Potential of maize (*Zea mays* L.) populations derived from commercial single-cross hybrids for extraction of partially inbred lines under different nitrogen availability

Potencial de poblaciones de maíz (*Zea mays* L.) derivados de híbridos comerciales simples para extracción de líneas parcialmente endogámicas cultivadas bajo diferentes disponibilidades de nitrógeno

Rafael Heinz [1], Larissa Pereira Ribeiro Teodoro [2], Manoel Carlos Gonçalves [3], Leonardo de Azevedo Peixoto [1], Leonardo Lopes Bhering [4], Paulo Eduardo Teodoro [2*]

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Abstract

Extraction of inbred lines is a very important step in maize breeding since these lines will be used to obtain hybrids intended for the market. However, this expensive process, hinders genotype evaluation in contrasting environments, especially regarding nitrogen (N) content. This study aimed to evaluate the potential of maize populations for line extraction and select partially inbred lines under different soil nitrogen (N) availability. Five populations were evaluated regarding their potential for line extraction. Fifty-five S1 partially inbred lines were extracted from these populations. The top-cross method was used to evaluate lines by crossing them with two testers. Hybrids evaluation used 110 top-cross hybrids, five base populations, and six checks. Two trials were carried out in Dourados and Caarapó. One trial had adequate fertilization (high N) while the other was under stress condition (low N). Hybrid DKB 789 showed potential for extraction of partially inbred lines, aiming at selecting N use efficiency. Base population BP (07) was the most suitable for the extraction of partially inbred lines aiming at N use efficiency. Partially inbred lines BP (07) 13, BP (07) 14, and BP (07) 17 are the most suitable for the extraction of top-cross hybrids with high grain yield, efficiency, and responsiveness to N.

Keywords
breeding population • maize breeding • nitrogen • top-cross • *Zea mays*

1 Monsanto do Brasil. Av. das Nações Unidas, 12901, CEP 04578-000. São Paulo. SP. Brazil.
2 Federal University of Mato Grosso do Sul (UFMS/CPCS). Department of Crop Science. Chapadão do Sul. MS. Brazil. L.P.R. * eduteodoro@hotmail.com
3 Department of Crop Science, Federal University of Grande Dourados (UFGD). Dourados. MS. Brazil.
4 Federal University of Viçosa (UFV). Department of General Biology. Biometrics Laboratory. Viçosa. MG. Brazil.

Resumen

La extracción de líneas endogámicas es un paso muy importante para el mejoramiento del maíz, ya que estas líneas se utilizan para obtener híbridos destinados al mercado. Sin embargo, este es un proceso costoso que dificulta la evaluación de genotipos en ambientes contrastantes, especialmente respecto del contenido de Nitrógeno edáfico. El objetivo de este estudio fue evaluar el potencial de las poblaciones de maíz para la extracción de líneas y seleccionar líneas parcialmente endogámicas con diferente respuesta a la disponibilidad de nitrógeno (N). Se evaluaron cinco poblaciones en cuanto a su potencial de extracción de líneas. A partir de estas poblaciones, se extrajeron cincuenta y cinco líneas S1 (parcialmente endogámicas). El método de top-cross se usó para evaluar líneas cruzándolas con dos probadores. La evaluación de los híbridos utilizó 110 híbridos superiores, cinco poblaciones base y seis controles. Se realizaron dos ensayos en Dourados and Caarapó, uno con una fertilización adecuada (alto N) y otro en condiciones de estrés (bajo N). El híbrido DKB 789 mostró potencial para extraer líneas parcialmente endogámicas con el objetivo de mejorar la eficiencia de uso de N. La población base BP (07) fue la más adecuada para la extracción de líneas parcialmente endogámicas destinadas a eficiencia de uso de N. Las líneas BP (07) 13, BP (07) 14 y BP (07) 17 son las más adecuadas para la extracción de híbridos top-cross con alto rendimiento de grano, eficiencia y capacidad de respuesta a N.

