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Maize yield and quality in response to plant density and application of a novel plant growth regulator

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ABSTRACT

Farmers in China have gradually increased plant density in maize to achieve higher yields, but this has increased risk of lodging due to taller and weaker stems at higher plant densities. Plant growth regulators can be used to reduce lodging risk. In this study, for the first time, the performance of a mixture of the plant growth regulators ethephon and diethyl aminoethyl hexanoate (DA-6), called EDAH is tested at different plant densities and in different cultivars. Grain yield, yield components and grain quality as well as plant height and lodging percentage were determined in two years (2012 and 2013), using two maize hybrids, ZD 958 and Pioneer 335 at densities of 4.5, 6.0, 7.5 and 9.0 plants m^{-2} with and without foliar application of EDAH at 7 expanded leaves stage. EDAH significantly increased grain yield (by 7.8–8.0%), kernel number per ear (by 2.9–4.0%) and 1000-kernel weight (by 3.3–5.1%). Lodging percentage increased with plant density and was decreased by EDAH application in 2013. Optimal density was 7.5 plants m^{-2}. The number of ears per unit ground area increased linearly with plant density, but number of kernels per ear and kernel weight showed an optimum. The two tested cultivars differed in yield and quality. No effects of EDAH on grain quality parameters (protein, oil and starch content) were found. We conclude that EDAH can improve lodging resistance and yield in maize, and that the yield effect of EDAH also occurs if lodging is not reduced.

1. Introduction

Maize (*Zea mays* L.) is one of the most important crops in the world. With the rapidly increasing demands for food, livestock feed and bio-fuel at a global scale, the demand for maize is increasing (Cassman and Liska, 2007; Cassman et al., 2003; Grassini et al., 2011). China is the second largest maize producer in the world (Ci et al., 2012). The total maize area in China was more than 33 million ha in 2011, with a total production of 192 million t (National Bureau of Statistics of China (NBSC), 2012). Maize production in Heilongjiang province, northeast China, accounted for about 13.9% of the national total. This area has many large scale national farms with mechanized crop management and high yields (Liu et al., 2012).

High plant densities are needed to obtain high yield in maize (Tokatlidis et al., 2011). However, high plant densities result in thinner maize stems that increase the risk of lodging, which has a detrimental effect on yield (Tokatlidis et al., 2010; Esechie, 1992; Cardwell, 1982), e.g. 5–25% yield loss annually in America due to lodging (Norberg et al., 1988). Using conventional breeding and biotechnology, maize cultivars have been produced that are shorter and have stronger stems (Teng et al., 2013; Hu et al., 2013; Tang et al., 2007).

Shorter plants can also be obtained by applying plant growth regulators (PGR) (Shekoofa and Emam, 2008). PGRs have only recently been introduced to control lodging in maize (Schluttenhofer et al., 2011) and spring wheat (Wiersma et al., 2011). PGRs can optimize plant morphology and increase yield through regulation of plant endogenous hormone signaling and metabolism (Zeng et al., 2012; Naeem and Khan, 2012). A number of different PGRs have been applied in crop production, such as ethephon (Tripathi et al., 2003), chlonitequat chloride (Ramburan and Greenfield, 2007; Dahnous et al., 1982) and uniconazole (Schluttenhofer et al., 2011).

Ethephon (2-chloroethyl phosphonic acid) is a plant growth regulator that inhibits stem elongation and promotes stem thickness, thereby improving plant morphological resistance to

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lodging (Dahnous et al., 1982). Application of ethephon is associated with reductions in plant height, leaf area index and crop growth rate (Shekoofa and Emam, 2008), decreasing lodging by 85–93% but also slightly decreasing yield, by 2–6% (Khosravi and Anderson, 1991). Yield reduction in maize increases with the rate of ethephon (Early and Slife, 1969).

DA-6 (diethyl aminoethyl hexanoate) is a new plant growth promoter (He et al., 2013), which is applied in China on vegetables, maize, soybean, cotton, tomato and peanut to increase chlorophyll content and photosynthesis rate (Jiang et al., 2012). DA-6 can increase yield of summer maize (Nie et al., 2010). An analytical method for determination of DA-6 in plants and soil is described by Zhang et al. (2008).

Dong et al. (2006) investigated whether combining ethephon with DA-6 could offset the yield disadvantages of ethephon, and thus achieve higher yield in combination with lower risk of lodging. They found that the combination of ethephon and DA-6 shortened length and increased diameter of internodes below ear position at 6 plants m^{-2}, improving lodging resistance and yield of maize. The mixture of ethephon and DA-6, termed EDAH, was issued an invention patent in 2006 (CN1278611C, China, 2006). EDAH has since been used in maize production on more than 0.3 million ha per year in the northeast of China, the so-called Golden Maize Belt. Limited information is yet available on the effectiveness of EDAH at different plant densities, in different maize genotypes, and under varying environmental conditions. Moreover, the relationships between yield increase and lodging in response to EDAH have been little explored. Therefore, the objectives of this study were to (i) quantify the effects of plant density, EDAH and their interactions on maize yield, yield components and quality for two maize cultivars in two years, and (ii) derive optimal management strategies for improvement of yield in northeast of China. This is, to our knowledge, the first report on the effects of EDAH on maize yield, quality, plant height and lodging in relation to plant density.

