Success in Maize Acid Soil Tolerance

R. Magnavaca and A.F.C. Bahia Filho
EMBRAPA\CNPMS
Sete Lagoas, MG, Brazil

ABSTRACT

The success of the EMBRAPA maize improvement program in developing aluminum tolerant maize cultivars and hybrids adapted to Brazilian acid savannas or "Cerrado", made possible the incorporation of 727,500 ha for maize production. The association of better soil management with tolerant genotypes, through a multidisciplinary research approach, made it possible to increase yield in such environments. The development of methodology for selection in field conditions and nutrient solution with varying levels of Al is reported. Aspects of balance between P and Al levels in soils and nutrient solution for discrimination of maize genotypes is the principle aspect of the methodology developed. The breeding procedure used in the program, describes the search for variability in tropical germplasm, the recurrent selection scheme for cultivar improvement, and inbred line and hybrid development and evaluation. Two cultivars, CMS 36 and CMS 30, were released and are being used in tropical areas of the world as a gene source for Al tolerance. One of the commercially produced hybrids BR 201, confirms the possibility of associating high yield potential and stability with Al tolerance. This hybrid currently occupies 14% of the market share of hybrid maize seed sales in Central and Southern Brazil.

INTRODUCTION

The acid savannas or "Cerrado" is an ecosystem that covers an extension of 205 million ha, of which 175 million ha are in Central Brazil. Today, 12 million ha of the Brazilian "Cerrado" are in crop production. The area planted with maize covers 3.5 million ha. Approximately 112 million ha of the "Cerrado" area are considered adequate for sustainable crop production.

Oxisols are the most frequent soil type in the "Cerrado" ecosystem. These are strongly weathered soils with low cation exchange capacity (CEC) and exhibit major mineral element deficiencies. (P, Ca, Mg, and Zn) toxic exchangeable Al, and extensive P fixation by soil particles.

A high percentage of Al saturation in soils is toxic to plant growth. Aluminum affects many physiological, biochemical and metabolical processes in plants (Foy et al., 1978). Roots injured by high Al are usually stubby, thick, and become dark-colored, brittle, poorly branched, and suberized. As a consequence, root length and volume is decreased. However, root dry weight may not be altered.

The development of maize production to Brazilian acid soils stressed the need for better adapted cultivars with Al tolerance for sustainable economic cropping. Lime application to acid soils have been used to decrease toxic effects of Al to the roots, but practical mechanical methods for deep lime incorporation have not been developed. Therefore, the combination of liming practices for neutralization of soil acidity at the surface together with selection for more tolerant plants to Al toxicity is a more economical approach.

The research program to adapt maize to "Cerrado" acid soils began in 1975 at the National Maize and Sorghum Research Center. The results reflects the efforts of a multidisciplinary maize improvement team, involving breeders, soil and plant nutrition specialists, and phytopathologists. The program was directly aimed at overcoming soil constraints by using genetic resources more efficiently in soil nutrient uptake, transfer, and utilization.

METHODOLOGY DEVELOPMENT

Selection in Field Conditions

Yield evaluations in our program have been made in a Red Dark Latosol, alic, clay texture "cerrado" phase soil at the National Maize and Sorghum Research Center, in Sete Lagoas, Minas Gerais State, Brazil. The latitude is 19°28'8"S, longitude 44º 15'W Gr, altitude of 732m, with a climate classified as Aw (Köpen), with the temperature of the coldest month above 18°C.

The level of Al saturation, in relation to the effective CEC was the indicator for Al toxicity level. Initial evaluations were made at 55% Al saturation. Later, based on response curves to limestone applications, the level of 45% Al saturation was selected as the most adequate to discriminate tolerant genotypes with good yield potential (Table 1 and 2). Higher levels of Al saturation permit the selection of genotypes with greater tolerance, but are associated with low yield potential.

In the soils used for testing genotypes, P availability is characterized by low P in soil solution, high P adsorption, and low reversibility of the added P (Bahia Filho et al., 1983a). Under such conditions 100 kg ha^{-1} P_2O_5 (as single super phosphate) was broadcasted and 60 kg ha^{-1} P_2O_5 applied at

Table 1. Al saturation and pH values at two soil depths and three liming levels in a Red Dark Latosol at Sete Lagoas, Brazil.