Palabras clave

Población reproductora • mejoramiento de maíz • nitrógeno • top-cross • *Zea mays*

Introduction

Maize (*Zea mays* L.) is the most cultivated cereal in the world, being the main raw material for the production of poultry and swine feeding (15). Currently, Brazil is the third largest world producer, with 15.9 million ha and a total production of 66.5 million t (6). However, the average Brazilian yield (4.1 t ha^{-1} in the 2015/2016 harvest) is considered low when compared with the yield potential of the genotypes available in the market.

One of the main reasons for this low yield is the high demand for nitrogen (N) of the currently available genotypes. Nitrogen is essential for maize development since it acts in key biochemical processes, being part of proteins, coenzymes, nucleic acids, phytochromes, ATP, and chlorophyll (14). In Brazil, considering that maize is predominantly grown in the Cerrado region, which is characterized by soils with low organic matter content and unable to retain large amounts of N, the identification of genotypes with high N use efficiency may contribute to increasing the national average yield.

Maize breeding programs do not perform selection in poor-N environments due to the high environmental variation, consequently reducing heritability of grain yield (18). Selection in these environments is necessary given that the alleles that control yield under abiotic stress conditions are different from those that control yield under optimum conditions (9). Extraction of inbred lines is a very important step in maize breeding since these lines will be used to obtain the hybrids that will be distributed in the market (4). However, this process is expensive, which hinders the evaluation of these genotypes in contrasting environments in relation to N content.

In this context, using base populations to obtain partially inbred lines with high yield potential and N use efficiency is a promising strategy. The use of commercial hybrids as base population is a promising strategy mainly because these hybrids have already been tested in several environments and are associated with high yield with a large proportion of already fixed favorable loci (1). Thus, the identification of promising populations derived from superior hybrids is an interesting strategy to increase the efficiency of breeding programs (3).

Therefore, the objectives of this study were to (i) evaluate the potential of maize base populations to extract partially inbred lines with better efficiency under different N availability, and (ii) select superior lines to serve as parents of hybrids with higher N use efficiency.

Material and methods

Obtaining S1 progenies and top-cross hybrids

Five maize populations were evaluated for the potential of extraction of partially inbred lines. From these populations, 55 S1 partially inbred progenies were extracted, being 11 progenies from each base population studied. S1 Table shows the agronomic traits of the base populations evaluated.

Initially, S1 progenies of each population were obtained by self-pollination as described by Borém, 2009. In each population, 100 S0 plants were selected for vigor and type of plant. These plants were self-pollinated, and only upright plants were harvested. After harvesting, ears that had few seeds and showed disease symptoms were discarded, and the 11 best S1 progenies from each population were evaluated in top-cross. Self-pollination was carried out during the second half of 2011.

To obtain the top-cross hybrids, the progenies were sown in two isolated fields, interspersed with the testers. Two testers were used (T1 - a commercial single cross hybrid with good yield potential, and T2 – made up by f S1 progenies). Top cross hybrids were obtained in the 2011/2012 season, resulting in 110 hybrid progenies, which were denominated as top cross hybrids. The experiments evaluated 110 top cross hybrids, five base populations, and six commercial checks. The agronomic traits of the evaluated checks are shown in Table S1.

Top-cross hybrid evaluation

Evaluation trials of top-cross hybrids were carried out in 2012 off-season in the municipalities of Dourados and Caarapó, located in the state of Mato Grosso do Sul, Brazil. The trials were installed at the Experimental Farm of Agricultural Sciences of the Federal University of Grande Dourados (UFGD) (lat. 22°14'02" S, long. 54°59'17" W, at 406 m a. s. l.). In Caarapó, trials were installed at Urtigão Farm (lat. 22°38'45" S, long. 55°00'28" W, at 482 m a. s. l.). The climate of the region is classified as Cwa type; the temperature of the coldest month is lower than 18°C, and of the hottest month is higher than 22°C, with an accumulated average rainfall of 1,427 mm. Table S2 (Supplementary tables) shows the values for the chemical and granulometric analysis of the 0-20 cm soil layer of the experimental areas.

