Sorghum for Acid Soils

Proceedings of a Workshop on Evaluating Sorghum for Tolerance to Al-Toxic Tropical Soils in Latin America held in Cali, Colombia, 28 May to 2 June, 1984.

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Technical editors: Lynn M. Gourley and José G. Salinas

INTSORMIL International Sorghum and Millet Program

ICRISAT International Crops Research Institute for the Semi-Arid Tropics

CIAT Centro Internacional de Agricultura Tropical

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Cover: INTSORMIL research assistant, Manuel Coronado, compares aluminum-tolerant variety IS 3071 (right) with a susceptible variety in screening trials at Santander de Quilichao, Cauca, Colombia. Photo: Lynn M. Gourley.

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Foreword

The vast expanses of underutilized land areas in the tropics are the agricultural frontiers of today. One of the predominant reasons that these areas remain marginal for agricultural production is their infertile acid soils. The technology to permit these acid soil areas to reach the agricultural production potential equal to that of areas found in temperate zones has been known for many years. However, this technology has not been successfully adopted in most of the tropical countries because of limiting factors including: lack of access to capital; inadequate transportation and marketing systems; and the high cost and inadequate supply of production inputs for resource-poor farmers. Thus, most of the chronically poor, undernourished populations of the world are found in countries in the tropics.

Few conventional crop species grow well in these leached acid soils, primarily because of soil constraints such as aluminum toxicity, phosphorus fixation, macro- and micro-element deficiencies, and manganese toxicity. These constraints pose additional challenges to most commercial and many subsistance crop species. Genetic variability among and within cultivated plant species for tolerance to acid soil constraints has been identified, negating the requirement of large quantities of production inputs.

Among all of the major cereals, grain sorghum production has the largest per annum growth rate in Latin America, in terms of both area planted and total production. Grain sorghum yields are decreasing as more marginal lands are brought into production. The genetic variability of sorghum for tolerance to acid soils, using low-input technology, has not been measured. Few of the more than 22,000 accessions in the sorghum world collection have been evaluated in acid soils in the tropics. Many of the published aluminum-tolerance screening techniques have not been field validated and few have measured the final product of production—grain yield.

At the invitation of the Centro Internacional de Agricultura Tropical (CIAT), the International Sorghum and Millet Collaborative Research Support Program (INTSORMIL-CRSP) initiated a project to screen and breed sorghum for adaptation to acid-soil ecosystems. The project is currently in the third evaluation season (first semester 1984).

At the outset of this project, a small sharp-focused workshop was planned to inform Latin American National Programs (of countries with large areas of acid soils) of the purpose of the INTSORMIL Colombian program. Speakers were selected to share their thoughts and results of tropical acid soil field-screening techniques used for evaluating tolerance to aluminum toxicity in sorghum and other crops.

The purpose and goals of this workshop were to:

Bring together plant breeders, plant physiologists, soil scientists, and agricultural administrators involved in tropical acid soils research in a state-of-the-art workshop.

Define areas in Latin America where aluminum-tolerant sorghum cultivars would have the greatest initial production and utilization impact. (It is understood that the research reported in these proceedings would also be useful to scientists in other tropical regions where acid soil limits crop production.).

Discuss the future exchange of information and sorghum germplasm with all research programs in Latin America and international research agencies.

Project the roles of Latin American national programs, INTSORMIL, and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in conducting sorghum research in acid-soil ecosystems for the next five years.

The support of the sponsors INTSORMIL, ICRISAT, CIAT, and Instituto Colombiano Agropecuario (ICA) is gratefully acknowledged, as is CIAT's contribution as host in providing facilities and staff for the workshop, and publication of these proceedings.

Lynn M. Gourley
Mississippi State University, USA

José G. Salinas
CIAT, Cali, Colombia

REPRESENTATIVES OF SPONSORING INSTITUTIONS

Welcome to CIAT and the Need for Sorghum Research in Latin America

*Douglas R. Laing**

On behalf of Dr. John Nickel and my colleagues, I would like to extend to you a warm welcome to the Centro Internacional de Agricultura Tropical (CIAT). It is a great pleasure for me to have the opportunity to say a few words at the opening of this workshop on sorghum and its adaptation to the acid soils of the tropics.

As you are all very well aware, the tropics are well endowed with acid soils and this is particularly so in Latin America where large areas of well watered acid savannas remain to be developed for arable agriculture. CIAT has focused attention on these areas in the Tropical Pastures Program with the aim of developing grass-legume pasture combinations adapted to acid soils. In addition, research in the Cassava and Rice Programs has for some years aimed at developing crop alternatives with similar adaptation.

Our objective is clearly to develop technology components, in cooperation with national research institutions, which will be adapted to these particular climatic and edaphic conditions and which could form an integral part of farming systems involving both pasture and crop phases.

The accelerated adoption of the new pasture systems being developed in the network in Latin America will depend, to a certain degree, on the existence of a viable cropping phase which can provide the necessary economic stimulation for the integrated development of stable farming systems in these frontier regions.

In all of this work, one of the key factors guiding the research is the need to develop low-cost technology components which do not require heavy application of purchased inputs, and which

* Deputy Director General, Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia.

certainly do not attempt to drastically lower the level of soil acidity through liming.

This leads me to sorghum. In **CIAT Long Range Plan for the Decade of the Eighties,** published in 1981, we analyzed the future scenarios for various crop commodities that are grown in the Latin American region, including those in CIAT's mandate. It was concluded that two crops, namely sorghum and soybeans, were not receiving the level of research attention, either internationally or nationally, consistent with the expected future demand for these commodities. In **CIAT Plan for the Eighties,** we foresaw the possibility of research collaboration with other institutions in order to stimulate research on these crops, particularly for the acid soils of the tropics, which would complement our own work in CIAT's mandated commodities.

Accordingly, in 1980, we approached both the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the International Sorghum and Millet Program (INTSORMIL) with the idea that CIAT could host a sorghum research project directed towards these ends. Agreement was rapidly reached and a tripartite Memorandum of Understanding was signed by ICRISAT, INTSORMIL, and CIAT. INTSORMIL subsequently developed the project at CIAT with the initial appointment of Dr. Lynn Gourley, professor of agronomy (sorghum breeder), Mississippi State University.

CIAT has actively supported the project through the provision of infrastructure at headquarters and through our international cooperation channels already in place. We have also actively encouraged the excellent research collaboration which the project has developed with Instituto Colombiano Agropecuario (ICA) in Colombia. We are very pleased to have seen the very respectable progress in breeding for tolerance to soil acidity which is being reported in this workshop. We, at CIAT, are also very pleased to see the excellent research progress being made by other institutions in the Americas on the overall subject of acid soil adaptation, which is the subject of this workshop.

I wish you well in your discussions and would like to indicate our sincere interest in continuing to provide a home for this important collaborative initiative.

The Role of INTSORMIL and Other Collaborative Research Support Programs in International Research

*R. Rodney Foil**

It is a pleasure and an honor to participate in this workshop, and to share with you a few thoughts regarding the role of the International Sorghum and Millet Program (INTSORMIL) and other collaborative research support programs (CRSP's) in international research. In 1975, the Congress of the United States accomplished a major revision of our foreign assistance legislation, including the passage of Title XII, "Famine Prevention and Freedom from Hunger." This title, jointly developed by representatives of higher education in the United States and such long-time political leaders as Senator Hubert Humphrey and Congressman Paul Findley, established several significant new programs for involvement of U.S. universities with problems in the developing world. One section of that title called for the creation of a program to "provide for more effective agricultural sciences—to increase long-term support for the application of science to solving the food and nutrition problems of the developing countries."

From this general language has grown the Collaborative Research Support Program—known by the short title of CRSP, and through INTSORMIL—one of the sponsors of this workshop.

Several factors make the CRSP effort different from other domestic and international programs. To a degree, these are embodied in the title.

First, these programs are truly collaborative. They represent a partnership between U.S. institutions, cooperating institutions overseas, and the United States Agency for International Devel-

* Director, Mississippi Agricultural and Forestry Experiment Station, Mississippi State University, Mississippi State, MS, USA, and member of the Joint Committee on Agricultural Research and Development (JCARD) of the Board for International Food and Agricultural Development (BIFAD).

opment (USAID). The cooperating institutions include national research institutions in host countries, the international centers, and universities. As designed, the programs are collaborative in planning, implementation, and funding. The collaboration and funding deserve mentioning. Unlike other USAID programs, CRSP's require matching funds in the amount of 25% of the USAID contribution. While not always required, cooperating overseas institutions in almost every case provide additional matching support.

The concept of collaboration and funding is very important. According to the architects of the program, the match was conceived primarily as an expression of evidence that the true mutuality of interest was present. That is, that the U.S. institution, and cooperating overseas institutions, would enjoy direct benefit from participation, and demonstrate this benefit by exhibiting locally funded research capacity which can be focused on global problems to the benefit of all parties. As the CRSP's mature, this mutuality of interest has become more and more evident.

A second and more important aspect of the program is that it is truly a research program. CRSP's are not designed to provide technical assistance, participant training, institution building, or technology transfer. In almost every CRSP, these other aspects of development are beneficially impacted, but in every case this is a byproduct of research rather than a major objective.

As research programs, CRSP's are funded by grants and not contracts. The CRSP's are recognized as long-term in nature and are jointly planned to focus on constraints to food production on a global or regional basis.

A related, and equally important, characteristic is that these are support programs. They are designed, not only to provide applicable technology, but to create and nurture a base of scientific capability, with linkage to USAID strategies, sustained by a cadre of scientists with global outlook and experience.

With these as foundation principles, USAID and the Joint Committee on Agricultural Research and Development (JCARD) of the Board for International Food and Agricultural Development (BIFAD) have moved to institutionalize the concept. Almost six years ago, the first CRSP, focusing on small ruminants, was approved. Since then, six more have been created and another, in fisheries stock assessment, is nearing approval. Although planning mechanisms and governance procedures have evolved differently for each, they all have commonalities. In every case, a land-grant institution is the management entity, joining with other institutions to direct the effort. Administrative guidance is through boards of institutional representatives. Technical direction is through committees of scientists, and external evaluation panels provide periodic judgment on progress.

These are not small or insignificant efforts. Forty U.S. institutions cooperate with 63 overseas entities. Work is underway in thirty countries. The USAID commitment has grown to US$20 million annually, and total commitment from all collaborating parties no doubt exceeds US$30 million.

It is too soon to evaluate the scientific impact of this young research program, but significant accomplishments are already being cited. Results of U.S. domestic research have already been validated overseas, and in several instances implementation is in sight. Perhaps more important, international networks have been created and are functioning well, as is evidenced by this workshop. In effect, new research institutions have been created and are now taking on lives of their own. The multi-institutional, multidisciplinary nature of the research effort is exciting to scientists and administrators alike. It is significant that the mutual benefit concept is being proven. With few exceptions, participating U.S. scientists and institutions can already point to scientific benefits that have or will accrue to U.S. agriculture from the effort, and agricultural science in the less developed nations is clearly responding to this new initiative.

It should be of particular interest to this group to learn that some of the first linkages developed by the CRSP's have been with the international centers of the Consultative Group on International Agricultural Research (CGIAR) network. The collaborative work here at the Centro Internacional de Agricultura Tropical (CIAT) is only an example of the kinds of activity that are underway around the world at other centers and with other CRSP's. Interest and support from USAID missions are growing rapidly. In every case, the CRSP's have involved the very best U.S. scientists in the subject or commodity of interest and have established a system for access by the mission and potential host country institutions that was badly needed.

Although the success of the CRSP concept has now been well proven, the outlook for future growth and the creation of additional CRSP's is somewhat clouded. There is strong support for the continuation of currently established CRSP's for at least an additional research cycle. Resources have not been made available to establish additional CRSP's, however, and the approval of the fishery stock assessment CRSP will round out the first set of high priority areas identified and approved for funding by USAID.

Although obtaining additional resources is not likely to be easy, leadership in the U.S. is already focusing on the need to reexamine global priorities and seeking to establish additional research thrusts. The Joint Committee on Agricultural Research and Development of BIFAD has committed itself to a review of the recently developed research priorities of the regional bureaus of USAID, with the goal of identifying constraints that meet the tests of mutuality of interests required for the establishment of a CRSP. When this review is completed, resources will be sought to create additional CRSP's.

As the programs have developed, they have identified the role within the larger international research community that appears to be well-suited to the needs of today and tomorrow. Through the CRSP's, the long-term experience and commitment to research in the land-grant institutions of the U.S. have been wedded to the rapidly developing capability of the international centers and host country institutions to establish a continuum of science that can address the major problems of the world with bigger and positive effects.

A recent summary evaluation of one of the CRSP's, conducted by a panel of world experts in agricultural research, provided an evaluation of the CRSP concept that says better than I can the progress and potential of this unique concept. I'll close by quoting part of this report.

"Similar to the movement of several decades ago which began the establishment of a network of international agricultural research centers (IARC's), CRSP's were introduced into an evolving international agricultural research and development system as a new and needed component. Their unique characteristics present a cost effective model, a model that can perform a critical international role beyond the mandates and capabilities of the IARC's and similar research organizations. Critical among the model's characteristics, as demonstrated by this particular CRSP are:

"The tremendous size of the resource base including the

> professional expertise, the research facilities, and the administrative support structure represented by the U.S. Land-Grant system.
>
> "The diversity of professional disciplines available to be called upon as appropriate to contribute to the problem solving efforts.
>
> "The working partnerships of committed colleagues rewarded for collaborating across national boundaries with other participating nations.
>
> "The management structure whose sole function is the integration and coordination of all the above components while maintaining a focus on overall program goals.

"Thus, as a member of the new CRSP initiative, this program complements and supplements IARC's and other public and private research organizations by broadening and deepening the overall research support base. It has shown itself to be a highly acceptable, interactive mode for technical assistance which brings diverse, largely untapped resources of U.S. centers of excellence into collaborative international research and training activities. Through these efforts, the CRSP extends the worldwide network of institutions and individuals cooperating in this research. More broadly, over time, it helps fashion and strengthen enduring linkages throughout the international agricultural research and development system."

INTSORMIL — What We Have to Offer

*Glen J. Vollmar**

Welcome to the first Sorghum/Acid Soils Workshop. The International Sorghum and Millet Program (INTSORMIL) is most happy to be one of the sponsors and a participant in this important event. We, in INTSORMIL, view workshops such as this as a method of exchanging information and challenging research procedures and findings. This workshop contributes to a research effort that involves several nations in South and Central America. This is a productive process, for it contributes to better research and a sharing of knowledge within and among nations where acid soils are a constraint to sorghum production.

By means of a series of slides let me tell you who we in INTSORMIL are and what we have to offer. Sorghum and millets are major food crops for the least developed and most marginal agricultural areas of the world. These crops were chosen as the highest priority food and feed grains requiring research in the Title XII Collaborative Research Support Program (CRSP). As a result, the Sorghum/Millet CRSP (INTSORMIL) was activated on July 1, 1979. Its overall objective is to improve human nutrition through research and technology development. To accomplish this, training of host-country scientists and strengthening host-country research facilities and procedures are given high priority.

INTSORMIL's specific objectives are to:

Link institutions having common interests in sorghum and millet research;

mobilize and coordinate research talent;

achieve optimum collaboration and information exchange with AID (Agency for International Development) Missions,

* Director INTSORMIL, University of Nebraska, Lincoln, NB, USA. Paper presented by Dr. Lynn M. Gourley.

international research centers, U.S. and LDC (less developed country) institutions; and

be responsible for the program and its fiscal management.

INTSORMIL is an international network of research workers and organizations working to improve human nutrition and prosperity. Some 82 scientists from eight U.S. land-grant universities are collaborating with scientists and in-country programs of host countries on problems of sorghum and millet production and utilization for human food.

INTSORMIL is funded by the U.S. Agency for International Development, participating land-grant universities, host country research agencies, and private donors.

Collaborative activities include research and training support at:

U.S. Land-Grant Institutions

University of Arizona
Florida A & M University
Kansas State University
University of Kentucky
Mississippi State University
University of Nebraska
Purdue University
Texas A & M University

Host Countries: INTSORMIL is involved with the following in-country research programs and the international research centers: Mali, Sudan, Botswana, Honduras, Philippines, India, Mexico, Tanzania, Colombia, Niger, Burkina Faso, Egypt, and Brazil.

International Research Centers

CIAT (Centro Internacional de Agricultura Tropical)
CIMMYT (Centro Internacional de Mejoramiento de Maíz y Trigo)
ICRISAT (International Crops Research Institute for the Semi-Arid Tropics)
IRRI (International Rice Research Institute)

Also, there are cooperative relationships with SAFGRAD (Semi-Arid Food Grain Research and Development), FAO (Food and Agriculture Organization of the United Nations), and other organizations where improvement of sorghum and millet production is an objective.

INTSORMIL researchers located in the United States of America and in host countries conduct sorghum and millet research projects in the following areas:

Agronomy, cultural practices;
physiology, especially plant stress;
breeding, genetics, and varietal improvement;
entomology and pest control;
plant pathology;
storage, utilization, and nutrition; and
socioeconomic considerations.

INTSORMIL stresses "collaborative research" among researchers working with sorghum and millet. INTSORMIL scientists work cooperatively with scientists of other nations in a joint research venture which includes sharing knowledge, research techniques, and plant materials. They are active in training LDC scientists through university graduate programs and workshops.

Seed of selected, improved materials is made available to sorghum and millet workers worldwide. INTSORMIL scientists are cooperating with an international germplasm network which tests sorghum and millet genetic plant materials throughout the world. An international bank of sorghum and millet genetic materials is maintained at ICRISAT, Hyderabad, India, and INTSORMIL contributes material to it.

INTSORMIL supports the publication of sorghum-millet workshop proceedings and research reports. As an example, INTSORMIL is helping to fund the publication of proceedings of a recent "Sorghum in the 8O's" workshop. It also gives financial support to the Sorghum Newsletter published by SICNA (Sorghum Improvement Conference of North America).

INTSORMIL scientists in the U.S. and host countries exchange information regarding their research. This is done at symposia, workshops, through individual correspondence and discussions, research reviews, professional journals, and newsletters.

INTSORMIL gives high priority to training host country scientists who will have major sorghum and millet research responsibility in their home countries. Training ranges from workshops and scientist exchanges to formal master and doctor degree graduate programs. Some graduate students are following a program of completing their course work in the U.S. and their thesis or dissertation research in their home countries.

In summary, INTSORMIL's sorghum research role is one of joining with others who have an interest in sorghum and millet with leadership and research collaboration. The collaboration of national research programs, the international centers (in this case CIAT and ICRISAT), and INTSORMIL gives the kind of research expertise and momentum that can and will lead to improvement of sorghum production and utilization where there are problems with acid soils, production stress related to drought and other weather conditions, insects, diseases, and problems of storage and utilization.

We believe the workshops and the training of Latin American students will spread the state-of-the-art knowledge and will lead to a continuation of the work done by Dr. Lynn Gourley and others of you with acid soils research. The results so far have been impressive, but I believe that you will agree there is still a lot of research to be done.

The INTSORMIL input into sorghum-acid soils research has strong support from the INTSORMIL Technical Committee, Board of Directors, and the External Evaluation Panel. Mississippi State University has the leadership with the project for INTSORMIL and is in the process of recruiting a sorghum research scientist who will continue the research when Dr. Gourley returns to the U.S. in November of this year.

I challenge you all to participate and to do what you can to contribute to this important research effort.

ICRISAT's Sorghum Research in the Semi-Arid Tropics

*J. M. Peacock**

About ICRISAT

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is one of 13 international centers in a worldwide research network devoted to improving food production in less-developed countries (CGIAR, 1980). ICRISAT's mandate is to improve the yield, stability, and food quality of five crops basic to life in the semi-arid tropics (SAT), and to develop farming systems that will make maximum use of the human and animal resources and the limited rainfall of the region. The crops are sorghum, pearl millet, pigeon pea, chickpea, and groundnut. Groundnut, rich in oil, is an important cash crop for the SAT farmer, while the others are all primarily subsistence food crops.

The seasonally dry semi-arid tropics are spread over nearly 20 million square kilometres and cover all or parts of 50 nations on five continents. They include much of South Asia, parts of Southeast Asia, West Asia, and Australia, two wide belts of Africa, areas of South America and Central America, and much of Mexico (Figure 1).

