Field Crops Research 200 (2017) 71–79

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Effects of EDAH, a novel plant growth regulator, on mechanical strength, stalk vascular bundles and grain yield of summer maize at high densities

Cailong Xu, Yingbo Gao, Beijing Tian, Jianhong Ren, Qingfeng Meng, Pu Wang*

College of Agronomy and Biotechnology, China Agricultural University, Beijing 100193, China

ARTICLE INFO

Article history:
Received 24 May 2016
Received in revised form 11 October 2016
Accepted 12 October 2016
Available online 19 October 2016

Keywords:
EDAH
High density
Stalk mechanical strength
Vascular bundle
Grain yield

ABSTRACT

High yields of modern maize are typically obtained at high plant densities. However, maize lodging rates also increase at high densities. In China, EDAH (a plant growth regulator containing 27% ethephon and 3% DA-6) has been widely used by farmers to increase yield in maize at high densities, but the underlying mechanism is unclear. In this study, we conducted experiments during the 2014 and 2015 growing seasons. Hybrid maize cultivars 'Xundan20' (lodging-susceptible) and 'Zhengdan958' (lodging-resistant), which are widely planted in China, were grown at a density of 90,000 plants ha^{-1}. EDAH solution at a concentration of 2 mL L^{-1} was sprayed onto summer maize foliar surfaces at the seven-expanded-leaves stage. Grain yield, stalk quality (rind penetration strength, dry weight per cm, amount and area of vascular bundles, and bleeding sap) and leaf area were determined. EDAH significantly decreased lodging rate (by 60.1% on average), plant height, ear height and the location of the center of gravity in both varieties over two years, and increased rind penetration strength, dry weight per cm, cross section area, cortex thickness, and number and area of stalk vascular bundles. EDAH also significantly decreased leaf area by 26.8% among upper leaves and by 13.3% among ear leaves. Additionally, EDAH significantly increased grain yield by 14.3% by increasing kernel number and thousand-kernel weight resulting from optimization of the leaf layer structure and higher bleeding sap levels. Lodging-resistance indicators and yields of 'Xundan20' increased more greatly than those of 'Zhengdan958' under the EDAH treatment. In conclusion, the risk of lodging at high plant densities can be avoided by spraying EDAH at a proper growth stage due to the improved stalk quality, and an optimized canopy structure can be achieved, proving a stable method to increasing grain yield of maize.

1. Introduction

Maize (*Zea mays* L.) is one of the important cereal crops in the world. As the global population continues to grow, food requirements and demand for maize will increase (Parry et al., 2009; Grassini et al., 2011). High yields of modern maize cultivars are obtained at high plant densities (Tokatlidis et al., 2011; Van Ittersum and Cassman, 2013; Ma et al., 2014), which enables plants to intercept and use solar radiation more efficiently (Tokatlidis and Koutroubas, 2004). However, at high densities, per-plant growth rates decline and young kernel abortion is exacerbated (Sangoi, 2001; Tollenaar et al., 2006; Borrás et al., 2007). Furthermore, high plant densities often result in thinner and taller maize stalks that increase the risk of lodging, which has a detrimental effect on yield (Gou et al., 2007; Novacek et al., 2013), e.g. 5–25% yield loss annually in America due to lodging (Norberg et al., 1988) and the grain yield decreases about 108 kg ha^{-1} when lodging rate increases 1% (Sun et al., 1989). Therefore, maize yields could be increased by improving the lodging resistance of individual plants.

Lodging occurs either as stalk lodging resulting from the bending or breaking of the lower internodes or root lodging resulting from a failure in root soil integrity (Sterling et al., 2003; Gou et al., 2007). Pellerin et al. (1990) and Islam et al. (2007) reported that extensive stalk lodging destroyed normal canopy structure, resulting in reduced photosynthetic activity, dry matter production, and an increased cost of time and labor at harvest. Previous studies have reported that plant height, ear height, and center of gravity height were key indicators of stalk lodging resistance in maize; a negative correlation was found between lodging resistance and each of these indicators (Esechie, 1985; Albrecht et al., 1986; Gou et al., 2010).

---

* Corresponding author.
E-mail address: wangpu@cau.edu.cn (P. Wang).

http://dx.doi.org/10.1016/j.fcr.2016.10.011
0378-4290/© 2016 Published by Elsevier B.V.

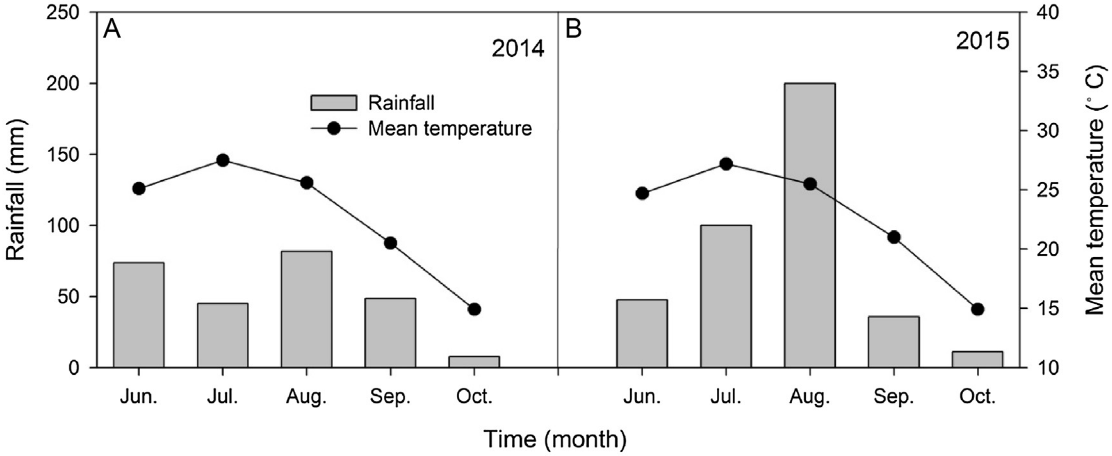

Fig. 1. Mean temperature and rainfall during the growing seasons in 2014 and 2015.