Two trials were carried out on each site. One trial was adequately fertilized (High N) and the other was kept under stress condition (Low N). The experiment consisted of an 11x11 lattice design, with two replications. The experimental unit consisted of a 5 m row, spaced by 0.90 m between rows and 0.20 m between plants, in Dourados; and by 1.0 m between rows and 0.18 m between plants, in Caarapó.

In the High N environment, a total of 120 kg ha^{-1} of N was used, incorporating 20 kg ha^{-1} at sowing and 100 kg ha^{-1} in topdressing. In the Low N environment, a total of 20 kg ha-1 was applied at sowing. The N levels were defined to induce stress in the genotypes, without reducing the genetic variability of the populations (13).

The experimental area of Dourados was cultivated under conventional tillage. Seeds were manually sown on February 15, 2012, using two seeds per furrow. The experimental area of Caarapó was cultivated under the no-tillage system, and sowing was carried out in succession to a soybean crop. Seeds were manually sown on March 09, 2012. In both sites, sowing fertilization consisted of 20 kg ha^{-1} of N, 50 kg ha^{-1} of Potassium, and 50 kg ha^{-1} of Phosphorus, according to the recommendations performed by (7), using the formula 08-20-20 + 0.4% Zn.

Crop thinning was performed at 15 days after emergence, by adjusting the density to 55,000 plants/ha. The first topdressing was performed when maize plants had four to five fully expanded leaves, and the second was carried out when plants had eight to ten fully expanded leaves (7). Other cultural practices were carried out according to the technical recommendations for maize cultivation. The central rows of each plot were manually harvested, and grain yield was extrapolated to t ha^{-1} and corrected to 13% moisture.

Analysis of variance

Individual analysis of variance for high and low N environments and joint analysis of variance for both environments were performed. Analyses were carried out using the SAS statistical software (16).

Individual analyses of variances for each environment (high and low N) were performed based on the following statistical model:

$$\mathbf{Yijk = \mu + ti + bj(k) + rk + eijk}$$

where:
Yij = value of treatment i in block J within replication k
μ = overall mean of the experiment
ti = effect of the hybrid (i = 1, 2, 3, ..., h) considered as fixed
bj(k) = random effect of the block within the replication (j = 1, 2, 3, ..., b)
rk = random effect of the replication (k = 1, 2)
eijk = random error associated with the Yijk observation.

Afterward, joint analysis of variance was performed considering the following mixed model:

$$\mathbf{Yijkl = \mu + al + bj(kl) + rk(l) + ti + (ta)il + eijkl}$$

where:
Yijkl = value of treatment i in block j within replication k in environment l
μ = overall mean of the experiment
ti = ixed effect of treatments (i = 1, 2, 3, ..., h)
al = random effect of environment l (l = 1, 2)
bj(kl) = random effect of the block within the replication in environment l (j = 1, 2, 3, ..., b)
rk(l) is the random effect of the replication (k = 1, 2) in environment l
(ta)il = effect of hybrids x environments interaction

eijkl = error associated with the Yijkl observation. Means were clustered according to the origin of the lines for the verification of whether the most yielding top-cross hybrids came from the same population. After the clustering, the Scott-Knott test (at 5% probability level) was used to compare the behavior of the hybrids.

Nutritional efficiency

The nutritional efficiency of the top-cross hybrids and base populations was evaluated using the method proposed by Fox (1978), which is based on the representation of the graphical position of the cultivars in the Cartesian plane, in order to classify them according to their nutritional efficiency and response to nitrogen. In this method, genotypes that appear in the first quadrant above and to the right of the point of origin are efficient in N use and responsive to N application. Genotypes that appear in the second quadrant above and to the left of the point of origin are efficient in N use and unresponsive to N application; genotypes that appear in the fourth quadrant below and to the left of the point of origin are inefficient in N use and unresponsive to N application; genotypes that appear in the fourth quadrant below and to the right of the origin point are inefficient in N use and responsive to N application.