The SAT is a harsh region of limited, erratic rainfall and nutrient-poor soils (Sivakumar and Virmani, 1982). It is populated by more than 700 million people, most of them living at subsistence levels and dependent on limited food production on their small farms. ICRISAT's headquarters is at Patancheru, India, 26 km northwest of Hyderabad, but it also has scientific staff posted in nine countries of Africa, in Mexico, in Syria, and at a number of research stations in India. Principal operations in Africa are in Niger, Burkina Faso, Mali, Senegal, Nigeria, Sudan, Kenya, Malawi, and Zimbabwe.

* Principal physiologist, Sorghum Improvement Program, ICRISAT, Patancheru, Andhra Pradesh, India.

Figure 1. *Semi-arid areas (shaded) covered by ICRISAT's mandate. Dots indicate location of ICRISAT Center in India, Sahelian Center in Niger, and collaborative research stations with resident ICRISAT staff.*

Training

As this is an international teaching and training workshop, I will, at the outset, comment on ICRISAT's training activities which are one of the most important aspects of our work and provide one of the main channels through which we transfer our technology to the developing world. Each year, agricultural scientists and technical assistants come from many countries to learn about our research and improve their own skills. In 1983, a total of 144 persons from 37 countries came for training. These included 66 inservice trainees, 22 research scholars, 12 inservice fellows, and three research fellows. Four additional scientists completed their postdoctoral studies. Ninety ICRISAT scientists helped with this training program.

Our training in other countries included 15 scientists who worked with our sorghum breeders and agronomist posted in Mexico, and Malian students who worked on their theses with our agronomist and cereals breeder in Mali. We are particularly encouraged with the progress our scientists have made in Central America and in Mexico. Since 1975, 27 people have been trained from the following countries: El Salvador, Colombia, Costa Rica, Dominican Republic, Honduras, Ecuador, Nicaragua, Guatemala, Haiti, Panama, and Venezuela, plus more than 60 people from Mexico who have participated in short-term courses. In the course of this workshop, we shall hope to identify further candidates for training from Latin America.

Another channel is the Sorghum and Millets Information Centre (SMIC) which produces a newsletter and a sorghum and millet Annual Bibliography (SMIC, 1984). SMIC will provide, on request, any reprint, specific bibliography, or status report. ICRISAT also produces a wide range of publications on sorghum through its Information Services. These are listed in our catalogue (ICRISAT, 1984a) and can be obtained from Information Services.

Sorghum: its world distribution, domestication, and uses

It is not known when sorghum (*Sorghum bicolor* (L.) Moench) was first brought into cultivation, but Murdock (1959) suggests that with several other West African crops, it was first domesticated in eastern Africa some 7000 years ago. It is thought to have reached India no earlier than 1500 B.C. and China by A.D. 900.

Cultivated sorghum were first introduced to the Americas and Australia about 100 years ago, and domestication and cultivation of sorghum has now spread throughout the world. Today, it is grown on 47.8 million hectares (FAO, 1982), ranking fifth among cereals behind wheat, rice, maize, and barley in area sown. The major production areas today include the Great Plains of North America, sub-Saharan Africa, northeastern China, the Deccan plateau of central India, and Argentina.

Potential grain yields of sorghum are similar to those of the other important cereals. Yields in excess of 14,000 kg/ha have been reported by Pickett and Fredericks (1959) and Fischer and Wilson (1975). However, sorghum has achieved its importance not as a high-yielding cereal, but as a well-adapted crop of the arid and semi-arid tropics. Average yields in the developing world are near 1000 kg/ha, ranging from as low as 660 kg/ha in parts of Africa to as high as 3127 kg/ha in Latin America. Present-day uses are numerous, but the grain is most important as a human food in tropical zones, and for animal feed in the more temperate climates. Sorghum stems and foliage are often used for animal fodder and, in some areas, the stems are used for building and fuel purposes.

Overall objective of the sorghum improvement program

We all recognize that low yields in the developing world are the result of actions and interactions of many factors, and that there are no simple, easily implementable solutions. ICRISAT's primary concern is with the interactions of biological, climatic, edaphic, and management factors, and the development of production technologies that in the appropriate socio-political-economic climate will result in increased sorghum production on a sustained basis. To achieve this objective, the program has identified a number of priority traits for sorghum improvement (Table 1), and these form the basis of our research program.

In brief, our overall objective is to develop high and stable yielding varieties and hybrids with acceptable food quality. Our

Table 1. **Priority traits in ICRISAT's sorghum improvement program.**

Trait	Description
Grain yield	Higher and more stable
Grain quality	Acceptable food and nutritional quality
Stress resistance	
Abiotic stresses:	
Drought	Water, temperature, and nutrient stress
Crop establishment	Seedling emergence through crust and high surface temperature
Biotic Stresses:	
Pests	Shoot fly, stemborer, midge, and head bugs
Diseases	Grain mold, stalk rots, downy mildew, leaf diseases
Witchweed	*Striga hermonthica* and *S. asiatica*

ultimate aim is to improve the sorghum production of the poor farmers in the developing countries of the world.

Organization and research strategy

The area of the SAT for which ICRISAT has the mandate has been divided into nine geographical regions (Table 2) (ICRISAT, 1980), each consisting of between 8 and 12 contiguous countries. Table 3 shows the five regions designated as priority zones, together with data on average yields and areas under cultivation. ICRISAT now has research programs in these five regions. As these programs are established and work most closely with national programs, their main responsibility is for regional research activities. However, there is strong interaction with center scientists which includes visits by scientists, exchange of germplasm and breeder lines, collaborative workshops, and annual in-house reviews.

The Center program is multidisciplinary and is supported by: five scientists in breeding; three scientists each in physiology, pathology, and entomology; and one scientist each in microbiology, biochemistry, and genetic resources. The microbiology,

Table 2. **Geographic regions for sorghum production.**

Indian subcontinent and Southeast Asia (India, Bangladesh, Pakistan, Sri Lanka, Thailand)
West Africa and Sudan (Benin, Cameroun, The Gambia, Ghana, Guinea, Guinea-Bissau, Mali, Niger, Nigeria, Sierra Leone, Senegal, Burkina Faso)
East Africa and Yemen Arab Republic (Burundi, Ethiopia, Kenya, Rwanda, Somalia, Tanzania, Uganda, Yemen Arab Republic)
Southern Africa (Angola, Botswana, Madagascar, Malawi, Mozambique, Zambia, Zaire, Zimbabwe)
Central America and Mexico (Costa Rica, Dominican Republic, El Salvador, Guatemala, Haiti, Honduras, Mexico, Netherlands Antilles, Nicaragua)
South America (Argentina, Bolivia, Brazil, Colombia, Paraguay, Venezuela)
Far East (China, Japan, Korea)
Temperate America
Oceania (Australia)

SOURCE ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) 1982.

Table 3. **Average yields, area under cultivation, and percentage of world area in the five geographic functional regions for sorghum production showing where ICRISAT scientists are located.**

Functional region	Average yield (kg/ha)	Area (thousand ha)	Percent of sorghum-growing total world area
Indian subcontinent and Southeast Asia	840	16,672	35
West Africa and Sudan	755	11,697	24
East Africa and Yemen	917	2,970	6
Southern Africa	805	1,295	3
Central America and Mexico	2,238	1,723	5
Mean	1,111	-	-
Total	-	34,357	73

SOURCE: FAO (Food and Agriculture Organization of the United Nations). 1982.

biochemistry, and genetic resources programs have responsibility across all ICRISAT's mandate crops. Scientists in the farming systems and economics programs are also actively involved in sorghum research.

It is visualized that the Center program, apart from coordinating all regional activities, will serve the Indian subcontinent and Southeast Asia. In our other collaborative programs, several scientists were placed in countries in West Africa and it is hoped to have a multidisciplinary regional team for this region in the near future. A regional program for Southern Africa (Southern African Development Coordination Conference (SADCC) countries) has just been funded and the first sorghum scientist is in post. A breeder stationed in Kenya serves as coordinator of the Consultative Advisory Committee on Semi-Arid Food Grain Research and Development (SAFGRAD) sorghum and millet trials for Eastern and Southern Africa.

In Central America, our regional program is comprised of two scientists—a breeder and an agronomist—based at the Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) in Mexico and serving Central America and the Caribbean.

As the center and regional programs develop, a research strategy has evolved which identifies four stages in sorghum improvement (Table 4). In keeping with the priorities of the Ten-Year Plan (ICRISAT, 1982), the first five years of the 80's will be largely devoted to establishing and perfecting screening procedures to handle large numbers of germplasm and breeder lines.

Table 4. **Stages in sorghum improvement.**

1. Identification of yield-limiting factors
2. Development of screening methods
3. Development of products of research (i.e., varieties and hybrids)
4. Transfer of technology to national programs and farmers

Sorghum germplasm

Before going on to the specific objectives of the disciplines within the program, it is vitally important to introduce sorghum germplasm. It is our most valuable resource and forms the nucleus of all our research activities. There are now more than 22,000 accessions from 70 countries in the world collection of sorghum maintained by the Genetic Resources Unit at ICRISAT Center (Table 5).

To make the collection more useful to scientists involved in crop improvement, both conversion and introgression activities involving selected entries are undertaken. The conversion program has been developed using the Texas A&M University/United States Department of Agriculture (USDA) program model of back-crossing to introduce genes contributing to photoperiod insensitivity and shorter plant height. ICRISAT has participated on a joint committee with the International Board for Plant Genetic Resources (IBPGR) to develop and publish a descriptor list (IBPGR/ICRISAT, 1980) for characterizing sorghum germplasm. All information is now being stored on computer and is available to users. This list is useful to a crop improvement program and needs to be more widely distributed in Latin America. Scientists who collect sorghum in Latin America are encouraged to send seed and related biological and environmental data to ICRISAT for inclusion into the world collection. This is clearly an important area for collaboration. It will also be appreciated if, as you evaluate and use these accessions, you will send your results to the Genetic Resources Unit at ICRISAT Center.

Table 5. **Status of sorghum germplasm collection at ICRISAT.**

Cultivated lines	Wild relatives	Countries represented	Evaluated at Patancheru	Distributed	Recipient countries
22,553	345	79	20,355	214,950	73

Specific objectives

The specific objectives of the disciplines concerned with alleviating abiotic and biotic stress are essentially the same, viz., within the priority areas of research, to develop techniques capable of screening large numbers of the germplasm and breeder lines, and to get these sources of resistance through breeding into the national programs.

For this reason, I propose to give detailed examples of our approach to our objectives in only one of the three concerned disciplines, that of physiology. I have chosen physiology for two reasons: it is one of the principal disciplines underlying this workshop; and as a physiologist I am better qualified to discuss the research of my own program. Notwithstanding this, I shall outline the priority areas of research within entomology and pathology and conclude by describing how sources of resistance, identified from the germplasm, have been utilized in our breeding program and disseminated to the national programs of the SAT.

Abiotic stress

The overall objectives of research on abiotic stresses are to assist the sorghum improvement program develop sorghums that are more stable and higher yielding under environmental stress. Since 1980, under this broad objective, we have confined our research activities to two priority areas:

Factors affecting crop establishment; and

response and adaptation to water, temperature, and nutrient stress, or what largely manifests itself as "drought" in farmers' fields.

During this period our specific objectives were as follows:

To develop simple, repeatable, inexpensive techniques capable of screening large numbers of the germplasm and breeder lines, and to get these sources of resistance (either directly or inderectly through breeding) into the national programs.

To ensure that these sources of resistance, together with sources of susceptibility, are freely available to physiologists working outside of ICRISAT in order that important basic research on these materials continues in parallel with our screening.

To better understand the physiological basis of existing management practices, and with the agronomists, to improve on these systems.

To train those working in the national programs in the SAT in screening techniques and management practices.

In the area of crop establishment, a number of screening techniques have been developed. The two examples highlighted here relate to screening for emergence at high soil-surface temperatures. The first method, which uses different soil surface treatments to modify soil temperature (Wilson et al., 1982), has shown that there is genetic variation in the ability of sorghum to emerge at high soil temperatures, and that some lines emerged even when soil temperatures were as high as 55°C.

Similar studies have been conducted using the second technique. Long clay pots (300 mm) filled with soil are placed in a water tank. Seeds are sown in the pots and temperatures between 35 and 50°C can be maintained by varying the heights of infrared lamps. Genotypic differences in emergence were most evident at 45°C. The advantage of this technique, although not as simple as the former, is that screening can be done while water is not limiting or the soil crusted.

In the area of drought, I will comment on two approaches. The first is the well known line source sprinkler irrigation system (Hanks et al., 1976), which exposes the crop to a gradient of soil water during different stages of growth. This technique allows us to test a number of genotypes under a continuous range of water levels. Figure 2 shows typical response curves for two contrasting sorghum lines and serves to illustrate the need to match varieties and hybrids to particular environments. Type 1 (continuous line) clearly does better in higher rainfall areas but fails completely in the dry zone. Type 2 (broken line) obviously has a much lower yield potential but will yield under severe stress.

Another approach has been to make up collections of material which are from a wide range of taxonomic groups, geographical regions, and climates and to screen these for particular phenological, morphological, and physiological traits under severe environmental stresses. An example would be our rainfall collection which, in addition to the above listed variability, is stratified into three rainfall zones, viz., those with an annual rainfall of 250-600 mm, 600-900 mm, and 900+ mm.

Each collection comprises about 200 lines and is sown in the summer season at Patancheru, India. Severe stress is imposed from about 30 days after sowing. Maximum temperature during this rainfree period exceeds 40°C, with pan evaporation rates reaching 16 mm/day. One important trait we are looking for is the ability of the growing leaves to avoid desiccation (Figure 3). A number of resistant and susceptible lines were selected in 1983

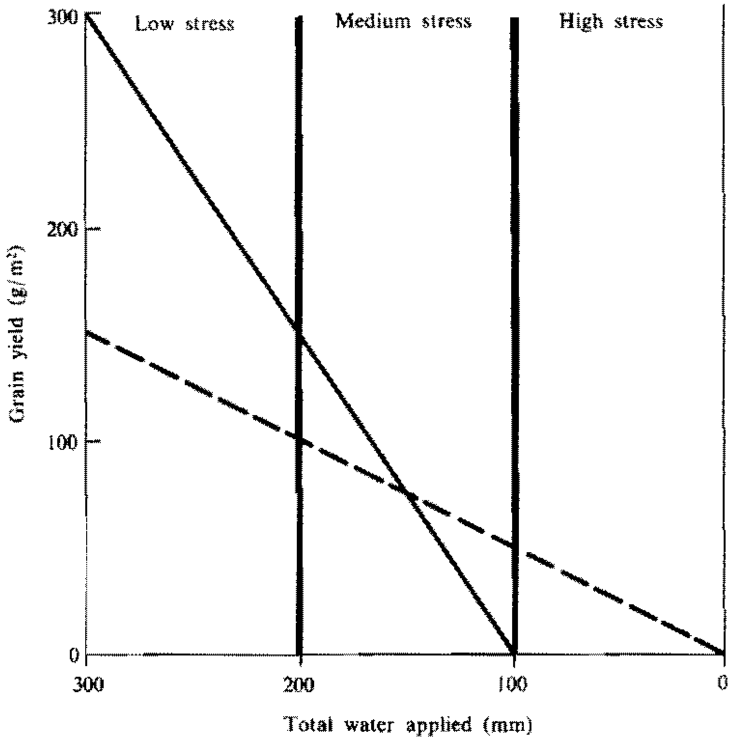

Figure 2. *Relationship between water applied and grain yield in two contrasting sorghum lines.*

and, in accordance with our second major objective, seed from these lines have been sent to other physiologists working outside of ICRISAT who are interested in the underlying mechanisms.

One example of this collaborative research is a project being conducted at the Welsh Plant Breeding Station (WPBS) in the United Kingdom where scientists have shown that emergence at high temperature is highly correlated with its embryo protein synthesis (WPBS, 1983). The research has not only led to the development of a screening method which will screen a large number of lines, but has attempted to establish the underlying biochemical processes associated with poor crop establishment.

Existing projects with organizations such as the Indian Council of Agricultural Research (ICAR), International Development Research Centre (IDRC), International Sorghum and Millet Program (INTSORMIL), and Official Development Assistance

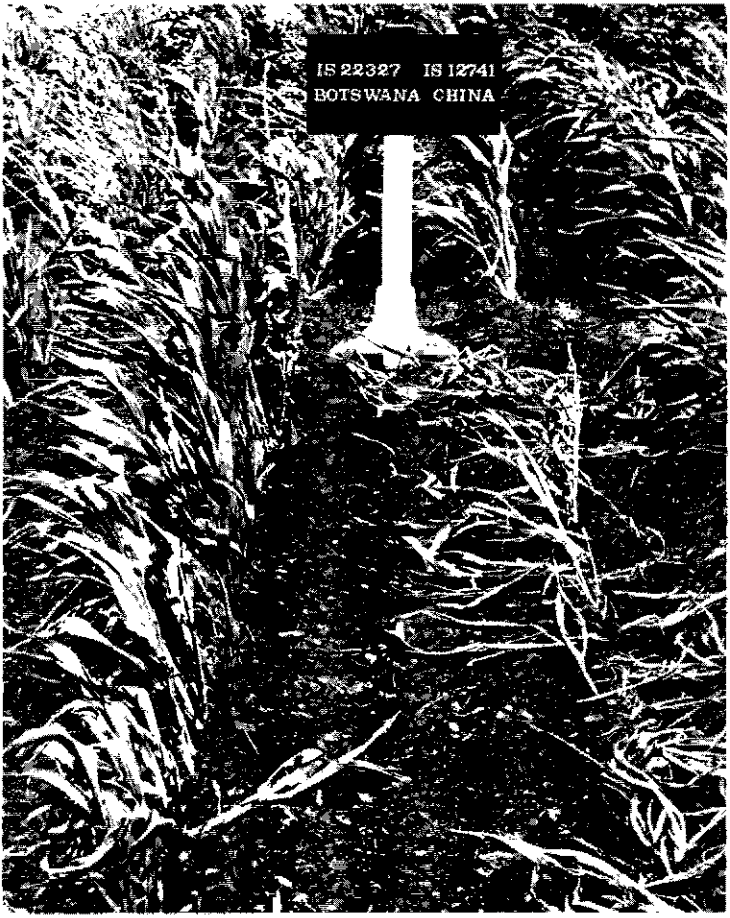

Figure 3. *The effect of extreme heat and water shortage on sorghum cultivars grown at Patancheru, India. The leaves of the line from China are severely desiccated in contrast to the line from Botswana whose leaves have remained green.*

(ODA) are proving to be very effective and we must strive to encourage further projects and strengthen existing links.

I believe that the problem of acid soils in Latin America lends itself very much to this approach, and I hope that in the course of this week, concerned scientists and organizations will have worked out an effective research strategy to deal with one of the most serious problems of sorghum production in Latin America.

Biotic stress

Disease stress (including *Striga*).

Priority diseases of global importance on which research is conducted at the Center and locations in India are:

Grain mold (preharvest biodeterioration of grain) caused by a complex of fungi;

root stalk rots that usually result in plant lodging, caused by *Macrophomina phaseolina* and *Fusarium* spp. (ICRISAT, 1984b); and

downy mildew caused by Peronosclerospora sorghi.

Research is also conducted on diseases of regional importance if they also occur in India. These include anthracnose and rust. The establishment of multidisciplinary regional teams will facilitate research on diseases of regional and local importance (such as viruses in Central America, leaf blight, grey leaf spot in eastern Africa, and sooty stripe and smuts in West Africa) for which screening opportunities do not exist in India.

Striga is a parasitic weed which is a major problem in India and West Africa. The Center program works on *S. asiatica* and scientists in the program in Burkina Faso work on *S. hermonthica*. Fortunately, *Striga* is not found in Latin America. Two information bulletins are available from ICRISAT on the identification of sorghum and pearl millet diseases and *Striga* (Williams et al., 1978; Ramaiah et al., 1983).

The specific research areas are:

Biology of pathogens and epidemiology of the diseases they cause. This information is essential for the development of meaningful resistance screening techniques.

Development of resistance screening techniques;

Identification of resistance both in source material and in breeding progenies.

Multilocational testing of identified resistance at "hot spot" locations for stability of resistance.

Nature of resistance and its utilization in breeding projects.

