Ridge and furrow systems with film cover increase maize yields and mitigate climate risks of cold and drought stress in continental climates

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Abstract:

Ridge-furrow tillage and plastic film cover are widely applied in China to mitigate climate risks, e.g. cool temperature and low rainfall. This study aimed to quantify the effects of ridge-furrow tillage and film cover on maize growth and yield in an environment with frequent seasonal drought and cold spells. Field experiments were carried out in 2013 and 2014 in Jilin and Inner Mongolia, northeast China. Maize yield without film cover increased 15% by ridging, and further increases of 9 % or 16% were achieved by applying 58% or 100% film cover, respectively. Maize growth rate was significantly enhanced by both partial and full film cover, but not significantly increased by ridging alone. The time reached to the maximum growth rate was significantly advanced. The growing duration of maize was significantly shortened by film cover while ridging did not affect. The increase of maize yield by ridge and film cover was associated with significant increases in kernel number per ear, kernel weight and harvest index. Harvest index of maize increased with 11% by ridge-furrow tillage and with a further 15-17% by film cover. We conclude that maize with ridge and film cover increases crop yield by enhancing crop growth and development and could also reduce risks of crop failure due to drought or cold spells. The results could help optimize maize management in arid continental regions where yields are constrained by drought and a short growing season due to low temperature.

Keywords: growth; climate change; yield components; instantaneous growth rate; phenology

1. Introduction

Maize (*Zea mays* L.) is one of the most important crops worldwide. In northeast China maize growing area is 6.5 million ha, mostly rain-fed, and accounting for 31% of the national total. Maize yield is around 5.3 t ha⁻¹ in this region. Although this is 13% higher than the national average, the yield gap to the potential of 10.9 t ha⁻¹ is substantial (Liu et al., 2012). The main factors limiting maize yield and quality in northeast China are frequent summer drought caused by an uneven distribution of rainfall during the growing season and low temperature in spring. Due to the global warming and higher expected frequency of extreme climate events (IPCC, 2007), climate risks for agricultural production have changed and in many regions increased (Craufurd and Wheeler, 2009). An increase in the frequency and severity of droughts has been indicated in various locations such as in northeast China (Xu et al., 2013; Song et al., 2014; Yu et al., 2014), United Kingdom (Burke et al., 2010), Italy (Brunetti et al., 2002) and Iran (Farhangfar et al., 2015). Cold stress has occurred frequently under climate change in northeast China, especially at crop seedling stage. Global climate changes further aggravate the effects of drought (Li et al., 2015) and variation in temperature (Fan et al., 2013).

Changes in agricultural practices may alleviate the negative impact of climate change (Liu et al., 2014; Liu et al., 2010), e.g. increased fertilizer application (Xiao et al., 2015), more irrigations (Arora et al., 2011), use of tolerant varieties (Tao et al., 2012), tillage techniques such as ridge-furrow cultivation (Jin et al., 2010), and film cover (Li et al., 2007; Zhou et al., 2009). Two methods of ridge-furrow cultivation are

common in farmers' practice. First, plants are sown on the ridges because of a warmer soil temperature and commonly combining with plastic film to further increase soil temperature. This is mostly practiced in regions with a low spring temperature at the seedling stage (Jin et al., 2010). Second, plants are sown in the furrows to collect rainfall from the plastic-covered ridges. This is usually practiced in semi-arid regions where water is a major limiting factor (Li et al., 2013; Wu et al., 2015).

In the northwest of China, both low spring temperatures and insufficient rainfall are major limitations for maize growth. For this reason, an asymmetric ridge-furrow-ridge-furrow pattern was developed over the last decade (Wang et al., 2015; Zhou et al., 2009; Liu et al., 2009); maize is grown in strips of two rows, separated by ridges. The maize rows are grown in narrow furrows with a narrow ridge in between. Usually, only the wide ridge is covered by plastic film, but systems with film cover on both the wide and narrow ridge occur as well (Fig. 1). Compared to the symmetric ridge-furrow system in which all ridges are of the same width, this system increases soil temperature and water harvesting efficiency, resulting in a yield increase (Zhou et al., 2009; Liu et al., 2009). Furthermore, the wider space allows a easier management (Balkcom et al., 2010) and almost without a reduction of crop stand per unit area (Wang et al., 2015).

While the asymmetric ridge-furrow-ridge-furrow with plastic film cover is already in practical use, it is unknown how crop yield and growth are affected in poor versus rich rainfall years. And there is little information available on the effects of ridge-furrow tillage and film cover on crop phenology. Furthermore, it is unknown

whether covering the wide ridges is economically justified by yield increases that can offset the costs of labor and film. There is also little information on the effectiveness of uncovered versus film-covered ridges on water harvesting and yield in rain-fed maize with high seasonal climate risks.

Therefore, in this paper, we quantified maize growth and development in four systems: flat tillage, ridge-furrow tillage, ridge-furrow tillage with film cover on the wide ridges, and ridge-furrow tillage with film cover on both the narrow and wide ridges and furrows. Growth patterns were mathematically described using parameter values of beta-growth functions fitted to the data. These parameter values provide a robust measure of trait values associated with the temporal patterns of crop growth that would otherwise be difficult to characterize (Meade et al., 2013, Yin et al., 2003).

