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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.

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 and Brown, 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 and Tao, 2015), more

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

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 an 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 (Meada 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 m^2 (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 in2014 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%, P_2O_5 10%, K_2O 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

2.3.1. 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