUE_{DM} of DRF_0 was not different with that of NRF. LUE_{DM} of DRF_{100} was 4.52 g MJ PAR^{-1} across two years and 17% higher than that of NRF. LUE_{DM} of DRF_{100} was 8% higher than that of DRF_{58}. The slight difference between LUE_Y and LUE_{DM} was due to the changes in maize HI. The HI was slightly (not significantly) increased (5%) by ridge–furrow (DRF_0), but significantly increased by 23% in film cover treatments (DRF_{58} and DRF_{100}), compared with

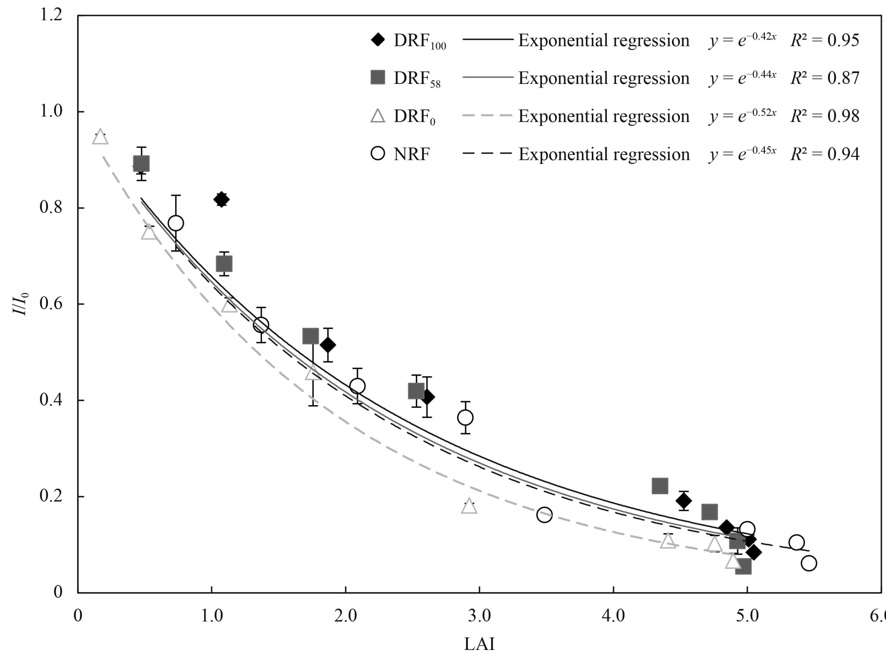

Fig. 5. Light extinction coefficient (k) derived from exponential regression between I/I_0 and leaf area index (LAI) under ridge and film treatments in 2014. Error bar indicates the standard error for replicates.

Table 2. Maize yield, final above-ground dry matters (DM), light interception (LI), light use efficiency for yield (LUE_Y), and harvest index (HI) as well as associated variance analysis results under ridge–furrow and film cover treatments in 2013 and 2014 in Jilin Province, China

Year	Pattern	Yield	DM	LI	LUE_Y	HI
		t ha^{-1}	t ha^{-1}	MJ m^{-2}	g MJ PAR^{-1}	g g^{-1}
2013	DRF_{100}	13.9a	24.9a	677ab	2.06ab	0.56a
	DRF_{58}	14.0a	24.8a	669b	2.09a	0.56a
	DRF_0	12.5a	27.0a	702a	1.78b	0.47a
	NRF	11.7a	25.3a	655b	1.78b	0.46a
	s.e.	0.76	0.69	10.0	0.12	0.04
2014	DRF_{100}	17.3a	29.7a	669a	2.59a	0.59a
	DRF_{58}	14.0b	25.9b	683a	2.05b	0.54ab
	DRF_0	12.8b	25.6b	692a	1.85b	0.50ab
	NRF	11.6b	25.4b	628b	1.86b	0.46b
	s.e.	0.96	0.96	14.6	0.15	0.04
Mean	DRF_{100}	15.6a	27.3a	673a	2.33a	0.58a
	DRF_{58}	14.0ab	25.4a	676a	2.07ab	0.55ab
	DRF_0	12.6bc	26.3a	697a	1.82b	0.49bc
	NRF	11.6c	25.3a	642b	1.82b	0.46c
	s.e.	0.64	0.82	8.8	0.10	0.03
P	Ridge	0.092	0.128	0.002	0.928	0.399
	Ridge × year	0.762	0.737	0.514	0.859	0.634
	Film	0.023	0.177	0.092	0.010	0.123
	Film × year	0.177	0.021	0.500	0.137	0.895

