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Yield potential and yield stability of Argentine maize hybrids over 45 years of breeding

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ABSTRACT

Maize (*Zea Mays* L.) grain yield have increased during the last decades and there is an ample range of rates of grain yield increments reported in the literature. Maize hybrids comparison at their optimum plant density might contribute to elucidate the yield potential increments during the last decades. In addition, high plant density testing and multi-location trials in modern breeding programs might have contributed to greater stress tolerance in modern hybrids. Then, a close relationship between tolerance to high plant density and yield stability in hybrids released in different decades is expected. The objectives of this study were (i) to determine the optimum plant density and the gain in yield potential and its components, and (ii) to test the hypothesis that tolerance to high plant densities and yield stability are strongly associated, for Argentinean maize hybrids released between 1965 and 2010. One set of experiments was conducted at Balcarce, Argentina during five growing seasons (Exps. 1–5), each experiment included a combination of plant densities (1.5–20 plants m^{-2}) and hybrids released in different years (1965–2010). Data from these experiments were used to estimate optimum plant density, gains in yield potential and tolerance to high plant density. Another experiment (Exp. 6) included 18 trials conducted in a wide range of environments and data from these trials were used to estimate yield stability. The optimum density to attain the maximum yield ranged from 9.7 to 16.4 pl m^{-2} and it did not present a clear trend with the year of hybrid release. Yield potential increased at a rate of 0.83% or 107 kg ha^{-1} $year^{-1}$ ($p < 0.001$) and yield increments were attributed mainly to gains in kernel number per unit area and to biomass production steady increments during the 1965–2010 period. Harvest index contributions to yield increments were important for the period 1980–1993, but HI remained stable during the last two decades. Yield stability increased with the year of hybrid release, in accordance with higher mean yields and lower CV (coefficient of variation) across environments of modern compared with older hybrids. Tolerance to high plant densities increased during the last 45 years and it was direct and significantly associated with yield stability, providing strong bases for the use of high plant densities as a method to attain gains in yield stability.

1. Introduction

Maize (*Zea mays* L.) grain yield has increased at a rate of 110 kg ha^{-1} $year^{-1}$ between 1965 and 2014 in Argentina (FAOSTAT, 2016) and this increment was attributed to genetic gains, the improvement of management practices and an interaction between these two factors (Eyherabide et al., 1994). Genetic gain in grain yield ranged from 74 to 170 kg ha^{-1} yr^{-1} for different time periods between 1930–2004, in the US corn belt, Argentina and Brazil (Cunha Fernandes and Franzon, 1997; Duvick, 2005; Eyherabide et al., 1994; Eyherabide and Damilano, 2001). In particular, genetic gain in yield potential (i.e. when hybrids were grown in environments to which they are adapted and with no resource availability limitations) ranged from 132 to 166 kg ha^{-1} yr^{-1} in Argentina between 1965 and 1997 (Echarte et al., 2000; Luque et al., 2006). Genetic gains in yield potential ranged from null to as high as 196 kg ha^{-1} yr^{-1} for hybrids released in USA from 1985 (Campos et al., 2006). Contrasting results among studies could be related

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to the sampling method (i.e. machine- vs. hand-harvested crops), the approach to calculate genetic gain (i.e. average yield at different plant densities vs. yield at optimum plant density), the period under study and the interaction between genotype and environment (Tollenaar and Lee, 2002).

Comparison of hybrids released at different decades at their optimum plant density (D_{op}) should better reflect the genetic yield potential increments with the year of hybrid release. The response of maize grain yield to plant density (D) is curvilinear and the plant density that results in the highest grain yield is defined as the optimum plant density for grain yield. Maize hybrids differ in their response to plant density (Echarte et al., 2000; Sangoi et al., 2002). In Argentina, hybrids released in the 1990s out-yielded older ones in a wide range of plant densities (Echarte et al., 2000; Luque et al., 2006). In contrast, little or no increments in grain yield at low plant densities were reported for the US corn belt hybrids (Duvick and Cassman, 1999; Tollenaar and Wu, 1999). In France, the optimum plant density increased about 0.96 plants m^{-2} every 10 years for the 1950–1985 period (Derieux et al., 1987); and similar optimum plant density increments were reported for the U.S. Corn Belt for the 1920–1980 period (Russel, 1984). In addition, (Tollenaar, 1989) reported higher optimum plant densities for 1980s hybrids than for hybrids released in the 1950s.

During the last decades, breeding programs have increased the plant densities at which they test hybrid performance (Tokatlidis and Koutroubas, 2004; Troyer, 1996). In particular, plant density used in breeding programs in Argentina were 4 plants m^{-2} in the 1960s and 8.5 plants m^{-2} currently (Eyherabide et al., 1994). Therefore, higher optimum plant density might be expected in modern than in older maize hybrids. In addition, modern breeding programs test inbred lines and hybrids in a large number of locations (Troyer, 1996). It has been suggested that this type of maize testing (i.e. high plant density and multi-location trials) has contributed to stress tolerance in modern maize hybrids (Tokatlidis and Koutroubas, 2004; Troyer, 1996). Accordingly, performance of hybrids at high plant density (Duvick et al., 2004; Echarte et al., 2000; Tollenaar and Lee, 2002), low soil N availability (Echarte et al., 2008; Rajcan and Tollenaar, 1999), and low soil water availability (Duvick and Cassman, 1999; Nagore et al., 2014) was better in modern than in older maize hybrids. A close relationship between tolerance to high plant density and yield stability across hybrids released in different decades is expected. To the best of our knowledge there is no report in the literature testing this hypothesis.

