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Effects of nitrogen application rate on grain yield and grain nitrogen concentration in two maize hybrids with contrasting nitrogen remobilization efficiency

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ABSTRACT

A target in crop production is to simultaneously increase grain yield (GY) and grain nitrogen concentration (GNC). In maize, nitrogen (N) and genotype are two major factors affecting GY and GNC. Both N remobilization from vegetative tissues and post-silking N uptake contribute to grain N, but their relative contributions are genotype specific, and are affected by the N application rate. It is unclear whether the responses of GY and GNC to N application differ between genotypes with different post-silking N uptake and vegetative N remobilization characteristics. We investigated the effect of N application rate on post-silking N uptake, vegetative N remobilization, GY, and GNC of two high-yielding maize hybrids, ZD958 and XY335, which have contrasting N remobilization characteristics. We tested five N application rates (0, 60, 120, 180, 240 kg N ha^{-1}) in a 4-year field study (from 2010 to 2013). There was a significant year × N × genotype interaction in the amount of vegetative N remobilization and N remobilization efficiency (NRE), and residual stalk N concentration at maturity. Compared with the low-NRE cultivar ZD958, XY335 showed the same GY but higher GNC because it had higher vegetative N remobilization, NRE but lower residual stalk N concentration under the favorable weather condition in 2010. The response of GNC to increasing N levels was the same between XY335 and ZD958 and was not affected by year conditions. The N level required to obtain the highest GY was the same in the two hybrids (156 ± 13 kg ha^{-1} and 159 ± 19 kg ha^{-1}), but that required to obtain the highest GNC was greater in XY335 (216 ± 30 kg ha^{-1}) than in ZD958 (195 ± 23 kg ha^{-1}). From these results, we conclude that precise N fertilizer management as well as the selection of high-yielding hybrids with high NRE can increase GNC without negatively affecting GY or leading to surplus N storage in vegetative organs.

1. Introduction

Along with rice and wheat, maize (*Zea mays* L.) is one of the three major cereal crops worldwide. Maize accounts for more than one-third of cereal production in China (FAO, 2012). During the past 40 years, maize breeding has resulted in dramatic increases in grain yield (GY) (Chen et al., 2013). In contrast, the grain nitrogen concentration (GNC) has become lower in recent modern hybrids (Ciampitti and Vyn, 2012, 2013; Duvick, 2005). For example, in the United States from the 1930s to the 1990s, maize GY per unit area increased by approximately 120%, while the GNC decreased by approximately 35% (calculated from the results of Duvick and Cassman, 1999). Therefore, how to achieve high GNC and high GY simultaneously in maize is an important problem facing global food security and nutritional quality (Onimisi et al., 2009).

In maize, nitrogen (N) availability and genotype are two major factors affecting GY and GNC. Both remobilization of vegetative N, and N taken up at the silking and post-silking stages contribute to grain N. Unfortunately, high GY also relies on leaf longevity, which depends on the balance between post-silking N uptake and remobilization of vegetative N. Because of the complex interactions among N uptake, N remobilization, dry matter (DM) production,

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Abbreviations: DM, dry matter; DW, dry weight; GNC, grain nitrogen concentration; GY, grain yield; NRE, nitrogen remobilization efficiency.

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GY, and GNC, selecting hybrids with a high GNC as the sole target has often resulted in low GY (Uribelarrea et al., 2007). This is because more efficient N remobilization from the leaves leads to a decrease in DM production at the post-silking stage. The relative contributions of remobilized vegetative N and N taken up at the silking and post-silking stages to grain N are affected by the level of N application (Chen et al., 2013; Mi et al., 2003), and by genotype (Ciampitti and Vyn, 2012; Coque and Gallais, 2007). Increasing the amount of N fertilizer applied to maize can increase post-silking N uptake, delay leaf senescence, and maintain photosynthetic activity, thereby increasing GY (Ding et al., 2005; Huang et al., 2007; Wada et al., 1993). However, increasing N supply may simultaneously decrease N remobilization efficiency (NRE) of the N accumulated at the pre-silking stage (vegetative N), and therefore does not necessarily increase GNC (Fowler, 2003). A N supply higher than optimum rate for GY can increase GNC (Berenguer et al., 2009; Chen et al., 2010; Masoero et al., 2011), but may increase the amount of residual N in vegetative organs (Chen et al., 2010; Hou et al., 2012). During breeding of modern stay-green varieties, maize plants are generally grown under high N inputs and in fertile soils (Bertin and Gallais, 2000). Compared with the older senescent hybrids, the stay-green cultivars typically show higher post-silking N uptake, but lower N remobilization (He et al., 2004; Mi et al., 2003; Pommel et al., 2006; Rajcan and Tollenaar, 1999b; Ciampitti and Vyn, 2012, 2013). For these kinds of cultivars, supra-optimum N supply may further decrease N remobilization, resulting in more residual N in straw, but not an increase in GNC (Matson et al., 1997; Kosgey et al., 2013; Shanahan et al., 2008). The desired trait would be that increasing N supply increases GNC without substantially affecting the amount of residual N in vegetative organs.