Pest stress

The priority insects of global importance are stemborers, shoot fly, midge, and head bugs. There are several important stemborers, viz., Chilo, Sesamia, Eldana, Busseola, and Distreae. The latter is found in the Americas. In India, 90% of sorghum damage is caused by the head bug, *Calorcoris angustatus*. An Information Bulletin is available from ICRISAT on sorghum insects (Teetes et al., 1983).

The specific areas of research are:

To develop reliable screening methods;

to identify sources of resistance; and

to incorporate this resistance into agronomically good backgrounds.

Breeding for yield, stability, quality, and resistance

The overall objective of breeding is to develop high-yielding cultivars that will increase and stabilize sorghum production in the SAT. This is achieved by breeding for improved yields, agronomic eliteness, incorporation of good grain quality characteristics, and resistance to abiotic and biotic stress. Both conventional and population breeding methods are used in the development of varieties and hybrids.

At ICRISAT, populations were developed from original populations from Nebraska and Purdue Universities, USA; Serere, Uganda; and Samaru, Nigeria. In the future, these populations will be merged into five populations in which a broad range of germplasm and sources of resistance will be utilized (Table 6).

Several high-yielding varieties have been developed (Table 7) and distributed to national programs mainly through the Sorghum Elite Progeny Observation Nursery, the International Sorghum Variety Adaptation Trial, and the International Sorghum Drought Observation Nursery. In addition, several hundred breeding lines in various stages of development have been distributed to breeders in national programs for further selection and incorporation in their programs.

Table 6. **Planned multifactor resistant (MFR) sorghum populations.**

Population designation	Origin	Traits[a] to be incorporated and selected	Monitored traits
ICSP1-R/MFR	US/R Rs/R	Improved grain yield[b]. Resistance to grain mold, stemborer, shoot fly and midge.	Charcoal rot, stand establishment[c], *Striga*, food quality.
ICSP2-B/MFR	US/B Rs/B	Improved grain yield. Resistance to grain mold, stemborer, shoot fly and midge.	Charcoal rot, stand establishment, *Striga*, food quality.
ICSP3-R/MFR	US/R	Improved grain yield. Resistance to grain mold and *Striga*, and improved stand establishment.	Charcoal rot, stemborer, shoot fly, midge, food quality.
ICSP4-B/MFR	US/B	Improved grain yield. Resistance to grain mold and *Striga*, and improved stand establishment.	Charcoal rot, stemborer, shoot fly, midge, food quality.
ICSP5-BR/MFR	WAE	Improved grain yield. Resistance to stemborer, shoot fly, *Striga*, and high food quality.	Charcoal rot, grain mold, midge, stand establishment.

a. Highly heritable traits such as disease resistance to downy mildew, rust, anthracnose, etc., to be fixed during population development by mass selection.

b. Grain yield evaluation would include tests under optimum management, low fertility, and moisture-deficient conditions.

c. Stand establishment includes several components emergence through a soil crust, emergence through a hot soil-surface, seedling vigor, and seedling resistance to moisture stress and/or recovery from moisture stress

Table 7. **ICRISAT varieties/hybrids released and in prerelease and advanced stages of testing in various countries.**

Country	Released	Prerelease stage	Advanced
India	1	3	7
Cameroun	-	-	2
Burkina Faso	2	-	-
Ethiopia	1	-	-
Sudan	1	-	-
Yemen Arab Republic	-	1	1
Zambia	1	-	-
Zimbabwe	-	-	4
El Salvador	2	-	-
Guatemala	-	-	2
Mexico	2	-	-
Nicaragua	-	-	1
Venezuela	1	-	-
China	4	-	-

In the hybrid program, the breeding material was screened for potential restorers with good combining ability. Selected lines were used to produce experimental hybrids on female parents developed by the All India Coordinated Sorghum Improvement Project (AICSIP). Several hundred experimental hybrids have been evaluated at different locations in India and 60 high-yielding hybrids were identified and have been distributed to AICSIP and other national programs in the SAT. As indicated in the introduction, it is essential that sorghum cultivars recommended to farmers are acceptable for food. Priority areas of research are:

To identify the major sorghum food products and their desired quality characters;

to identify grain characters contributing to desired food quality;

to devise simple and rapid physicochemical tests useful to breeders in quality improvement programs; and

to evaluate elite breeding material for food quality (see ICRISAT, 1982).

A number of varieties and hybrids from the ICRISAT program are now in advanced stages of testing, pre- or postrelease, and being grown on farmers'fields in a number of countries (Table 7).

Products of this research and their impact

Several screening techniques are now being used in national programs. Of particular interest are the following:

The checkerboard field layout and its statistical analysis for evaluation of resistance to *Striga* is used by the Indian national program.

The technique developed to select lines capable of emerging through soil at high temperature has been successfully used by scientists in national programs in Senegal, Mali, and Niger.

The large-scale, field-screening technique for resistance to downy mildew (DM) has been adopted by the national program in India.

Progress, although slow, has been encouraging. In Mexico and Central America, despite the few number of scientists involved, the impact has been impressive. We hope that the participants of this workshop will work together to enable sorghum improvement to spread more rapidly into other parts of Latin America.

Summary

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has its headquarters near Hyderabad, India. Its mandate is to improve the yield stability and food quality of sorghum, pearl millet, pigeon pea, chickpea, and groundnut; and to develop farming systems that will make maximum use of human and animal resources and the limited rainfall of the region. Training and the dissemination of information are vital roles of the Institute.

Average yields of sorghum in the developing world are only 1000 kg/ha and fall as low as 600 kg/ha in parts of Africa. The ultimate aim of ICRISAT's sorghum improvement program is to produce higher and more stable yielding lines.

Five regions, namely the Indian subcontinent, East Africa, West Africa, Southern Africa, and Central America, including Mexico, have been designated as priority zones. This paper outlines the priority problems in these regions; describes the

specific objectives of the sorghum physiology, pathology, entomology, and breeding programs; and lists the lines and techniques which are now being utilized in different countries.

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Sorghum Production in Colombia and Its Perspectives in the Acid Soils of the Eastern Plains

*Manuel Torregroza C.**

Introduction

Five of the main factors that have justified the increase of sorghum production in Colombia are:

The development of the country's poultry industry, which uses sorghum grain as one of its basic raw materials in the manufacture of foodstuff.

The excellent adaptation of this cereal to warm climate regions found between sea level and 1200 meters elevation, where neither rice nor maize constitute an adequate agro-economic alternative.

The relatively short vegetative period of this plant species, which can be recommended as a rotational crop.

Its easy agronomic management.

Its lower commercial value per ton of grain, in comparison to maize, a phenomenom which has contributed to sorghum being substituted for maize in the preparation of foodstuffs.

The purpose of this article is to point out the fundamental aspects of sorghum production in Colombia and present a short report on the agronomic performance of sorghum grain genotypes, tolerant to aluminum (Al) toxicity, grown in the acid soils of the Eastern Plains.

Evolution of the crop and imports

Grain sorghum production was enhanced starting in 1957 when Purina de Colombia planted three hybrids in the cotton-growing region of the Atlantic Coast.

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In 1960, 6300 tons of sorghum grain were harvested from 2800 hectares. In 1970, these figures increased to 118,000 and 54,000, and reached 431,000 and 206,000, respectively, in 1980. During 1983, 593,000 tons were produced when 270,000 hectares were planted. As a consequence of the spectacular evolution of this crop, sorghum today occupies third place in area planted of the five cereals (rice, barley, maize, sorghum, and wheat), being surpassed only by rice and maize. In 1983, 3,317,000 hectares were planted to these five crops, with a total production of 3,339,000 tons of grain, of which 21 and 18%, respectively, corresponded to sorghum.

However, in spite of the enormous development of this crop, grain sorghum production has not satisfied the increasing demand of the feed processing industry. Therefore, starting in 1972, deficits have had to be met through imports. To date, 500,000 tons of sorghum grain have come into the country, of which 51,000 tons were imported in 1983.

Sorghum growing regions

In Colombia, grain sorghum is planted in four large agricultural regions: the Atlantic coast, the Central zone, the Cauca River Valley, and the Eastern Plains. During the period 1980-1983, 37, 30, 22, and 11% of the sorghum planted occurred in the first, second, third, and fourth regions, respectively. Due to sorghum's short vegetative period and the rainfall patterns existing in these regions, it is possible to plant and harvest the crop twice during one agricultural year. However, to enable harvest to take place during the dry period when pest and disease incidence is lower, it is recommended that this crop be planted only once a year in the Eastern Plains, during the second semester. The 20,000 hectares planted to sorghum annually make up part of the 160,000 hectares of Class I soils in this zone which are characterized by their high fertility, variable texture, good drainage, and small danger of flooding. Besides this cereal, these soils are planted to maize, upland rice, cotton, peanuts, sesame, cassava, plantains, and African palm tree, among other annual and perennial crops. Sorghum varieties and hybrids yield between 2 and 4.5 t/ha. According to Sánchez and Owen (1983), these soils contain an average of approximately 0.72 meq Al/100 g of soil. Under these conditions, crops susceptible to Al toxicity can be grown by applying low amounts of corrective amendments.

Main characteristics of the Class IV soils of the Eastern Plains

The Eastern Plains, due to their enormous area, geographic location, mechanization possibilities, and well-defined climatic conditions constitute a privileged region for an expected intensive and prosperous agricultural development. Soil fertility constraints, especially the excessive amounts of exchangeable Al, have been the factors hindering the incorporation of this region into the economy of the country.

The Food and Agriculture Organization of the United Nations (FAO) has classified 12,936,621 hectares (of a total 17-19 million ha of savanna in the plains) of the Eastern Plains into eight classes according to their potential for use and management. Of the 27% (Class I through IV) considered to be agriculturally promising, approximately 2 million hectares catalogued in Class IV are characterized by their low fertility and excessive amounts of exchangeable Al (Sánchez and Owen, 1983).

According to the data in Table 1, these soils are characterized by their extreme acidity; of the 343 samples studied, 86% had a pH between less than 4.6 and 5.5, averaging 4.6. It is likely that pH values higher than 5.5 resulted from samples coming from previously limed ground. These soil types have high levels of exchangeable Al. Exchangeable Al was higher than 1.00 meq/100 g of soil in 81% of the samples analyzed and averaged 2.56 meq/100 g. In general, Class IV soils contain an adequate amount of organic matter—an average of 3.39%, and 76% of the samples contained more than 1.9% organic matter. Out of 343 samples, 53% showed less than 5 ppm of phosphorus. Therefore, phosphorus deficiency and Al toxicity constitute the main constraints limiting the establishment of crops in Class IV soils. Potassium (K) represents another constraint as can be seen from the fact that 59% of the samples contained less than 0.10 meq/100 g of soil, for an average of 0.09 meq/100 g. These soils contain small quantities of calcium (Ca) and magnesium (Mg). Out of the 86 samples studied, 83% contained less than 2.00 meq Ca/100 g of soil, for an average of 0.80 meq/100 g. In the case of magnesium, of the 81 samples analyzed, 95% did not contain more than 1.00 meq/100 g, and averaged 0.37 meq/100 g.

Table 1. **State of five chemical components and two soil characteristics in Class IV soils of the Eastern Plains, Colombia.**

	pH	%	Al^{+++} (meq/100 g)	%	O.M. (%)	%	P Bray II (ppm)	%	K (meq/100 g)	%	Ca^{++} (meq/100 g)	%	Mg^{++} (meq/100 g)	%
	<4.6	36	>2.0	45	<1.9	24	<4.9	53	<0.04	23	<1.1	60	<0.51	81
	4.6-5.5	50	2.0-1.0	36	1.9-4.0	53	4.9-10.0	24	0.04-0.10	36	1.1-2.0	23	0.51-1.00	14
	5.6-6.5	12	0.9-0.5	17	>4.0	23	10.1-15.0	9	0.11-0.15	21	2.1-5.0	11	1.01-1.50	2
	>6.5	2	<0.5	2			15.1-30.0	8	0.16-0.30	16	>5.0	6	>1.50	3
							>30.0	6	>0.30	4				
Average	4.6		2.56		3.39		5.0		0.09		0.80		0.37	
Samples analyzed	343		343		343		343		135		86		81	

SOURCE: Sánchez, L. F. and Owen, E. B. 1983.

Headquarters for research activities

Research directed to select improved grain sorghum genotypes was started by the Maize and Sorghum Program of the Instituto Colombiano Agropecuario (ICA) during the second semester of 1983 at the Regional Research Center (CRI) "La Libertad," located near the city of Villavicencio, department of Meta, approximately 140 kilometers east of Bogotá. The principal meteorological data and the location of this center are included in Table 2. This area has 2614 mm of annual precipitation, the wet season being from April to November.

The following eight soil characteristics are from 60 samples analyzed at La Libertad, where experimental plantings are being carried out.

pH	4.43
Organic matter (%)	3.75
Aluminum (meq/100 g)	3.99
Potassium (meq/100 g)	0.11
Calcium (meq/100 g)	0.59
Magnesium (meq/100 g)	0.26
Sodium (meq/100 g)	0.37
Phosphorus (ppm)	8.14

Since the objective of the project is to study genotype adaptation and tolerance to acid soils, this experimental field has been amended with 500, 100, 75, and 45 kg/ha of dolomitic lime, N, P_2O_5, and K_2O, respectively.

Table 2. **Location of the Regional Research Center La Libertad and its main meteorological data.**

City	Villavicencio
Department	Meta
Latitude	4º 03' N
Longitude	73º 29' W
Altitude	336 masl
Mean temperature	26ºC
Annual precipitation	2614 mm
Relative humidity	77%
Monthly evaporation	134 mm
Hours of full sunlight/day	5 hours

Results and discussion

In order to incorporate Class IV soils of the Eastern Plains into national agricultural production systems, the hypothesis of changing the chemical characteristics of these soils was initially adopted so that the nutritional requirements of the plants would be met. This type of research was carried out by the ICA Soil Program during the 1960's after evaluating diverse genotypes of rice, sesame, beans, cowpea, peanuts, maize, sorghum, soybean, and cassava, among other crops. The results were not as good as expected. However, it was found that there were crop species, such as peanuts, cowpea, tobacco, cassava, and African palm tree, which are more tolerant to acid soils than other species. Spain (1976) has referred to research carried out by the Centro Internacional de Agricultura Tropical (CIAT) at ICA's C.N.I. Carimagua Experiment Station with the object of identifying genotypes tolerant to acid soils, where he observed that rice, cassava, and many forage species were among the crops having a wide range of tolerance, being very tolerant, or well-adapted to acid soils, respectively. One of Spain's recommendations for an effective use of the genetic tolerance variability to these soil types was the formation of multidisciplinary teams, made up of breeding, soil, and plant physiology specialists. Sánchez and Owen (1983), based on a series of experiments conducted in the soils of the Eastern Plains including the type IV soils, made a series of economic-feasibility recommendations on fertilizer use and management for the principal annual crops in this region of the country.

Since solving the crops' maladjustment to acid soils by improving the environment where they grow and develop did not give the expected results, another solution is being studied: genetic management and selection of material resistant or tolerant to mineral toxicities. For this reason, we are working in collaboration with the International Sorghum and Millet Program (INTSORMIL), an international agency which conducts research on breeding sorghum genotypes tolerant to acid soil constraints.

The first planting was carried out during the second semester of 1983 (1983B) at CRI La Libertad using 1400 breeding lines. This material was selected among and within lines, choosing 150 lines and 300 panicles, respectively. To speed up the selection and adaptation process, the 590 selections saved in 1983B were planted in 1984A (first semester) together with 600 more introductions from INTSORMIL. Yield trials were conducted using the best lines which had been previously selected. Table 3 shows the ranges and averages of agronomic characteristics for the 90 best lines planted in 1983B. Table 4 shows the 12 lines with the highest grain weight per plant of the 90 mentioned in Table 3. Yields of (SEPON 79-35 X IS 7542C)-5, (IS 7542C X SEPON 79-2)-6, (IS 7542C X SEPON 79-2)-2 (NB 9040 X IS 7173C)-140-3, and (SEPON 79-29 X IS 7542C)-8 were more than 30 grams per plant, and the first two lines were outstanding since their yields were more than 50 grams per plant. It is expected that this promising material, as well as other material from INTSORMIL, will become the base for future selections, evaluations, and seed

Table 3. **Variation and averages of three agronomic characteristics of 90 sorghum genotypes selected on terrace soils, Regional Research Center La Libertad, Villavicencio, Meta, Colombia, 1983B.**

Characteristic	Unit	Variation	Range	Average
Weight grains/plant	Grams	7.3-56.3	49	16.1
Days to flowering	Days	53.0-70.0	17	58.6
Plant height	Centimetres	83.0-196.0	113	124.2

Table 4. **Performance of three agronomic characteristics of the 12 best sorghum genotypes selected on terrace soils, Regional Research Center La Libertad, Villavicencio, Meta, Colombia, 1983B.**

Pedigree	Days-to-flowering	Plant height (cm)	Weight grains/plant (g)
(SEPON 79-35 X IS 7542C)-5	63	116	56.3
(IS 7542C X SEPON 79-2)-6	68	132	56.0
(IS 7542C X SEPON 79-2)-2	69	96	37.2
(NB 9040 X IS 7173C)-140-3	57	106	32.8
(SEPON 79-29 X IS 7542C)-8	59	137	30.5
(IS 7542C X SEPON 79-2)-9	58	150	27.0
(SEPON 79-1 X IS 7173C)-13	58	157	26.0
(SEPON 79-35 X IS 7542C)-19	61	130	25.9
(SEPON 79-54 X IS 7173C)-6	60	122	25.7
(SEPON 79-20 X IS 7173C)-10	57	155	25.7
(SEPON 79-54 X IS 7173C)-25	58	130	25.6
(IS 7542C X SEPON 79-20)-4	57	163	24.7
Average	60	133	32.8

increases at La Libertad and in regional trials in farmers' fields (located in Class IV soils) resulting in the first improved sorghum variety in Colombia tolerant to acid soils.

Summary and conclusions

The need to reach self-sufficiency in the main raw material of the feed processing industry, especially for poultry, thus eliminating the burden of sorghum importations, requires a search for alternatives to broaden the agricultural frontier of this crop. Part of this frontier is the Class IV acid soils of the Eastern Plains, comprising almost two million hectares. For this reason, the ICA Maize and Sorghum Program, in collaboration with INTSORMIL, started a project in 1983B at CRI La Libertad for the selection and evaluation of sorghum genotypes tolerant to aluminum toxicity. The preliminary results have been very promising and we expect to record in the near future the first improved variety adapted to the acid soils of the Eastern Plains.

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TROPICAL SOILS

Soil in the Tropics: Classification and Characteristics

*S. W. Buol**

Introduction

In 1950, C. E. Kellogg predicted that as detailed maps became available more distinct soil types would be found within the tropics than in the other parts of the world. Moormann (1972) attributed the lack of appreciation for soil variability in the tropics by agricultural and other scientists to the generalized, small-scale soil maps by which they were guided. Buol and Sánchez (1978) were even more harsh in their appraisal, stating that "the reality of soil variability has been masked by small scale reconnaissance soil surveys that portray a false sense of uniformity and serve only to widen the gap between scientists, who overinterpret such maps, and farmers, who know what the soils are like."

The realities of working in the tropics, regardless of how mindful we are of soil variability, are that research sites are sparse and detailed assessment of soil characteristics equally sparse. To compensate for the lack of available characterization data, agronomic researchers have to assume greater responsibility in characterizing the sites where they work in order to enhance the validity of technology transfer. Any agronomic study that fails to quantitatively identify the soil in field studies, or the soil material in the case of a greenhouse or laboratory study, severely limits the value of the data generated. Dismissing this responsibility by giving a geographic place or name, such as a country or region of a country, or a soil map unit name or even a soil taxonomic order, connotes a false sense of quantification that frequently does more harm than good.

The objectives of this paper are to: point out some agronomically important variabilities known to exist within and between soils in tropical areas; and suggest some minimum measurements that can be conducted to improve site identification and characterization and thus the value of the research to other locations.

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No single parameter such as soil characterization totally quantifies the uncontrolled variables in an agronomic experiment, but the closer we can define these variables, the closer we are to understanding, evaluating, and extrapolating the results.