2. Materials and methods

2.1. Experimental design

Field trials were conducted in 2012 and 2013 at Heilongjiang National Model Agriculture Demonstration Zone (Long. 126°36′ E, Lat. 45°42′ N, Elev. 135 m) in Harbin, Heilongjiang province, China. The soil is a typical black soil (typic hapludoll in USDA soil taxonomy), characterized by a deep, high organic matter content, nutrient-enriched upper layer with pH 7.2, 33.7 g kg^{-1} of organic matter, 1.5 g kg^{-1} of total N, 45.6 mg kg^{-1} of available P, and 226.6 mg kg^{-1} of available K in the top 0–40 cm arable soil layer. Climate in the region is a temperate continental monsoon. Weather data in 2012 and 2013 are given in Table 1.

Maize was hand-sown at 7 cm depth and 70 cm row distance on May 1 in 2012 and on May 6 in 2013. Seeds were coated to prevent pests and fungi. Two commonly used hybrid cultivars were used in the trials: the comparatively short-stemmed hybrid Zhengdan 958 (ZD 958) and the taller hybrid Pioneer 335. EDAH, a commercially released product (Haolun Co., China) containing 27% ethephon and 3% DA-6 as active ingredients, was applied by a back-pack sprayer at a rate of 450 ml ha^{-1} at the stage of 7 expanded leaves stage (V7) (Abendroth et al., 2011), in the afternoon (16:00–19:00). The tested plant densities were 6.0, 7.5, and 9.0 plants m^{-2} in 2012, and 4.5, 6.0, 7.5 and 9.0 plants m^{-2} in 2013.

Both experiments were laid out as a split plot design with three replicates. The main plot treatment was plant density. The sub-plot treatments were cultivar and EDAH, which were randomized within the main plot. Each sub-plot consisted of 15 rows of maize and had a total area of 52.5 m^2 (10.5 m wide and 5 m long). Fertilizer application followed high yield practice with a base fertilizer gift of 75 kg N ha^{-1}, 75 kg P_2O_5 ha^{-1}, 90 kg K_2O ha^{-1}, and a top dressing with 150 kg ha^{-1} of urea at 7 expanded leaves stage and 75 kg ha^{-1} (46% N) at tassel stage (VT). The experiment was rain-fed. No herbicides or pesticides were applied during the growing season.

2.2. Measurements

To determine yield, fourteen square meters of maize (5 rows × 4 m row length) were hand harvested from each plot at crop maturity on 27th and 28th September, 2012 and 2013. All harvested areas were surrounded by 2 guard rows. Ear density (number of ears per unit ground area), ear weight, ear size (ear length and ear diameter) were measured. Kernel number per ear and 1000-kernel weight (TKW) was measured on 10 randomly selected ears per sub-plot. Grain moisture content was determined on 5 replicate samples using the M-8188 NEW Grain Moisture Analyzer (KETT, Japan). Grain yield and 1000-kernel weight were converted to yield using a fixed grain water content of 14.0%.

Grain quality (protein, oil and starch content) was measured in 2013 by near-infrared reflectance spectroscopy (NIRS; Vector 22/N, Bruker, Germany) (Jiang et al., 2007). Each sample was tested 3 times to eliminate measurement error.

All plants in 14 m^{-2} in each plot were evaluated at milk stage (R3) (18th August) and subsequently at dough (R4) stage (18th September) in both years to determine the percentage of lodged plants. If the plant stem angle with the vertical at the basis was greater than 30°, we classified a plant as lodged. Lodging at milk stage was minimal (<3%) in both years and mainly caused by field management. In 2012, all plants had lodged in all treatment plots due to a typhoon (maximum wind speeds of 18 m s^{-1}) on 29th August, and they did not recover. Hence, lodging was uniformly 100% at dough stage in 2012. In the analysis, we focus on lodging effect at dough stage in 2013.

Table 1
Daily mean values of weather variables at experimental site during each of six months of the maize growing season in 2012 and 2013.

Month	Average temperature (°C)		Precipitation (mm)		Sunshine hours (h)		Maximum instantaneous wind speed ($m\,s^{-1}$)	
	2012	2013	2012	2013	2012	2013	2012	2013
April	7.8	4.4	38.1	10.8	183.0	202.3	10.55	11.60
May	16.4	17.9	28.8	73.5	230.5	240.7	8.84	11.65
June	21.3	21.4	154.7	86.4	167.5	151.7	8.11	9.82
July	23.9	23.9	129.9	198.0	135.7	195.1	7.16	8.59
August	21.8	22.5	214.7	125.7	203.8	163.7	7.22	9.20
September	16.4	15.8	81.9	31.5	155.8	230.1	6.94	8.95
Total[a]	17.9	17.7	648.1	525.9	1076.3	1183.6	8.13	9.96

[a] Precipitation and sunshine are monthly sums, while temperature is a monthly mean of daily means, and maximum instantaneous wind speed is a monthly mean of the daily maximum values.