Limestone $t\ ha^{-1}$	Depth cm	pH	Al saturation %
0	00-20	4.7	64
	20-40	4.6	72
2	00-20	4.9	46
	20-40	4.8	63
7	00-20	5.3	5
	20-40	5.0	33

Table 2. Grain yield ($kg\ ha^{-1}$) and relative grain yield (%) of inbred lines grown at three levels of limestone (0, 2 and 7 $t\ ha^{-1}$) (Naspolini Filho et al., 1981).

	Yield (kg ha-1)			Relative yield (%)		
Inbred line	0	2	7	0	2	7
L 69	1,500	1,540	1,410	97	100	92
L 153	1,450	2,400	2,350	60	100	98
L 297	1,900	2,500	3,575	53	70	100

planting to assure a reasonable level of P availability, without interference with the Al toxicity level.

More recently in our program, the concept of critical level has been used to establish the amount of P to be added. If the extractant is representative to variations in P buffering capacity and clay content (Bahia Filho et al., 1983b), the utilization of a critical level concept makes it easier to compares among P levels in different soils.

The relationship between P recovered by the extractant and the amount of P added to the soil is linear, but the ratio of P recovered to P added to the soil varies inversely with clay content (Freire et al., 1979; Novais and Kamprath, 1979; Bahia Filho et al., 1983b). As an example, in the soil used in our program, the ratio of P recovered to P added is 0.02 using Mehlich 1 extractant; the initial P content in the soil is 2,0 $\mu g\ g^{-1} P$, and the critical level is $10 \mu g\ g^{-1}$. Therefore to obtain a 60% critical level (60% critical level = 0.6 x 10 = $6 \mu g\ g^{-1}$), the amount of P_2O_5 to be applied to the soil is: $(6 - 2)0{,}02^{-1}$ = 200 kg $P_2O_5\ ha^{-1}$. In order to obtain an increase of $1 \mu g\ g^{-1}$ P in the soil, it is necessary to add 50 kg $P_2O_5\ ha^{-1}$.

Selection in Nutrient Solution

The nutrient solution technique is useful to evaluate the isolated effects of Al in the plant in contrast with field evaluations where a complex of factors related to nutrient and water availability as well as climate effects may interfere with plant response to Al stress.

The nutrient solution technique that has been used in our program was developed by Furlani and Clark (1981) and Magnavaca (1982). The most critical point is the ratio of Al:P in the solution (Magnavaca, 1982). The P level in the solution can not interfere with the Al stress level. Otherwise, genetic discrimination of tolerant genotypes (a desirable P:Al ration is 1:5) would not be possible. The appropriate nutrient solution to which 222 µmol Al L^{-1} is added as $KAl(SO4)_2$ is described in Table 3. The initial pH is adjusted to 4.0 and monitored daily. Seeds treated with captan [N-(trichloromethy-ithio)-4-cyclohexene-1,2-dicarboximide] are germinated for seven days in rolled paper towels kept moist with aerated distilled water. Seven-day-old uniform sized seedlings without visual root injury are transferred to plastic support plates (49 plants per plate) and grown in 8.0 L of aerated nutrient solution for about seven days. Water is added daily to maintain solution volumes. Plants are grown in greenhouse without artificial lights at a temperature varying from 25° C to 35° C.

Table 3. Composition of basic nutrient solutions used for determining Al tolerance in maize (Magnavaca, 1982).

Stock solution			Full-strength nutrient solution					
Name	Chemical	Conc.		Cation	Anion	Total composition		
		gL^{-1}	ml stock L^{-1}	mg element L^{-1}		element mg L^{-1}		µM
Ca	$Ca(NO_3)_2.4H_20$	270.0	3.08	Ca=141.1	NO_3-N=98.6	Ca	141.1	3527
	NH_4NO_3	33.8		NH_4-N=18.2	NO_3-N=18.2	K	90.1	2310
						Mg	20.8	855
K	KCl	18.6	2.31	K=22.5	Cl=20.4	NO_3-N	152.0	10857
	K_2SO_4	44.0		K=45.6	SO_4-S=18.7	NH_4-N	18.2	1300
	KNO_3	24.6		K=22.0	NO_3-N=7.9	P	1.4	45
						S	18.8	587
Mg	$Mg(NO_3)2.6H_20$	142.4	1.54	Mg=20.8	NO_3-N=24.0	B	0.27	25
						Cl	21.05	595
P	KH_2PO_4	17.6	0.35	K=1.7	H_2PO_4=1.4	Fe	4.3	77
						Mm	0.50	9.1
Fe*	$Fe(NO_3)_3.9H_20$	20.3	1.54	Fe=4.3	NO_3-N=3.3	Cu	0.04	0.63
	HEDTA	13.4			HEDTA=20.6	Mo	0.08	0.83
						Zn	0.15	2.29
Micro	$MnCl_2.4H_2O$	2.34	0.77	Mn=0,50	Cl=0.65	Na	0.04	1.74
	H_3BO_3	2.04			BO_3-B=0.27	HEDTA	20.6	75
	$ZnSO_4.7H_2O$	0.88		Zn=0.15	SO_4-S=0.07			
	$CuSO_4.5H_20$	0.20		Cu=0.40	SO_4-S=0.02			
	$Na_2MoO_4.2H_20$	0.26		Na=0.04	MoO_4-Mo=0.08			