The P-value of ridge indicates the significance of an F-test comparing DRF_0 and NRF. The P-value of film indicates the significance of an F-test comparing the three treatments with DRF. Same small letters (a, b, c, ab, etc.) indicate no significant difference between all four treatments. Data were given in mean values of replicates. The s.e. indicates a marginal standard error for all treatments with replicates within the same year.

NRF (Table 2). The highest HI was observed in DRF_{100}.

3.4 *Dry matter partitioning to leaves*

Compared with NRF, the ridge–furrow with film cover (DRF_{58} and DRF_{100}) reduced the ratio of vegetative organs over total above-ground dry matter by 6%, while DRF_0 had no effect on this ratio (Figs. 7a, b). Film cover caused less biomass allocated into leaves. The ratio of leaves over total vegetative dry matter in DRF_{100} was 15% lower than that in NRF (Figs. 7c, d).

4. Discussion

Higher LAI and earlier time reaching its maximum un-

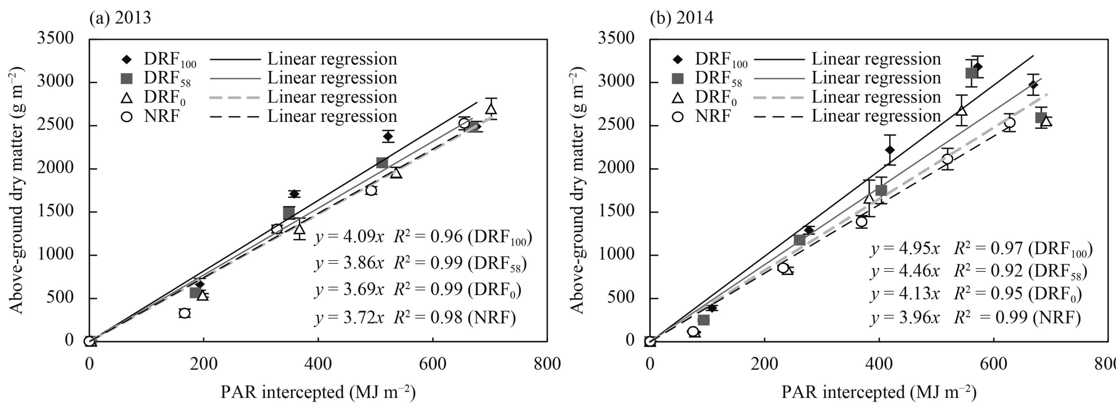

Fig. 6. The relationships between light interception and above-ground dry matter in (a) 2013 and (b) 2014. The slope of the linear regression is light use efficiency (LUE) for biomass. Error bar indicates the standard error for replicates.

der ridges and film treatments resulted in a higher LI (Mattera et al., 2013). This was caused by the improved growth and development of maize under ridges and film cover (Dong et al., 2017). The result was consistent with previous studies on maize (Flénet et al., 1996; Barbieri et al., 2000) and sunflower (Zaffaroni and Schneiter, 1989). However, *k* was higher in DRF_0 than in NRF, which would cause a higher LI. But measured LI in DRF_0 was lower than in NRF in our study. This might be explained by a greater LAI in DRF_0 that has offset the negative effect caused by an increased *k* on LI. In addition, white film increased radiative reflection and would affect crop canopy microclimate environment (Oebker and Hopen, 1974; Ding et al., 2013), especially at the early stage (Fan et al., 2017). The lower *k* value in DRF_{100} and DRF_{58} implied a possibility to increase optimal plant density in this region.

