## CHAPTER 10

# Maize Varieties for Acid Soils

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## Contents



## Abstract

Maize (*Zea mays* L.) is grown throughout the world on about 130 million hectares. Of these, 60% are in developing countries where maize is both a staple food and animal feed, especially for poultry. Because demand for maize is greater than its production, developing countries import at an increasing rate of 1.5 million tons per year and, thus, urgently need to increase their maize production. Because the best lands are occupied by cash crops, marginal environments with acid low-fertility soils must be developed. Such soils can be improved by using amendments,

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complemented by planting adapted cultivars. Because the first option is usually out of reach for resource-poor farmers, the Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT), based in Mexico, in collaboration with several national agricultural research programs, has developed four maize populations that tolerate acid soils. These populations are all heterotic, two are yellow (SA-3 and SA-4), and two are white (SA-6 and SA-7). They are being improved, and are used to develop cultivars. Grain yield of cultivars already developed from these populations has increased dramatically from less than 0.4 t/ha for the cultivars used to form the base populations to 3.0 t/ha for open-pollinated cultivars, and 4.5 t/ha for hybrids. Yield of these same materials is also very high in medium to highly fertile soils, with some hybrids yielding more than 11 t/ha. One physiological mechanism found as contributing to acid-soil tolerance is the release of citric acid from roots. Also being studied are alternatives for crop management that would help improve the productivity of maize-cropping systems while preserving the environment.

## Resumen

El maíz (*Zea mays* L.) se cultiva en 130 millones de hectáreas en el mundo, de las cuales el 60% se encuentran en los países en desarrollo donde es básico para la alimentación de la población humana o como alimento para animales, principalmente aves. Debido a que la demanda por maíz es mayor que el incremento en la producción, las importaciones en estos países están creciendo a un ritmo de 1.5 millones de toneladas por año, siendo urgente incrementar la producción de este cultivo. Para ello, se requerirán tecnologías que aseguren buenos rendimientos en suelos marginales, ya que las zonas de mayor fertilidad serán ocupadas por cultivos más rentables. Los suelos disponibles para la expansión de la frontera agrícola son generalmente de baja fertilidad, siendo la acidez una de sus principales características. Para aumentar la producción en estos suelos se puede mejorar la fertilidad utilizando enmiendas, o se pueden generar cultivares que crezcan en estas condiciones. Aunque la primera opción tiene algunas limitaciones prácticas para la adopción por el pequeño agricultor, ambas son complementarias. El Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT), con sede en México, conjuntamente con varios programas nacionales de investigación, han optado la segunda estrategia, o sea, la obtención de cultivares tolerantes a suelos ácidos. Para ello se formaron poblaciones base a partir de las cuales por selección se generaron, primero variedades de libre polinización y, luego, líneas sintéticas e híbridos. Se ha venido trabajando con dos poblaciones amarillas (SA-3 y SA-4) y dos blancas (SA-6 y SA-7), que son heteróticas entre sí. El incremento en rendimiento en las variedades generadas ha sido significativo, si se considera que en suelos ácidos el rendimiento de los materiales que constituyeron las poblaciones base fue menor que 0.4 t/ha, mientras que el promedio de rendimiento de las nuevas variedades de libre polinización es 3 t/ha, y el de los híbridos de 4.5 t/ha. Estos mismos cultivares tienen, también, buen rendimiento en suelos de media a alta fertilidad, existiendo híbridos que producen más de 11 t/ha. En el campo de la fisiología se está trabajando para explicar los mecanismos fisiológicos responsables de la tolerancia a suelos ácidos. En

el germoplasma existente en el CIMMYT se ha identificado que la exudación de ácido cítrico por las raíces es un mecanismo de esta tolerancia. Simultáneamente se trabaja en la agronomía del cultivo para encontrar las alternativas que contribuyan al incremento de la productividad de los elementos que componen los sistemas del cultivo de maíz y, a la vez, mantengan la sostenibilidad del ambiente en el que desarrollan las actividades.

# Introduction

Maize (*Zea mays* L.) is the third most important crop in the world, after rice and wheat. It is cultivated on about 130 million hectares, of which more than 60% are found in developing countries. This cereal grain, which is a staple food for millions of people in Latin America and the Caribbean, Asia, and Africa, provides 10% of protein and 8% of calories found in their diets.

The annual increase in maize production (3%) is less than that of world demand (4%), the deficit being greater in developing countries. Thus, imports by these countries grow at an annual rate of 1.5 million tons. Increasing maize production in new areas means using marginal low-fertility soils, which are subject to other types of abiotic stress. A leading cause of these soils' low fertility is acidity (i.e., low pH), which is primarily related to high aluminum saturation and low phosphorus uptake. These soils are found in the tropics, especially in savannas, which are considered as highly important for producing food in the near future. For example, on the assumption that the current per capita consumption is not increasing, we needed, at the beginning of the new millennium, about 200 million additional hectares to feed the world's population.