The objectives of this study were (i) to determine the optimum plant density and the gain in yield potential, and (ii) to test the hypothesis that tolerance to high plant densities and yield stability are strongly associated, in Argentinean maize hybrids released between 1965 and 2010.

2. Material and methods

2.1. Optimum plant density and yield potential

2.1.1. Site and crop management

Crops were grown at Balcarce, Argentina (37°45′S, 58°18′W; elevation 130 m) during 1996–1997 (Exp. 1), 1998–1999 (Exp. 2), 2009–2010 (Exp. 3), 2010–2011 (Exp. 4) and 2012–2013 (Exp. 5). The soil was a Typic Argiudoll with a depth of 1.5 m and with 5.6% topsoil organic matter. Hybrids were sown on October 10 (Exp. 1), October 15 (Exp. 2), October 14 (Exp 3), October 20 (Exp 4) and October 24 (Exp 5). Crops were fertilized with 35 kg P ha^{-1} before sowing and with 150 kg N ha^{-1} at V6 (Ritchie and Hanway, 1982). These rates were calculated using locally adjusted models based on soil analysis and target yield for modern maize hybrids (Barbieri et al., 2008). Soil water to 1 m depth was kept over 60% of available water by sprinkler irrigation in all experiments. Weeds and insects were adequately controlled. Mean temperature and mean daily incident photosynthetically active radiation per month from October to April of each experiment are shown in Table 2; average silking dates were January 14th, 6th, 6th, 14th, 10th for Exps. 1–5, respectively.

2.1.2. Plant material and experimental design

Table 1 shows hybrids used in each experiment and their characteristics. Hybrids selected for this study were among the eight most cultivated hybrids in the Argentinean Pampas for at least 5 years after their release. In addition, seven of the eight hybrids were developed by Dekalb-Monsanto, which had a high level of participation in the Argentinean market since its introduction; and currently has more than 50% of the market. In Exps. 1 and 2, the experimental design was a split plot randomized complete-block with three replications, in which plant density treatments were assigned to main plots and hybrids to subplots. In Exps. 3–5, the experimental design was a randomized complete-block design with three replications.

Plant densities were 5, 8, 11 and 14.5 plants m^{-2} in Exp. 1; 2, 4, 8 and 16 plants m^{-2} in Exp. 2; 5, 9.5, and 14 plants m^{-2} in Exps. 3 and 4 and 8, 14 and 20 plants m^{-2} in Exp. 5. Plots were over-sown and thinned to the desired densities at V3 (Ritchie and Hanway, 1982). Subplots comprised 4–7 rows, 7 m long in Exps. 1 and 2 and plots comprised 4 rows, 10 m long in Exps. 3, 4 and 5. Rows were 0.7 m apart in all the experiments.

2.1.3. Measurements

Grain yield per plant (Yp) and shoot dry matter per plant (Bp) were determined at physiological maturity; samples of 10–30 individual plants (depending on the plant density) were collected from the two central rows of each plot in a 3 m^{-2} area. Sample areas were bordered by at least 2 guard rows and at least 1 m in the row. Each plant was oven-dried (forced air at 65 °C) to constant weight, and weighed. Dry individual ears were separated from the plant and shelled. Grain yield per plant and its components were determined by counting and weighing all the kernels per uppermost and second ear. Individual kernel weight was calculated as kernels weight per ear divided by kernel number per ear; and values from all the plants in a plot were averaged to obtain mean individual kernel weight per plot. Grain yield results were expressed at 0% humidity.

2.1.4. Data analysis

Optimum plant density was estimated using a modified version of (Sarlangue et al., 2007) methodology; this methodology was chosen to obtain a more precise estimation of D_{op}. Poor estimates of D_{op} might be expected when fitting a quadratic function to the relationship between grain yield and plant density; since the degree of curvilinearity might be different at both sides of D_{op} due to distinctive processes affecting yield at low and at high plant densities (Echarte et al., 2004).

To calculate D_{op}, (i) the relationship between Bp and D was fitted with Eq. (1); this was done for each hybrid and experiment, since dry matter production is highly influenced by the environmental conditions (Aguilar and López-Bellido, 1996).

$$Bp = a_1 + (Bmax - a_1) * \left[1 - e^{\left(-b_1 * \frac{1}{D} \right)} \right] \quad If\ Bp > 0 \qquad (1)$$

This equation presents biologically meaningful parameters. Thus, *a1* is the intercept of the function and it represents the minimum ground area per plant required to produce shoot biomass; *b1* is the degree of curvature of the function; *B*max is the maximum

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