In short, the objectives of this study were to: (1) quantify the asymmetric ridge-furrow and film interactive effects on growth, development and yield formation in rain-fed maize in different years and locations; and (2) explore possible mechanisms underlying crop yield improvement in this system as related to the phenology and crop growth.

2. Materials and Methods

2.1 Experimental sites

The field experiments were carried out in 2013 and 2014 at two locations in Shuangyang (43°33'N and 125°38'E), Jilin, and Chifeng (42°30'N and 118°88'E), Inner Mongolia, China. The climates of both Shuangyang and Chifeng are dry and

windy with a low temperature in spring and uneven distribution of rainfall over the year. Crop growth at the two sites is generally suffering from cold stress at the seedling stage and drought stress during summer. In shuangyang, the soil is a loam, with a pH of 5.6, a bulk density of 1.43 g cm^{-3} , a total N content of 1.15 g kg^{-1} . In Chifeng, the soil is a sandy loam, with a pH of 8.23, a bulk density of 1.37 g cm^{-3} , a total N content of 0.68 g kg^{-1} . Rainfall during the growing season (from April to September) was 737 mm in 2013 and 365 mm in 2014 in Shuangyang, and 354 mm in 2013 and 332 mm in 2014 in Chifeng. The daily average air temperatures and rainfall during the growing seasons at the two experimental sites and years are shown in [Table 1](#).

2.2 Experimental design

The same experimental designs were used at both sites and years. The asymmetric ridge and furrow system (DRF) tested in this study consisted of a wide ridge (70 cm width, 15 cm height), a narrow furrow (10 cm width), a narrow ridge (40 cm width, 20 cm height) and another narrow furrow (10 cm width). Maize was planted in the furrows ([Fig. 2](#)). The experiments comprised four treatments, including a control without ridges or plastic film cover, and three asymmetric ridge-furrow systems (DRF) with different fractions of film cover. The treatments were (1) no ridge or film control (NRF); (2) DRF without plastic film cover (DRF_0); (3) DRF with plastic film cover only on the wide ridge (DRF_{58}), covering 58% of the surface by plastic film; and (4) DRF with full plastic film cover on all ridges and furrows (DRF_{100}). The treatments

were replicated four times in a complete randomized block design at each site and year. The plot size was 60 m² (6 m in width × 10 m in length). Plastic film was transparent with a thickness of 0.008 mm.

In Shuangyang, the maize was sown on 8 May 2013 and 23 April 2014, and it was harvested on 26 September in both years. In Chifeng, the maize was sown on 9 May 2013 and 13 May 2014, while it was harvested on 26 September 2013 and 13 October 2014. Maize cultivars were Fuyou 968 in 2013 and Tunyu 98 in 2014 in Shuangyang. The cultivar used in Chifeng was Jingdan 128 in both years. The two cultivars have a similar genetic background and were commonly used locally at both sites. Compound fertilizer (N 25%, P₂O₅ 10%, K₂O 12%) was applied once at sowing. Dosages were 500 kg ha⁻¹ in 2013 and 450 kg ha⁻¹ in 2014 in Shuangyang, 665 kg ha⁻¹ in 2013 and 600 kg ha⁻¹ in 2014 in Chifeng. The experiments were rain-fed and weeds were removed by hand. Plastic film cover was applied immediately after maize was sown and removed after harvest.

2.3 Measurements

Yield and yield components. Final maize grain yields (g m⁻²) and total aboveground dry matter were determined by harvesting all maize in a sampling area of 4.4 m wide × 1 m row long in each plot. Ear density (number of ears per m² ground area) was counted in the whole sampling area. Kernel number per ear of each plot was counted by taking a random sample of 10 plants. Kernel weight was determined by randomly selecting 1000 kernels from all kernels in the 10 plants sub-sample. 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 a 14% water content. Harvest index (HI), the ratio of the grain yield to aboveground dry matter, was calculated by grain yield and final dry matter.

Biomass growth. To determine biomass growth, samples were taken five times in 2013 and six times in 2014 in Shuangyang. Three plants in a sub-sampling area in each plot were taken randomly. The sub-sampling area was 1 m² and at least 1 m away from the plot edges and 0.5 m away from any previous sub-sampling area. Sampled plants were subdivided into leaf, stem and reproductive organ and then oven-dried at 105 °C for one hour, then at 80 °C for 48 hours to constant weight. Only the final dry matter was measured in Chifeng.

Phenology. Growth and development stages were recorded as the times at which 50% of plants reached the stage ([Abendroth et al., 2011](#)). We distinguished emergence (VE, defined as leaf one sticking approximately 2 cm above the soil surface), 3 fully expanding leaves (V3, collar appearance of leaf 3), flowering (VB, with the pollen shed) and physiological maturity (R6, with bracts yellow, silk dry and grain hardening). Growing degree days (GDD) were calculated using daily mean temperatures measured in a Stevenson screen at the site, and a base temperature of 10 °C.