To use these marginal soils, appropriate technology must be developed, including modification of edaphic conditions to permit crop development and manipulation of the plant's genetic structure so that it will grow well under these conditions. CIMMYT, in collaboration with several national research programs, decided to work with the latter option to develop cultivars—both synthetic (i.e., open-pollinated) varieties and hybrids—that perform well in acid soils and thus constitute a permanent, environmentally clean, and economically feasible solution to increased food needs, as well as generate technologies that can be easily adopted by farmers.

The first part of this paper deals with the genetic manipulation of the maize plant; the second reviews the probable mechanisms responsible for the plant's tolerance, permitting it to grow in acid soils. A better understanding of these mechanisms is fundamental to obtaining greater efficiency in genetic improvement. Also being developed are genetic materials needed for marking genes and ascertaining tolerance mechanisms related to maize yield on acid soils. Finally, some advances CIMMYT made in agronomic research are presented as a fundamental complement to technology adoption by farmers in different regions of the world.

# Genetic Improvement

## *Germplasm development*

The initial step in developing maize germplasm for acid soils consists in forming basic populations for the improvement program. The first population of maize developed that was tolerant of acid soils was SA-3, with yellow semiflint grains, followed by SA-8, derived from cycle 2 of full siblings (FS) of the SA-3 population (Granados et al. 1993, 1995).

To respond to national program requirements and to future needs of hybrid production, heterotic populations were formed: two yellow (SA-4, dent; and SA-5, flint) and two white (SA-6, dent; and SA-7, flint). The methodology for forming these populations is described by Granados et al. (1995) and Pandey et al. (1995).

The current priority is to orient the improvement program toward line production, to form both synthetics (open-pollinated varieties) and hybrids. Accordingly, germplasm is being grouped into two heterotic groups: one for yellow maizes and the other for white (Narro et al. 1997). In accordance with interpopulational heterosis, populations SA-3 and SA-5 were brought together into a single population (new SA-3), and population SA-7 was joined to population SA-8 (new SA-7). Then, a program of reciprocal recurrent selection was adopted for the yellow group, including populations SA-4 and the new SA-3; and for the white group, including populations SA-6 and the new SA-7.

## Germplasm improvement

***Environments and selection methods.*** Different methods of recurrent selection have been used in the program, including modified ear-to-row (MER), FS, and selection based on $S_1$ families ($S_1$). International trials of progeny were carried out in all cases. At Palmira (Colombia), with high-fertility soils, the progenies are recombined and generated for subsequent evaluation at three or more sites within the country. The evaluations were carried out at (1) the Carimagua Research Center, on soils with 55% Al saturation and 10 ppm P (Bray-II); (2) Santander de Quilichao, under conditions similar to those of Carimagua; and (3) Villavicencio, on two soils, one with 55% Al saturation, the other with 65%, and both with 10 ppm P. In addition, where possible, the progenies were evaluated in Brazil, Indonesia, Peru, the Philippines, Thailand, and Venezuela. The selection of the best-performing progenies across sites and their recombination made possible the development of maize populations with improved tolerance of acid soils.

Once the base population was formed, the intrapopulation selection process was initiated to increase the frequency of favorable genes in each population.

Population SA-3 was submitted to an intense selection process (Granados et al. 1993) over 16 selection cycles, using the MER method (Pandey et al. 1984). The SA-8 population underwent three FS and $S_1$ selection cycles. Currently, a program for reciprocal recurrent selection is under way for both yellow and white populations.

***Selection criteria.*** The principal selection criterion in the reciprocal program is high yield under both acid and fertile soil conditions. Indirect selection, which considers traits that are easier or faster to evaluate, is useful when strong genetic correlation exists between the two traits included in the selection process and when the heritability of the trait under indirect selection is greater than that of the principal trait. For population SA-3, efficiency was only 88.7% when the number of ears per plant was considered as the trait to improve yield (Pandey et al. 1994).

Selection, using nutrient solutions or pots with soil, has been less efficient in improving maize yield in acid soils than evaluating yield directly in experimental plots (Kasim et al. 1990; Magnavaca et al. 1987).

***Selection gain.*** In each population, a variable number of selection cycles were completed. Since the mid-1970s, the selection method for the SA-3 population was MER. Subsequently, the FS and/or $S_1$ methods were used for all populations, including the SA-3. Another important aspect of the selection methodology used was that the evaluation of progenies and cycles was done in environments with either acid or fertile soils.