Results and discussion

Analysis of variance

Individual analysis of variance of 110 top-cross hybrids and 11 checks, evaluated in two sites and in environments with high and low N level, was carried out to verify the significant differences between hybrids and checks. Significant effects of hybrids were observed for grain yield in both sites and in environments with high and low N level (S4 Table). Coefficients of variation of the experiments were lower than 25%. This value is similar to those found by other studies that evaluated maize populations at different N levels (2, 8, 11, 14, 18). Considering that genetic variability is essential for the success of a breeding program, these results are promising for the selection of partially inbred lines with N use efficiency.

After verifying that the relationship between the highest and the lowest mean square of the different N levels in each site was lower than seven, joint analysis of variance was performed in each site (S5 Table). Results revealed genetic variability among hybrids (H), which reinforces the possibility of selection of efficient lines and populations in relation to N use. The effect of nitrogen (N) levels was also significant in both sites, which shows that the levels used in this study were contrasting and adequate. However, the interaction between hybrids and nitrogen levels (HxN) was not significant in the sites, corroborating the results of Fidelis *et al.* (2005) and Silva Filho *et al.* (2001). Results indicate the possibility of selecting lines and populations that contribute to high yielding hybrids, regardless of the N level.

By unfolding the sources of variation as a function of the two testers used in this study, a significant effect for site (S), nitrogen (N), and hybrid (H) were observed (table 1, page 37). Nevertheless, interactions between these factors were not significant for any of the testers used, which shows the similar performance of the hybrids when evaluated at different N levels and sites. Moreover, a small decrease in the coefficients of variation was observed when the sources of variation were analyzed as a function of the testers.

Table 1. Summary of the joint analysis of variance for grain yield of 110 top-cross hybrids and 11 checks under high and low nitrogen (N) level in two sites regarding the testers.

Tabla 1. Resumen del análisis conjunto de la varianza para el rendimiento de grano de 110 híbridos top-cross y 11 controles en alto y bajo nivel de nitrógeno (N) en dos locales con respecto a los probadores.

Sources of variation	**DF**	**Mean Square**	
		Tester 1	Tester 2
Sites (S)	1	79632327.8*	27223697.5*
Nitrogen (N)	1	67062131.2*	11598608.7*
Hybrids (H)	54	2199956.9*	3083440.6*
SxN	1	3522541.3ns	1371787.8ns
SxH	54	1014538.5ns	1093413.6ns
HxN	54	871280.7ns	8394150.5ns
SxNxH	54	742528.0ns	756661.3ns
Residual	219	1301717.8	1346016.5
Mean		5085.8	4410.4
CV%		20.7	20.5

ns and *: not significant and significant at 5% probability by the F test, respectively; DF: degrees of freedom; CV: coefficient of variation.

ns y *: no significativo y significativo al 5% de probabilidad por la prueba F, respectivamente; DF: grados de libertad; CV: coeficiente de variación.

Performance of the top-cross hybrids under different N conditions

Regardless of the tester used to obtain the top-cross hybrids, the mean yield was higher under high N level (table 2, page 38). The mean among testers showed that top-cross hybrids yield in the high N environment was 5.0 t ha^{-1}, while the yield in the low N environment was of 4.5 t $ha^{-1.}$ Therefore, a decrease of 10.98% was reported in mean grain yield, demonstrating that maize is a plant with high response to N level, which evidences the adaptation of the materials to nitrogen stress. Souza *et al.* (2008) found a reduction of 23.20% in the mean grain yield in maize grown in low N soil in relation to maize grown in high N soil. Fidelis *et al.* (2005) reported a reduction of 60% in the mean grain yield in maize from different germplasm sources grown in low N environments when compared to those grown in high N environments.