By the structural plasticity of maize in ridge–furrow and film cover, characterized with thinner leaves (higher LAI) and lower *k*, maize intercepted more light in DRF than in NRF. Smaller SLA in ridges and film treatments was likely an adaptation for more efficient light interception (Niinemets et al., 2001) due to an increase of intraspecific competition. Konôpka et al. (2016) indicated that highest SLA values were found at lowest light availability under the canopy. Previous studies have shown that canopy architecture played an important role in increase of crop yield (Ku et al., 2016; Wang et al., 2017). The morphological traits such as leaf angle (Wang N. et al., 2015) and SLA were closely associated with LI. Our results found that leaf angle was increased by DRF. This suggested that the optimal plant density under ridge–furrow systems could be higher than flat cultivation. Plant morphological features (SLA and leaf angle) were often responsive to soil water conditions (French and Turner, 1991; White and Scott, 2006). Ridges with film cover increased soil moisture content (Wang et al., 2011; Gao et al., 2014) and affected plant architecture, thus improving photosynthetic capacity (Pierce et al., 1994), light utilization, and grain yield.

LUE was higher in DRF with film cover than in other treatments, which might also be due to the improved soil water availability by reducing soil evaporation, especially at early stage (Han et al., 2008; Liu F. D. et al., 2010). Film cover increased top soil temperature (Zhou et al., 2009) and accelerated the process of maize growth in the ridge with film cover (Dong et al., 2017), resulting in a higher LUE. The increase of LUE_Y (21% more relative to NRF) was greater than LUE_{DM} (13%) in DRF_{58} and DRF_{100} when film cover was applied. This was mainly due to an increase of biomass allocation to reproductive organs, as indicated by an increasing HI in this study. The partitioning of biomass could be affected by water and nutrient availability (Vieira et al., 2004; Marcelis et al., 2006). The effect of film cover on biomass in the studied region was not significant due to the sufficient rainfall in experimental years. The film effect was stronger in a dry year (2014) than in a wet year (2013), especially for full film cover treatment. This result was coincidence with Zhang et al. (2018), who reported that the average yield increased 66% by using film cover in the area with rainfall less than 600 mm but only increased 20% in the area with precipitation greater than 600 mm. Using ridges in the rain-fed maize could harvest rainwater into furrows where plants grow, and crop yields increase by 15%, compared with no ridge control (Dong et al., 2017). Without plastic film, the ridge–furrow system in this study had no effect on LUE for both yield and biomass. Our results suggested that the effect of rainwater harvesting on LUE by ridge cultivation was probably much smaller compared with the effects of reducing soil evaporation and increasing soil temperature by film cover.