*FeHEDTA (Fe hydroxyethylenediaminetriacetate) was prepared by dissolving the HEDTA in water plus addition of 1N NaOH. After it was dissolved, $Fe(NO_3)_3$ was added to the solution and dissolved by stirring. The pH was adjusted to 4.0 ± 0.2 by small additions of 1N NaOH and made to volume.

The initial length of the seminal roots are measured when seedlings are transferred to treatment solutions. After completion of the experiment, the final seminal root lengths are measured Relative seminal root length (RSRL) is used to evaluate plants for Al tolerance. RSRL values are determined by dividing the final seminal root length by the initial length. This trait was chosen to assess Al tolerance because it has been found to be the best one to assess Al toxicity due to: a) It is desirable when inbred lines are evaluated because it gives low correlation with initial length of the seminal root; b) It gives a lower coefficient of variation (Magnavaca, 1982). The greater the RSRL value, the greater the Al tolerance.

GENETIC VARIABILITY AND BREEDING PROCEDURE

The search for Al tolerance in maize began in 1975 through the evaluation of 363 inbred lines from the CNPMS germplasm collection. These lines were not originally selected for acid soils, but random fixation of genes for tolerance may have occurred during development. Phenotypic evaluation based on a 1 to 5 scale was used to access survival of inbred lines in an acid soil with 55% aluminum saturation (Bahia Filho et al., 1978). Although about 70 % of the tested lines died within 60 days, it was possible to select 30 lines that yielded at least of 2 t ha^{-1} of grain (Table 4). This selected group of lines was tested in an acid soil at three levels of Al saturation (Naspolini Filho et al., 1981) and in nutrient solution with different levels of Al (Magnavaca et al., 1987a) (Tables 2 and 5). The results for three representative lines demonstrate the correlation between plant response in field and nutrient solutions (Table 5 upper part). Lines such as L69 are low yielding and are not affected by the level of aluminum in nutrient solution or soil. Lines like L153 produce high yield per se at an intermediate level of Al saturation and are not affected by low levels of Al saturation. L297 is linear to Al neutralization in soil and nutrient solution. These three type of

Table 4. Phenotypic evaluation (1 to 5 scale) of 363 maize inbred lines at 15 and 60 days after germination, tested in an acid soil with 55% Al saturation. Sete Lagoas. (Bahia Filho et al., 1978).

	Distribution (%)	
Classes	15 days	60 days
Dead	19.3	68.7
1 (Poor development)	35.5	7.0
2	30.0	12.2
3	10.7	8.4
4	3.6	3.6
5 (Best development)	0.7	0.0

Table 5. Relative seminal root length (cm) of American and Brazilian maize inbred lines grown in nutrient solution at different Al levels (Magnavaca, 1982).

		Al levels (μ mol L^{-1})			
Origin	Inbred line	0	74	148	222
Brazil	L69	2.45	2.33	1.99	2.25
	L153	2.98	3.04	2.36	2.11
	L297	3.82	3.75	2.23	1.87
Average		3.08	3.04	2.19	2.07
U.S.	B73	1.97	1.65	1.35	1.32
	Mo17	2.99	2.59	1.99	1.64
	N28	3.48	3.00	1.94	1.42
Average		2.81	2.41	1.76	1.46

responses were quite common and gave the opportunity to select genotypes useful for different breeding objectives. The correlation between results from nutrient solution and field experiments in acid soil is not expected to be high. The nutrient solution technique is specific for Al toxicity effects on root development. Field test measures the effects of a nutritional complex that includes Al as one of the factors involved in the crop yield. However the field and nutrient solution tests usually agree in terms of results when the genotype tested is highly tolerant to toxic aluminum.

