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Characterization of the plant traits contributed to high grain yield and high grain nitrogen concentration in maize

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ABSTRACT

During the past several decades, maize (*Zea mays* L.) grain yield (GY) has increased dramatically, while grain nitrogen concentration (GNC) has declined in modern hybrids. Genetic improvement to increase both high GY and GNC is necessary to improve maize nutritional quality. In the present study, we characterized the plant traits in three maize cultivars (YD13, ZD958, XY335) with contrasting GY and GNC in a two-year field experiment in two soils (Fu-jia-jie with infertile sandy soil and Quan-yan-gou with fertile clay soil). The hybrid YD13 as a control had low yield and high GNC. In comparison to YD13, ZD958 had higher GY but lower GNC, whereas XY335 had higher GY and similar GNC. Both ZD958 and XY335 had higher total and post-silking dry matter (DM) accumulation and N uptake than YD13, and were also characterized by delayed leaf senescence and a sustained net photosynthetic rate after silking. In addition, XY335 also had higher N remobilization efficiency (NRE) and higher photosynthetic nitrogen use efficiency (PNUE) than ZD958. It is supposed that higher NRE together with higher N and DM accumulation are the target traits to improve the modern stay-green cultivars to increase GNC without penalty in GY in the area of northeast China. Increasing PNUE of the leaves may be a possible way to maintain whole-plant photosynthesis and DM accumulation under efficient N remobilization.

1. Introduction

Modern agriculture is concerned with crop yield and nutritional quality, as well as the impact of environmental conditions. Maize (*Zea mays* L.) is one of the world's three major cereal crops (along with rice and wheat). Breeding for high yielding hybrids with high grain nitrogen concentration (GNC) is important for improving the nutritional quality of maize used as animal feed. During the past 40 years, maize breeding has been largely responsible for dramatic increases in grain yield (GY) (Duvick, 1992; Khush, 1999; Tollenaar, 1989). In contrast, GNC has declined in more recent modern hybrids (Ciampitti and Vyn, 2012, 2013; Duvick, 2005). From the 1930s to the 1990s, for example, maize GY per unit area increased in the United States by about 120%, while GNC declined by about 35% (calculated from the results of Duvick and Cassman, 1999). Based on the declining GNC trend, Ciampitti and Vyn (2012, 2013) have shown that modern hybrids have achieved superior N use efficiency. One reason for the declining of GNC may be that leaves tend to stay green at maturity in the new high-yielding hybrids (Duvick, 2005; Tollenaar and Lee, 2006). This stay-green character is dependent on increased post-silking N absorption from the soil and decreased N remobilization from vegetative organs (Mi et al., 2003; Rajcan and Tollenaar, 1999b). Unfortunately, grain N is also derived from post-silking N uptake and remobilization from pre-silking accumulated N of vegetative organs. In the review of Hirel et al. (2007), 45–65% of the grain N is provided from pre-existing N in the stover. An early study by Swank et al. (1982) suggested that GNC in maize was best related to variations in the availability of N from the vegetative organs. Compared to senescent hybrids, stay-green maize hybrids have lower N remobilization efficiency (NRE) and slightly higher post-silking N uptake (He et al., 2004; Mi et al., 2003; Pommel et al., 2006). Although high GNC can be theoretically achieved by improvement of remobilization of pre-silking accumulated N in stalks, increasing N remobilization may facilitate leaf senescence, decrease post-silking dry matter (DM) production and lead to GY reduction. In addition, several authors have uncovered a strong negative association between N remobilization and post-silking N uptake (Ciampitti and Vyn, 2012; Coque and Gallais, 2007, 2008; Pan et al., 1986). Modern breeding has been typically conducted at high N input and in fertile soils and breeders have paid much more attention to N uptake, stay-green and GY (Bertin and Gallais, 2000). Plant traits related to the coordination between GY and GNC, and between post-silking N uptake and N remobilization are largely overlooked. Without this knowledge in

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mind, breeding for high GNC may result in a GY penalty (Uribelarrea et al., 2007). There are significant genotypic differences in N uptake and utilization efficiency, GNC and amino acid concentration in maize germplasm (Feil et al., 1990; Moll et al., 1982; Scott et al., 2006; Uribelarrea et al., 2007, 2009). To explore the maize germplasm for breeding high GNC and high GY cultivars, an understanding of the plant traits related to the coordination of GNC and GY is essential.

The Northeast China Plain is one of the most important areas in China for spring maize production, producing 35% of the total maize production in China (Yang et al., 2007). As found in the USA (Ciampitti and Vyn, 2012, 2013; Duvick, 2005), modern hybrid planted in this area also showed a increase in stay-green and a decrease in GNC although the yield level of the high-yielding hybrids in rain-fed conditions was only about 12 Mg ha^{-1} (Chen et al., 2013). Based on the previous study in Chen et al. (2010, 2013), we identified three maize hybrids with contrasting yield potential and GNC. Hybrid YD13 had low yield (about 10 Mg ha^{-1}) with high GNC, ZD958 had high yield (about 12 Mg ha^{-1}) with low GNC and XY335 had high yield (about 12 Mg ha^{-1}) with high GNC. Taking advantage of these hybrids, we further analyzed their N and DM accumulation and remobilization in the stalk and leaves, leaf area and photosynthesis in different environments. The genotype × environment on these parameters were also evaluated. The aim was to characterize the plant traits contributing to the coordination of high GY and high GNC in maize.