Selection progress, measured in acid soils for the SA-3 population over 14 cycles, gave an average gain of 40 kg/ha, using the MER method and 310 kg/ha (average 2 cycles) with the FS method. For the other populations (SA-4, SA-5, SA-6, and SA-7), two selection cycles were completed with the FS method, with gains of 48, 7, 119, and 185 kg/ha per cycle, respectively.

When evaluation was carried out on fertile soils, the average gain per cycle in the SA-3 population, using the MER method, was 47 kg/ha after 14 cycles and 145 kg/ha after 2 cycles with the FS method. For populations SA-4, SA-6, and SA-7, the gains were 263, 360, and 703 kg/ha per cycle, respectively. In population SA-5, yield dropped by 131 kg/ha per cycle. When interpreting such results, the number of cycles and sites where the evaluations were made should be considered.

The most important conclusions in the evaluation of selection cycles are as follows:

- The selection methodology used should permit yield increase on both acid and fertile soils. The populations that yielded best on acid soils also gave high yields on fertile soils. A similar trend was observed for lower yielding populations.

- When the selection method included progeny evaluation in trials with replicates, as occurs with the FS method, the gains per selection were greater.

- Gain per selection depended on the population under study and on the precision with which the selection and evaluation of progenies were carried out.

## *Cultivar development*

National research programs can immediately use experimental varieties. Thus, at different sites around the world, trials are carried out with replicates to compare the patterns of those formed in the Program with the best checks available in each national program.

Since 1992, different types of trials (I, II, III, IV, and V) have been established for acid soils, where the evolution of cultivars obtained by the Program can be observed. During 1992 to 1993, acid-soil trial II was established at 24 sites: 4 in fertile soils and 20 in acid soils. The results indicated that, in acid soils, the yield of the CIMMYT-CIAT maize varieties (CIMCALIs) was slightly higher (about 2.8 t/ha) than that of the best regional checks (about 2.5 t/ha).

Trial type III was planted at 13 sites with acid soils and at 2 with nonacid soils. Across environments with acid soils, the best variety (CIMCALI) yielded 3.51 t/ha, while the best check yielded 3.67 t/ha and the var. Tuxpeño Sequía yielded 2.31 t/ha. This series of trials resulted in the release of experimental varieties by national programs in Indonesia (Antasena) and Colombia (ICA-Sikuani V-110).

Trial type IV for acid soils initiated the evaluation of eight unconventional hybrids (line × variety), together with eight open-pollinated varieties (CIMCALIs 95) and four checks (Sikuani, Tuxpeño Sequía, and two local varieties). The trial was planted at six sites with acid soils and three with nonacid soils. Results show that, on nonacid soils, the yield of the best hybrid surpassed that of var. Sikuani by 50% (Table 1). On acid soils, the yields of vars. Sikuani and Tuxpeño Sequía, and the best CIMCALI were 3.07, 2.51, and 3.18 t/ha, respectively, while the yield of the best hybrid was 4.53 t/ha.

The results of 13 type V trials (six on acid soils and seven on nonacid soils) show that the yield of the best hybrids is 50% or more than that of var. Sikuani (open-pollinated) (Table 2). On acid soils, the yield of var. Sikuani was 1.9 t/ha, while that of the best hybrid was 44% higher (3 t/ha). Stress conditions were very severe, which is why yields were very low.

What this series of results shows is that a production system that includes the maize crop as a component does

Table 1. Grain yield of maize varieties and nonconventional hybrids evaluated at six sites with acid soils and three sites with nonacid soils.

| Material | Acid soils | | Nonacid soils | |
|---|---|---|---|---|
| | (t/ha) | (%) | (t/ha) | (%) |
| Checks: | | | | |
| Var. Sikuani | 3.07 | 100 | 3.65 | 100 |
| Var. Tuxpeño Sequía | 2.51 | 82 | 3.86 | 106 |
| Local variety 1 | 3.10 | 101 | 4.81 | 132 |
| Local variety 2 | 3.64 | 118 | 5.54 | 152 |
| Average for 8 CIMCALI varieties | 2.47 | 80 | 2.67 | 73 |
| Best CIMCALI variety | 3.18 | 104 | 3.77 | 103 |
| Average for 8 hybrids | 3.84 | 125 | 4.70 | 129 |
| Best hybrid | 4.53 | 148 | 5.48 | 150 |

Table 2. Grain yield of maize varieties and hybrids evaluated at six sites with acid soils and seven sites with nonacid soils.

| Material | Acid soils | | Nonacid soils | |
|---|---|---|---|---|
| | (t/ha) | (%) | (t/ha) | (%) |
| Checks: | | | | |
| Var. Sikuani | 1.90 | 100 | 3.54 | 100 |
| Local variety 1 | 2.11 | 111 | 5.35 | 163 |
| Local variety 2 | 1.72 | 90 | 4.87 | 138 |
| Average for varieties | 2.27 | 119 | 4.74 | 134 |
| Hybrids: | | | | |
| Best simple variety | 2.50 | 132 | 5.98 | 169 |
| Best triple variety | 2.74 | 144 | 5.30 | 150 |

well when the best available technology is used. The variety (or cultivar or genotype in general) is a key factor that can, in many cases, decide whether a technology is adopted or not.