2.3 Data analysis

To characterize the temporal pattern of maize growth, we fitted observed data with

a beta-function (Yin et al, 2003).

$$W = W_{\max} \left(1 + \frac{t_e - t}{t_e - t_m}\right) \left(\frac{t}{t_e}\right)^{\frac{t_e}{t_e - t_m}} \quad (1)$$

where W (g m^{-2}) is maize aboveground dry matter, t is the number of days after sowing (DAS). $W_{\max}$ (g m^{-2}) is the maximum value of W , and t_e (d) is the time when $W_{\max}$ is reached. t_m (d) is the time when maize achieves maximal growth rate (C_m , $\text{g m}^{-2} \text{d}^{-1}$). C_m is given by Eq. 2 (Yin et al. 2003). The growth function (Eq. 1) is defined for t greater than zero and less than t_e .

$$C_m = \frac{2t_e - t_m}{t_e(t_e - t_m)} \left(\frac{t_m}{t_e}\right)^{\frac{t_m}{t_e - t_m}} W_{\max} \quad (2)$$

ANOVA was used to assess treatment effects on the phenology, total dry matter, yield, yield components and fitted growth parameters, using the General Linear Model Univariate in SPSS 17.0. The ridge-film treatment, site and year were put into the model as fixed factors, while the replicate was as a random factor. The least significant difference (*LSD*) test was used for comparing treatment differences in means at $\alpha = 0.05$.

3 Results

3.1 Yield and yield components

Maize yield was significantly ($P < 0.01$) affected by ridge and film treatment, site, year, and their interactions (Table 2). The lowest yields were observed in Chifeng in 2014, due to a low and uneven distribution of rainfall in July and August (Table 1), when it was water sensitive period of maize growth.

Overall, the use of ridges without film cover (DRF₀) increased yield by 15.3% across years and locations, when compared to the control treatment without ridges or film (NRF) (Table 2). Partially and fully adding film cover further increased yield 9.2% and 15.5% comparing with DRF₀, respectively (Fig. 3), which increased 25.8% and 33.1% comparing with NRF (Table 2). Yield increases by ridges and film cover varied significantly between locations and years (Table 2).

Ridges with or without film cover did not significantly increase maize ear density, except for DRF₁₀₀ in 2014 in Shuangyang, which indicates that the treatments overall did not result in more than one ear per plant. Kernel number per ear was significantly increased, by 15%, in DRF₀ on average over two years and locations, compared to the control (NRF). Kernel number per ear was also significantly increased by partial (DRF₅₈) or full (DRF₁₀₀) film cover (Table 2). The 1000-kernel weight was not affected by ridge or film treatments. Kernel weight was only increased by DRF₁₀₀ in Shuangyang.

The increase in yield by the ridge and film treatments was in part attributable to an increase in the allocation of biomass to the grains, Thus the harvest index (HI) was on average increased by 11% under using ridges (DRF₀ vs NRF) and a further 16% increase was obtained by partial and full film cover (DRF₅₈ and DRF₁₀₀ vs DRF₀). The highest HI was observed in DRF₁₀₀ (Table 2).

3.2 Phenology

The whole developmental duration of maize was not significantly affected by DRF,

but it was significantly shortened, by 11.8 ± 0.7 days (82 ± 5.4 °Cd), by adding plastic film to the ridges as an average over all film treatments in two years and locations (Table 3). The thermal time requirement (GDD) to reach physiological maturity was decreased by 54 ± 6.5 °Cd (6.0 ± 0.7 days) as a result of increasing film cover from 58% to 100%.

3.3 Temporal patterns of biomass accumulation

The observed trends of above-ground dry matter growth of maize were captured quite well by the beta-function ($R^2 > 0.98$) (Fig. 4 A and B). In the comparatively wet year of 2013, maximum growth rate (C_m) was similar between the treatments NRF, DRF₀ and DRF₅₈, but it was significantly greater in DRF₁₀₀ (Table 4). In the drier year of 2014, maximum growth rate was lowest in NRF, and significantly greater in the other three treatments. But there were no significant difference between three ridge and film treatments. Ridging did not affect the time of reaching maximum growth rate (t_m) in any year, but film cover resulted in a significantly earlier time reached to maximum growth rate in both years. Both partial and full film cover advanced the time of reaching maximum biomass (t_e), while ridging affected the time of reaching maximum biomass only in 2014. Effects of treatments on maximum biomass W_{max} differed between the two years. Overall, the fitted growth trends (Fig. 4) showed clearly that ridging and film cover increased growth rate. Furthermore, the fitted curves showed that the gap between ridging and film cover treatments and the control initially became greater. But it diminished at the end of the growing season, when the

crops with ridging and film cover were already fully mature, whereas the control treatment without ridging and film cover was still accumulating biomass. Overall, the tillage and film cover treatments had thus a large effect on the temporal pattern of biomass accumulation, giving the same or greater yield in a shorter period of time.

4 Discussion and conclusion

Asymmetric ridge and furrow systems (DRF) significantly enhanced maize yield, and adding plastic film cover on DRF further increased yields. The effects of ridging and film cover depended on climate conditions, i.e. temperature and rainfall. The yield increase was mainly due to a higher growth rate and a greater biomass accumulation due to the ridge and film effects, and increased harvest index was also important. Use of plastic film significantly promoted growth and development, increased kernel number per ear and harvest index, especially with full film cover, due to an improved coordination of natural resources (heat and rainfall) and peak requirements by crops.