2. Materials and methods

2.1. Plant materials

Three maize hybrids were used in this study. YD13 was developed at the Laizhou Academy of Agricultural Sciences in 1989, Shandong, China (Zhao et al., 2011). ZD958 was developed by the Henan Academy of Agricultural Science, Henan Province, China, in 1996. XY335 was developed in 2000 by Pioneer Technology Co., Tieling, Jilin Province, China. These hybrids were the dominant hybrids used in Northeast China during the decades of their release (Zhao et al., 2011), and ZD958 and XY335 are still the dominant ones now.

A portion of the data (GY, GNC and N uptake of the whole plant) for the tested three genotypes collected from Quan-yan-gou and averaged over 2 years has previously been published in Chen et al. (2013), which focused on the effect of breeding on maize yield potential. In the study presented here, we focused on the comparison of plant traits related to N and DM accumulation and remobilization in leaves and stalks among three cultivars with contrasting GY and GNC. Consequently, data collected from Quan-yan-gou in 2010 and 2011 are presented here in greater detail.

2.2. Experimental design

Field experiments were conducted in 2010 and 2011 at two sites, Fu-jia-jie and Quan-yan-gou, located near Siping (43°17′ N, 124°26′ E), Jilin Province, China. This area is typical of rain-fed spring maize regions in Northeast China. The two sites were 50 km apart. In Fu-jia-jie, the soil is sandy and is classified as Cryopsamments according to the USDA Soil Taxonomy system (Soil Survey Staff, 1998). Soil physical and chemical characteristics at the onset of the experiment 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). In Quan-yan-gou, the soil is a black soil and is classified as Hapludoll according to the USDA Soil Taxonomy system (Soil Survey Staff, 1998). Its physical and chemical characteristics at the onset of the experiment were: bulk density 1.68 g cm^{-3}, organic matter 17.5 g kg^{-1}, total nitrogen (N) 1.2 g kg^{-1}, alkali-hydrolyzable N 176 mg kg^{-1}, available phosphorus (Olsen-P) 28.4 mg kg^{-1}, ammonium acetate extractable potassium (K) 110.0 mg kg^{-1} and pH 5.4 (1:2.5 g/v).

The experimental design was a randomized block design with four replicates at each site in each year. The plots were 4 m long, with six rows spaced 60 cm apart. Plots were fertilized with 240 kg N ha^{-1}, 85 kg ha^{-1} P_2O_5 and 90 kg ha^{-1} K_2O. Phosphorus and potassium fertilizer were applied before sowing. Half of the N fertilizer was applied before sowing, and the other half was applied at the V8 stage.

Maize was over-seeded on 7 May 2010 and 8 May 2011 in Fu-jia-jie, and on 9 May 2010 and 4 May 2011 in Quan-yan-gou. At the V3 stage at both sites, seedlings were thinned to a density of 60,000 plants ha^{-1}, which is the optimum population for maize hybrids grown in the experimental areas. Hybrids were harvested on 25 September 2010 and 27 September 2011 in Fu-jia-jie, and on 18 September 2010 and 6 October 2011 in Quan-yan-gou. Plots were kept free of weeds, insects and diseases with chemicals based on standard practices. No irrigation was applied. Daily rainfall data were obtained through the Siping Meteorological Bureau from an automated weather station approximately 20 km from the experimental field. Rainfall was 580.1 mm and 400.7 mm in 2010 and 2011, respectively (Fig. 1S). The higher seasonal rainfall in 2010 was mostly due to a heavy rain of about 110 mm occurred approximately 90 days after sowing. A severe spring drought also occurred in that year. In 2011, rainfall was relatively evenly distributed throughout the growing season, although little rainfall was recorded in late autumn.

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2014.01.002.

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 the dry weight (DW), and then ground into fine powder. Appropriate amounts (0.3–0.5 g) of ground plant materials were used to determine total N content by a modified Kjeldahl digestion method (Nelson and Somers, 1973). At maturity, two rows were harvested for yield measurement. Grain was oven-dried to determine grain moisture at harvest. Grain yield was standardized to 14% moisture. One hundred-grain weights were determined and grain number per ear was calculated.

Based on these measurements, we calculated the following parameters (Chen et al., 2013; Mi et al., 2003):

Stalk DM remobilization efficiency (%) = 100 × (stalk DW at silking − stalk DW at maturity)/stalk DW at silking.
Leaf DM remobilization efficiency (%) = 100 × (leaf DW at silking − leaf DW at maturity)/leaf DW at silking.
Contribution to grain DM by stalk DM remobilization (%) = 100 × (stalk DW at silking − stalk DW at maturity)/grain DW at maturity.
Contribution to grain DM by leaf DM remobilization (%) = 100 × (leaf DW at silking − leaf DW at maturity)/grain DW at maturity.
Stalk N remobilization efficiency (%) = 100 × (stalk N content at silking − stalk N content at maturity)/stalk N content at silking.