## Physiological Studies

Aluminum toxicity is more widely distributed in acid soils, where it is the most important constraint. The search for tolerant genotypes is thus a fundamental step for crop adaptation. For barley and wheat, adaptation to acid soils and Al tolerance are closely correlated (Reid et al. 1969), a trait that appears to be also true for maize.

Aluminum mainly affects the plant's root system, producing a toxic effect and inhibiting P and water uptake. Reduction in growth of the root system can be measured some hours after the onset of stress (Horst et al. 1992). However, other more sensitive indicators of Al toxicity exist, including callus formation in the roots (Schreiner et al. 1994; Wissemeir et al. 1987) and inhibition of the net efflux of K (Cakmak and Horst 1991; Sawasaki and Furlani 1987).

The mechanisms responsible for plants' tolerance of Al toxicity are not well known. As the effects of Al toxicity are observed primarily in the root system, a close relationship may exist between Al concentration in the root apex and the degree of root growth.

Evidence suggests that Al toxicity and tolerance are manifested in the cellular area. If true, this will facilitate the development of evaluation methods based on cell and tissue culture, thus permitting the possible development of important tools for identifying tolerance of this element on the basis of an individual plant or, perhaps, cell. This methodology would also pave the way for applying nonconventional techniques for improving the maize plant's adaptation to acid soils.

Phosphorus is another important limiting element in acid soils, and its use depends on the plant's capacity for absorbing and transporting the element to the leaf surface, and on the plant's metabolism and growth. As this nutrient scarcely mobile in the soil, plants with well-developed root systems have greater access to it. Similarly, plants with greater capacity to secrete hydrolytic enzymes and organic acids, and evolve $CO_2$, all of which, in their turn, increase the decomposition of organic matter, also make greater use of available P in the soil.

To identify individuals tolerant of acid soils, various evaluation techniques have been tried, taking into consideration root traits. In 1987, 17 maize populations were evaluated with different degrees of tolerance of Al toxicity, according to the net length of their seminal root (final seminal root length minus initial seminal root length). Plants were grown in nutrient solutions containing 0, 4.5, 6, or 8 ppm Al. In materials tolerant of acid soils (e.g., var. CMS-36), the length of the seminal root (19.9 cm) was double that of the susceptible materials (e.g., var. Tuxpeño Sequía = 9.9 cm), although some materials that were highly tolerant in the field did not perform better in nutrient solutions (Pandey 1991).

In the acid soils of the CIAT Carimagua and Quilichao experiment stations, the tolerance of maize genotypes of acid soils was evaluated under field conditions, in pots in the greenhouse, and in nutrient solutions (Urrea 1994). The seedlings grew for 2 weeks, during which the morphological traits used to separate susceptible and tolerant genotypes were measured. The first trial was a dialellic experiment with eight progenitors (six tolerant of and two susceptible to Al) and their possible combinations. The second consisted of the evaluation of 10 varieties, two of which were susceptible. Results suggested that the pot technique is effective for distinguishing between tolerant and susceptible genotypes. The correlations among the best traits between evaluations with the pots and yields in the field ranged from 0.45 to 0.55.

## Agronomic Studies

The release of var. Sikuani by the Colombian Corporation for Agricultural Research (CORPOICA) in 1994 created the need for obtaining complementary agronomic data related to fertilization, use of amendments, and feasibility of incorporating maize into agropastoral systems. For this purpose, trials in experimental fields and on farms were initiated in coordination with national programs. Progress in these trials is reported below.

### *On-farm fertilization trials*

In the Colombian Eastern Plains, on those farms that traditionally grew maize, two trials were established in lots where maize was traditionally planted. The soils at the experimental sites (Guacavía and Guamal) have low Al saturation, so lime was not applied. The maize variety Sikuani (five levels of N-P-K) and the local variety (high levels of fertilization, with N = 100, P = 100, and K = 120) were used. In addition, a treatment was included to represent farmers' management practices, that is, local variety planted to a density of about 40,000 plants/ha, with very low fertilization, manual weeding, and no pest control. Var. Sikuani yielded more (>3 t/ha) than the local variety, which yielded 1.9 t/ha with the farmers' technology and 2.3 t/ha with high fertilization. The largest net gain was obtained with var. Sikuani and the application, at kg/ha, of 100, 60, and 60 N-P-K, respectively (Table 3).