4.1 Yield formation in response to microclimate as affected by ridge and film

The increase in kernel number in the ridge and film treatments was likely due to an increase in moisture in the topsoil (Zhou et al., 2009). Improving soil water contents in the root zone tends to increase kernel number per unit area (Nemali et al., 2015), especially when these conditions occur during the period of kernel number determination, i.e. V6 (Andrade et al., 1999). Plastic film cover could dramatically

increase soil temperature during the crop seedling stage, up to 60 days from sowing (Lu et al., 2008), and greatly enhance early vigor of crops. Increasing soil temperatures in root zone accelerates phenological development (Liu and Siddique, 2015), and advances the timing of anthesis (Asseng et al., 2011). As a result of faster early growth and development, the crop could better use the natural resources such as solar radiation and soil water in July and August, allowing a high photosynthesis (Ryyppö et al., 1998). Promoted growth and development in maize by ridge and film in our study confirms previous studies that the high yield was a result of a high kernel number, which was strongly linked to assimilate supply during flowering (Otegui and Andrade, 2000).

4.2 Maize growth and development promoted by ridge and film

As top soil temperature was increased by DRF with film cover (Zhou, et al., 2009), maize development was significantly advanced. We found no significant effect of using ridges on crop development. This suggests that the effect of ridging on top soil temperature was rather small; however, it needs to be quantified in future studies. In Shuangyang, the effect of film cover on maize development was much greater in 2014, a year with a cool spring, than in 2013 when the first three weeks after sowing (in May) were 4.5 °C warmer than that in 2014. Low air temperature delays phenological development (Asseng et al., 2011). The results imply that film cover could reduce risk of cold stress when the frequency of extreme weather increases under climate change (Sankaranarayanan et al., 2010).

Biomass growth was accelerated by ridging and film cover. Fast initial crop growth would lead to a quick build-up of optimal canopy for capturing light and water resources, especial during early growth, eventually resulting in an increase of kernel set, HI and yield (Severini, et al., 2011). The effects of ridge and film on maize growth parameters (t_m and C_m) were significantly different between years. When the water supply was sufficient, for example in 2013 in Shuangyang, the positive effect of film cover and ridge was reduced. That implied water collection by the wide ridge into planting rows probably was only a major reason on increasing yield and water use efficiency in a dry year (Ren et al., 2010). Similarly, crop yields in DRF systems increased 60-95% in dry years, but only increased 20-30% in wet years compared to no ridge and film control (Li et al., 2001). Our results confirm that the ridge effect on water collection would reduce the drought risk when precipitation was insufficient. In the semi-arid region, the main advantage of film is to increase soil temperature and then accelerate early build-up of canopy, especially in a cool spring.

In 2013, Shuangyang had a good rainfall, but the yield in NRF had no difference with dry 2014. It was because of a very low air temperature in April, this delayed sowing date and shortened (8 days) crop growing duration. The film effect (DRF₁₀₀ and DRF₅₈) on maize yield in 2014 were significantly higher than in 2013 at both sites (Fig. 3), mainly due to the lower air temperature at seedling stage in May (15.0 °C), was 2.7 °C lower than in 2013 (Table 1). The very low yield at Chifeng in 2014 was due to a extreme drought stress during maize flowering stage in July and August, only 63.6 mm rainfall during these two months, which was much lower than that of 138

mm in 2013 and 193 mm for the historical average (Table 1). The cultivars used in this study were common with farmers, therefore, it differed between sites and years. Although all cultivars were similar in genetic traits, the year and site effects would probably slightly affected by the difference in cultivars.

4.3 Implications under climate change

Faster and higher rates of crop establishment and earlier maturation are beneficial for reducing or avoiding climate risks. For example, at higher latitudes where crop establishment dates are limited by frost or low temperatures, plastic film enables earlier establishment, better use of the longer summer days and reduced risk from damage by late frost due to earlier maturation (Kwabiah, 2004) and extremes in rainfall (Chiroma et al., 2006). Farmers can sow earlier when they use plastic film, which extends the potential crop growth duration (Brown, 2014; Nhamo et al., 2014), and increases yield potential (Wang et al., 2005).

4.4 Conclusion

Ridging and film cover provide opportunities for increasing yields in cool and drought environment by enhancing soil temperature and water availability. Covering plastic film only on the wide ridges is economically justified by yield increases that can offset the costs of labor and film in semi-arid region, and full covering film in ridges and furrows can reduce the climate risk of cold stress during early maize growing season. Further studies are needed to quantify soil temperature, as well as

water, radiation use to assess and to further characterize the benefits of these intensification measures. By the quantitative knowledge of crop responses to modified microclimate factors by DRF and film cover, the techniques associated with adjusting sowing windows (Liu et al., 2013) and cultivars (Liu et al., 2012) could be explored to adapt climate change, especially with increasing frequency of extreme weather events (Sankaranarayanan et al., 2010; Asseng et al., 2011; Lobell et al., 2013). Our study could help farmers to increase crop productivity and mitigate climate risks (drought and cold stress) in dry land maize production in continental regions globally, e.g. in northeast China, America and Africa.

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References

- Abendroth, L.J., Elmore, R.W., Boyer, M.J., Marlay, S.K., 2011. Corn Growth and Development. PMR 1009. Iowa State University Extension, Ames, Iowa, USA. www.extension.iastate.edu/documents/test/PMR1009corn0405.html.
- Andrade, F.H., Vega, C., Uhart, S.A., Cantarero, M., Valentinuz, O.R., 1999. Kernel

353 number determination in maize. *Crop Sci.* 39, 453-459.

354 Arora, V.K., Singh, C.B., Sidhu, A.S., Thind, S.S., 2011. Irrigation, tillage and
355 mulching effects on soybean yield and water productivity in relation to soil
356 texture. *Agric. Water Manag.* 98, 563-568.