This same group of Brazilian lines was compared with lines from the U.S. in nutrient solution at four levels of Al. (Table 5). The average performance of Brazilian lines was superior to U.S. lines for Al tolerance. Considering that the Brazilian lines were not specifically selected (*apriori*), for acid soils, the random fixation of genes for tolerance is a demonstration of the variability for Al tolerance. Since such cultivars were not exposed to Al toxicity stress during the breeding process, what other soil factors may be linked to Al tolerance genes that allowed for the random fixation of genes for Al tolerance is not known. One possible explanation is linkage (or pleiotropic effect) between Al tolerance and P use efficiency.

Simultaneously to the search for variability to Al tolerance several studies related to the inheritance of the trait have been conducted and reported (Naspolini et al., 1981; Magnavaca et al., 1987 b; Lopes et al., 1987; Eleutério et al., 1988). Generation mean analysis in nutrient solution detected that additive gene effects explained most of the genetic variation, but dominance contributed with a significant amount of variance. The frequency distributions of the F2 generation of crosses were continuous, unimodal, and typical for a quantitatively inherited trait, with a preponderance of genes dominant for susceptibility to Al tolerance. In studies based on diallel crosses of inbred lines and cultivars evaluated in nutrient solution and acid soil, the variance for general combining ability explained most of the variation, but specific combining ability was always important. Specific combining ability for maize is better exploited in hybrid combinations. Al tolerance in maize is quantitatively inherited and evidence does not support the concept that a single major gene controls Al tolerance in maize.

Considering that Al tolerance is quantitatively inherited, cultivar improvement by recurrent selection is a desirable method. However, hybrid combinations are important to exploit specific combinations. Progress has been made by recurrent selection. Two populations, CMS 36 and CMS 30, selected at Sete Lagoas in acid soil, have a high frequency of genes for Al tolerance when tested in nutrient solution (Table 6) (Lopes et al., 1987). The tolerance is much higher for CMS 36 and CMS 30 than for non-selected populations. Both are being used in tropical areas of the world as a source of genes for tolerance to toxic levels of Al saturation.

One concern at the beginning of our program related to the selection of Al tolerant genotypes was the possibility of associating Al tolerance with high grain yield potential. We were concerned about the possibility of Al tolerance being associated with low yield potential. Trials were performed at Sete Lagoas for two years comparing the yield potential of cultivars and hybrids of Al tolerant and non-tolerant genotypes (Table 7) (Gama et al., 1986). Among the cultivars tested, CMS 36 and CMS 30 produced the highest yield in acid soil, but CMS 36 demonstrated yield limitations in fertile soil. Among the hybrids tested, CMS 200X and Cargill 511A were the best in acid soil; however CMS 200X, had a low yield potential in fertile soil compared to Cargill 511A. These results stressed the need for evaluating Al tolerant hybrids, not only in acid soil trials, but also in fertile soils. In our program, selection has been based on results from trials performed in acid and fertile

Table 6. Relative seminal root length (%) of maize cultivars grown in nutrient solution with 0 and 222 μ mol Al L^{-1}, and relative root length as percentage of control with 0 Al (d), (Lopes et al., 1987).

	Al levels (μ mol L^{-1}		
Variety	0	222	d
CMS 36	88.9 cde†	64.4 b	27.5 b
CMS 30	113.9 ab	71.4 ab	37.2 b
CMS 14c	107.2 abc	23.7c	77.8 a
CMS 04c	81.7 de	17.2 c	78.9 a
BR 105	81.9 de	25.2 c	69.3 a
BR 126	100.1 bc	24.3 c	75.7 a

†Duncan multiple range test at 5% probability.

soils, and results from nutrient solution with varying levels of Al. A large number of field test locations are used to detect improved yield stability.

This principle of selecting under these three conditions was applied to 429 S_2 inbred lines originating from 6200 S_1 plants. The 429 S_2 lines were crossed with a single-cross tester having with Al tolerance. These top-crosses were evaluated at three fertile soil sites, two acid soil sites, and in nutrient solution with 222 mol Al L^{-1}. Responses among the 429 top-crosses tested, in comparison with two commercial check hybrids that were extensively planted at that time are reported (Table 8). Top-crosses 1 and 45 performed well across conditions and are desirable for selection. Top-cross 77 performed well in both acid and fertile soils, but it did not show Al tolerance when tested in nutrient solution. This response may be due to a better efficiency for P uptake or better internal efficiency in P utilization, but this is a point yet to be confirmed. The relationship of Al and P mechanisms may offer the

Table 7. Mean ear weight of 10 maize cultivars tested in fertile and acid soil environments at Sete Lagoas. (Gama et al., 1986).