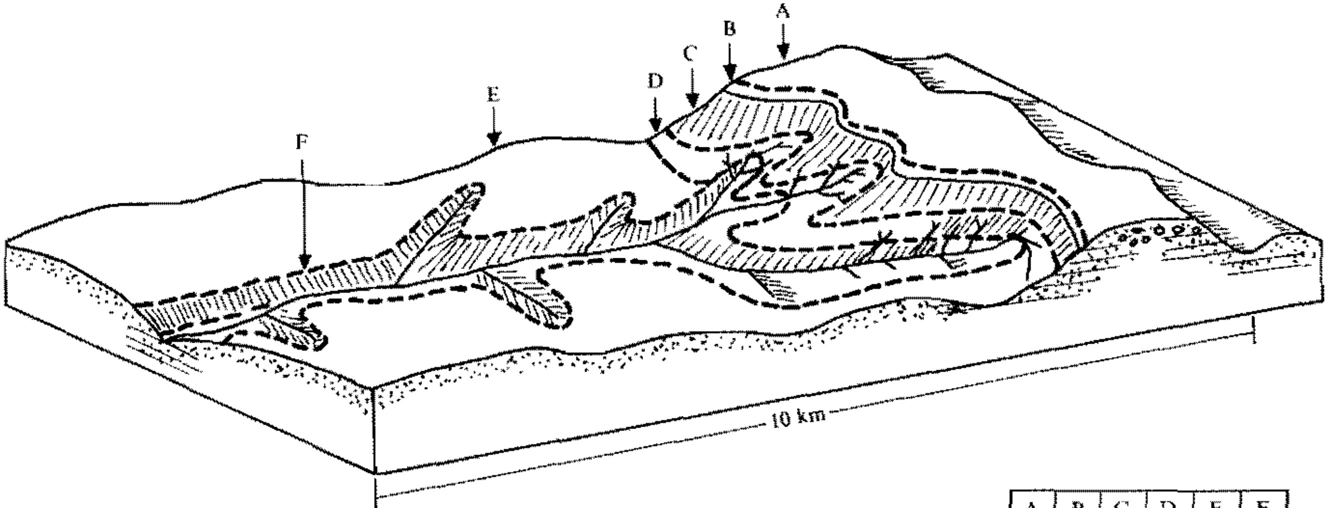
Map units

Perhaps more than other disciplines soil classification further confuses many people whose first contact with the soil classification is via a soil map. Mapping is the representation of a naturally occurring area, at a much reduced scale, and does not represent a soil classification unit. Unfortunately, in soil science, not unlike other disciplines, taxonomic names are used to name soil map units. Many people seem to lose sight of this obvious fact and attempt to name the soil they work with from the name given on a soil map that may be on some minute scale that allows for areal inclusions of several hundreds of hectares of contrasting soil. The sample site may be less than 10 cm in diameter or the experimental plot well less than 1 hectare. No map, except possibly those done under very controlled conditions at scales larger than 1:10,000, can possibly be reliable in identifying such small areas (Buol et al., 1980).

Every soil map unit contains soil types not identified in the name given to that map unit. One example of soil variability in an area properly identified on general soil maps as Oxisols is presented in Figure 1. Detailed maps identify Oxisols, Ultisols, Inceptisols, Alfisols, and Mollisols, and mean values of selected surface soil properties from map units delineated on detailed maps clearly illustrate agronomic contrast.

Taxonomic units

While the map unit limitations are readily understood by most scientists, ranges of characteristics defined in taxonomic units of soils are, in my experience, not as easily understood or accepted. Although I will use examples from Soil Taxonomy (Soil Survey Staff, 1975), the same problems exist in other systems to an even greater degree because of less rigid definitions and fewer categories and classes. To understand the inherent problems of classifying soil, one has to realize that in no one place can an entire taxa, be it



	A	B	C	D	E	F
Bases (meq/100 soil)	0.6	1.6	5.1	1.4	0.3	0.8
Exchangeable Al (meq/100 g soil)	0.9	0.1	0.0	0.1	1.3	0.7
Clay (%)	18	11	10	6	12	10
Carbon (%)	0.6	0.6	1.0	0.6	0.6	0.5

Figure 1. *Mean values of selected soil properties for the 0-20 horizons in detailed soil map units of an Oxisol dominated landscape in São Paulo, Brazil. (Adapted from I. F. Lepsch, et al., 1977.)*

soil series or soil order, be seen, sampled, or described. Individual soils defined by every category of a classification system exist *in toto* only as abstractions defined by the words and phrases of the classifications system. **Examples** of the various kinds of soil are observed and characterized at specific sites. Too often, persons form rather firm concepts of the characteristics of specific examples and falsely assume that all sites classified by that name have **all** the properties they observed in the examples they know best. The example is not unlike taking a person to a mature field of sorghum so he can observe the morphological characteristics of the crop. At another site, perhaps a nutrient-deficient, weed-infested, and insect-damaged site of another cultivar, that person remarks that this doesn't look like sorghum. Because individual examples of soils are often separated by great distances and the opportunity for examination limited by the necessity to confine complete observations of soils to pits or road banks, this problem is exacerbated.

Table 1 briefly highlights some of the properties permitted in the range of soils properly named Oxisols, one of the 10 soil orders common in tropical areas. Essentially the only soil properties identified by the order name Oxisols are low cation exchange capacity (CEC) values, the lack of weatherable minerals, and exclusion of soils with less than 15 clay or argillic horizons in the subsoil. No limits are made on soil temperature or moisture regimes, thus Oxisols are present in arid regions as well as in the most humid of tropical areas. Mean annual temperatures range from the warmest known to no defined limit, although no Oxisols have been reported in regions colder than 8°C mean annual temperature. No limits are made on the pH value or degree of base saturation, at the Oxisol order level. Perhaps most Oxisols are acid and have low base saturation, but "Eutr" great groups are from 35% to 100% base saturated (Table 2). The critical point to remember is that a classification name defines only those properties of the soil used as criteria to define that class.

Invariably, these limits are far less confining than a person's concept of that soil gained from personal experience at one, or even several sites. Also, it is highly probable that no two persons will acquire the same personal impression of a kind of soil unless their experiences are totally parallel. As an aside, this is no different than the perception of a cow a person from India may have compared to the perception of a person from the Netherlands—a Brahman versus a Holstein-Friesian.

Table 1. **Synopsis of Oxisol properties.**

Division	Some of the major criteria to define classes
Oxisol order:	CEC less than 16 meq/100 g clay in some 30 cm thickness within 2 m of the surface and only traces of weatherable minerals in the silt and sand.
Oxisol suborders:	Perudic, Udic, Ustic, Aquic, or Aridic soil moisture regimes (this means Oxisols are present in every rainfall regime found in the tropics).
Oxisol great groups:	"Acr": effective CEC less than 1.5 meq/100 g clay. "Eutr": more than 35% base saturated. "Hapl": less than 35% base saturated. "Umbr": more than 1% but probably less than 20% organic matter content in surface. "Plinth": continuous plinthite within 30 cm of surface.
Oxisol subgroups:	"Quartzipsammentic": 15 to 20% clay in some part above 1.25 m. "Epiaquic": yellow color over redder subsoil. "Ultic": 40% more clay (relative) in subsoil than topsoil.
Families:	"clayey": more than 35% clay. "fine-loamy": 18 to 35% clay. "ferritic": more than 40% ferric oxide (Fe_2O_3). "kaolinitic": more than 50% kaolinite (kaolin clay).

Table 2. **Examples of contrasting Oxisol profiles.**

Tropeptic Eutrorthox (Puerto Rico)				Typic Acrorthox (Puerto Rico)			
Depth (cm)	Clay (%)	Base saturation[a] (%)	pH (1:1 H_2O)	Depth (cm)	Clay (%)	Base saturation[a] (%)	pH (1:1 H_2O)
0-20	73.1	72	5.6	0-28	54.5	11	5.1
21-46	81.2	68	5.4	29-46	57.7	1	5.0
47-69	85.5	83	5.9	47-71	59.6	-	5.0
70-99	89.5	83	5.6	72-96	55.7	-	5.2
100-130	90.6	89	5.7	97-120	59.7	2	5.5

a. Base saturated by pH 7 method.

SOURCE: Soil Survey Staff 1975

Soil dynamics

Soil is an entity, unique in its position at the interface between the organic and inorganic worlds, and composed of solid, liquid, and gas. The characteristics of a soil are very dynamic, easily manipulated by the whims of weather and vegetation. In addition, one also has to include the whims of man who cuts, burns, plants, and harvests vegetation; and who fertilizes, drains, irrigates, and physically manipulates the soil.

A few of the dynamic aspects of soil that are frequently of concern in characterizing soils in the tropics are best illustrated by the following changes that take place in the soil after clearing natural rain forests. Data compiled by Sánchez and Salinas (1981) consistently showed increases in pH value, available calcium (Ca), magnesium (Mg), phosphorus (P), and potassium (K) contents in the topsoil after burnings, thereby decreasing exchangeable aluminum (Al) contents. For a year or more after the start of cultivation organic matter contents decrease actively releasing organically bound nutrients. Organic matter content then stabilizes at a level reflecting the new environment and, since organic matter is not rapidly decomposing, few nutrients are released for plant growth. Although sites differ rather markedly, the pattern is clear. The interpretation of the available data that I believe is of greatest significance is that no fertility requirement or soil suitability conclusions should be made on the basis of field data during the first two years after clearing. Similar errors are introduced by taking soil into the greenhouse. Certainly the chemical and probably the physical and microbiological composition of the soil as it undergoes the "shock" of changing from a forest to cultivated site, is considerably different than it was before clearing or the character of the soil after continuous or rotational cultivation has been established. Management techniques found suitable during the first two years after clearing will undoubtedly not identify the soil nutrient problems, nor will weed and disease problems likely be encountered until after the soil system has stabilized to its new environment.

Of equal concern in evaluating crop technology on kinds of soils are the changes imparted to the soil by past management practices. This is frequently of greatest concern with trials on experiment stations. The residual effects of lime in the topsoil of Oxisols are clearly illustrated in Table 3. Not all of the residual effects are confined to the topsoil, and marked subsoil improve-

Table 3. **Effects of lime application rates on the topsoil of annually-cropped Oxisol, 6 and 66 months after application.**

Lime applied (t/ha)	pH ($1:1 H_2O$)		Al saturation (%)		Exchangeable Ca + Mg (meq/100g)	
	6	66	6	66	6	66
	(months)		(months)		(months)	
0	4.7	3.9	63	80	0.6	0.3
1	5.0	4.2	45	61	1.1	0.6
2	5.1	4.3	25	46	1.5	1.0
4	5.6	4.8	6	15	3.1	2.1
8	6.3	5.2	2	2	4.4	4.0

SOURCE: Sánchez, P. A. and Salinas, J. G. 1981.

ment has been recorded following several years of continued cultivation, liming, and fertilization (Sánchez et al., 1983).

The evidence is clear. Soil properties, especially topsoil properties that have direct relevance to crop plant growth, are significantly altered by the manipulation of vegetative cover, fertilizers, and lime.

Classifying soil

Faced with the dynamics of soil properties, not unlike the dynamics of plants and animals, how do soil scientists classify the object of their attention? Quite simply, they use measurable criteria that have been found to be least changed by expected soil management techniques. Soil classification has to avoid features of the soil changed by plowing or the result is mapping units reflecting corn soils and forest soils. While such a soil boundary would be easy to see and measure, it does absolutely nothing to help predict what kind of response can be expected when the forest is cleared and the area planted to corn. Likewise, it would not help predict what site quality could be expected if the corn fields were planted to trees. Thus, a soil classification system based solely on properties of agronomic significance, i.e., exchangeable and/or available quantities of nutrients in the topsoil, would have no value in evaluating the potential of virgin soil but merely reflect the accumulated past management. This apparent "no win" scenario can be resolved most satisfactorily by a combination of classification to efficiently identify the soil properties that are not easily changed by expected management and a "check plot" characterization of available nutrient and pH status at the beginning of any field experiment. This available nutrient status must also be reported in the publication of the results of the experiment.

Volcanic ash (Andept) heterogeneity

Soils developed on volcanic ash are common in some tropical areas and are generally associated with high phosphate fixation. There are outstanding examples of high P fixation in volcanic ash soils, but by no means do all such soils cause fixation problems. The distribution of those soils with high P fixation properties may be identified in local patterns, but because the factors that lead to the formation of this problem are strongly related to age and nature of volcanic ejecta, their spacial distribution is usually very heterogeneous. Figure 2 is a plot of data from volcanic ash soil samples from Chile, Ecuador, Guatemala, and Costa Rica showing the relationship of ammonium oxalate, extractable Al content, and P retention percentages. Clearly not all Andepts are alike, but P retention can be predicted by oxalate extractable Al. Alvarado (1982) has shown that a 10-minute field test using NaF and thymolphalein indicator will predict the high P-retaining soils. Care must be taken to adjust the 1*M* NaF pH to 8.2. The thymolphalein color changes above pH 10.7 indicate soil with P retention above about 90%. Many of the sites in Chile and Ecuador were field checked by this method by Alvarado and myself while on the tour with very satisfactory results. Either the oxalate Al, NaF, or P retention method of characterizing the field sites is strongly suggested as future research attempts to evaluate methods of phosphate fertilization in volcanic ash soils.

It should also be remembered that P retention is not usually well correlated with oxalate Al or NaF pH value in most other soils. Juo and Fox (1977) showed some variation related to parent material but overall agreement with BET-N_2[1] surface area of the sample. Since surface area is well related to the amount of clay, a reasonable prediction of P retention can be made from particle size analysis data (Pope, 1976; Figure 3). Attempts to use BET-N_2

1. Based on the Brunauer-Emmett-Teller (BET) method devised for the Manhattan project but which uses N_2 to scan and analyze the soil surface.

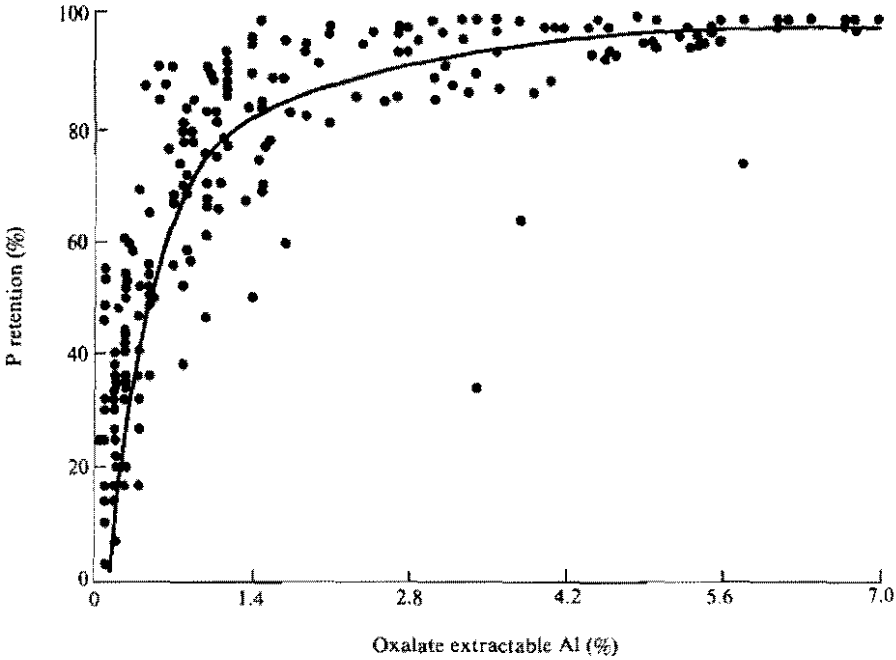


Figure 2. *Percent P retention versus percent oxalate extractable Al in Andepts from Ecuador, Chile, Costa Rica, and Guatemala. (Adapted from the United States Department of Agriculture (USDA)-Soil Conservation Services (SCS), and Alvarado, A., 1982.)*

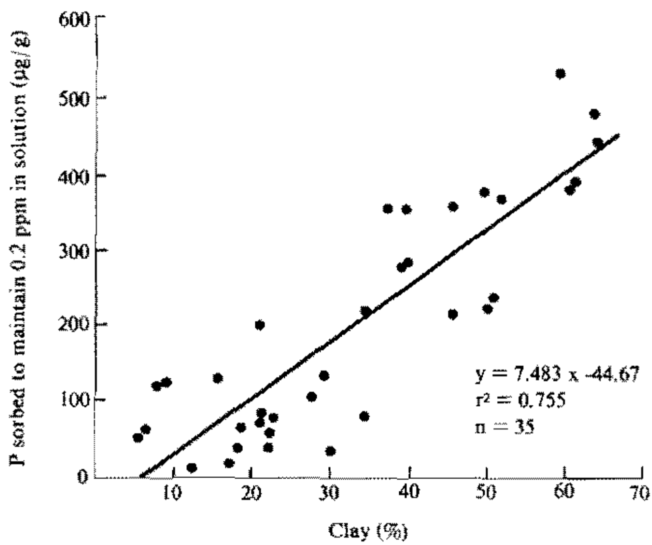


Figure 3. *Relationship between P sorption at 0.2 mg/kg P in solution and percent clay in kaolinite dominated systems. (Adapted from R. A. Pope, 1976.)*

surface area data or particle size in volcanic ash (Andepts) soils have been unsuccessful (Alvarado, 1982). It is clear that in Oxisols, Ultisols, and Alfisols, P fixation can be overcome by initial applications with reasonable residual effects. Where amorphous Al is present, as in some if not most of the volcanic ash (Andept) soils, each addition of phosphate initiates a reaction exposing more Al thus residual effects are much less (Veith and Sposito, 1977). Thus, there is no residual effect of P fertilization when the fixation is an amorphous Al component in the soil.

Acid soil conditions in the tropics

Evaluations of existing data and small-scale maps estimate that 43% of the tropical areas are dominated by Ultisols and Oxisols which, in the main, are acid soils. In tropical America the relative area of acid soil is placed at 70% (Sánchez and Salinas, 1981). One should quickly add that regardless of soil type, with a few exceptions, all soils can develop acid plow layers and, in a like fashion, all types of soil can have a neutral plow layer following the burning of fallow or lime application. Therefore, for soil management, soil acidity is more a soil property resulting from management practice and timing than a natural soil property. Subsoil acidity, with subsoil being defined as those layers of soil immediately below the layer disturbed by cultivation, is really what is being addressed in estimates of the extent of acid soil. This subsoil acidity is important because it limits the depth of rooting of aluminum-sensitive cultivars, thereby reducing both the amount of available water during rainless periods and the subsoil nutrient uptake (Bandy, 1980). Also, it is a slow process by which even heavily fertilized and limed soils can translocate bases into the subsoil. However, this does happen more rapidly in low CEC soils than in high CEC soils.

Fluctuations in surface soil acidity occur in response to several factors. Most significant in tropical areas are decreased acidity from ash after either the burning of fallow or from additions of lime where used. Acidification occurs in response to additions of acid-forming fertilizer, or more commonly from the organic acids released during decomposition reactions involved in organic matter decomposition which is especially active after the initiation of cultivation (Stevenson, 1982). Duration and intensity of the surface soil pH and exchangeable Al flux after any of the above cultural events depend upon a multitude of parameters and are more easily measured than predicted. Some examples of nearly 3 unit increases in pH have been reported due to the influence of burning (Sánchez, 1975). As a generalization, sandy textured surface soils respond more dramatically because of their low CEC and low organic matter contents than do finer textured soils.

Summary

The characteristics of soils in the tropics are probably even more diverse than those of soils in temperate areas. Certain subsoil properties are mapable and defined by the taxonomic classification of the soil. Classification and mapping of soils can be used to transfer the results of agronomic research only when several surface soil properties are known at both the site of the research and the site of the extrapolation. Foremost among the surface soil properties that have to be known in addition to classification are: pH value and/or exchange Al percent; and P fixation capacity and ambient available P level. Both characterization of soil by classical soil classification parameters and documentation of transient surface soil properties are necessary to the successful delivery of quality agronomic research.

Soil properties in the tropics are discussed from the point of view of both semipermanent properties used to classify the soil, and dynamic, management-related properties that have to be characterized on site. Most soil classification criteria are subsoil properties because they permit uniform classification regardless of vegetative cover or management practice. This permits better evaluation of potential uses of land. For the extrapolation of management-related research results, documentation of the management induced characteristics, usually in the surface horizons, has to be provided by measurements prior to plot establishment and reported as one of the conditions of the experiment.