357 Asseng, S., Foster, I., Turner, N., 2011. The impact of temperature variability on
358 wheat yields. *Glob. Chang. Biol.* 17, 997-1012.

359 Balkcom, K.S., Price, A.J., Santen, V.E., Delaney, D.P., Boykin, D.L., Arriaga, F.J.,
360 Bergtold, J.S., Kornecki, T.S., Rapere, R.L., 2010. Row spacing, tillage
361 system, and herbicide technology affects cotton plant growth and yield.
362 *Field Crop Res.* 117, 219-225.

363 Brown, C., 2014. Research into early planting heats up. *Spotlight periodical*, 27-28.

364 Brunetti, M., Maugeri, M., Nanni, T., Navarra, A., 2002. Droughts and extreme events
365 in regional daily Italian precipitation series. *Int. J. Climatol.* 22, 509-621.

366 Burke, E.J., Brown, S.J., 2010. Regional drought over the UK and changes in the
367 future. *J. Hydrol.* 394, 471-485.

368 Chiroma, A.M., Alhassan, A.B., Yakubu, H., 2006. Growth, nutrient composition and
369 straw yield of sorghum as affected by land configuration and wood-chips
370 mulch on a sandy loam soil in Northeast Nigeria. *Int. J. Agric. Biol.* 8,
371 770-773.

372 Craufurd, P.Q., Wheeler, T.R., 2009. Climate change and the flowering time of annual
373 crops. *J. Exp. Bot.* 60, 2529-2539.

374 Fan, L.J., Chen, D.L., Fu, C.B., Yan, Z.W., 2013. Statistical downscaling of summer

375 temperature extremes in northern China. *Adv. Atmos. Sci.* 30, 1085-1095.

376 Farhangfar, S., Bannayan, M., Khazaei, H.R., Baygi, M.M., 2015. Vulnerability
377 assessment of wheat and maize production affected by drought and climate
378 change. *Int. J. Disaster Risk Sci.* 13, 37-51.

379 IPCC Climate change, 2007. The physical science basis. In, Solomon, S., Qin, D.,
380 Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L.,
381 (Eds). Contribution of working group I to the fourth assessment report of
382 the intergovernmental panel on climate change. Cambridge University Press,
383 Cambridge, pp. 996.

384 Jin, Y.H., Zhou, D.W., Jiang, S.C., 2010. Comparison of soil water content and corn
385 yield in furrow and conventional ridge sown systems in a semiarid region of
386 China. *Agric. Water Manag.* 97, 326-332.

387 Kwabiah, A.B., 2004. Economic evaluation of production methods for sweet corn in a
388 cool climate. *J. Veg. Crop. Prod.* 10, 73-87.

389 Li, R., Hou, X.Q., Jia, Z.K., Han, Q.F., Ren, X.L., Yang, B.P., 2013. Effects on soil
390 temperature, moisture, and maize yield of cultivation with ridge and furrow
391 mulching in the rainfed area of the Loess Plateau, China. *Agric. Water*
392 *Manag.* 116, 101-109.

393 Li, X.L., Su, D.R., Yuan, Q.H., 2007. Ridge-furrow planting of alfalfa (*Medicago*
394 *sativa* L.) for improved rainwater harvest in rainfed semiarid areas in
395 Northwest China. *Soil Tillage Res.* 93, 117-125.

396 Li, X.Y., Gong, J.D., Gao, Q.Z., Li, F.R., 2001. Incorporation of ridge and furrow

method of rainfall harvesting with mulching for crop production under semiarid conditions. *Agric. Water Manag.* 50, 173-183.

Li, X.Z., Zhou, W., Chen Y.D., 2015. Assessment of regional drought trend and risk over China, a drought climate division perspective. *J. climate*, 28, 7025-7037.

Liu, C.A., Jin, S.L., Zhou, L.M., Jia, Y., Li, F.M., Xiong, Y.C., Li, X.G., 2009. Effects of plastic mulch and tillage on maize productivity and soil parameters. *Europ. J. Agron.* 31, 241-249.

Liu, C.A., Siddique, K.H.M., 2015. Does Plastic Mulch Improve Crop Yield in Semiarid Farmland at High Altitude?. *Agron. J.* 107, 1724-1732.

Liu, X.E., Li, X.G., Hai, L., Wang, Y.P., Li, F.M., 2014. How efficient is film fully-mulched ridge-furrow cropping to conserve rainfall in soil at a rainfed site?. *Field Crop Res.* 169, 107-115.

Liu, Y., Wang, E.L., Yang, X.G., Wang, J., 2010. Contributions of climatic and crop varietal changes to crop production in the North China Plain, since 1980s. *Glob. Chang. Biol.* 16, 2287-2299.

Liu, Z.J., Hubbard, K.G., Lin, X.M., Yang, X.G., 2013. Negative effects of climate warming on maize yield are reversed by the changing of sowing date and cultivar selection in Northeast China. *Glob. Chang. Biol.* 19, 3481-3492.

Liu, Z.J., Yang, X.G., Hubbard, K.G., Lin, X.M., 2012. Maize potential yields and yield gaps in the changing climate of northeast China. *Glob. Chang. Biol.* 18, 3441-3454.

419 Lobell D.B., Hammer, G.L., Mclean, G., Messina, C.D., Roberts, M.J., Schlenker, W.,
 420 2013. The critical role of extreme heat for maize production in the United
 421 States. *Nat. Clim. Change* 3, 497-501.