	Ear weight (kg ha^{-1})	
Genotype	Acid soil (1 meq Al)	Fertile soil (0 meq Al)
Cultivar		
CMS 14	2,580 fgh[†]	7,870 abcd
CMS 36	4,520 a	6,550 d
CMS 30	3,120 cdef	7,050 bcd
CMS 04	2,190 gh	7,660 abcd
CMS13	1,800 h	6,745 cd
Hybrid		
Cargill 511	2,650 efg	7,515 bcd
Cargill 511 A	3,980 abc	8,335 ab
Agroceres 301	3,450 bcde	7,940 abcd
Dina 3030	3,240 bcdef	8,990 a
CMS 200 X	4,020 ab	6,875 bcd

[†]Duncan multiple range test at 5% probability.

Table 8. Relative grain yield of top-crosses and check hybrids compared to highest yielding entry, in fertile and acid soil. Relative seminal root length (RSRL) measured in nutrient solution with 222 μ mol Al L^{-1}, for these materials are also shown.

	Fertile soil			Acid soil			
Hybrid	Sete Lagoas	Ituiutaba	Goiânia	Sete Lagoas	M. Carmelo	Average	RSRL %
Top-cross 1	82	90	64	97	83	83	75
Top-cross 45	79	85	91	85	73	83	69
Top-cross 77	76	100	74	94	88	86	46
Cargill 111S	83	79	100	79	46	77	47
Agroceres 301	78	85	60	67	46	67	43

possibility of improvement for both nutritional aspects. The performance of top-crosses 1 and 45, for example, in comparison with non-tolerant tester hybrids, demonstrates the possibility of selecting lines for producing hybrids with both tolerance to Al and high yield potential.

The best lines selected in these top-crosses have been used for double-cross hybrid production. Double-cross hybrids are commonly used in Brazil due to low seed cost. A total of 20 double-cross hybrids were evaluated at five sites with soil fertility varying from medium to high. The yield and stability of Al tolerant hybrids were then compared to commercial hybrids without Al tolerance. The Al tolerance response of these hybrids was measured in nutrient solution using relative seminal root length (RSRL). The results for six of these experimental hybrids is presented in Table 9. (Magnavaca et al., 1988).

Double-cross hybrids 7,8, and 9 were obtained by crossing Al tolerant single-crosses with the same tester, a single-cross with high Al tolerance but limited in yield potential. The single-cross tester for producing the double-crosses 14,15 and 20 had lower Al tolerance in nutrient solution, but a high grain yield potential. The yield potential of the first group (DC 7,8,9) was lower than the second group (DC 14,15,20), but with better Al tolerance as measured by RSRL, and a linear regression coefficient (b) that measured yield stability of less than 1. b values less than 1 are an indication of adaptation to poor environments, and b values greater than 1 indicate better response to improved environments. The second group presented higher yield and b values above 1. DC 14 and 15 had a relatively high level of Al tolerance in nutrient solution. The commercial hybrids used for comparisons

Table 9. Relative seminal root length (RSRL), grain yield (kg ha^{-1}), linear regression coefficient (b) and deviation from linear regression (s^2d) of experimental and commercial hybrids evaluated at five fertile soil sites in Brazil. (Magnavaca et al., 1988).

Hybrids	RSRL (%)	Yield kg ha^{-1}	b	s^2d
DC 7	130 a	6,620 k	0. ± 0.08	-14607
DC 8	73 bcd	7,260 j	0. ± 0.04*	-129047
DC 9	107 ab	7,080 j	0. ± 0.09	-2049
DC 14	92 abc	8,710 ab	1. ± 0.04*	-132525
DC 15	76 bcd	8,870 a	1. ± 0.10	62595
DC 20	59 cd	8,410 cd	0. ± 0.09	4274
Cargill 111 S	48 de	7,810 hi	1. ± 0.03*	-139363
Dina 3030	61 cd	7,970 gh	1. ± 0.11	77103
Agroceres 401	46 de	7,245 j	0. ± 0.06	-86952
Pioneer 6875	16 e	8,050 efgh	1. ± 0.14	250015

*Significant at $\alpha = 0.05$.

had lower Al tolerance than the experimental hybrids, and produced lower yields in relation to the second group. Performance of DC 14, confirms the possibility of associating high yield potential and stability to Al tolerance. DC 14 was recently released as the commercial hybrid BR 201. Hybrids like BR 201 make it possible to improve cropping systems in "Cerrado" soils of Brazil with less risk to the farmers.