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Phosphorus Availability in the Acid Soils of Tropical America

*Luis A. León**

Introduction

Phosphorus (P) is one of the most limiting elements to plant growth in the acid soils of the tropics (Guerrero, 1971; van Wambeke, 1974). Its use as fertilizer is restricted due to current world scarcity, high prices, and costs of transporting it to places which lack an adequate infrastructure (Kirkwood et al., 1973). In addition, the high P-fixing capacity of some of these soils makes its use even more expensive (Gil, 1971).

A better understanding of the mechanisms of phosphate reactions in acid soils of the tropics can be of great help in order to predict their performance regarding fixation, diffusion, transformations, residual effect, and availability. It is also useful when choosing the best forms of application.

Forms of soil phosphorus

According to an estimate based on information provided by the Land Resource Unit (CIAT, 1981), approximately 40% (358 million ha) of the central region of tropical South America can be included in the category of acid soils (aluminum saturation levels higher than 70%). More than 80% of the area used for agriculture, including natural pastures, has soils with acid characteristics. A large majority of these can be classified as Ultisols, Oxisols, and Inceptisols.

To illustrate this, Table 1 shows the forms and amounts of native soil P for various soils in the Colombian tropics, as determined by the Chang and Jackson method (1957), with modifications introduced by Sem Gupta and Cornfield (1962).

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Table 1. **Forms and amounts of phosphorus in surface soils of tropical regions of Colombia.**

Soil	Total P		Forms of total P[a]													
			Easily replaceable P		Nonapatite P, and Ca		Apatite P, and Ca		P and Al		P and Fe		Organic P		Inert P	
	ppm	%	ppm	%	ppm	%	ppm	%	ppm	%	ppm	%	ppm	%	ppm	%
Oxisols (Eastern Plains)	436	100	-	-	19	4	-	-	30	7	66	15	272	62	38	9
Andosols (Pasto plateau)	1467	100	10	1	106	7	27	2	214	14	207	14	136	9	765	52
Ultisols (Jamundi)	387	100	5	1	4	1	11	3	8	2	56	14	51	13	250	64

a. ppm of total P.

SOURCE: Guerrero, R. R. 1974.

Highly weathered soils (Oxisols) contain relatively low total amounts of P. It is practically impossible to obtain detectable amounts of phosphate soluble in water and in NH_4Cl (easily replaceable P). The inorganic P is found in iron, aluminum, and nonapatite calcium phosphates, a higher proportion corresponding to the first two (22% vs. 4% of total P). A considerable amount of inert P is also found which cannot be extracted with any of the solutions used. The content of inorganic P is relatively high (62% of total P), but it must be kept in mind that the content of organic matter in these soils can be considered as average (4.0%). Nonapatite calcium phosphates have been found. It is not surprising that these soils are so deficient in P because of their low amounts of this element and the low solubility of the forms present.

Soils derived from volcanic ash deposits (Andosols of the Pasto plateau) contain high amounts of P if compared with the Ultisols and Oxisols. Inert P and aluminum, iron, and nonapatite calcium phosphates predominate in this region.

Apparently, the Colombian Andosols are formed by recent materials and weathering seems to be very limited. Even though total P is high, crops growing in these soils respond markedly to phosphorus fertilization. To predict the possible response of crops by means of phosphate fractioning seems not a very appropriate method, at least in volcanic soils.

Phosphate distribution in the Ultisols of Jamundi is very similar to that of the Oxisols, except that the Ultisols have a higher proportion of inert phosphorus and a smaller proportion of organic P.

Organic P and its metabolism

Studies conducted by Blasco (1974) in soils of 12 regions of Colombia with elevations ranging from 50 to 3500 m and with a wide variation of organic P content (2-873 ppm), indicated that with a soil of Coconucos (Figure 1), the phenomenon of immobilization surpasses that of mineralization. According to the author, it is possible that the abundance of Inositols with which P is associated makes it biologically difficult to degrade; in other words, this form in which P is found is partially responsible for the problem of retention of this element in acid tropical soils.

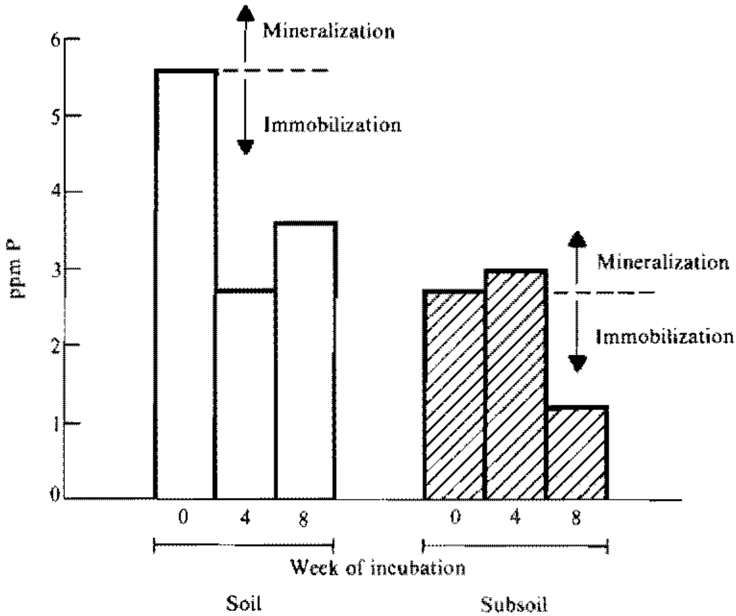

Figure 1. *Metabolism of phosphorus in soils of Coconucos, Cauca, Colombia. (Adapted from M. Blasco, 1974.)*

Inorganic phosphorus and factors influencing present soil forms

The degree of chemical weathering which has taken place is related to the forms of inorganic P present in the soil. Table 2 shows an example of Venezuelan soils studied by Westin and De

Table 2. **Distribution of inorganic active phosphorus in tropical soils in relation to their degree of weathering.**

Degree of weathering	Percentage distribution of active inorganic phosphates		
	P-Ca	P-Al	P-Fe
Very strong	4	0	96
Strong	6	20	74
Moderate	23	13	64
Weak	38	16	46

SOURCE: Westin, F. C. and De Brito, J. C. 1969.

Brito (1969). Calcium phosphates decreased as weathering increased. However, the iron phosphate (more insoluble) increased considerably. It also seems that occluded phosphates predominate over the forms of inorganic P in old soils classified as Oxisols (Dahnke et al., 1964).

Among the factors which determine the formation of P compounds in the soil are: pH, cation activity in which P compounds are soluble, mineralogic properties of the soil, and topographic and drainage conditions (Hsu and Jackson, 1960).

The pH mainly controls the transformation of phosphates from one compound to another. As soils are acidified, the relatively-soluble calcium phosphates are transformed into iron and aluminum compounds which are less soluble. When soil pH is higher than 6.0, as is the case of the alluvial soils found in some valleys of Colombia, a high percentage of inorganic P is found in the form of calcium compounds (Guerrero, 1974).

Another important effect is the soil-moisture regime. Soils found in areas with a marked seasonal drought and moisture stress, as is the case in the Colombian Eastern Plains, contain a high proportion (52%) of their inorganic P in the form of iron phosphates. Impeded drainage seems to favor the formation of aluminum phosphates. A typical example can be found in the soils of the Sibundoy Valley (Colombia), where aluminum phosphates represent 50% of the inorganic P (Guerrero, 1974).

Soil reaction to phosphate fertilization

When a phosphorus fertilizer is added to the soil, it starts becoming soluble and reacts more or less rapidly with soil compounds. The speed of the reaction depends on, among other things, the solubility rate of the fertilizer, the pH surrounding the fertilizer, and the nature of the soil components.

In a mineral acid soil, phosphates react with the iron and aluminum compounds to form less soluble compounds. In soils derived from volcanic ash, generally high in organic matter content, it seems that these phosphates react with aluminum components to form phosphorus complexes (Ospina, 1974). According to numerous researchers cited by Ospina (1974), the retention of phosphate by organic matter seems to be low or none at all.

The role played by aluminum, in all of its forms, in the retention of P is not very well defined for the Andosols. However, as shown in Figure 2, Schalscha and collaborators (1972), found a high correlation between the fixation of phosphates and "reactive" aluminum, determined by potentiometric titration at a pH of 8.2-8.5, in Chilean soils derived from rhyolite ashes. This aluminum seems to be associated to a great extent with the mineral fraction. Apparently, in the case of the Andosols, allophanes intervene actively in the retention of phosphates and crystalline compounds having a chemical composition similar to the taranakites can be formed (Wada, 1959).

Fassbender (1974) used the technique of the phosphate solubility diagram, which considers the phosphate (pH + pH_2PO_4), calcium (pH - 0.5 pCa), and aluminum (pH - 0.33 pAl) potentials to identify the inorganic phosphates in a group of forest soils derived from volcanic ashes in Antioquia, Colombia.

From Figure 3, it can be assumed that the predominant form of inorganic phosphate is found associated with aluminum, this being amorphous. Fassbender did not find crystalline aluminum phosphates in these soils as is the case with soils of Central America. As shown in Figure 4, the degree of soil development can be related to the major or minor reaction of phosphates with the soil (Ospina, 1974).

In the case of acid mineral soils, as was indicated at the beginning of this section, iron and aluminum compounds react with applied phosphates to form relatively insoluble compounds. If free iron and aluminum oxides are removed from the soil, the amount of adsorbed phosphates is notably reduced (Coleman et al., 1960).

Table 3 presents data provided by Pratt et al. (1969) on phosphate fixation of Brazilian soils related to their content of iron oxides. If the soils are grouped taxonomically, a high correlation between fixed P and free iron oxide content can be observed, but the Oxisols adsorb less P than the Ultisols at a determined content of these oxides.

These differences in adsorption can be attributed to differences in the forms of iron oxide and/or to differences in the exposed surface. It is possible that iron found in the Oxisols may have a more crystalline nature than that found in the Ultisols (Kamprath, 1974).

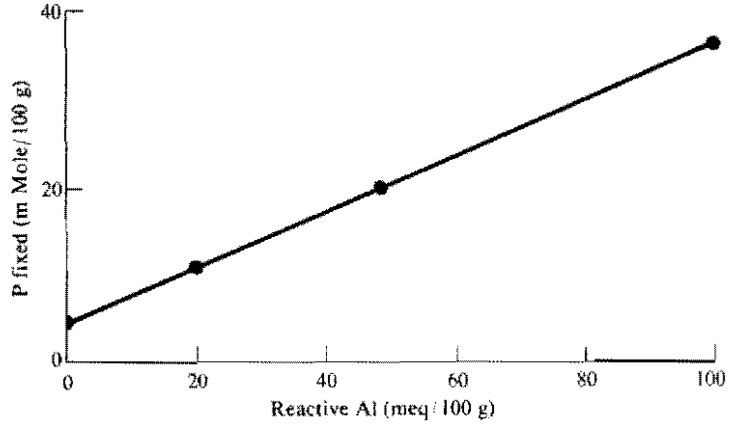

Figure 2. *Relation between reactive Al and P fixed in Andosols of Chile. (Adapted from E. P. Schalscha et al., 1972.)*

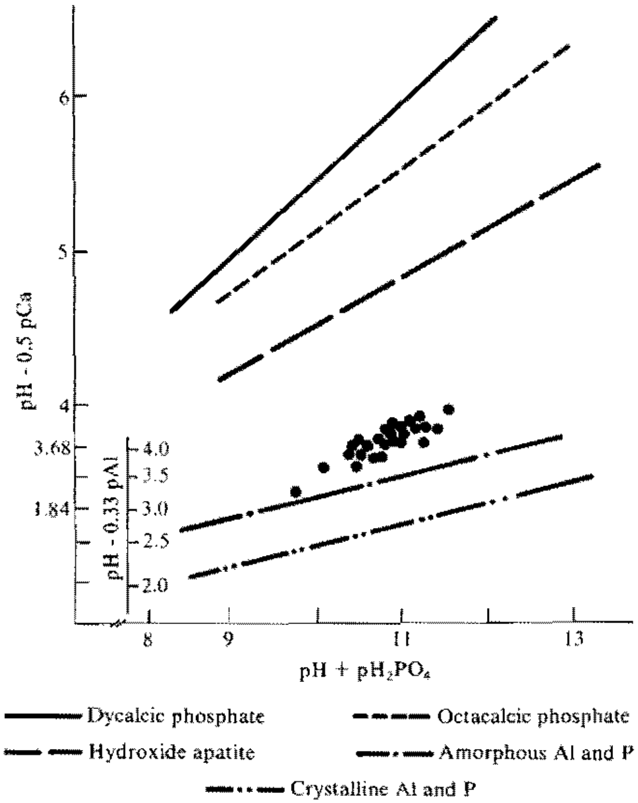

Figure 3. *Identification of inorganic phosphates cultivated with cypress in Medellín, Colombia. (Adapted from H. W. Fassbender, 1974.)*

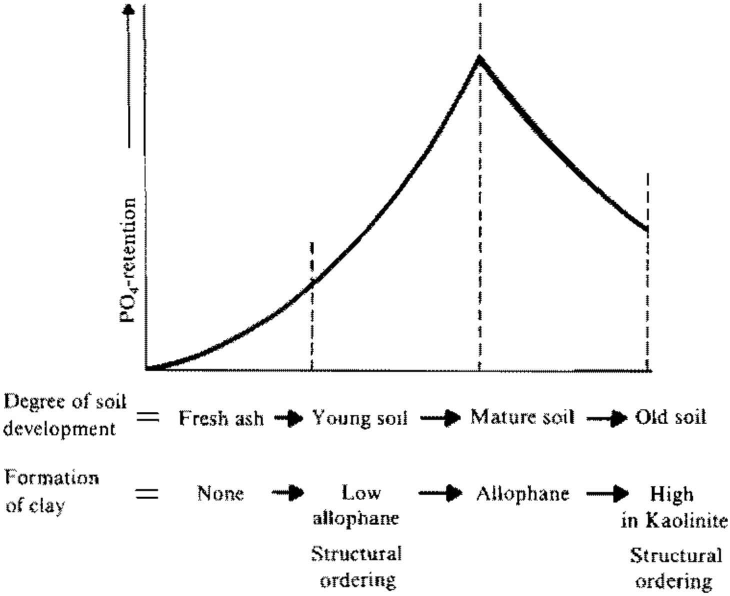

Figure 4. *Possible relation between degree of soil development and PO_4-retention. (Adapted from O. Ospina, 1974.)*

Table 3. **Phosphorus fixation in soils of Brazil in relation to their content of iron oxide.**

Soil	Free iron oxides (%)	Phosphorus fixation (meq/ha of soil)
Ultisol	2.1	1.5
	6.5	4.5
Oxisol	4.0	1.8
	19.9	4.5

SOURCE Pratt, P. F.; Peterson, F. F.; and Holzhey, C. S. 1969.

Another important mechanism in the fixation of P in acid mineral soils is the reaction with exchangeable Al and the products resulting from this hydrolysis (Coleman et al., 1960).

The following scheme has been suggested for this reaction:

$$2Al\text{-}Clay + 2MH_2PO_4 + 4MOH \overset{MCl}{\rightleftharpoons} 2M_3\text{-}Clay + 2Al(OH)_2.H_2PO_4 + 2H_2O$$

where M can be calcium, potassium, or sodium.

Table 4 shows evidence of phosphate reactions with highly weathered soils. As can be observed, the forms of P extracted from the soil after applying this element were mainly iron and aluminum phosphates. The Ultisols, which contained large quantities of kaolinite, showed a higher increase in the fraction of phosphate linked to aluminum than the fraction linked to iron. Instead, the Oxisols, with small amounts of kaolinite and a high content of iron oxide, showed a notable increase in the P linked to iron (Dunbar and Baker, 1965).

According to research carried out by Tennessee Valley Authority (TVA) scientists (Lindsay and Stephenson, 1959), products formed from the reaction between soils and a monocalcium phosphate are complex P compounds which contain aluminum, iron, potassium, and calcium.

Table 5 shows the transformations, as a function of time, of phosphates formed in the soil. With time, aluminum phosphates

Table 4. **Forms of phosphorus extracted when phosphates were added to an Oxisol and an Ultisol.**

Soil	Free iron oxide (%)	Distribution of applied phosphorus (ppm)		
		P-Ca	P-Al	P-Fe
Ultisol	2.3	7	296	133
Oxisol	12.7	14	95	300

SOURCE Dunbar, A. D. and Baker, D. E. 1965.

Table 5. **Changes in the phosphates formed in a Carimagua Oxisol in relation to the time of contact with the applied P[a].**

Forms of P (ppm)	Days after P was applied			
	0	20	35	50
Easily replaceable P	0	0	0	0
Nonapatite P and Ca	1.5	10	8	8
P-Al	15	80	70	70
P-Fe	30	180	200	200
Apatite P and Ca	3	5	5	12
Mineral P	49.5	275	283	290
Organic P	71.5	185	177	170

a. 350 ppm P.

SOURCE: Gil, F. 1971.

formed in the soils of Carimagua (Oxisols) decreased, while iron phosphates increased. Possibly, aluminum phosphates were partially used by the plants and some part was transformed into more insoluble iron phosphates.

Alternatives to improve available soil phosphorus

Since the use of highly concentrated soluble phosphates results in more expense or implies a high risk for the farmer, the alternative of using local, finely-ground rock phosphate seems to be very promising. Studies carried out by the International Fertilizer Development Center (IFDC)/CIAT Phosphorus Project (CIAT, 1982) in Latin America indicate that direct application of rock phosphate is more effective when done in acid soils (pH 4.0-5.5) very low in calcium and in available P. Certain crops, such as forage legumes and grasses, cassava, irrigated and upland rice, peanuts, and cowpea, can use the phosphorus from rock phosphate more efficiently than cereals, maize, potatoes, and beans, However, in highly acid soils very deficient in P and with low P-fixing capacity, almost all crops have shown some degree of response to rock phosphate applications, especially if the materials are of sedimentary origin and of high or medium reactivity.

When the use of rock phosphate is restricted due to its low reactivity, the crop planted, or the adverse soil properties (such as high P fixation), it is necessary to transform rock phosphate through chemical or thermic processes to increase water-and citrate-soluble P (León, 1980).

Using rock phosphate of medium or low reactivity, excellent agronomic results have been obtained with bean, maize, and potato crops when it has been partially acidulated with sulphuric or phosphoric acid. Similar results have been found when rock phosphate is granulated together with triple superphosphate (CIAT, 1982; Hammond et al., 1980).

Use of lime and silicates to improve phosphorus availability

Much research has been conducted on the use of lime and silicates, generally finding positive responses, especially when using very soluble sources of P (Bornemisza and Alvarado, 1974; Sánchez, 1976). The effect of lime and silicates in the case of rock phosphate has been researched extensively in the tropics, but some studies indicate that results obtained vary tremendously and depend upon, among other things, properties of the soil, type of rock phosphate, and crop studied (CIAT, 1976).

Improvement of efficiency with methods of applying phosphorus sources

High P-fixing soils are generally managed in such a way that water-soluble phosphate fertilizers are applied in strips to decrease the soil volume which could react with this element. In most cases, phosphorus fertilization is costly in Latin America. Therefore, Sánchez and Salinas (1983) have proposed various alternatives among which is the selection of more effective fertilizer application methods.

Many alternatives have been proposed and studied with good results, depending on the soil and crop under study (Sánchez, 1976). Variations of these application methods are being evaluated today in some tropical countries of Latin America. Among them are:

Broadcasting of rock phosphate and band or strip application of triple superphosphate at different levels and proportions.

Application of P sources in such a way that the P content in the soil increases by only 10% to 15% of the total plowed surface area. Fertilizers (simple or in mixtures) are applied in strips (wide band) on the surface and then incorporated; or large granules of triple superphosphate are broadcast in such a way that a high phosphorus-content area is formed around each granule.

Broadcast application and incorporation of rock phosphate in granules of various sizes.

Broadcast application of fertilizer without incorporation, such as in irrigated rice and pastures.

Selection of species and varieties tolerant to low available phosphorus

Just as there are differences among species and varieties in their tolerance to high aluminum concentrations and to low lime concentrations in a soil solution (Foy, 1974), there are also plants that require very little phosphorus to achieve maximum yields, or can use P from low soluble sources such as some rock phosphates (Sánchez, 1976; Sánchez and Salinas, 1983).

Differences can be measured among crops and varieties using the so-called external and internal requirements, by means of absorption and translocation rates or by the effects in the rhyzosphere (Sánchez and Salinas, 1983). Deist and others (1971) observed that dicotyledon plants can better use P from rock phosphate than can monocotyledon plants. A trial conducted at CIAT showed that ecotypes and varieties of *Stylosanthes* can take up phosphorus from sources having low available P, such as Huila rock phosphate. Here also, yield differences among ecotypes and varieties were observed (CIAT, 1976).