Hybrids evaluated in Dourados had a higher yield than those grown in Caarapó, regardless of the tester. By using the mean between testers, the mean yield obtained in Dourados was 5.1 t ha^{-1}, while in Caarapó, the mean yield was 4.4 t ha^{-1}. The difference may be related to soil conditions since the soil of Caarapó is sandy and less fertile (S3 Table). Thus, besides the N level, other factors, such as soil texture and fertility, also influence grain yield in maize.

Table 2. Mean grain yield of top-cross hybrids evaluated under high and low nitrogen (N) levels in two sites regarding the testers.

Tabla 2. Rendimiento promedio de grano de los híbridos top-cross evaluados en niveles altos y bajos de nitrógeno (N) en dos locales con respecto a los probadores.

Sites	Tester 1	Tester 2
Dourados	5.1 a	5.1 a
Caarapó	4.2 b	4.6 b
High N	5.0 a	5.0 a
Low N	4.3 b	4.7 b
Mean	4.6	4.8

Means followed by the same letter in the row and column do not differ from each other by the Scott-Knott test at 5% probability.

Las medias seguidas por la misma letra en la fila y en la columna no difieren entre sí por la prueba de Scott-Knott al 5% de probabilidad.

Table 3 shows the grain yield means of the top-cross hybrids clustered according to the base populations that originated the partially inbred lines. Commercial checks DKB 390, AG 30A91, and DKB 789 were the most yielding, regardless of the N level evaluated. Results demonstrated that these hybrids (DKB 390, AG 30A91 and DKB 789) could be used as base population to select lines adapted to different N levels in the soil for maize breeding programs that aim at tolerance to abiotic stresses. Base population BP (07) proved to be the most promising to obtain partially inbred lines aiming at N use efficiency. These results were expected since this population is originated from the hybrid DKB 789, which has high yield potential, regardless of the N availability in the soil.

Table 3. Mean grain yield of top-cross hybrids clustered according to the base populations and 11 checks evaluated under high and low nitrogen (N) levels in two sites.

Tabla 3. Rendimiento promedio de grano de los híbridos top-cross agrupados de acuerdo con las poblaciones base y 11 controles evaluados en niveles altos y bajos de nitrógeno (N) en dos locales.

Hybrids	High N	Low N
BP(01)	5.0 c	4.5 b
BP(02)	5.0 c	4.2 b
BP(05)	4.5 c	4.2 b
BP(07)	5.6 b	4.8 b
BP(13)	5.0 c	4.7 b
UFGD 1	2.8 d	3.3 c
BRS SOL	3.2 d	3.5 c
BRS 3035	3.2 d	3.2 c
BR 106	3.0 d	3.3 c
BRS 1010	4.8 c	3.2 c
XB 9003	5.9 b	4.7 b
XB 8010	4.8 c	4.1 c
OMEGA	5.8 b	4.9 b
DKB 390	7.6 a	6.1 a
AG 30A91	8.3 a	6.5 a
DKB 789	6.9 a	5.2 b
Mean	5.1	4.4

Means followed by the same letter in the row and column do not differ from each other by the Scott-Knott test at 5% probability.

Las medias seguidas por la misma letra en la fila y en la columna no difieren entre sí por la prueba de Scott-Knott al 5% de probabilidad.

Similar results were found by Bison *et al.* (2003), who verified the potential of the commercial single cross hybrids AG9012 and DKB333 as sources for extracting partially inbred lines. Amorim and Souza (2005) reported that single cross commercial hybrids are priority germplasms for the extraction of lines in a breeding program since they have been extensively improved and have a high frequency of favorable alleles.