422 Lu, Q., Xiong, Y., Chen, M.C., Fu, G.Z., Li, Y.J., 2008. Effects of different mulching
 423 on root growth and soil environment of tobacco. *Agric. Res. Arid Areas* 26,
 424 86-89.

425 Meada, K.A., Cooper, M., Beavis, W.D., 2013. Modeling biomass accumulation in
 426 maize kernels. *Field Crop Res.* 151, 92-100.

427 Nemali, K.S., Bonin, C., Dohleman, F.G., Stephens, M., Reeves, W.R., Nelson, D.E.,
 428 Castiglioni, P., Whitsel, J.E., Sammon, B., Silady, R.A., Anstrom, D., Sharp,
 429 R.E., Patharkar, O.R., Clay, D., Coffin, M., Nemeth, M.A., Leibman, M.E.,
 430 Luethy, M., Lawson, M., 2015. Physiological responses related to increased
 431 grain yield under drought in the first biotechnology-derived
 432 drought-tolerant maize. *Plant, Cell Environ.* 38, 1866-1880.

433 Nhamo, N., Donald, M., Fritz, T.O., 2014. Adaptation strategies to climate extremes
 434 among smallholder farmers, a case of cropping practices in the Volta Region
 435 of Ghana. *Br. J. Appl. Sci. Technol.* 4, 198-213.

436 Otegui, M.E., Andrade, F.H., 2000. New relationships between light interception, ear
 437 growth and kernel set in maize, in Westgate, M.E. and Boote, K. (Eds.),
 438 *Physiology and Modeling Kernel Set in Maize*, CSSA Spec. Publ. pp.
 439 89-102.

440 Ren, X.L., Jia, Z.K., Chen, X.L., 2010. Effect of micro-catchment rainwater

441 harvesting on water and nutrient use efficiency in farmland under different
 442 simulated rainfall conditions. Trans. CSAE 26, 75-81.

443 Ryypö, A., Iivonen, S., Rikala, R., Sutinen, M.L., Vapaavuori, E., 1998. Responses
 444 of Scots pine seedlings to low root zone temperature in spring. Physiol.
 445 Plant. 102, 503-512.

446 Sankaranarayanan, K., Praharaj, C.S., Nalayini, P., Bandyopadhyay, K.K.,
 447 Gopalakrishnan, N., 2010. Climate change and its impact on cotton
 448 (*Gossypium* sp.). India J. Agr. Sci. 80, 561-575.

449 Severini, A.D., Borrás, L., Westgate, M.E., Cirilo, A.G., 2011. Kernel number and
 450 kernel weight determination in dent and popcorn maize. Field Crop Res.
 451 120, 360-369.

452 Song, X.Y., Li, L.J., Fu, G.B., Li, J.Y., Zhang, A.J., Liu, W.B., Zhang, K., 2014.
 453 Spatial-temporal variations of spring drought based on spring-composite
 454 index values for the Songnen Plain, Northeast China. Theor. Appl. Climatol.
 455 116, 371-384.

456 Tao, F.L., Zhang, S., Zhang, Z., 2012. Spatiotemporal changes of wheat phenology in
 457 China under the effects of temperature, day length and cultivar thermal
 458 characteristics. Europ. J. Agron. 43, 201-212.

459 Wang, R., Cheng, T., Hu, L.Y., 2015. Effect of wide-narrow row arrangement and
 460 plant density on yield and radiation use efficiency of mechanized
 461 direct-seeded canola in Central. Field Crop Res. 172, 42-52.

462 Wang, X.L., Li, F.M., Jia, Y. Shi, W.Q., 2005. Increasing potato yields with additional

463 water and increased soil temperature. *Agric. Water Manag.* 78, 181-194.

464 Wu, Y., Jia, Z.K., Ren, X.L., Zhang, Y., Chen, X., Bing, H.Y., Zhang, P., 2015. Effects
 465 of ridge and furrow rainwater harvesting system combined with irrigation
 466 on improving water use efficiency of maize (*Zea mays* L.) in semi-humid
 467 area of China. *Agric. Water Manag.* 158, 1-9.

468 Xiao, D.P., Tao, F.L., 2015. Contributions of cultivar shift, management practice and
 469 climate change to maize yield in North China Plain in 1981–2009. *Int. J.*
 470 *Biometeorol.* 1-12.

471 Xu, X.C., Ge, Q.S., Zheng, J.Y., Dai, E.F., Zhang, X.Z., He, S.F., Liu, G.X., 2013.
 472 Agricultural drought risk analysis based on three main crops in
 473 prefecture-level cities in the monsoon region of east China. *Nat. Hazards* 66,
 474 1257-1272.

475 Yin, X.Y., Goudriaan, J., Lantinga, E.A., Vos, J., Spiertz, H.J., 2003. A flexible
 476 sigmoid function of determinate growth. *Ann. Bot.* 91, 361-371.

477 Yu, X.Y., He, X.Y., Zheng, H.F., Guo, R.C., Ren, Z.B., Zhang, D., Lin, J.X., 2014.
 478 Spatial and temporal analysis of drought risk during the crop-growing
 479 season over northeast China. *Nat. Hazards* 71, 275-289.