The Northeast China Plain accounts for 35% of the total maize crop in China (Yang et al., 2007). From their release until the present day, XY335 and ZD958 have been the main hybrids cultivated in Northeast China (Zhao et al., 2011). Compared with ZD958, XY335 has the same GY potential but higher GNC and NRE (Chen et al., 2014). It remains unclear whether the responses of post-silking N uptake and N remobilization to increasing N supply differ between these two cultivars. In this study, we analyzed the responses of GY, GNC, DM accumulation, and N remobilization in these two high-yielding maize hybrids to increasing levels of N supply. The aim of this study was to understand the physiological mechanism to achieve high GY and high GNC by combining precise N fertilizer management with a suitable hybrid.

2. Materials and methods

2.1. Plant materials

We used two maize hybrids in this study. ZD958 was developed in 1996 by the Henan Academy of Agricultural Science, Henan Province, China. XY335 was developed in 2000 by the Pioneer Technology Co., Tieling, Jilin Province, China. The green leaf area at physiological maturity was 2000–3000 cm^2 $plant^{-1}$ and 660–1000 cm^2 $plant^{-1}$ in ZD958 and XY335, respectively. XY335 was susceptible to northern corn leaf blight.

2.2. Field site, cultural practices and treatment arrangements

Field experiments were conducted over four consecutive years (2010–2013) at Fu-jia-jie, located near Siping (43°17′ N, 124°26′ E), Jilin Province, China. This area is typical of the rain-fed spring maize regions in Northeast China. The soil is sandy and is classified as Cryopsamments according to the USDA Soil Taxonomy system (Soil Survey Staff, 1998). The physical and chemical characteristics of the soil (0–30 cm) at the start of the experiment were tested on 28 April 2010. These characteristics were as follows: bulk density 1.47 g cm^{-3}, organic matter 8.3 g kg^{-1}, total N 0.66 g kg^{-1}, alkali-hydrolyzable N 59.2 mg kg^{-1}, available phosphorus (Olsen-P) 31.0 mg kg^{-1}, ammonium acetate extractable potassium (K) 100.0 mg kg^{-1}, and pH 6.24 (1:2.5 g/v).

We used a split-plot experimental design with four replicates, with N fertilizer treatments in the main plots and the two maize hybrids in the sub-plots. The sub-plots were 4-m long, with six rows spaced 60 cm apart. Plots were fertilized with 85 kg ha^{-1} P_2O_5 and 90 kg ha^{-1} K_2O before sowing. The five N-fertilization treatments were: (1) no N application (N0); (2) 60 kg N ha^{-1} (N60, as urea); (3) 120 kg N ha^{-1} (N120); (4) 180 kg N ha^{-1} (N180); and (5) 240 kg N ha^{-1} (N240). For the N60 treatment, all of the N fertilizer was applied before sowing. For N120, N180, and N240 treatments, half of the N fertilizer was applied before sowing and the other half at the V8 stage. The same sub-plots were used for each treatment in successive years.

Maize seeds were seeded with hand broadcast on 7 May 2010, 8 May 2011, 3 May 2012, and 1 May 2013. At the V3 stage, seedlings were thinned to a density of 60,000 plants ha^{-1}, which is the optimum population density for maize hybrids in this region. The plants were harvested at physiological maturity on 25 September 2010, 27 September 2011, 20 September 2012, and 25 September 2013. Plots were kept free of weeds, insects, and diseases with chemicals based on standard practices. No irrigation was applied. Daily rainfall data were obtained from the Siping Meteorological Bureau, and were collected at an automated weather station located approximately 20 km from the experimental field. Rainfall was 580 mm, 401 mm, 407 mm, and 502 mm in 2010, 2011, 2012, and 2013, respectively (Fig. 1S). Based on the evapotranspiration in this area (Zhang et al., 2006), the calculated potential soil moisture deficit in each season was 106, −67, −73, and 28 mm, respectively. Among the experimental years, the weather in 2010 was most favorable for maize growth. In 2011, apart from the low rainfall (especially in the autumn), there was severe stalk rot disease during grain filling stage which resulted in early senescence of the plants. The rainfall in 2012 was also low but evenly distributed throughout the growing season. The high rainfall in 2013 was mostly due to heavy rain approximately 110 d after sowing, whereas rainfall was scare in the early spring (Fig. 1S).

Supplementary Fig. 1S related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.eja.2014.09.008.

2.3. DM and N accumulation and remobilization, and yield measurement

At silking (R1 stage) and physiological maturity (R6 stage), three plants from each plot were cut at the soil surface and separated into leaves, stalks (leaf sheaths, tassel, husks, and either cobs at R6 or ear-shoots at R1), and grain. All samples were heat-treated at 105 °C for 30 min, dried at 70 °C to a constant weight, weighed to obtain dry weight (DW), and then ground into fine powder. Appropriate amounts (0.3–0.5 g) of ground plant materials were used to determine the total N content by a modified Kjeldahl digestion method (Nelson and Somers, 1973). At physiological maturity, two rows were harvested to measure yield. We counted the number of ears in the two harvested rows. Grain was oven-dried to determine the grain moisture content at harvest. Grain yield was standardized to 14% moisture. We determined 100-grain weights and calculated the grain number per ear based on grain yield, ear number, and grain weight.