Response to mycorrhizae inoculation

The presence of an infection in some plant roots with vesicular-arbuscular mycorrhizae increases their ability to take up phosphorus, especially in P-deficient soils.

This type of fungus produces a network of hyphae that extends far from the roots, increasing the volume of exploited soil and improving the efficiency of P absorption by the plant (Howeler, 1983). There is evidence that some crops respond to mycorrhizae inoculation. It is possible that inoculation with these microorganisms is another way of decreasing P requirements for certain crops.

Summary

Phosphorus is one of the most limiting elements to plant growth in the acid soils of the tropics which have a high percentage of aluminum saturation. Phosphorus use is also restricted due to world scarcity, high prices, and costs of transporting it to places of

consumption where there is not an adequate infrastructure. In addition, the high-fixing capacity of phosphorus in some of these soils causes its use to be more expensive.

Highly weathered soils contain relatively low total quantities of P. The inorganic P in these soils is found in iron, aluminum, and nonapatitic calcium phosphates. There are considerable amounts of inert (occluded) P and the organic P content is relatively high.

The degree of chemical weathering is found to be related to the forms of inorganic P present in the soil. Calcium phosphate decreases as weathering becomes stronger and the more insoluble aluminum and iron phosphates increase considerably.

In the acid mineral soils, phosphates added as fertilizers generally react with the iron and aluminum components to form less soluble phosphates. If the free iron and aluminum oxides are removed from the soil, the amount of absorbed phosphates is considerably reduced. In the case of Andosols, allophanes seem to actively interfere in the retention of phosphates and crystalline compounds such as taranakites are also formed.

Today, it is not feasible to try to saturate the P-sorption capacity through the use of soluble, highly concentrated sources of this element. The use of less expensive P sources, such as local rock phosphate, basic slags, and chemical or thermic (partial acidulation) alterations of rock phosphate, can offer the opportunity to provide required P at a lower investment. In addition, it is possible that P applications might be made more economical by searching for different application methods and using mixtures of rock phosphate with acid-forming compounds such as sulphur, pyrites, superphosphate, and aluminum sulphate. Efficiency of applied soluble phosphate can be increased in certain cases by adding lime or silicates. Another alternative is the use of species or varieties adapted to acid soils having low available P, or which are capable of utilizing P from less soluble sources, directly or with the help of native or soil inoculated mycorrhizae.

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Analysis Methodology for Tropical Soils

*Octavio Mosquera V.**

Introduction

In establishing an analysis methodology for "tropical soils," it must be kept in mind that the tropics do not have a homogeneous group of soils where a single technology can be developed for all of them. In fact, soils representative of every order, from Entisols to Histosols, can be found in tropical regions (Table 1). When we talk about the acid and infertile soils of tropical America, we are generally referring to the vast areas of Ultisols and Oxisols found in this region. These soils are not fully exploited for agricultural production, due to edaphic limitations (Table 2), as well as to the lack of an adequate infrastructure—especially roads. In order to respond to the food requirements of a fast-growing population, it is necessary to push the agricultural frontier toward zones that, being technically exploited, could support continuous agriculture. And to technically exploit these soils, it is important to know their limitations and advantages.

The characterization of acid soils is different from the characterization of soils in temperate zones. In the case of acid soils, it is very important to determine exchangeable aluminum (Al) which,

Table 1. **Approximate distribution of main soil orders in tropical America.**

Order	Area (million ha)
Oxisol	502
Ultisol	320
Inceptisol	204
Alfisol	183
Entisol	124

SOURCE: Sánchez, P. A. and Salinas, J. G. 1983.

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Table 2. **Areas of tropical America having the main edaphic constraints where acid and infertile soils predominate.**

Edaphic constraint	Tropical America[a] Area (million ha)	Tropical America[a] (%)	Acid infertile soil regions[b] Area (million ha)	Acid infertile soil regions[b] (%)
N deficiency	1332	89	969	93
P deficiency	1217	82	1002	96
K deficiency	799	54	799	77
High P fixation	788	53	672	64
Al toxicity	756	51	756	72
Ca deficiency	732	49	732	70
Mg deficiency	731	49	739	70
Low cation exchange capacity (CEC)	620	41	477	55

a. Total area of 1493 million ha.
b. Total area of 1043 million ha.
SOURCE: Salinas, J. G. 1981.

many times is a high percentage of the effective cation exchange capacity (CEC). On the other hand, the fact that most of these soils have a charge depending on their pH makes their CEC, if determined by the ammonium acetate method, not reflect their real capacity to retain useful plant nutrients.

Analysis methodology

Aluminum (Al) ions are strongly absorbed by the soil's exchange complex. In addition, displaced Al remains in solution only at a pH lower than 5.0. Therefore, to extract exchangeable Al, a high concentration of the ion which displaces it is necessary and the pH of the solution must be low enough to keep it in a soluble form. This can be achieved using a 1N KCl solution which does not have buffer capacity as does the ammonium acetate traditionally used to extract exchangeable cations.

The Al concentration in the soil solution is related to soil pH, to Al saturation percentage, and to the concentration of salts of the system. When soil pH decreases to 5.5, Al concentration increases markedly. The same happens when Al saturation exceeds 60% (Figure 1).

It is currently accepted that if soil pH (in water, 1:1 ratio) is lower than 5.5, exchangeable Al, calcium (Ca), and magnesium (Mg), must be extracted with a 1N KCl solution, while if the pH is

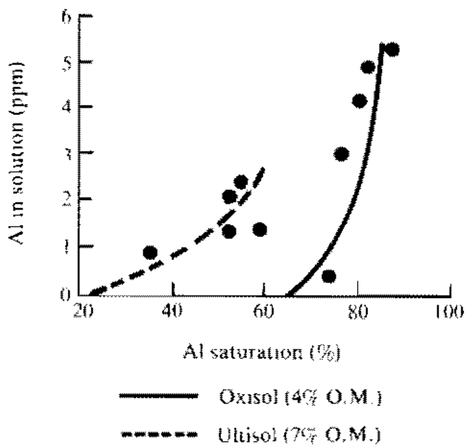

Figure 1. *Relation between Al saturation and Al in soil solution. The influence of organic matter (O.M.) is also observed.*

higher than or equal to 5.5, exchangeable cations can be extracted with a 1N ammonium acetate solution. Once the concentrations of Al, Ca, and Mg have been determined, their respective saturation percentages can be calculated. In the case of Al, this value is obtained with the formula:

$$\% \text{ Al saturation} = \frac{\text{Al (meq 100 g)}}{\text{Al} + \text{Ca} + \text{Mg}} \times 100$$

This has been widely used to characterize acid soils in terms of their possible Al toxicity and the tolerance of species and cultivars to this effect. Figure 2, for example, presents the relation between cassava yields and percent Al saturation. As can be noted, cassava is highly tolerant to the presence of Al—drastic yield reductions occur only when Al saturation is more than 80%. Something very different occurs with beans—a crop susceptible to Al. With beans, an Al saturation higher than 10% causes severe production losses.

Variations in performance and response of species and cultivars to acid conditions have resulted in the establishment of a strategy for the management of soil acidity, including the following points:

Lime applications to reduce Al saturation below the toxic levels for specific agricultural systems;

lime applications to provide Ca and Mg to plants and to stimulate their movement towards the subsoil (where they can be considered as reserves); and

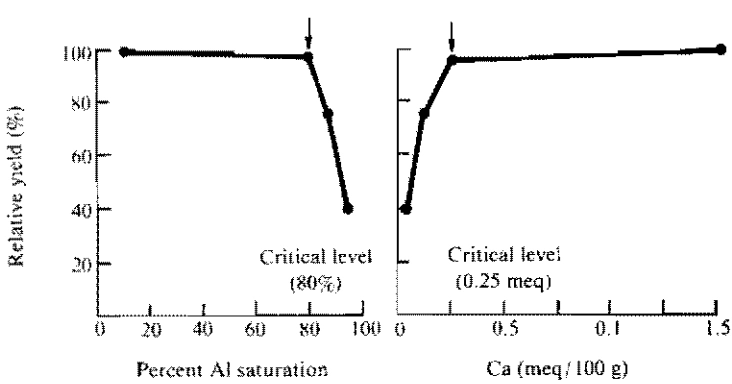

Figure 2. *Relation between the relative cassava yield (average of 42 varieties) and percent Al saturation and Ca content. (Adapted from CIAT, 1978.)*

the use of species and cultivars tolerant Al and manganese (Mn) toxicities.

For two decades, recommendations for liming of mineral soils were based on the equation:

$$\text{meq Ca}/100\text{ g soil} = 1.5\text{ meq Al}/100\text{ g soil}$$

instead of recommending a specific amount of lime to obtain a given value of soil pH. However, lately it has been found that for various crops, this equation overestimates lime requirements due to the differential degree of tolerance expressed by different species and cultivars. To avoid this problem, Cochrane et al. (1980) developed the following equation:

$$\text{t lime/ha} = 1.5\,[\text{Al} - \text{RAS}\,(\text{Al} + \text{Ca} + \text{Mg})]\,D_a$$

where Al, Ca, and Mg are expressed in meq 100 g by the soil analysis, D_a is the apparent soil density and the concept of Required Aluminum Saturation (RAS) is introduced. This is a characteristic of each species or cultivar being considered. With this method, large amounts of lime are saved, thus reducing production costs and avoiding over-liming problems, especially induced deficiencies of the micronutrients.

The effect of lime application on Al in the soil solution and on the yield of various species can be seen in Figures 3 and 4. It is observed that at levels of applied lime between 1.5 and 2 t ha, Al

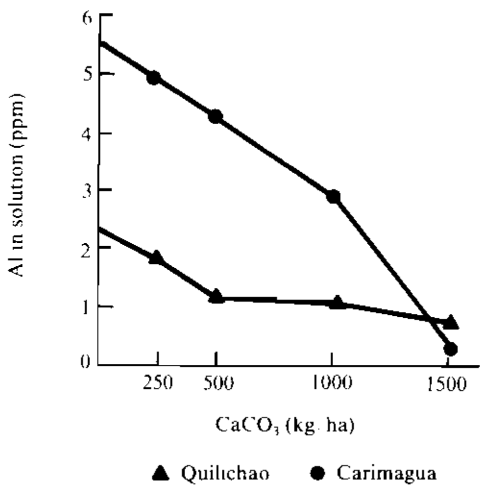

Figure 3. *Effect of levels of lime over the concentration of Al in soil solution in Carimagua and Quilichao. (Adapted from M. A. Ayarza and J. G. Salinas, 1982.)*

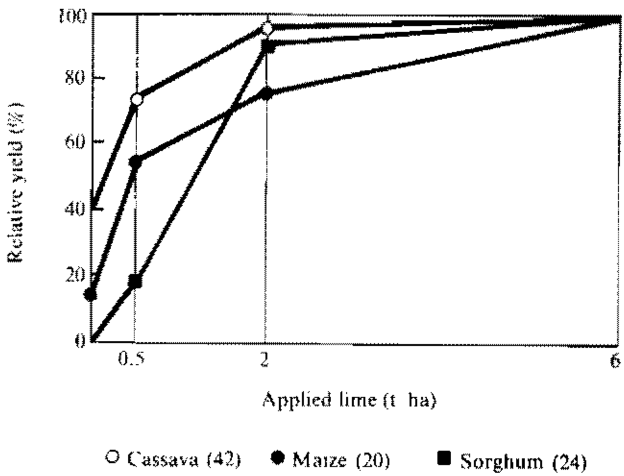

Figure 4. *Relative yield of three species in relation to four levels of lime in a Carimagua Oxisol, Colombia. Figures in parentheses indicate the number of varieties tested. (Adapted from CIAT 1977.)*

concentration in the solution is reduced to less than 1 ppm (decreasing the risk of toxicity) and yields, especially for cassava and sorghum, surpass 80% maximum yield. Table 3 shows the liming effect on certain chemical properties of an Ultisol in Quilichao, Colombia. As the pH and Ca content increase, Al and Al saturation decrease considerably.

Phosphorus (P) deficiency is one of the most widespread edaphic constraints in tropical America. Approximately 96% of the area covered by Oxisols and Ultisols are P deficient. The problem becomes worse due to the high phosphorus-fixing capacity, also common in the region. The high cost of phosphate fertilizers demands the development of technologies for these soils to more efficiently utilize applied P. With this goal, a strategy has been developed for the adequate management of P for crops and pastures in acid soils, consisting of the following points:

Determination of the most appropriate combination of methods and rates to apply P to stimulate initial and residual effects; and

improvement of soil fertility evaluation procedures to recommended P applications.

Figure 5 presents the results of a study carried out with the object of improving the sensitivity to determine available P in diluted fluorine and acid. It can be observed that as the NH_4F concentration in the solvent increases, the values of available P increase which in turn is reflected in the response of *Brachiaria decumbens* to the application of P. Since NH_4F is capable of extracting part of the P linked to the Al and iron (Fe), these fractions can be playing an important part in the liberation of P for plant use.

Table 3. **Liming effect on the chemical characteristics of a CIAT-Quilichao soil.**

Lime		Elements in soil (meq/100 g)				Al saturation	Elements in soil (ppm)	
(t/ha)	pH	Al	Ca	Mg	K	(%)	Mn	P
0	4.05	3.90	0.69	0.23	0.15	77	49	21.8
0.5	4.17	3.57	1.13	0.25	0.15	69	51	20.9
2.0	4.55	2.07	3.01	0.28	0.15	37	35	17.1
6.0	5.30	0.20	7.09	0.28	0.16	2	19	17.1

SOURCE: CIAT (Centro Internacional de Agricultura Tropical). 1977, 1978, 1979, 1980.

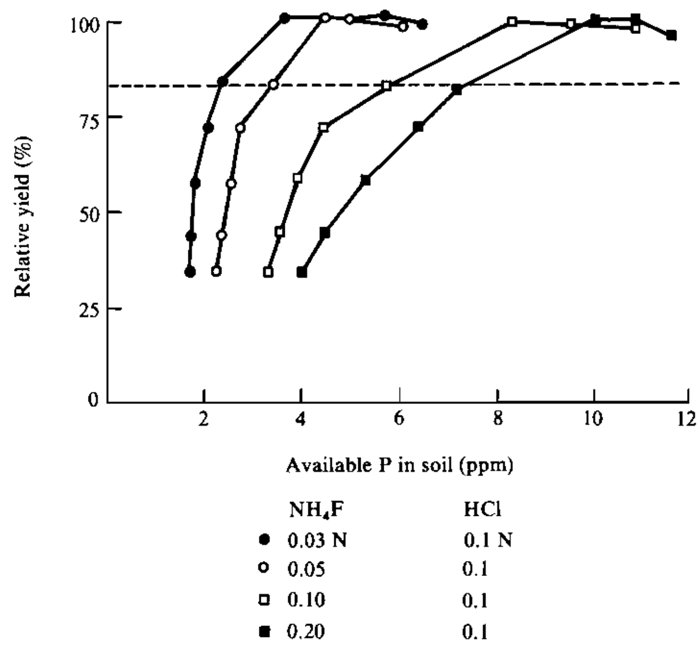

Figure 5. *Effect of different levels of available P obtained with four extracting solutions on dry matter production of* Brachiaria decumbens *in a Carimagua Oxisol. (Adapted from J. G. Salinas, 1981.)*

The third component in the strategy for efficient P management consists of the use of P sources less expensive than soluble ones—for example, rock phosphate alone or in combination with superphosphates.

The fourth component consists of the use of moderate amounts of lime to increase availability of soluble sources of P. The influence of liming over Al saturation and concentration in the soil and over the values of soil pH have been mentioned previously. Figure 6 shows the influence these factors, combined with the level of P, have over the production of dry matter of cassava plants in nutrient solution. Concentrations of over 3 ppm Al in solution cause a drastic yield reduction in spite of the presence of 4 ppm P (in the solution), while in the absence of Al, the plants responded well to the levels of P.

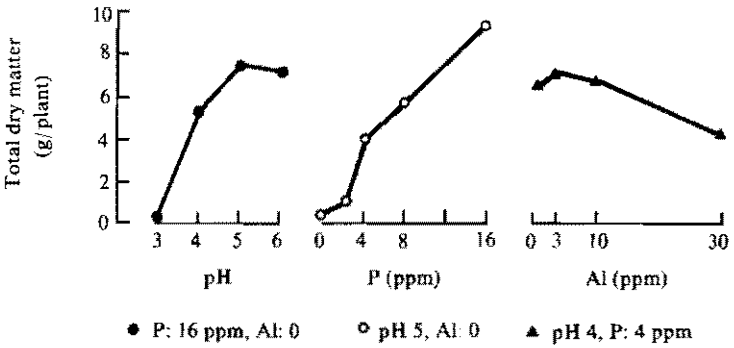

Figure 6. *Effect of P and Al concentrations and pH of the nutrient solution on cassava dry matter production of 35-day-old plants. (Adapted from CIAT, 1978.)*

The fifth component is the selection of species and varieties which grow well under conditions of low available P in the soil.

Finally, within the global strategy, emphasis must be made on the search for practical possibilities of mycorrhizae associations to increase plant absorption of P. Figure 7 shows the importance that mycorrhizae inoculation has on cassava yields and on the determination of the external critical P level for this crop. Inoculated plants reach 95% maximum yield when available P is 15 ppm, while non-inoculated plants require a level of 190 ppm available P to achieve the same yield.

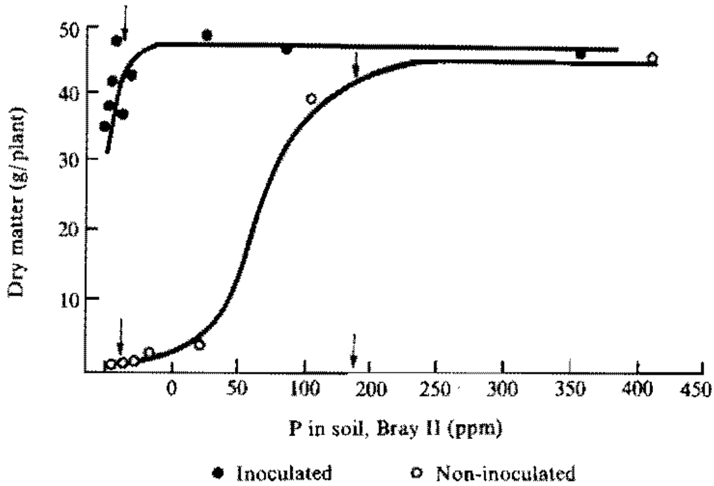

Figure 7. *Relation between dry matter production of the cassava cultivar M Mex 59, inoculated and non-inoculated with mycorrhizae, and postharvest P content in the soil. The arrow indicates the critical levels of P for 95% maximum productivity.*

Summary

In interpreting soil analysis results and in recommending fertilizers and/or amendments, it must be kept in mind that the critical level of a nutrient distinguishes soils with a high response potential to the application of this element from soils with a low response potential but does not indicate the amount of fertilizer to be applied. The precision with which soil analysis data can be interpreted will depend on the type and quality of the research work done in the field on which these correlations have been based. Having clearly made these points, critical levels for soil macro and micronutrients, and critical external levels required by cassava and for the establishment of forage species in acid soils are presented in Tables 4, 5, and 6.