In the same region, var. Sikuani was also evaluated in those farm fields located in Pachaquiaro, Santa Cruz, and La Esperanza. Maize had not been planted at these sites because the high Al saturation did not permit growth of the available, but susceptible, varieties. Given that the soils had an Al saturation of more than 60%, 400 kg/ha of dolomitic lime had to be applied to reduce this level to 55%. Four levels of N-P-K were applied (Table 4). The results showed differences in yield among sites but not in the response to fertilization rates at any one site. What was most important in these trials was the yield and response

Table 3. Yield and net gains per hectare obtained with the local variety and improved maize variety ICA-Sikuani V-110 under different crop management systems, Guacavía and Guamal, Colombia, 1994.

| Benefits | Local variety | | Var. Sikuani | |
|---|---|---|---|---|
| | Farmers' management | N (100), P (100), K (120) | N (50), P (100), K (60) | N (100), P (60), K (60) |
| Production costs (Col$/ha)[a] | 115,125 | 262,815 | 238,125 | 241,365 |
| Maize yield (t/ha) | 1.9 | 2.3 | 3.3 | 3.5 |
| Value of maize (Col$/ha)[a] | 349,100 | 425,500 | 556,750 | 595,000 |
| Net profit (Col$/ha)[a] | 233,975 | 162,685 | 318,625 | 353,635 |

a. 1994 exchange rate: Col$900 = US$1.

Table 4. Production (t/ha) of maize variety Sikuani with N-P-K application in farm fields, Colombian Eastern Plains, 1994.

| Farm | Treatment | | | Site | | |
|---|---|---|---|---|---|---|
| | N | P | K | Pachaquiaro | Santa Cruz | La Esperanza |
| 1 | 100 | 100 | 120 | 4.58 | 2.62 | 3.07 |
| 2 | 100 | 100 | 60 | 4.27 | 2.45 | 2.68 |
| 3 | 100 | 60 | 60 | 4.10 | 2.85 | 2.98 |
| 4 | 50 | 100 | 60 | 4.01 | 2.02 | 2.20 |
| Average | | | | 4.24 | 2.46 | 2.73 |
| CV (%) | | | | 11.95 | 13.21 | 11.66 |
| LSD (5%) | | | | 1.01 | 0.68 | 0.64* |

* = $P < 0.01$.

to fertilization of var. Sikuani (>4.5 t/ha) in Pachaquiaro, where the level of Al saturation was 55%.

At the Carimagua Research Center (Colombian Eastern Plains), the response of the maize varieties Sikuani, CIMCALI 93 SA3, CIMCALI 93 SA6, and an experimental hybrid to fertilization with P and K (0, 40, 80, and 120 kg/ha $P_2O_5$ and $K_2O$) plus 120 kg N/ha was evaluated. In general, response to the application of K was slight, especially when applied as $K_2O$ at 40 kg/ha (2.92 t/ha for the check versus 3.33 t/ha). In contrast, the response to P applications was greater, with yields of 1.38, 3.09, 4.17, and 4.41 t/ha, with $P_2O_5$ at 0, 40, 80, and 120 kg/ha, respectively (Table 5). No differences were found in the responses of genetic materials to applications of P and K.

To study the residual effect of the treatments in this trial, the same cultivars were planted on the same plots corresponding to the previous year, and N at 80 kg/ha was applied. The average yield was 2.02 t/ha versus the average mean of 3.26 t/ha for the previous year, when P and K were applied. This indicates that the investment in fertilizers is profitable if the value of the additional production (1.24 t) is greater than the cost of fertilizing, which was, at that time, a highly profitable investment in Colombia. It is likely that this profitability will be higher, to the extent that the best available technological alternatives are used in terms of

Table 5. Maize grain production (t/ha) with P and K applications on an Oxisol, Colombian Eastern Plains.

| $P_2O_5$ (kg/ha) | $K_2O$ (kg/ha) | | | | Average[a] |
|---|---|---|---|---|---|
| | 0 | 40 | 80 | 120 | |
| 0 | 1.52 | 1.54 | 1.27 | 1.20 | 1.38 |
| 40 | 2.87 | 3.10 | 3.22 | 3.16 | 3.09 |
| 80 | 3.45 | 4.47 | 4.18 | 4.58 | 4.17 |
| 120 | 3.83 | 4.20 | 5.07 | 4.55 | 4.41 |
| Average[b] | 2.92 | 3.33 | 3.44 | 3.37 | |

a. $LSD_{0.05}$ for P rate = 0.29 t/ha.
b. $LSD_{0.05}$ for K rate = 0.27 t/ha.

variety, fertilizer rates, and forms of use. In this case, no differences were observed, due to the residual effect of the K application, but there were for P: 1.46, 1.99, 2.24, and 2.38 t/ha when P was applied as $P_2O_5$ at 0, 40, 80, and 120 kg/ha, respectively (Table 6).