Identification of promising genotypes for nitrogen use efficiency

The commercial checks AG30A91, DKB390, DKB789, Omega, and XB9003 and the progenies from the base population BP (07) were classified as efficient in N use and responsive to N application (figure 1). Progenies from the base populations BP (13) and BP (01) were classified as efficient in nitrogen use, but unresponsive to the nitrogen application. Progenies from the BP (05) and BP (02) populations and the checks XB8010, BRS Sol da Manhã, BRS 3035, BRS1010, and UFGD01 were classified as inefficient in nitrogen use and unresponsive to N. Thus, crosses between the checks AG30A91, DKB390, DKB789, Omega, XB9003, and the base population BP (07) can be efficient in obtaining partially inbred lines efficient in N use and responsive to N application.

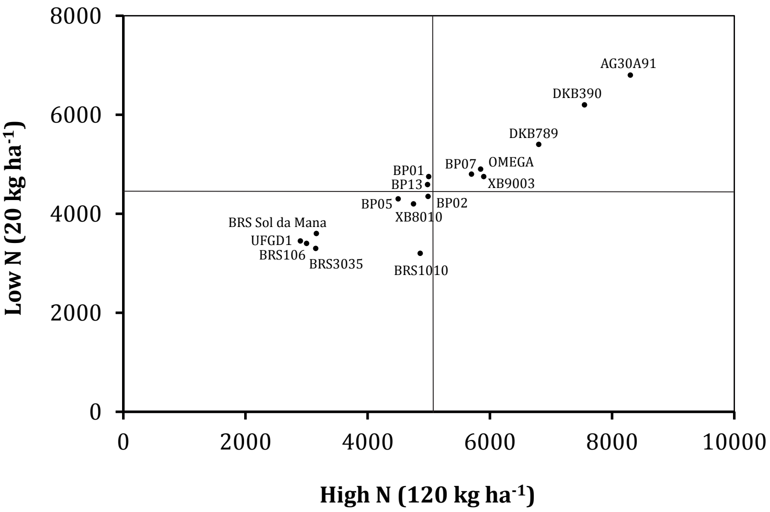

Figure 1. Behavior in relation to the nitrogen use efficiency and response to nitrogen fertilization on base populations and checks in relation to grain yield for the means of environments.

Figura 1. Comportamiento con respecto a la eficiencia del uso de nitrógeno y la respuesta a la fertilización con nitrógeno en poblaciones base y los controles en relación con el rendimiento de grano para los medios de ambientes.

After identifying that the top-cross hybrids from the base population BP (07) were efficient in N use and responsive to N application, means of the partially inbred lines from this population were clustered. Hybrids from BP (07) 13, BP (07) 14, and BP (07) 17 lines showed the highest yields in both high and low N environments (table 4). In addition, they can be classified as efficient in N use and responsive to N application, as shown in figure 2 (page 41). Therefore, these partially inbred lines should be used in future researches aiming at obtaining germplasm with overall adaptability to different N levels in Brazilian Cerrado soils.

The extraction and evaluation of inbred lines are the most expensive and time-consuming stages of any maize hybrids breeding program. One way to accelerate the process and reduce costs is by obtaining hybrids from partially inbred lines derived from commercial single-cross hybrids. This procedure has already been described as a viable alternative in maize breeding programs (3). In the present work, extraction of hybrids from partially inbred lines allowed the obtention of hybrids efficient in N use and responsive to N application. Hence, the materials indicated in this study could be used in maize breeding programs for obtention of hybrids with high efficiency in N use and responsive to N application.

Cost reduction in maize breeding programs can be achieved by using intermediary hybrids obtained from lines with partially inbred levels (5). Therefore, hybrids from partially inbred lines and F2 generations are an alternative to reduce the time and cost of hybrids extraction since the production system requires a smaller number of successive self-pollinations and a smaller area for the extraction and multiplication lines. Therefore, maize lines reach the market faster and maintain a higher yield when compared with fully inbred lines.

The identification of partially inbred lines for N use efficiency can be a major improvement for maize breeding programs in the Brazilian Cerrado environment. From the results reported in this work, other studies can be carried out using the BP (07) population to obtain new lines with higher inbreeding, and/or which combine high grain yield, efficiency to N use and responsiveness to N application.