Table 4. **Analysis methods, soil factors influencing this interpretation, and ranges of the critical levels of micronutrients.**

Element	Factors: Basic	Factors: Probable	Method	Range at the critical level
B	Texture pH	Lime	Hot water	0.1 - 0.7
Cu	-	O.M., Fe	$NH_4C_2H_3O_2$ (pH 4.8)	0.2
			0.5 M EDTA	0.8
Fe	pH	Lime	$NH_4C_2H_3O_2$ (pH 4.8)	2.0
			DTPA + $CaCl_2$ (pH 7.3)	2.5 - 4.5
Mn	pH	O.M.	0.05 N HCl + 0.025 N H_2SO_4	5.9
			H_2O	2.0
Zn	pH, lime	P	0.1N HCl	1.0 - 7.5
			EDTA + $(NH_4)_2CO_3$	1.4 - 3.0
			DPTA + $CaCl_2$ (pH 7.3)	0.5 - 1.0

Table 5. **Approximation of critical levels in the soil for cassava.**

Nutrient	Method	Level
P	Bray I	7 ppm
	Bray II	10 ppm
	Olsen-EDTA	8 ppm
	North Carolina	8 ppm.
K	NH_4Ac 1N	0.15 meq/100 g
	North Carolina	60 ppm
Al	KCl 1N	2.5 meq/100 g
Al saturation		75%
Ca	NH_4Ac 1N	0.25 meq/100 g
Zn	North Carolina	1.0 ppm
Mn	North Carolina	5.0-7.0 ppm
B	Hot water	0.4-0.6 ppm
pH	Soil:Water = 1:1	4.6-7.0

Table 6. **Approximate nutrient levels and soil pH in acid soils for the establishment of forage species.**

		Content		
Nutrient	Method	Low	Medium	High
P (ppm)	Bray II	< 2.0	2-5	6-10
K (meq/100 g)	Bray II	< 0.15	0.15-0.25	0.26-0.50
Al (meq/100 g)	KCl 1N	< 0.5	0.5-1.0	1.1 -1.5
Al saturation (%)	Calcu.	<10.0	10-40	41-70
Ca (meq/100 g)	KCl 1N	< 0.4	0.4-1.5	1.6-4.0
Mg (meq/100 g)	KCl 1N	< 0.2	0.2-0.8	0.9-1.2
S (ppm)		<10.0	10-15	16-20
Zn (ppm)	North Carolina	< 0.5	0.5-1.0	1.1-1.5
Cu (ppm)	North Carolina	< 0.5	0.5-.10	1.1-2.0
B (ppm)	Hot water	< 0.3	0.3-0.5	0.6-1.0
Mn (ppm)	KCl 1N	<20.0	20-50	51-80
		Very acid	Acid	Acid to neutral
Soil pH	Soil:Water = 1:1	< 4.5	4.5-5.5	5.6-7.0

SOURCE: Salinas, J. G. 1981.

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PLANT-SOIL RELATIONSHIPS

Strategies Implied in the Use and Management of Acid Soils in Tropical America

*José G. Salinas and Carlos E. Castilla**

Characteristics of the ecosystems in tropical America

Within a broad regional characterization, the American tropics present two predominant ecosystems: the savanna ecosystem, covering approximately 360 million hectares, and the forest ecosystem, with approximately 620 million hectares. The soils predominating in both ecosystems are classified in their majority (800 million ha) as Oxisols and Ultisols, according to the American system of soil taxonomy. The distribution of these soils at the country level reveals their importance in South and Central America and in the Caribbean region (Tables 1 and 2).

Table 1. **Distribution of Oxisols and Ultisols by country in South America.**

Country	Area covered (million ha)	Proportion of the country (%)	Importance[a]
Brazil	572.71	68.0	+++
Colombia	67.45	57.0	+++
Bolivia	39.54	57.0	+++
Venezuela	51.64	58.0	+++
Peru	56.01	44.0	++
Paraguay	9.55	24.0	+
Ecuador	8.61	23.0	+
Chile	1.37	2.0	
Argentina	1.28	0.4	
Uruguay	0.00	0.0	

a. +++ More than 50% of the country.
++ More than 25% of the country.
+ More than 10% of the country.

SOURCE: Cochrane, T. T. 1979.

* Soil scientists, Tropical Pastures Program, Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia.

Table 2. **Approximate distribution of Oxisols and Ultisols by country in Central America and the Caribbean.**

Country	Area covered (million ha)	Proportion of the country (%)	Importance[a]
French Guiana	8.61	94.0	+++
Trinidad	0.42	84.0	+++
Suriname	11.43	62.0	+++
Panama	12.25	62.0	+++
Guyana	3.59	63.0	+++
Jamaica	0.45	41.0	++
Nicaragua	3.92	30.0	++
Honduras	3.25	29.0	++
Cuba	2.42	21.0	+
Belize	0.40	18.0	+
Haiti	0.52	18.0	+
Puerto Rico	0.16	18.0	+
Costa Rica	0.70	14.0	+
Guatemala	0.98	9.0	
Dominican Republic	0.43	9.0	
El Salvador	0.00	0.0	

a. +++ More than 50% of the country.
++ More than 25% of the country.
+ More than 10% of the country.
SOURCE: Cochrane, T. T. 1979.

Most of the Oxisols in tropical America are confined to intertropical regions and ancient and stable geologic areas, identified by the Guyana and Brazilian continental shields; and to the eastern half of the Amazon Valley, formed by highly weathered sediments resulting from the erosion of the continental shields. In turn, Ultisols predominate in the wide sedimentary valleys making up the western half of the Amazon Basin, and were formed by fine sediments originating from the erosion of the Andean elevations; therefore, they occupy more recently formed areas than the Oxisols. They are also present in large areas of the more dissected parts of the Brazilian shield which have been affected by erosion and in some areas of the Orinoco Basin (Salinas and Valencia, 1984).

At the level of diagnosis for the use and management of acid soils, tropical America can be subdivided into two main regions based on its agricultural systems and soils constraints (Sánchez and Cochrane, 1980). Approximately 30% of tropical America (405 million ha) is made up of relatively fertile soils which have a high level of bases and which sustain dense populations. The remaining 70% is dominated by acid soils of the Oxisol and Ultisol orders, with relative low population densities and primarily under forest and savanna vegetation.

Based on preliminary estimates, the main soil constraints in tropical America and its acid soil regions are presented in Table 3. The most widely diffused limitations in the Oxisol-Ultisol regions are more of a chemical than a physical nature. Phosphorus and nitrogen deficiencies are the most important. In addition, these soils are deficient in potassium, sulphur, calcium, magnesium, and zinc, have problems with aluminum and/or manganese toxicity, and are high phosphorus-fixing. The most important physical soil constraints are the Oxisols' low capacity to retain available water and the sandy-textured Ultisols' susceptibility to erosion and compaction in their surface layer. The risk of laterite formations is present in minor areas and most of the soft plintites are present in the subsoil in plain topographies not exposed to erosion. In contrast, the most important soil constraints in tropical America in regions with high levels of bases are drought stress, nitrogen deficiencies, and erosion risks (Sánchez and Cochrane, 1980).

In spite of the widely diffused belief that tropical Oxisols and Ultisols cannot support intensive and sustained agriculture (McNeil, 1964; Goodland and Irwin, 1975), there is ample evidence that these soils can be continuously cultivated and intensively managed under annual crops (Sánchez, 1977; Mar-

Table 3. **Main edaphic constraints in tropical America (lat. 23°N. to lat. 23°S.).**

Edaphic constraint	Acid, infertile soil region[a]	
	Area (million ha)	Percentage of total area
Deficiency		
N	969	93
P	1002	96
K	799	77
Ca, Mg	740	70
S	742	70
Zn	645	62
Cu	310	30
Other		
Al toxicity	756	72
High P fixation	672	64

a. The area of the region of acid soils is approximately 1043 million hectares
SOURCE: Sánchez, P. A. and Salinas, J. G. 1983.

chetti and Machado, 1980), pastures, and perennial crops (Alvim, 1976). This is also the case of Oxisols and Ultisols in Hawaii and of Ultisols in southeast China, which support dense populations.

When chemical soil constraints are eliminated through liming and fertilizer application, the productivities of these Oxisols and Ultisols range among the highest in the world. For example, Figure 1 shows the annual dry matter production of elephant grass *(Pennisetum purpureum)* with intensive nitrogen fertilization in Ultisols of Puerto Rico, where all fertility constraints have been removed. This production level is close to the maximum potential of 60 t dry matter/ha per year calculated by De Wit (1967) for tropical latitudes. Figure 2 shows another example where excellent yields were obtained (in the order of 6.3 t maize grain/ha per harvest) in a clayey Oxisol near Brasilia, Brazil, after its high phosphorus requirement was supplied by broadcasting 563 kg P/ha and other chemical soil constraints were corrected through liming and fertilization.

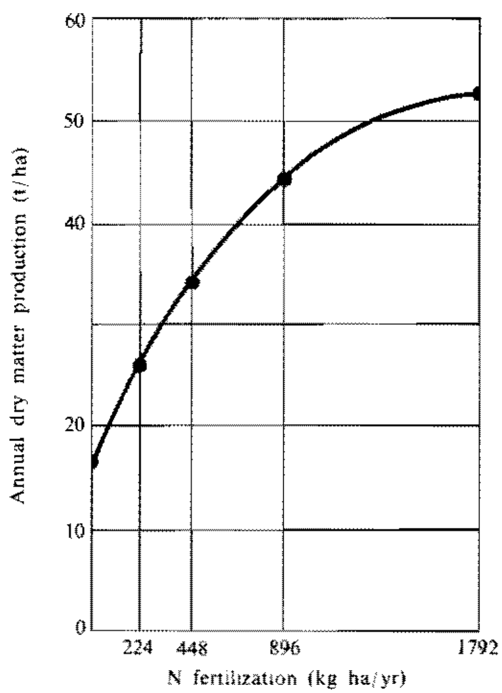

Figure 1. *Annual dry matter production of short-cut* Pennisetum purpureum *cv. Napier in an Ultisol of a rainy mountain range of Puerto Rico under intensive management. (Adapted from Vicente-Chandler et al., 1974.)*

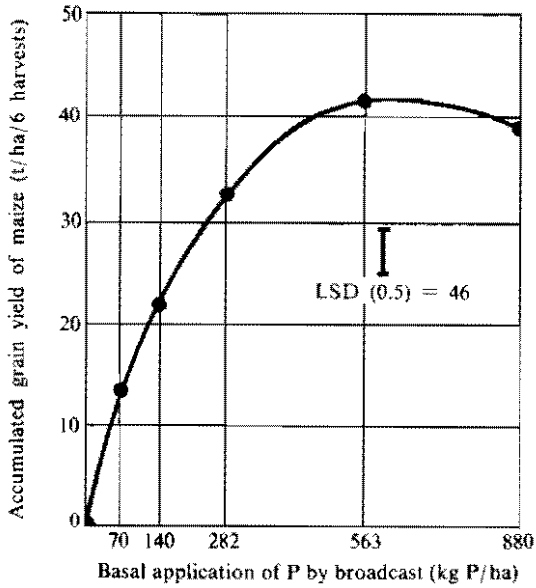

Figure 2. *Response of maize to phosphorus applications in an Oxisol (Typic Haplustox) in the Brazilian Cerrado. Accumulated grain yield of six continuous harvests. (Adapted from North Carolina State University, 1978.)*

These management strategies can be very beneficial when the market provides a favorable relationship between the prices of the crop and the cost of the fertilizer. Whenever economic infrastructure considerations make the strategy of high inputs profitable, it should be vigorously applied. However, in most tropical regions with acid soils (Oxisols and Ultisols), favorable market conditions do not exist.

Food production in acid soils of the tropics

In a very decisive way, it seems that the competition between population growth and food production will be defined in the tropics. This fact is related mainly to two factors continuously implying the need to produce more food: first, world population growth, and second, improvement of human life standards. It is estimated that for the year 2000, world population may reach 6 billion and, in consequence, the demand for food will be so high that serious and immediate consideration must be given to food production.

Broadly speaking, there are essentially three ways of increasing food production in the tropics: increasing yields by unit area in currently cultivated regions, expanding areas under irrigation, and extending the agricultural frontier. The first and the last alternatives require that soil constraints be decreased or eliminated, while the second requires availability of water to solve the most important constraint. Bentley et al. (1980) examined these three alternatives and arrived at the conclusion that all three are necessary, even though the alternative of irrigating would have to be limited to relatively small areas and is the most expensive of the three. There is no doubt that increasing the productivity of cultivated lands is the main way to increase food production. However, yield increases per unit area will be achieved only in those regions having a favorable infrastructure where agriculture can be intensified and improved management practices introduced, interacting to result in higher yields and eliminate, in as much as possible, production risks.

Recent estimates by the Food and Agriculture Organization of the United Nations (FAO) (Dudal, 1980) show that food production must be increased by 60% in order to keep up with food demand. Approximately 200 million hectares would have to be incorporated to the area currently under agriculture. This increase in cultivated area will be possible, to a large extent, by the use of the acid soils of the tropics (Oxisols and Ultisols under savanna and forest vegetation).

A large portion of these extensive regions have favorable topography for agriculture, and have adequate temperatures for plant growth throughout the year. Rainfall is sufficient during the whole year in 70% of the region, and during six to nine months in the remaining 30% of the area (Sánchez, 1977). However, the main limiting factors that hinder agricultural development in these areas, besides their low natural soil fertility, are of a socioeconomic nature: limited transportation facilities, lack of a marketing infrastructure, and low population densities.

In the majority of these tropical areas, it is typical to find that those regions influenced by markets have land prices high enough to justify, to a great extent, the intensification of agricultural and husbandry systems. In turn, this is reflected by the use of high levels of inputs. As market centers are further away from production centers, a descending gradient is observed in the use of land and in the intensification of production systems, which become extensive in nature beyond the so-called "agricultural frontier," and are characterized by the use of low-input technologies. Consequently, the decision on the degree of intensification of agricultural or husbandry systems to be established in a tropical region must be a function of the site's location in relation to existing markets, to establish transportation infrastructure, and to the availability of inputs. In other words, the decision to apply a high- or low-input technology should be based on the economic feasibility of the production system.

Comparative evaluation of technologies for soil use and management

High-input technology

The main reason why food production increased at a higher rate than population growth in developing countries during the 1965-75 decade may be attributed to genetic improvement and the use of high-yielding crop varieties in conditions where water and soil are not limiting factors. Much progress has been achieved in applying this technology to the agricultural systems of the tropics, which are a synonym of the "green revolution." However, impact was only observed in fertile soil areas with existing infraestructure, which represent 30% of tropical America.

In the acid soils, the application of the high-input technology or, in other words, the "Production of Maximum Yields" according to Cooke's (1982) definition, implies the elimination of edaphic, climatic, and socioeconomic constraints limiting the obtainment of maximum yields. His basic concept is to change the soil so it adjusts to the plant's nutritional requirements. Consequently, research on maximum yields concentrates on studying one or more edaphoclimatic variables and their interactions under a multidisciplinary approach to achieve the highest possible yields under a given situation (Wagner et al., 1982). Therefore, the objective of a high-input technology is to find the best combination of the highest level of essential inputs required to maximize yields.

This is a dynamic concept since technological advances allow present high yields to continue increasing. Thus, it is necessary to introduce the economic analysis to determine the maximum economic yield, which is generally below the maximum yield (Potash and Phosphate Institute, 1983). This situation should not discourage the researcher to continue in the search for maximum yields, since the adverse economic conditions of the moment could be improved in the future through technological development. To summarize, the maximum yield technology, based on a high supply of inputs, is widely responsible for the world's current food production levels and must undoubtedly continue where the economic conditions permit.

In the specific case of the acid soils of tropical America, the traditional high-input technology is in fact valid from the agronomic point of view. If we were farmers in a region of Oxisols and Ultisols and had to choose between overcoming the main edaphic limiting factors through receiving financial support to make massive applications of phosphorus and sufficient lime and to install supplementary irrigation systems, and of not putting into practice these components, we would immediately choose the alternative of maximum yields and see our land increase in value as it is transformed from marginal land into excellent land because of the application of inputs.

However, these opportunities are the exception instead of the rule in marginal acid-soil regions in tropical America. The amount of capital necessary to invest in these soils and apply the technology of high inputs is much greater than the resources of most governments and private organizations.

Low-input technology

The term "low-input technology" is somewhat ambiguous in defining how low is low and compared to what. The terms "zero inputs" and "minimum inputs" have also been used. The first term is inappropriate, since in most systems, zero inputs result in zero production. Low inputs, as compared to intermediate or high inputs, deserve some quantification. Sánchez and Salinas (1983) suggest that the low-input technology for the acid soils of the tropics is that required to obtain approximately 80% of maximum yields of acid-tolerant germplasm. The same authors show that it is biologically feasible to reach adequate yield levels with available technology and germplasm using a level of inputs considerably lower than that needed with traditional technology and germplasm.

The growing costs of petroleum-related inputs and worldwide emphasis on conservation of natural land resources add an extra restriction to the "maximum inputs" approach. Development goals of many tropical countries require that producers, as well as consumers, having limited resources be the main beneficiaries of the improved agricultural technology. Nickel (1979) indicated that if low-income consumers were to be benefited, increases in food production had to be achieved at lower unit prices. These low unit prices can be reached through biologically-based technology which frequently is scale neutral. To ensure that low-income producers have access to this technology, it must not depend on large amounts of purchased inputs.

In the past, farmers adapted to their lack of purchasing power by applying low amounts of inputs to an agricultural system designed to operate better at higher levels of inputs. In Latin America, there are plenty of these examples where nutrient deficiencies are evident in many fields. Many farmers know their crops could produce better yields if fertilizers were applied to high-yielding varieties, but they cannot afford to buy more or do not dare do so because of the high risk involved. Another example is the attempt to establish large-scale beef production systems in the Oxisols and Ultisols of the Brazilian Amazon by planting *Panicum maximum* without phosphorus fertilization. This is clearly the case of ignoring obvious limiting edaphic factors. As has been mentioned repeatedly by Paulo Alvim in meetings regarding the Amazon, "agriculture is different from mining." Farmers have to add fertilizers in order to sustain production, even in the best soils of temperate regions.

The soil-management technology using low inputs for these acid soils is different from partial adoption of high-input technology. **The technology of low inputs is not a matter of using less or the same amount, but a different way of managing the soil.** The fundamental breakthrough has been the identification of species and important varieties tolerant to significant degrees of limiting factors imposed by soil acidity. Thus, it is a matter of determining the amount of fertilizer and lime that these tolerant species require to produce 80% of their maximum yield in a sustained form.

Consequently, **the main justification of the low-input technology of soil management in Oxisol-Ultisol regions of tropical America, is of socioeconomic and not of an agronomic nature.**

Productivity of the high- and low-input systems

Systems of soil management with agronomically-viable high inputs invariably produce higher yields than the systems of low inputs defined here. There are many reasons that substantiate this observation. When the limiting edaphic factors are eliminated through fertilization, liming, and irrigation, species and varieties having an absolute yield potential higher than that of varieties tolerant to soil acidity must be used, since the genetic yield and quality attributes of these former species or varieties were developed in nonlimiting edaphoclimatic conditions.

On the other hand, the fertility of these acid soils is relative since the low, medium, or high denomination given will depend on the species or variety grown. Thus, marginal soils for maize, sorghum, or soybean production may be excellent for perennial high-potential forage species.

It has been stated that species of plants tolerant to the limitations of acid soils, particularly those tolerant to low available phosphorus levels, can completely exhaust the low nutrient reserve in these soils and leave them completely useless. The low-input technology is sometimes considered as the ultimate effort to extract the last bit of fertility from the soil. However, this argument must be analyzed in terms of total soil reserves, amounts of fertilizers that must be added, and total extraction of nutrients.

Because of continuous plant growth, the availability of certain soil nutrients eventually falls below critical levels. In Oxisols and Ultisols, this happens in a relatively short time with nitrogen and potassium, which are mobile elements in their available form. Nitrogen depletion is less feasible due to the large reserve in the organic fraction and its repositioning by root decomposition, nitrogen fixation, and other agronomic factors. Organic matter contents are generally not different from those found in the principal soils of temperate regions (Sánchez, 1976). The situation with sulphur is similar. The rate of potassium depletion depends on the soil's reserve of this element's non-exchangeable form, found in the minerals of clays. Potassium reserves of these soils commonly provide less than the 0.15 meq/100 g critical level generally accepted. Therefore, an equilibrium is established between exchangeable and non-exchangeable potassium. This level is not able to maintain rapid plant growth, but will not reduce potassium reserves to zero in the soil. Since harvest or mature pasture residues generally contain high levels of this element, recycling of this nutrient generally occurs.

The "mining" potential of calcium, magnesium, zinc, iron, copper, boron, manganese, and molybdenum seems less feasible, since amounts removed in crop harvests are smaller than total Oxisol and Ultisol soil reserves. In the same manner, the available forms of these elements are less soil-mobile, and therefore, less subject to loss.