In the Colombian Eastern Plains, a trial was conducted to study the response of maize to the application of the trace elements B, Zn, Mn, and Cu at rates of 1.2, 8.8, 7.2, and 5.2 kg/ha, respectively, applied as sulfates and chelates. Results showed a clear response to applications of Zn. In the treatment containing all trace elements, the maize yield was 2.13 t/ha; when only Zn was included, it was 1.78 t/ha; and when Zn was not included, but the other trace elements were, yield was 0.29 t/ha (Table 7). No observed differences were seen between chelated and sulfate forms.

The principal results of on-farm trials carried out in collaboration with the national institutions of Colombia, Ecuador, and Peru were as follows:

- In areas of fertile lowlands and savannas of the Colombian Eastern Plains, the performance of var. Sikuani and the local variety was studied under two management technologies: recommended and traditional. The former consisted of fertilization (kg/ha) with N (100), $P_2O_5$ (60), and K (60); a sowing density of 50,000 plants/ha; and two applications of agrochemicals for controlling pests. The farmers' technology consisted of half of the above fertilizer rates, 37,500 plants/ha, and one application of pesticides. In both cases, herbicides were applied for weed control.

- There was a significant response for both the use of technology and adoption of variety. For the traditional maize variety, the recommended technology meant an average increase of 0.7 t/ha in yield over that of the traditional technology', and was greater on the fertile lowlands than on the savannas.

- Similarly, the adoption of the improved variety alone—in this case

Table 6. Residual effects of P and K applications on the grain yield (t/ha) of maize cultivars, Colombian Eastern Plains.

| K (kg/ha) | P (kg/ha) | | | | Average |
|---|---|---|---|---|---|
| | 0 | 40 | 80 | 120 | |
| 0 | 1.61 | 1.86 | 2.08 | 2.12 | 1.92 |
| 40 | 1.43 | 2.00 | 2.34 | 2.86 | 2.16 |
| 80 | 1.45 | 1.96 | 2.30 | 2.35 | 2.02 |
| 120 | 1.34 | 2.13 | 2.26 | 2.17 | 1.98 |
| Average[a] | 1.46 | 1.99 | 2.24 | 2.38 | 2.02 |

a. $LSD_{0.05}$ for P rate = 0.83 t/ha.

Table 7. Maize yields (t/ha) after applications of different trace elements (B, Zn, Mn, and Cu), Colombian Eastern Plains.

| Treatment[a] | Yield (t/ha) |
|---|---|
| C | 2.13 |
| C - B | 1.82 |
| C - Zn | 0.29 |
| C - Mn | 1.78 |
| C - Cu | 2.02 |
| B | 0.21 |
| Zn | 1.78 |
| C - Mn | 0.17 |
| C - Cu | 0.32 |
| $LSD_{0.05}$ | 0.32 |

a. C = B + Zn + Mn + Cu
C-B = Zn + Mn + Cu - B
C-Zn = B + Mn + Cu - Zn
C-Mn = B + Zn + Cu - Mn
C-Cu = B + Zn + Mn - Cu
B = B only
Zn = Zn only
Rates were, at kg/ha, B = 1.2; Zn = 8.8; Mn = 7.2; Cu = 5.2.

Sikuani—meant a greater yield increase in the savannas of 0.6 t/ha, and, in the fertile lowlands, of more than 1 t/ha (Table 8).

Table 9 gives the results of four trials conducted at Castilla, Grenada, Yopal, and Aimaral (all in the Colombian Eastern Plains) with var. Sikuani, a commercial hybrid, and the local variety when cultivated with the traditional and recommended technologies as described previously. Yields were higher when using the recommended technology than with the traditional practices (3.4 versus 2.2 t/ha). With the three cultivars, an average of more than 1 ton of additional of grain was obtained with the adoption of the recommended technology, although this difference was greatest when the commercial hybrid was used. In addition, the adoption of a new variety (Sikuani) or the commercial hybrid meant an increase of at least 0.6 t of maize over the local variety. This increase was greater with the commercial hybrid when using the recommended technology. The economic analysis of the impact of var. Sikuani showed a marginal rate of return of 60% over the technology used by farmers.

In Ecuador, four cultivars were evaluated in four environments with different levels of Al saturation in the Province of Napo. Variety Sikuani outyielded the two local checks: INIAP 526 (a variety for nonacid tropical soils improved by the Ecuadorian national research program), and the local cv. Tusilla. The average yield of var. Sikuani was 2.2 t/ha, that is, 48% more than the yield of the local check cv. Tusilla (at 1.49 t/ha) (Table 10).

In Peru, trials were established on farms in the Province of San Martín (Alto Mayo). Variety Sikuani and the local variety—an advanced generation of Marginal 28 Tropical, derived from CIMMYT population 28—were evaluated, using the recommended technologies and that of the farmers.