Table 4. Mean grain yield of top-cross hybrids from the base population BP (07) evaluated in two sites under high and low nitrogen (N) level.

Tabla 4. Rendimiento medio de granos de los híbridos de la población base BP (07) evaluados en dos locales con alto y bajo nivel de nitrógeno (N).

Hybrids	High N	Low N
BP(07) 7	5.5 b	4.5 b
BP(07) 8	5.7 a	4.6 b
BP(07) 10	5.4 b	4.8 b
BP(07) 11	5.5 b	4.8 b
BP(07) 13	5.6 a	5.2 a
BP(07) 14	6.8 a	5.7 a
BP(07) 15	5.9 a	4.7 b
BP(07) 17	5.7 a	5.4 a
BP(07) 19	5.2 b	3.7 b
BP(07) 20	5.3 b	4.1 b
BP(07) 21	4.9 b	4.7 b
Mean	5.6	4.7

Means followed by the same letter in the row and column do not differ from each other by the Scott-Knott test at 5% probability.

Las medias seguidas por la misma letra en la fila y en la columna no difieren entre sí por la prueba de Scott-Knott al 5% de probabilidad.

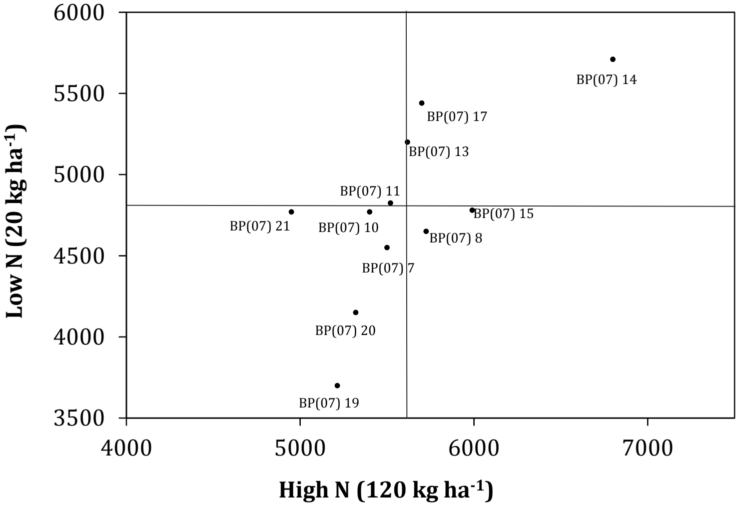

Figure 2. Behavior regarding the nitrogen use efficiency and response to nitrogen fertilization on top-cross hybrids from base population BP (07) in relation to grain yield for the means of environments.

Figura 2. Comportamiento con respecto a la eficiencia del uso de nitrógeno y la respuesta a la fertilización con nitrógeno en los híbridos top-cross de la población base BP (07) en relación con el rendimiento de grano para rendimiento de grano para el medio ambiente.

The use of BP (07) 1, BP (07) 14, and BP (07) 17 lines to obtain top-crosses efficient in N use and responsive to N application is another relevant finding. These hybrids could be sold to farmers at a lower price when compared with single cross hybrids. In addition, they may be grown regardless of the technological level of the farm.

Conclusions

Hybrid DKB 789 showed the potential to extract partially inbred lines aiming at the selection for N use efficiency.

Base population BP (07) was the most suitable for the extraction of partially inbred lines aiming at N use efficiency.

Partially inbred lines BP (07) 13, BP (07) 14, and BP (07) 17 are the most suitable for the extraction of top-cross hybrids with high grain yield, efficiency, and responsiveness to N.