Accordingly, lodging resistance can be significantly improved by reducing plant height (Shekoofa and Emam, 2008; Peng et al., 2014).

Stalk lodging is not completely prevented by just reducing plant heights under high densities (Wang et al., 1998; Chen et al., 2011). The stalk mechanical strength, including rind penetration strength and dry weight per cm of the third internode of maize stalks, is a good indicator of lodging resistance (Flint-Garcia et al., 2003; Gou et al., 2010); these indicators exhibit a positive correlation with lodging resistance (Martin et al., 2004; Gou et al., 2010). Selecting inbred lines with high rind penetration strength and dry weight per cm has already been used by maize breeders to improve stalk quality (Dudley, 1994; Gou et al., 2010). Another important indicator of stalk quality is vascular bundle structure (Cui et al., 2012; Li et al., 2012; Feng et al., 2014).

Vascular bundle number and its cross-section area not only determine stalk lodging resistance (Cui et al., 2012; Li et al., 2012), but also play a crucial role in the flow of nutrients, photosynthate, and water, permitting material communication and transportation between the roots and canopy (i.e. bleeding sap; Lalonde et al., 2003; Feng et al., 2014). Positively correlation was found between grain yield and the amount of bleeding sap in stalks (He et al., 2007; Bai et al., 2009). Because high density conditions impair mechanical strength and microstructure in the lower internodes of maize stalks, these are key targets for further genetic improvement in lodging resistance under high density conditions (Flint-Garcia et al., 2003; Martin et al., 2004; Gou et al., 2010; Feng et al., 2014).

In recent years, breeders have improved the genetic gains in grain yield and lodging resistance; the maize stalk lodging decreased significantly with year of cultivar release (Ma et al., 2014). Lodging rate increases with increasing planting densities, which harms the productivity (Gou et al., 2007; Novacek et al., 2013). Therefore, cultural methods, including the possible use of growth regulators, are still needed to improve grain yield and lodging resistance. Gadallah (1999) and Zeng et al. (2012) reported that plant growth regulators can optimize plant morphology and increase yield by regulating endogenous plant hormone signaling and metabolism. EDAH (called Yu-Huang-Jin in China), a combination of plant growth regulators (Haolun Co., China, 2006) containing 27% ethephon and 3% DA-6 as active ingredients, has been widely used in maize production in China in recent years (Zhang et al., 2014). Application of EDAH not only decreases plant lodging by reducing plant and ear height and increasing root activity, but also improves grain yield by reducing barren ear tips at high plant densities (Dong et al., 2005, 2006, 2008; Zhang et al., 2014). Because lodging resistance and high yield are associated with not only plant and ear height but also mechanical strength and vascular bundle structure, we hypothesized that applying EDAH during the seven-expanded-leaves stage (Zhang et al., 2014) under high plant density would (1) improve the mechanical strength (including rind penetration strength and dry weight per cm) of lower internodes of maize stalks; (2) optimize the number and structure of vascular bundle elements in the lower internodes of maize stalks; and therefore (3) increase amount of the bleeding sap in the stalk, thus increasing grain yield. This study employed field experiments to examine the effects of EDAH application on mechanical strength, vascular bundle structure, and grain yield.

2. Material and methods

2.1. Experimental site

Field experiments were carried out in 2014 and 2015 at the Wuqiao Experiment Station of China Agricultural University, Hebei province, China (37° 41′N, 116° 36′E). The soil at this experimental field is clay-loam. Organic matter, total nitrogen (N), readily available phosphorous (P), and readily available potassium (K) in the upper 0.4 m of soil were 10.31 g kg^{-1}, 0.85 g kg^{-1}, 30.46 mg kg^{-1} and 100.71 mg kg^{-1}, respectively. Climate in 2015 was substantially warmer and wetter than 2014, which may be suitable for maize growth (Fig. 1).

2.2. Experimental design

Experiments were laid out as a split plot design with three replicates in both years. The main plot treatment was cultivars. The sub-plot treatments were EDAH-treatment and the control, which were randomized within the main plot. Each plot was 240 m^2 in area (8 m × 30 m) with a 1-m buffer between plots. The summer maize cultivars ‘Xundan20’ (lodging-susceptible) and ‘Zhengdan958’ (lodging-resistant) were used as experimental materials; both are widely planted in China. Summer maize was sown at a density of 90,000 plants ha^{-1} with a row spacing of 0.6 m on June 15, 2014 and on June 19, 2015. Each plot was irrigated with 70 mm of water immediately after sowing. Each plot received 120 kg N ha^{-1}, 130 kg P_2O_5 ha^{-1}, and 130 kg K_2O ha^{-1} before sowing, and another 120 kg N ha^{-1} was top-dressed at the silking stage. 2 mL L^{-1} EDAH solution was sprayed on summer maize foliar surfaces at the seven-expanded-leaves stage in the afternoon (between 16:00 and 19:00) as described by Zhang et al. (2014). The plant growth regulator solution was sprayed at a rate of 225 L ha^{-1}. The same volume of water was applied to the control plants.