Table 8. Yield (t/ha) of two maize varieties—Sikuani and local variety—cultivated with two technologies in the fertile lowlands and savannas of the Colombian Eastern Plains.

| Technology | Fertile lowlands | | Savannas | | Average |
|---|---|---|---|---|---|
| | Sikuani | Local | Sikuani | Local | |
| Recommended | 3.45 | 2.35 | 2.20 | 1.65 | 2.41 |
| Traditional | 2.40 | 1.80 | 1.40 | 1.15 | 1.68 |
| Average | 2.92 | 2.07 | 1.80 | 1.40 | |

Table 9. Yield (t/ha) of two maize cultivars and a hybrid, cultivated under two technologies in farm fields, Colombian Eastern Plains.

| Material | Technology[a] | | Average |
|---|---|---|---|
| | Recommended | Traditional | |
| Var. Sikuani | 3.53 | 2.42 | 2.98 |
| Commercial hybrid | 3.85 | 2.51 | 3.18 |
| Local variety | 2.93 | 1.82 | 2.38 |
| Average | 3.44 | 2.25 | |

a. $LSD_{0.05}$ for technologies = 0.34.

Table 10. Yield (t/ha) of maize cultivars in the acid soils of the Province of Napo, Ecuador.

| Variety | Site | | | | Average |
|---|---|---|---|---|---|
| | El Heno | La Punta | San Carlos | Payamino | |
| Improved varieties | | | | | |
| CIM. 93 SA5 | 1.00 | 3.01 | 1.80 | 1.58 | 1.78 |
| Sikuani | 1.59 | 3.26 | 1.54 | 2.17 | 2.20 |
| Local checks | | | | | |
| INIAP 526 | 0.49 | 2.45 | 1.36 | 1.92 | 1.41 |
| Tusilla | 0.69 | 1.89 | 1.06 | 1.75 | 1.49 |
| Best check (%) | 231 | 133 | 133 | 113 | |

The principal difference between them was that farmers did not apply fertilizer, whereas, for the recommended technology, N (90) and P (90 as $P_2O_5$) were applied (at kg/ha). No K was applied. Results indicated that var. Sikuani (1.81 t/ha) had higher yields than did the local variety (1.22 t/ha) (Table 11).

Although different technological alternatives, cultivars, and agronomic practices were evaluated in these trials to identify maize varieties with potential in farmers' production systems, this crop should also play an important role in the management of agropastoral systems in the acid-soil savannas of tropical Latin America. Accordingly, the gradual improvement of germplasm oriented toward the search for cultivars with higher yields under these conditions will contribute to the better use of these environments. Currently, improved varieties have greater yield and better agronomic traits than do local cultivars. Evidence that hybrid vigor should be exploited to increase yields of acid-soil-tolerant materials makes it possible to accelerate hybridization to obtain useful lines for forming open-pollinated and superior hybrids for these environments. The response to P applications should also be highlighted, particularly when $P_2O_5$ is applied at 80 kg/ha. The high response to applications of Zn is also an important achievement that should be taken into account when formulating recommendations for production systems.

Table 11. Yield (t/ha) of two maize cultivars under two technologies, and evaluated in farm fields, Alto Mayo, Peru.

| Cultivar | Technology | | Average |
|---|---|---|---|
| | Recommended | Farmers' | |
| Sikuani | 2.00 | 1.62 | 1.81 |
| Local | 1.24 | 1.20 | 1.22 |
| Average | 1.62 | 1.41 | |

## *Using amendments*

At the CIAT Quilichao Experiment Station (Colombia), the effect of applying dolomitic lime and its interaction with P were evaluated in maize varieties Sikuani (tolerant of acid soils) and Tuxpeño Sequía (susceptible to acid soils). The effects were measured in one phase of the crop cycle and in a following crop with no P application. The Al saturation in the soil was 65%, 50%, or 35%, and P was applied as $P_2O_5$ at 0, 45, 90, or 135 kg/ha.

On the average, var. Sikuani produced 22% more grain than var. Tuxpeño Sequía (4.71 versus 3.87 t/ha). This difference was greater when plant stress increased with higher Al saturation or greater P deficiency. Thus, var. Sikuani yielded 80% more than var. Tuxpeño Sequía when the Al saturation was 64% and no P was applied to the soil (3.0 versus 1.7 t/ha). Both varieties responded to P applications, the response being greater with $P_2O_5$ at 0-45 kg/ha. At higher rates, the average yield of the varieties was 1.12 t/ha (data not shown).