The CNPMS/EMBRAPA breeding program for acid "Cerrado" soils is dynamic and a new group of double-cross hybrids have been tested in recent trials. Evaluation trials for 120 new experimental hybrids were conducted on 7 fertile soil sites (without Al toxicity problems), a site with 70% Al saturation, and in nutrient solution. The 18 new hybrids were superior to BR 201 in grain yield, while some were superior in acid soil tolerance based on RSRL in nutrient solution with Al (Table 10). Progress in grain yield can be made in relation to BR 201 without loosing Al tolerance. Other agronomic traits such as lodging resistance and shorter plant height have also been improved. The selection of three-way and single-cross hybrids is underway and is expected to further improve agronomic traits and yield levels.

Table 10. Average yield (kg ha^{-1}) of 18 selected experimental double-crosses evaluated in fertile and acid soils (70% Al saturation), and nutrient solution with 222 μ Al L^{-1}.

Hybrid	Ear weight (kg/ha) Fertile soil (7 sites)	Acid soil (1 site)	RSRL %
DC 9174	8,790	1,880	47
DC 9150	8,650	890	47
DC 9180	8,360	950	56
DC 9101	9,160	700	36
DC 9148	8,510	1,090	32
DC 9111	8,210	1,250	46
DC 9107	8,990	1,510	35
DC 9176	8,800	2,040	58
DC 9157	8,310	720	48
DC 9198	9,035	1,460	44
DC 9151	8,720	1,040	42
DC 9121	8,600	1,215	45
DC 9103	8,680	1,185	57
DC 91110	8,910	1,690	63
DC 9108	8,790	1,220	47
DC 9153	8,840	1,130	71
DC 91102	8,845	1,110	74
DC 9144	8,650	1,110	50
BR 201	8,310	1,350	62
LSD (0.05)	670	810	16

FARMER UTILIZATION

The high yielding double-cross maize hybrid tolerant to toxic aluminum, BR 201, was released in 1987. Approximately 10T of foundation seed was simultaneously distributed to 17 small and medium seed companies and four hundred observation and demonstration plots were installed collaboratively with producers and co-operatives.

In 1989, a system of rural franchising was introduced with the collaborating producers of commercial seed of BR 201. In this franchising scheme, EMBRAPA authorizes the use of its trademark, provides the foundation seed, transfers BR 201 seed production technology, provides training and technical assistance, and oversees a rigorous system of quality control. Financial resources have returned to EMBRAPA by two ways: through the sale of foundation seed and also as a five % royalty of gross seed sales of BR 201, paid by the collaborating seed companies. Since 1987, EMBRAPA has received approximately $ four million through this franchising and royalty arrangement.

Commercial seed of BR 201 is currently produced by 25 small and medium size seed companies. Approximately half of these seed companies have technical assistance programs for their clients. BR 201 currently occupies 14% of the market share of hybrid maize seed in Central and Southern Brazil. During 1992-1993, 727,500 ha of BR 201 was planted in this region (Table 11) (F.Almeida, personal communication). The interaction of the private sector initiative and the high yield genetic potential combined with yield stability has contributed to the rapid diffusion of BR 201. The characteristic of aluminum tolerance has not been proposed to substitute or reduce liming or reduce fertilizer use, but is promoted as an important factor contributing to both yield stability and risk reduction. The yield potential of BR 201 permits it to compete with the best hybrids on the Brazilian market. During 1991-1992, BR 201 won first place in the State of Minas Gerais maize productive contest, producing 15.75T of grain per ha. Two new hybrids of the same series, BR 205 and BR 206, are currently being released. The

Table 11. Market share of BR 201 in the Brazilian hybrid maize seed industry.

Year	Total seed sale	BR 201 sales	Market share	No. of franchises
	40 kg bags		%	
1988/89	2,820,000	23,050	0.8	17
1989/90	2,000,000	143,625	7.2	21
1990/91	2,875,000	168,614	5.9	22
1991/92	2,805,000	332,074	11.8	26
1992/93	2,628,000	363,750	13.8	25

private sector has contacted CNPMS/EMBRAPA regarding possible franchising and royalties for seed sales in selected African Countries.