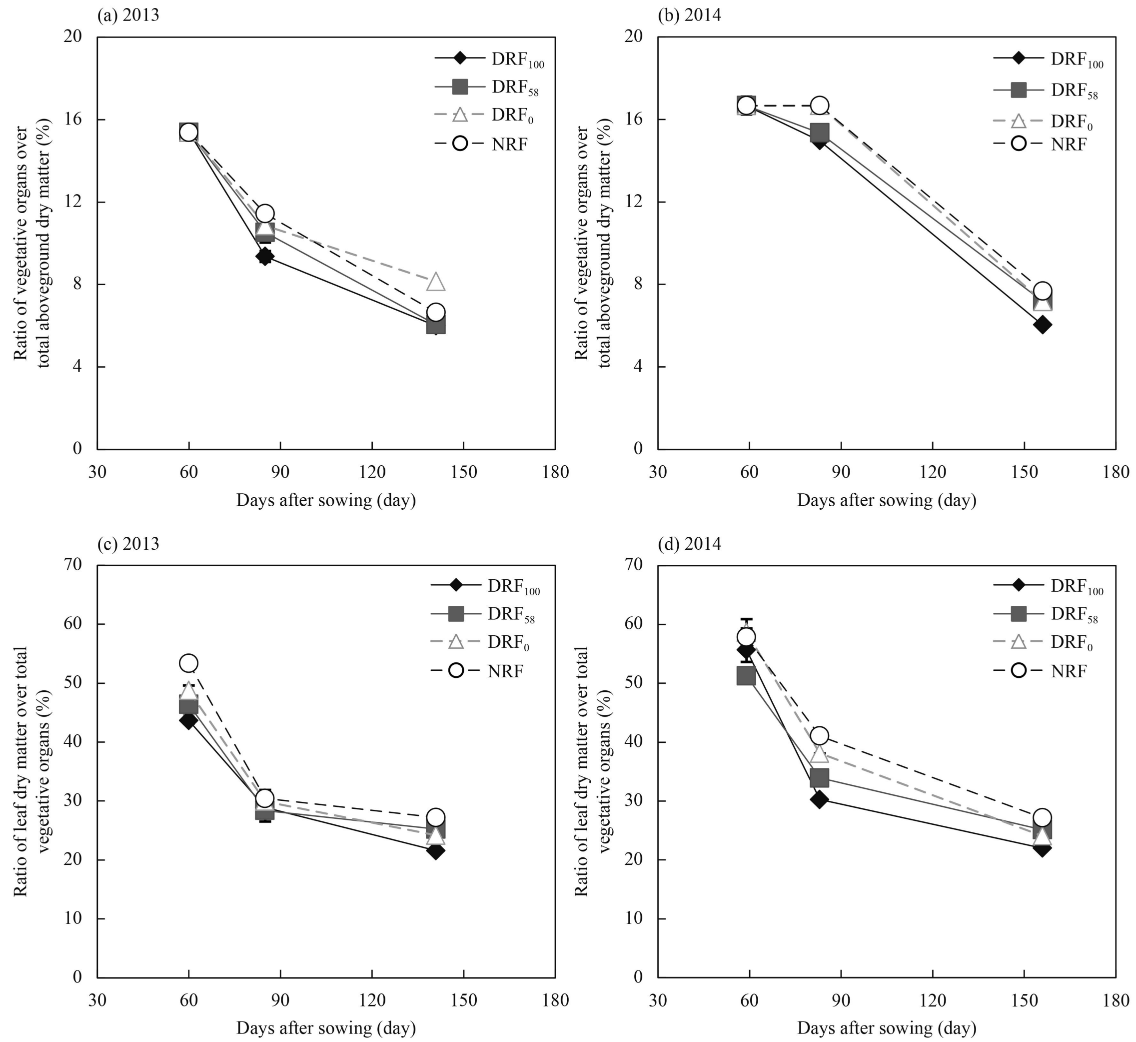

Fig. 7. (a, b) The ratio of vegetative organs to total above-ground dry matter and (c, d) the ratio of leaf dry matter to total vegetative organs, under ridge and film treatments in (a, c) 2013 to (b, d) 2014. Error bar indicates the standard error for replicates.

LUE for biomass in NRF (traditional practice without ridge and film) in our study was 3.84 g MJ PAR^{-1} across two years, which was consistent with previous studies ranging from 3.2 to 3.4 g MJ PAR^{-1} (Sinclair and Muchow, 1999) and 3.84 g MJ PAR^{-1} under optimal growing conditions (Lindquist et al., 2005). The high LUE in our study was due to the improved plant morphological traits and soil water availability (unpublished data), which promoted maize growth and development under ridge with film cover (Dong et al., 2017).

5. Conclusions

Light interception was significantly increased by asymmetric ridge and furrow system (DRF), but was not further increased by film cover. Light use efficiency was not increased by DRF_0, but significantly enhanced by adding plastic film on DRF, especially with 100% film cover (DRF_{100}). The increase of LI was due to the improvement of plant morphological traits (i.e., thin and erect leaves). The changes in leaf morphology also suggested a possibility to increase optimal plant density under ridge and film cover. The asymmetric ridge–furrow system combined with film cover might be a useful agronomy practice to alleviate the negative effect of climate change (e.g., drought and low temperature) globally. It is necessary to integrate our results at field level with crop models such as the Agricultural Production System sIMulator (APSIM); thus, better understanding on how to reduce climate risks and to alleviate the negative impacts of climate change through optimizing crop managements at the regional level could be achieved.

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