To evaluate the residual effect of lime and P, the experimental arrangement from the previous trial was used without fertilizers. There was a clear reduction in yield in vars. Sikuani (by 1.68 t/ha) and Tuxpeño Sequía (by 0.89 t/ha), being more drastic in the latter as stress became more severe. However, when Al saturation was 64%, the absence of P had no negative effect. Production in this case was also greater when $P_2O_5$ was applied at 45 kg/ha in the previous crop. In the check without P, production was 0.68 t/ha, whereas, when $P_2O_5$ was applied at 45 kg/ha, it was 1.27 t/ha (data not shown).

In a sandy Oxisol of the Colombian Eastern Plains, the application of soil amendments was evaluated. Sources used were dolomitic lime (1.03 t/ha, i.e., 57% $CaCO_3$ and 35% $MgCO_3$) and Sulcamag (1.3 t/ha, i.e., 25% CaO, 12% MgO, and 8% S) for var. Sikuani. The application methods used were a handful per plant, broadcast, band application, or a combination of the last two. In addition, fertilizer was applied to every crop, at 120, 80, and 80 kg/ha of N, $P_2O_5$, and $K_2O$, respectively.

When Sulcamag was applied, average maize yield was more than double that under dolomitic lime (3.45 versus 1.59 t/ha). For Sulcamag, no observable differences were seen among application methods nor for the interaction methods × source (Table 12). The broadcast application of Sulcamag is probably the most economical alternative for the sandy soils of the Colombian Eastern Plains. When the residual effects of applying Sulcamag was evaluated, trends similar to those observed in the first trial were observed, but yields were lower.

## *Establishing pastures in association with maize*

In the Colombian Eastern Plains, pasture establishment was evaluated, using the maize variety Sikuani as an associated crop. Treatments consisted of maize in monoculture, maize + grass, and maize + grass + legumes.

Table 12. Effect of method of applying lime and Sulcamag on first harvest of maize variety Sikuani and residual effects, Colombian Eastern Plains.[a]

| Application method | Amendments | | | |
|---|---|---|---|---|
| | First year | | Residual effects | |
| | Lime | Sulcamag | Lime | Sulcamag |
| Handful per plant | 1.20 | 3.43 | 0.96 | 1.41 |
| Band | 1.36 | 3.00 | 0.76 | 1.30 |
| Broadcast | 1.68 | 3.67 | 0.49 | 1.24 |
| Band + broadcast | 2.14 | 3.71 | 0.87 | 1.63 |
| Average | 1.59 | 3.45 | 0.84 | 1.40 |

a. $LSD_{0.05}$ between amendments = 0.54 t/ha.
$LSD_{0.05}$ between methods of application = 0.25 t/ha.

Table 13. Net profit per hectare of three production systems that include maize and grasses, Colombian Eastern Plains, 1994.

| Variable[a] | Maize monocrop | Maize + grass[b] | Maize + grass + legume |
|---|---|---|---|
| Production costs (Col$) | 380,000 | 416,000 | 670,000 |
| Maize yield (t/ha) | 2.9 | 3.1 | 2.7 |
| Value of maize (Col$) | 493,000 | 527,000 | 459,000 |
| Value of pasture (Col$) | — | 175,000 | 400,000 |
| Net profit (Col$) | 113,000 | 286,000 | 189,000 |

a. 1994 exchange rate: Col$900 = US$1.
b. + = grown simultaneously in same field.

The grass was *Brachiaria dictyoneura* Fig. & De Not. and the legumes were *Stylosanthes capitata* Vogel, *Centrosema acutifolium* Benth., and *Arachis pintoi* Krapovickas & Gregory.

Results obtained (Table 13) indicated the following:

- Maize yield changed significantly in the pasture association, whether with grass alone or with grass + legumes.

- The commercial value of the maize production covered the establishment costs of the associated pasture. This result is key to the more intensive use of pastures in the region.

- The costs of establishing the maize + grass + legume association increased because of the high cost of the legume seed and labor for sowing maize and pasture. In this trial, *A. pintoi* was planted in parallel, between every two rows of maize + grass, and at a distance of 15 cm from the maize + grass rows.

- The best net gain per hectare (US$358) was obtained with the maize/grass system.

The establishment of production systems that include annual crops and improved pastures in the acid-soil savannas of the Colombian Eastern Plains is an economically viable alternative. Native species have a carrying capacity as low as 1 animal/10 ha, with daily liveweight gains of 300 g/animal. This means an annual income of about US$110/10 ha. With improved pastures, the stocking rate can be increased to 2 animals/ha and the daily liveweight gain can reach 500 g/animal, thus increasing the annual income to US$365/ha. Taking into account that the liveweight gain can be increased between 10% and 15% on the grass-legume mixture, the farmer could obtain an annual income of US$400/ha. Consequently, this ecosystem is favorable for establishing profitable agropastoral systems, in which annual crops, improved pastures, and tree systems form parts of a production system that permits the rational and sustainable use of available natural resources.

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