REFERENCES

Bahia Filho, A.F.C., G.E.França, G.V.E. Pitta, R. Magnavaca, J.F. Mendes, F.G.F.T.C. Bahia, and P. Pereira. 1978. Evaluation of corn inbred lines and populations in high soil acidity conditions. (In Portuguese). p 51-58. *In* E. Paterniani (Ed.). Proc. XI Ann. Brazilian Maize Sorghum Conf., Piracicaba, S.P., Brazil. 26-30 jun. 1976.

Bahia Filho, A.F.C., J.M.Braga, M.Resende, and A.C.Ribeiro. 1983a. Relation between phosphorus adsorption and clay mineralogical components of latosols of the Central Plateau of Brazil. (In Portuguese). R. bras. Ci. Solo. 7(3):221-226.

Bahia Filho, A.F.C., J.M.Braga, A.C.Ribeiro, and R.F.Novais. 1983b. Sensitivity of chemical extractants to phosphorus buffering capacity. (In Portuguese). R. bras. Ci. Solo 7:243-249.

Eleutério, A., E.E.G. Gama, and A.R.Morais. 1988. Combining ability and varietal hybrid heterosis of maize populations adapted to "Cerrado" areas. (In Portuguese). Pesq. agropec. bras. 23:247-253.

Foy, C.D., R.L. Chaney, and M.C. White. 1978. The physiology of metal toxicity in plants. Ann. Rev. Plant Physiol. 29:511-566.

Freire, F.M., R.F. Novais, J.M. Braga, G.E.França, H.L.Santos, and P.R.R.S. Santos. 1979. Phosphorus fertilization for soybean based on phosphorus availability and the capacity factor. (In Portuguese). R. bras. Ci. Solo 3:105-111.

Furlani, P.R., and R.B.Clark. 1981. Screening sorghum for aluminum tolerance in nutrient solution. Agron. J. 73:587-594.

Gama, E.E.G., R. Magnavaca, A. R. Morais and A.C. Oliveira. 1986. Performance of five maize populations and their varietal crosses in fertile and acid soils. (In Spanish). p.77-96. *In* Proc. XII Andean Zone Maize Breeders Conf., Quito, Ecuador. 29 sept.-3 oct. 1986.

Lopes, M.A., R. Magnavaca, A.F.C. Bahia Filho, and E.E.G. Gama. 1987. Performance of maize populations and their crosses for aluminum tolerance in nutrient solution. (In Portuguese). Pesq. agropec. bras. 22(3):257-263.

Magnavaca, R. 1982. Genetic variability and the inheritance of aluminum tolerance in maize (*Zea mays* L.). Ph.D. diss. Univ. of Nebraska, Lincoln (Diss. Abstr. 43-2073B).

Magnavaca, R., C.O. Gardner, and R.B. Clark. 1987a. Evaluation of inbred maize lines for aluminum tolerance in nutrient solution. p.255-265. *In* H.W.Gabelman and B.C.Loughman (ed.), Genetic aspects of plant mineral nutrition. Martinus Nijhoff Publishers, Dordrecht/Boston/Lancaster.

Magnavaca, R., C.O. Gardner, and R.B. Clark. 1987b. Inheritance of aluminum tolerance in maize. p. 201-212. *In* H.W.Gabelman and B.C. Longhman (ed.), Genetic aspects of plant mineral nutrition. Martinus Nijhoff Publishers, Dordrecht/Boston/Lancaster.

Magnavaca, R., E.E.G.Gama, A.F.C. Bahia Filho, and F.T. Fernandes. 1988. Double-cross hybrid selection for aluminum tolerance. (In Portuguese). Pesq. agropec. bras. 23:971-977.

Naspolini Filho, V., A.F.C. Bahia Filho, R.T. Vianna, E.E.G. Gama, C.A. Vasconcelos, and R. Magnavaca. 1981. Performance of inbreds and single-crosses of maize in soils under "Cerrado" vegetation. (In Portuguese). Ci. and Cult. 33:722-727.

Novais, R.F., and E.J. Kamprath. 1979. Parameters of phosphorus adsorption isotherms as criterion of recommendation of phosphorus fertilization. (In Portuguese). R. bras. Ci. Solo 3:37-41.