480 Zhou, L.M., Li, F.M., Jin, S.L., Song, Y.J., 2009. How two ridges and the furrow
 481 mulched with plastic film affect soil water, soil temperature and yield of
 482 maize on the semiarid Loess Plateau of China. *Field Crop Res.* 113, 41-47.

483

Table 1 Monthly weather data in 2013-2014 and historical average during crop

growing season at Shuangyang and Chifeng

Month	Shuangyang						Chifeng					
	Mean air temperature (°C)			Precipitation (mm)			Mean air temperature (°C)			Precipitation (mm)		
	2013	2014	30 yr ^l	2013	2014	30 yr	2013	2014	30 yr	2013	2014	30 yr
April	3.9	10.6	8.3	48.7	5.7	30.8	4.5	11.8	9.6	45.0	8.2	20.7
May	17.7	15.0	15.5	38.8	96.6	55.4	18.8	15.8	16.8	4.9	69.1	36.2
June	21.2	21.8	20.9	159.1	80.0	98.2	20.8	20.2	21.6	139.0	141.3	72.1
July	23.1	22.8	23.0	288.3	105.1	190.9	23.7	24.5	23.8	74.3	23.3	111.8
August	22.2	21.8	21.8	139.4	32.6	143.3	23.4	21.8	22.8	63.9	40.3	80.8
September	15.6	14.8	15.4	58.7	44.9	47.9	16.0	15.5	17.1	27.2	49.7	38.0
Total	17.4	17.9	17.5	733.0	364.9	566.2	17.9	18.3	18.6	354.3	331.9	359.6

^lThe 30 years average is calculated from 1980 to 2010.

Table 2 Yield and yield components in maize under the asymmetric ridge and furrow system and film cover in Shuangyang and Chifeng sites in 2013 and 2014

Year	Site	Treatment	Yield	kernel number	1000-kernel weight	ear density	Final dry matter	Harvest index
			kg ha ⁻¹	# ear ⁻¹	g	# m ⁻²	kg ha ⁻¹	kg kg ⁻¹
2013	Shuangyang	DRF ₁₀₀	13911a	552b	387a	6.5a	24893a	0.56a
		DRF ₅₈	13995a	648a	333b	6.5a	24816a	0.56a
		DRF ₀	12491a	557b	345b	6.5a	26959a	0.47a
		NRF	11660a	554b	324b	6.5a	25271a	0.46a
		s.e.	764	28	9.3	0.00	688	0.04
	Chifeng	DRF ₁₀₀	12516a	541a	327a	7.1a	24360b	0.52a
		DRF ₅₈	13068a	544a	358a	6.7a	24840b	0.53a
		DRF ₀	13140a	531a	373a	6.7a	28775a	0.46a
		NRF	10746b	486a	356a	6.2a	28705a	0.38a
		s.e.	646	23	17.6	0.25	1089	0.03
2014	Shuangyang	DRF ₁₀₀	17315a	714a	378a	6.4a	29743a	0.59a
		DRF ₅₈	14021b	652b	351b	6.1ab	25931b	0.54ab
		DRF ₀	12777b	625bc	334bc	6.1ab	25550b	0.50ab
		NRF	11615b	593c	326c	6.0b	25345b	0.46b
		s.e.	955	22.3	6.8	0.22	964	0.04
	Chifeng	DRF ₁₀₀	8203a	359a	341a	6.7a	-	-
		DRF ₅₈	8026a	349ab	348a	6.7a	-	-
		DRF ₀	6581ab	322ab	308b	6.7a	-	-
		NRF	5014b	224b	345a	6.7a	-	-
		s.e.	1023	51	9.7	0.00	-	-
<i>P</i>	Treatment		0.000	0.003	0.051	0.064	0.175	0.001
	Site		0.000	0.000	0.120	0.043	0.114	0.119
	Year		0.000	0.000	0.613	0.000	0.122	0.728
	Site×Year×Treatment		0.000	0.000	0.000	0.159	0.002	0.930

DRF indicates double ridges and double furrow: alternating 70 cm wide ridge, 10 cm narrow furrow, 40 cm narrow ridge and 10 cm narrow furrow. Maize was grown in furrows. The number of 100 indicates full cover with plastic film on all ridges and furrows, 58 is for only covering the wide ridge, and 0 is for no film cover. NRF indicates the control treatment without ridges or film cover.

The *P*-value for treatment indicates the significance of an F-test comparing DRF and NRF. The *P*-value of film indicates the significance of an F-test comparing the three treatments with DRF.

Same small letters indicate no significance between treatments within a year and a site.

The s.e. indicates a marginal standard error for all treatments within a year and a site.

Table 3 Developmental durations of maize in relation to the ridges and plastic film at Shuangyang and Chifeng in 2013 and 2014