Supplementary tables

https://drive.google.com/file/d/1PILQxqRhVYkNgv6WrdgmAK4Bal1jdNdj/view?usp=sharing

References

1. Amorim, E. P.; Souza, J. C. 2005. Evaluation of inter and intrapopulation maize hybrids from S0 progenies of commercial single cross hybrids. Bragantia. 64: 561-567.
2. Bänziger, M.; Lafitte, H. R. 1997. Efficiency of secondary traits for improving maize for lownitrogen target environments. Crop Science. 37: 1110-1117.
3. Bison, O.; Ramalho, M. A. P.; Raposo, F. V. 2003. Potential of maize single hybrids to generate inbred lines. Ciência e Agrotecnologia. 27: 348-355.
4. Borém, A. 2009. Hibridação artificial de plantas. Editora UFV. 625 p.
5. Carvalho, A. D. F.; Souza, J. C.; Ramalho, M. A. P. 2010. Combining ability of partial inbred progeny from commercial corn hybrids. Revista Brasileira de Milho e Sorgo. 3: 429-437.
6. Conab-National Supply Company. 2017. Survey 2016/2017 harves. Conab. Brasília.
7. de Sousa, D. M. G.; Lobato, E. 2004. Cerrado: Soil correction and fertilization. Brasília. Embrapa Informação Tecnológica.
8. dos Santos, M. X.; de Oliveira Guimarães, P. E.; Pacheco, C. A. P.; França, G. E.; Parentoni, S. N.; Gomes, E. E. 1998. Improvement in the synthetic elite NT for soils with low nitrogen content. I. Genetic parameters for yield. Pesquisa Agropecuária Brasileira. 33: 55-61.
9. DoVale, J. C.; Fritsche-Neto, R.; Bermudez, F.; Miranda, G. V. 2012. Genetic effects of traits associated to nitrogen use efficiency in maize. Pesquisa Agropecuária Brasileira. 47: 385-392.
10. Fidelis, R. R.; Miranda, G. V.; dos Santos, I. C.; Galvão, J. C. C. 2005. Methodologies of selection of maize cultivars to efficient in nitrogen absorption and utilization. Revista Ceres. 52: 987-1002.
11. Fidelis, R. R.; Miranda, G. V.; dos Santos, I. C.; Galvão, J. C. C.; Peluzio, J. M.; Lima, S. O. 2007. Maize germoplasm to low nitrogen stress. Pesquisa Agropecuária Tropical. 37: 147-153.
12. Fox, R. H. 1978. Selection for phosphorus efficiency in corn 1. Communications in Soil Science & Plant Analysis. 9: 13-37.
13. Fritsche-Neto, R.; Borém, A. 2011. Melhoramento de plantas para condições de estresses abióticos. Editora UFV. 250 p.
14. Lopes Cancellier, L.; Afférri, F. S.; Carvalho, E. V.; Dotto, M. A.; Leão, F. F. 2011. Nitrogen use efficiency and phenotypic correlations of tropical maize populations in Tocantins. Revista Ciência Agronômica. 42: 139-148.
15. Ribeiro, L. P.; Teodoro, P. E.; Corrêa, C. C. G.; Oliveira, E. P.; Silva, F. A.; Torres, F. E. 2016. Correlations and genetic parameters in maize hybrids. Bioscience Journal. 32: 48-54.
16. SAS Institute. 2009. SAS/STAT: user's guide: version 9.2. SAS Institute. Cary.
17. Silva Filho, J.; Carvalho, S. F.; Ramalho, M. A. P. 2001. Response of endogamic families of three maize populations to side-dressing nitrogen fertilization. Ciência e Agrotecnologia. 25: 14-22.
18. Silva, R. G.; Miranda, G. V.; Cruz, C. D.; Galvão, J. C. C.; Silva, D. G. 2008. Genetic potential of the maize populations ufvm 100 and ufvm 200 evaluated in soils with low nitrogen availability. Revista Caatinga. 21: 22-29.
19. Souza, L. V.; Miranda, G. V.; Galvão, J. C. C.; Eckert, F. R.; Mantovani, E. E.; Lima, R. O.; Guimarães, L. J. M. 2008. Genetic control of grain yield and nitrogen use efficiency in tropical maize. Pesquisa Agropecuária Brasileira. 43: 1517-1523.

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