Year	Site	Treatment	Sowing to VE ¹		VE to V3		V3 to VB		VB to R6		Total	
			Days	GDD ²	Days	GDD	Days	GDD	Days	GDD	Days	GDD
2013	Shuangyang	DRF ₁₀₀ ³	8b	51b	15b	146b	46c	544d	50d	591	119c	1332d
		DRF ₅₈	8b	51b	18a	168a	49b	590c	54c	593	128b	1402c
		DRF ₀	13a	77a	16b	167a	50a	615b	57b	585	135a	1444b
		NRF	12a	77a	16b	162a	51a	627a	60a	598	139a	1464a
		s.e.	0.14	0.04	0.21	2.2	0.34	3.4	0.33	3.0	0.25	1.3
	Chifeng	DRF ₁₀₀	9b	67b	20c	211c	37c	447c	56a	691a	123c	1417c
		DRF ₅₈	9b	67b	21b	222b	43b	516b	53b	639b	126b	1445b
		DRF ₀	11a	77a	22b	225ab	45a	557a	53b	614c	130a	1474a
		NRF	11a	79a	23a	229a	44a	562a	53b	618b	130a	1488a
		s.e.	0.17	1.4	0.21	1.6	0.21	3.1	0.85	7.7	0.75	7.4
2014	Shuangyang	DRF ₁₀₀	11c	48c	25a	117c	39c	473c	51c	618b	125d	1257c
		DRF ₅₈	21b	73b	18b	147b	43b	512b	50c	607c	132c	1339b
		DRF ₀	24a	79a	19b	182a	43b	517b	59a	643a	144b	1420a
		NRF	22a	75b	19b	173a	48a	574a	58a	604c	147a	1426a
		s.e.	0.36	1.0	0.61	6.1	0.54	8.4	0.29	2.6	0.24	3.3
	Chifeng	DRF ₁₀₀	7b	45c	21b	218b	34b	410b	56b	691b	118c	1364c
		DRF ₅₈	9a	64b	21b	218b	34b	414b	59b	705a	123b	1400b
		DRF ₀	10a	72ab	24a	248a	35a	454a	63a	673c	132a	1447a
		NRF	10a	76a	24a	254a	36a	451a	63a	669c	132a	1449a
		s.e.	0.25	3.6	0.29	3.1	0.21	2.5	0.27	3.3	0.20	0.80

¹ VE, V3, VB and R6 indicates the phenological stages of emergence, three fully expanded leaves, flowering and physiological maturity, respectively.

² GDD is growing degree days (°Cd) above 10 °C using average daily air temperature measured at 2 m height in a Stevenson screen.

³ DRF indicates double ridges and double furrow: alternating 70 cm wide ridge, 10 cm narrow furrow, 40 cm narrow ridge and 10 cm narrow furrow. Maize was grown in furrows. The number of 100 indicates full cover with plastic film on all ridges and furrows, 58 is for only covering the wide ridge, and 0 is for no film cover. NRF indicates the control treatment without ridges or film cover. Same small letters indicate no significance between treatments within a year and a site.

The s.e. indicates a marginal standard error for all treatments within a year and a site.

Table 4 Fitted parameters of the beta growth function in relation to ridge-furrow and film cover in 2013 and 2014 in Shangyang

Year	Treatment	$W_{\max}$	t_e	t_m	R^2	C_m
		g m^{-2}	d	d		$\text{g m}^{-2} \text{d}^{-1}$
2013	DRF ₁₀₀	2673±24ab	129±2.1b	84±0.9b	0.990	36.1±1.8a
	DRF ₅₈	2500±49b	136±1.6b	87 ±2.0b	0.995	31.5±1.6b
	DRF ₀	2782±141a	154±2.7a	97 ±3.1a	0.989	30.5±1.7b
	NRF	2617±117ab	153 ±4.6a	100±3.3a	0.980	29.8 ±0.6b
2014	DRF ₁₀₀	3425±102a	141±2.6b	102±1.8b	0.993	48.0±2.7a
	DRF ₅₈	3283±139a	140±0.4b	107±2.6ab	0.982	51.5±4.3a
	DRF ₀	3058±206a	143±0.4b	110 ±3.4a	0.980	48.5±7.8a
	NRF	2568±111b	153 ±2.7a	110 ±0.4a	0.992	33.0±2.9b
<i>P</i>	DRF	0.048	0.127	0.582	-	0.056
	Film	0.648	0.000	0.001	-	0.647
	Year×DRF	0.463	0.087	0.001	-	0.017
	Year×Film	0.000	0.373	0.000	-	0.000

DRF indicates double ridges and double furrow: alternating 70 cm wide ridge, 10 cm narrow furrow, 40 cm narrow ridge and 10 cm narrow furrow. Maize was grown in furrows. The number of 100 indicates full cover with plastic film on all ridges and furrows, 58 is for only covering the wide ridge, and 0 is for no film cover. NRF indicates the control treatment without ridges or film cover.

The *P*-value for DRF indicates the significance of an F-test comparing DRF₀ and NRF. The *P*-value of film indicates the significance of an F-test comparing the three treatments with DRF.

Same small letters indicate a not significant different between all four treatments.

Data were given in mean values and s.e. of replicates.

Figure captions

Fig. 1. Asymmetric ridge-furrow-ridge-furrow system with complete plastic film cover, as practiced in north China.

Fig. 2. Layout of the asymmetric ridge-furrow-ridge-furrow system and film cover in four experimental treatments.

Fig. 3. The increment in yield (%) by ridges and film cover over the control without ridges or film. The interception of the regression line is the yield increased only due to ridges. The slope of the regression line is the rate of yield increase by film covering percentage.

Fig. 4. Fitted (lines) and observed (points) aboveground dry matter (A and B) and simulated daily crop growth rate (C and D) in maize under the asymmetric ridge and furrow system with full, partial or no film cover compared to a control without ridges or film cover in 2013 and 2014 in Shuangyang, Jilin. C_m indicates the maximum value of daily growth rate and t_m is the time reaching this maximum value.

519

520 **Fig.1**

521

Fig. 2

Fig. 3

Fig. 4