Finally, total content of phosphorus (P)—the element around which most of the arguments on "soil mining" are presented—ranges between 100 and 200 ppm in the surface layer of Oxisols and Ultisols, compared with levels of approximately 300 ppm P in temperate-region soils with high active clays having a high level of bases (Sánchez, 1976). However, some Oxisols, such as the Eutrustox of the Brazilian Cerrado, have very high levels of phosphorus (Moura et al., 1971). In spite of the fact that the limited information available indicates that most Oxisols and Ultisols contain low levels of phosphorus, the extraction of this nutrient by plants (deep rooting and efficient users of phosphorus) adapted to acid soils turns out to be minimal and is slowly restored to the soil through recycling. Consequently, the argument on mining the soil seems to have little validity.

Diverse aspects of soil management technologies that can be used in the acid soils of tropical America have been briefly described. Obviously, each component cannot be applied to all situations or agricultural systems in this extensive area since certain components are mutually exclusive. Also, there are various components which are reasonably well-developed and ready for local validation while others are only preliminary observations. However, they represent the overall philosophy of soil management in the tropics.

It must be emphasized that, independent from the technology to be applied, fertility management in acid soils must necessarily contemplate three components: the nutritional requirements of the plant; the physical-chemical properties of the soil; and the biological processes of the soil.

Research needs

The feasibility of the approach of high- and low-input technologies has been discussed in previous sections by presenting various components of both technologies for the management of acid soils in tropical America. Research institutions responsible for the development of agricultural and livestock systems for representative soils are the ones in charge of integrating the components pertinent to a given situation under different agricultural systems. Therefore, the first research priority, in most situations, will be to fully develop the components of those technologies for a specific agricultural or livestock system.

This paper has identified various important research gaps of which a partial list is summarized here:

1. Characterization is needed of promising species and varieties of annual crops, grasses, and perennial crops for their tolerance to different soil constraints in terms of quantitative critical levels.

2. There is a need to characterize critical levels by soil analytical tests to determine nutrient deficiencies or toxicities in the main soil types using species and varieties adapted to the agricultural and livestock systems.

3. Develop means to interpret land evaluation systems in terms of high- and/or low-input requirements.

4. Study changes produced with time in soil chemical as well as physical properties, and in the main situations of the edaphic and agronomic systems. These studies will allow predicting changes in nutrient dynamics and physical soil deterioration and enable correcting these changes before they occur. Information on soil dynamics is scarce and generally reflects a very short period of time. Also, long-term studies are required to observe changes in soil properties in order to better understand what happens in soils managed with systems of low inputs. Questions on the degree of nutrient recycling, amount of residual nitrogen in systems, including legumes, and efficiency in the use of fertilizers could be answered through these long-term studies on the properties of the soil and their relationships with plant production.

5. There is need to quantify agrosilvicultural systems. It is necessary to establish a data base on agricultural systems which include forest species alone or in combination with annual crops and pastures.

6. Research should focus on increasing the fertility of the subsoil. Better basic understanding of the chemistry of calcium and magnesium movement, as well as of other factors

which alleviate aluminum toxicity in the subsoil through leaching, is required.

7. Tolerance to low levels of available phosphorus needs to be better understood. Greenhouse theories and studies on the differential capacity of plants to acidify their rhizosphere must be proved and validated under Oxisol and Ultisol conditions.

8. The different components of the technology on phosphorus management should be grouped into one major research and validation package. It is possible to combine, for specific soil/agriculture systems, the best sources, rates, and application methods and their interactions with the use of varieties tolerant to low levels of available phosphorus, inoculation with *Rhizobium*, and potential inoculation with improved mycorrhizae strains. It is necessary to develop improved or less expensive sources of phosphorus fertilizer, depending on the intensification of the production system.

9. Adapt species or varieties of legumes tolerant to the acidity of the soil with *Rhizobium* strains in order to make both compatible, to the same degree, with the limitations imposed by soil acidity and to favor the persistence of *Rhizobium* in the soil.

10. Develop new methods to improve the efficiency of nitrogen fertilization on nonlegume crops and of potassium fertilization on all crops. Low recovery of nitrogen and potassium fertilizers is a considerable obstacle which does not allow reducing unit costs. It is necessary to develop alternative sources of potassium fertilizer with less soluble products.

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A New Methodology to Select Cultivars Tolerant to Aluminum and with High Yield Potential

*J. J. Nicholaides III and M. I. Piha**

Introduction

Recent years have evidenced an increased interest in the evaluation of various crops for their tolerance to aluminum in the soil. This interest is greater in developing countries where population pressures have forced agriculture to move to acid, marginal soils. Often, improved technologies, such as the varieties of the "green revolution," are not adapted to produce in these soils without applications of lime, which often is not available to farmers because of geographic location, lack of transportation, or economic reasons. What is necessary for farmers in these areas of acid soils is an "adaptive revolution," whereby improved varieties or lines adapted to acid soils can be identified for immediate use or use in breeding programs.

In the bibliography various works can be found on evaluation of cultivars of various crops for their tolerance to acidity or aluminum toxicity in the laboratory, greenhouse, or field, and sometimes combining some of these. In some of these works, the authors wished to evaluate a number of cultivars for their tolerance to Al toxicity. However, there was not a good method to evaluate cultivars for tolerance to high percentages of Al saturation and, at the same time, evaluating their high yield potential under these Al-toxic soil conditions. A method has now been developed which serves this objective.

Methods and materials

The work summarized in this paper was carried out between 1979

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and 1982 by the authors (Piha and Nicholaides, 1983) in a Typic Paleudult, fine loamy, siliceous, isohyperthermic soil near Yurimaguas, Peru, at Peru's Agricultural Experimental Station utilized by the Tropical Soils Research Program. More details of various experiments conducted with rice, sweet potato, soybean, peanut, and cowpea can be found in the 1980-1981 Technical Report of the Tropical Soils Research Program (Piha and Nicholaides, 1983).

Model

To evaluate data from a number of crop cultivars for their tolerance to Al toxicity and high yield potential under these Al-toxic conditions in the soil, a graph must first be constructed. The abscissa (X axis) is the absolute yield in Al-toxic conditions and the ordinate (Y axis) is the yield with Al toxicity relative to that without Al toxicity (Figure 1). Second, the graph must be divided in two areas by constructing a horizontal line with 85% relative yield to separate tolerant (above the line) from sensitive (below the line) cultivars. Many times in the literature, 80% relative yield is used to evaluate Al tolerance. In this case, we decided to use a stricter criterion and selected 85%.

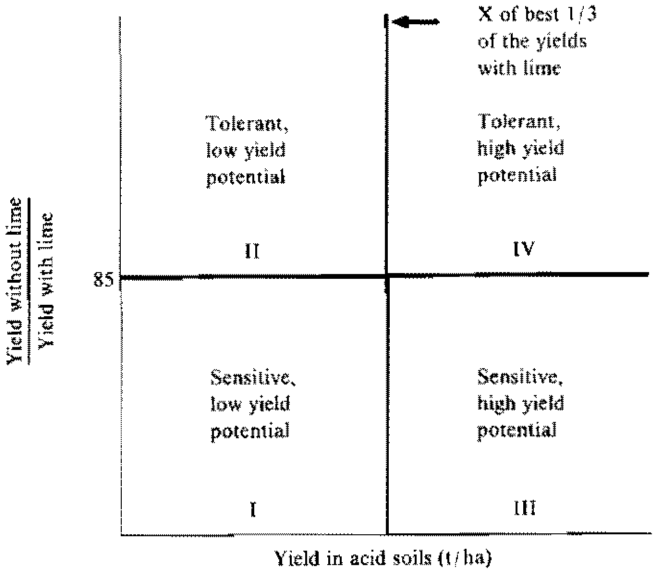

Figure 1. *Model to separate cultivars according to their tolerance to Al toxicity and their high yield potential under these stress conditions.*

To divide high from low yield potential cultivars, a line perpendicular to the abscissa has been constructed using average yields of the best one-third of the cultivars in the trial with lime application —in other words, without Al toxicity—to make sure we have high yields. Other criteria can also be used to determine this vertical line, but this method always gives an accurate indication of good crop yield under the trial's actual conditions.

The graph now has four quadrants. The cultivars falling in quadrant IV are those tolerant to Al toxicity and also with high yield potential under these toxic conditions. Cultivars falling in quadrant I are not Al tolerant nor do they have high yield potential. Those in quadrant II possess Al tolerance, while those in quadrant III have high yield potential under Al toxicity (very few cultivars fall in quadrant III).

Selected cultivars and breeding lines [52 rice, 25 sweet potato, 22 soybean, 11 peanut, and 27 (trial 1) and 10 (trial 2) cowpea] were evaluated by use of the model with field data from 1979 to 1982 near Yurimaguas, Peru, for tolerance to aluminum toxicity and high yield potential under these toxic conditions. Some properties of soils in the trial are shown in Table 1. Each trial had both Al-toxic and nontoxic (by liming) conditions. Neither phosphorus nor any other essential element was deficient in the soil since sufficient amounts of any essential element found by soil analysis to be deficient were applied to correct the deficiency.

Results and discussion

Rice

Of the 52 cultivars evaluated, 20 did not yield due to *Pyricularia* attack. The rest showed variable degrees of resistance. Using the new method to evaluate the remaining 32 cultivars, we found that three (Colombia 1, IR 9671-01141-5, and Suakoko 8) fell into quadrant IV, indicating tolerance to Al toxicity and high yield potential under these toxic conditions (Figure 2). The cultivar CICA 8 almost fell in quadrant IV, but its 77% relative yield placed it in quadrant III; however, its 3.25 t/ha yield in soil with 78% Al saturation was considered to be good. Data on yield of some selected varieties and lines are shown in Table 2. Two varieties, Colombia 1 and Suakoko 8, have the desired characteristics of both Al tolerance and high yield potential.

Table 1. **Selected soil properties in the trials to evaluate tolerance to Al in varieties and breeding lines of rice, sweet potato, soybean, peanut, and cowpea near Yurimaguas, Peru.**

Crop	Soil condition	pH	Al	CEC	Al saturation	P (Olsen modified)
			(meq/100 c³)		(%)	(ppm)
Rice						
	Unlimed	4.2	4.0	5.1	78	17
	Limed	4.9	1.7	5.4	31	19
Sweet potato						
	Unlimed	4.3	2.0	3.0	67	12
	Limed	4.9	1.1	3.2	34	13
Soybean						
	Unlimed	4.3	1.8	2.7	67	11
	Limed	5.3	0.2	2.9	7	25
Peanut						
	Unlimed	4.2	4.7	5.7	82	10
	Limed	4.9	1.9	5.4	35	10
Cowpea (trial 1)						
	Unlimed	4.2	1.2	1.9	63	13
	Limed	5.1	1.0	3.6	28	25
Cowpea (trial 2)						
	Unlimed	4.2	3.6	5.1	71	12
	Limed	5.0	1.2	4.9	24	11

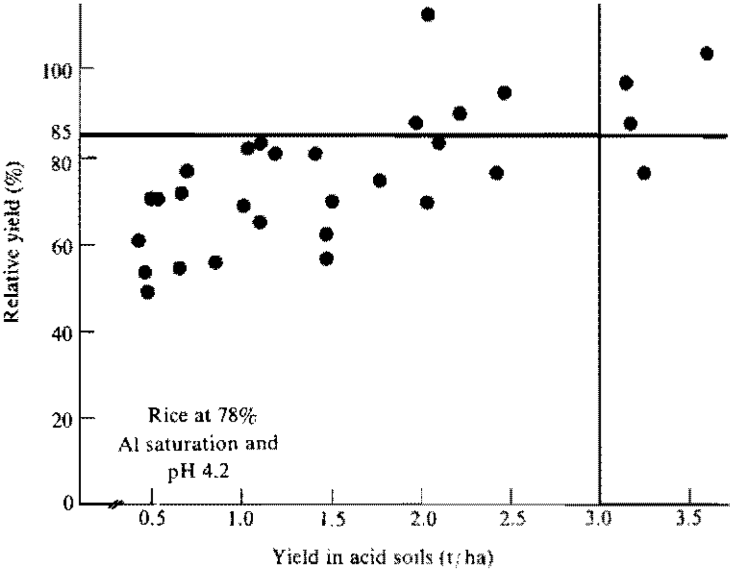

Figure 2. *Use of the model to indicate rice cultivars tolerant to Al and with high yield potential under Al toxicty stress.*

Table 2. **Some measurements of selected rice cultivars produced in soils with 78% and 31% Al saturation near Yurimaguas, Peru.**

Line or variety	Yield[a] (t/ha) Unlimed soil	Yield[a] (t/ha) Limed soil	Relative grain yield (%)	Relative weight of vegetation (green) (%)
IR 4422-62	2.03	1.81	113	103
Colombia 1	3.57	3.48	104	97
Suakoko 8	3.14	3.21	97	95
IR 4-2[b]	2.42	3.14	77	86
CICA 8	3.25	4.19	77	84
Tox 494	2.03	3.04	70	80
Carolino[b]	1.48	2.43	62	58
INTI	0.34	1.97	18	43

a Index of *Pyricularia* attack to leaf $\overline{X}$ for unlimed soil = 3.0

$\overline{X}$ for limed soil = 2.2

b. Local varieties.

Sweet potato

The 20 cultivars of sweet potato produced a wide range in the graph (Figure 3), but none fell into quadrant IV. Some cultivars, such as Modelo-2, had good relative yields (97%), but their absolute yields (Table 3) under Al toxic conditions were not better than the average of the best one-third of the cultivars without Al toxicity. Therefore, according to the model, none of the cultivars evaluated had both tolerance and high yield potential.

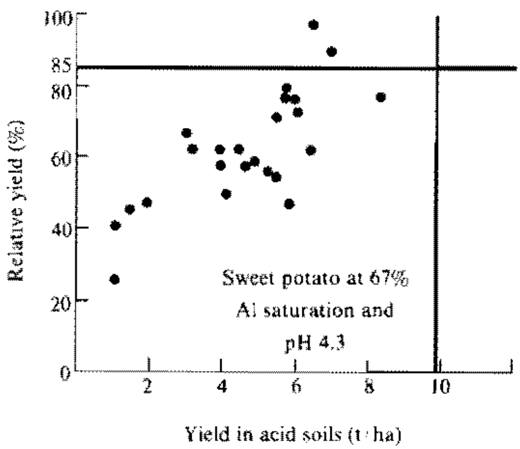

Figure 3. *Use of the model to indicate sweet potato cultivars tolerant to Al and with high yield potential under Al toxicity stress.*

Table 3. **Some measurements of selected sweet potato cultivars produced in soils with 67% and 34% Al saturation near Yurimaguas, Peru.**

Line name and number		Dry weight (t/ha) Unlimed soil	Dry weight (t/ha) Limed soil	Relative yield (%)	Relative yield of vegetation at harvest (%)	Relative crop index
Modelo-2	(Y-19)	6.6	6.7	97	111	100
Tambor	(Y-26)	8.4	11.0	77	80	98
Navarro	(Y-18)	6.0	7.9	76	123	62
—	(Y-06)	4.0	7.1	57	128	48
Modelo-1	(Y-20)	5.9	12.6	47	80	58
—	(Y-23)[a]	0.1	2.2	7	59	8

a. Peruvian line; all others from International Institute of Tropical Agriculture (IITA).

Soybean

This crop was more susceptible to Al toxicity than any other crop evaluated (Figure 4). The best relative yield was only 58% (Table 4). In a trial in North Carolina, no soybean varieties were found which entered quadrant IV by use of the Piha and Nicholaides' method (Gill, 1983). Dr. Tony Juo from the International Institute of Tropical Agriculture (IITA) says this institute has already found some soybean lines that are tolerant to Al. Evaluation of these lines with others not tolerant to Al toxicity using the proposed approach will be interesting.

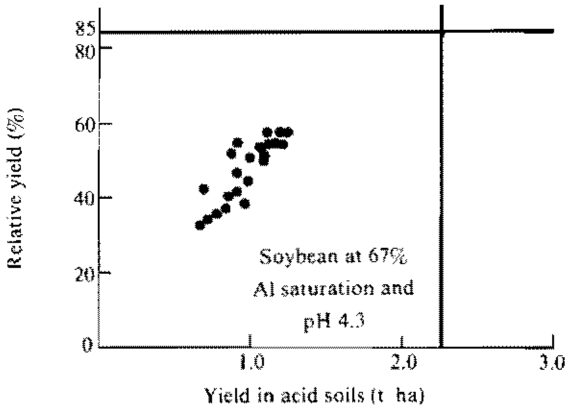

Figure 4. *Use of the model to indicate soybean cultivars tolerant to Al and with high yield potential under Al toxicity stress.*

Table 4. **Some measurements of selected soybean varieties grown in soils with 67% and 7% Al saturation near Yurimaguas, Peru.**

Variety	Yield[a] (t/ha) Unlimed soil	Yield[a] (t/ha) Limed soil	Relative grain yield (%)	Relative height (%)	Relative number of pods (%)
Hardee	1.23	2.13	58	74	75
SJ-2	1.20	2.07	58	72	70
Mineira	0.93	1.70	55	91	70
Jupiter[b]	0.93	2.23	42	72	90
Improved Pelican	0.76	2.20	35	82	52

a. Days to first harvest. $\bar{X}$ in acid soil = 84

$\bar{X}$ in limed soil = 89.

b. Local variety

Peanut

Peanut evaluation was very intriguing because, although none of the cultivars entered quadrant IV indicating tolerance and high yield potential (Figure 5), one line (UF 78307), supplied by Dr. Al Norden from the University of Florida, yielded more than 2 t/ha (Table 5) under very toxic Al conditions (82% Al saturation). This line has been used in breeding programs in North Carolina and Peru and its progeny has also demonstrated tolerance to Al (Katz, 1983). Evaluation of F_2 and F_3 lines continues.

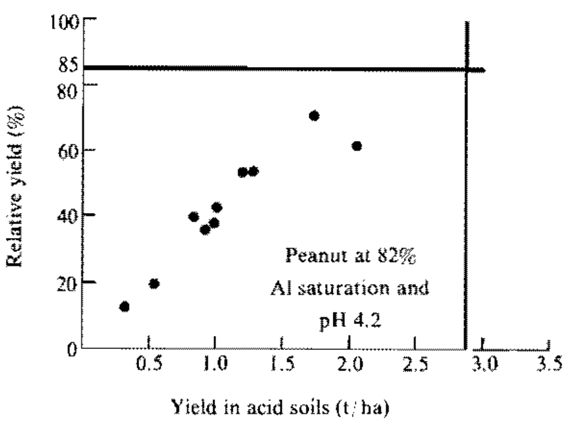

Figure 5. *Use of the model to indicate peanut cultivars tolerant to Al and with high yield potential under Al toxicity stress.*

Table 5. **Some measurements of selected peanut cultivars grown in soils with 82% and 35% Al saturation near Yurimaguas, Peru.**

Line or variety	Shelled yield (t/ha) Unlimed soil	Shelled yield (t/ha) Limed soil	Relative grain yield (%)	Relative shelling percentage (%)	Relative weight of vegetation (green) (%)
UF 78305	1.75	2.48	71	95	62
UF 78307	2.08	3.37	62	97	63
Florigiant	1.27	2.34	54	90	63
Tifrun	1.02	2.38	43	90	55
Blanco Tarapoto[a]	0.55	2.69	20	54	126
NC 6	0.31	2.30	13	57	108

a. Local variety.

Cowpea

The first trial with cowpea apparently did not have sufficient Al saturation percentage (63%) to create adequate stress, thus, most cultivars fell into quadrant IV (Figure 6). Of the 27 cultivars evaluated, nine (all from IITA) yielded more than 2 t/ha in soils with 63% Al saturation. Some examples are shown in Table 6.

Due to the lack of a good range for cowpea, another trial was placed in soils with higher Al saturation (71%) and a better range was obtained. Although none of the cultivars entered quadrant IV, the TVX 1836-013J cultivar from IITA almost fell into quadrant IV. Results of trials 1 and 2 with cowpea (Tables 6 and 7; Figures 6 and 7) emphasize the fact that the term "tolerant to Al" is only relative and its definition depends largely on the conditions where the evaluation is carried out. Whatever is tolerant to 63% Al saturation is not necessarily tolerant at 71% Al saturation.

However, it seems that cowpea, as a species, has a general tolerance to Al toxicity. In both trials, cultivar Vita 4 (from IITA) yielded more than 2 t/ha and showed 99% relative yields. Cultivars Vita 8, 6, and 7 yielded more than 1.7 t/ha and had relative yields of 85%. We believe there are cowpea varieties adapted to soils with a high percentage of Al saturation and which can yield well under Al toxicity.

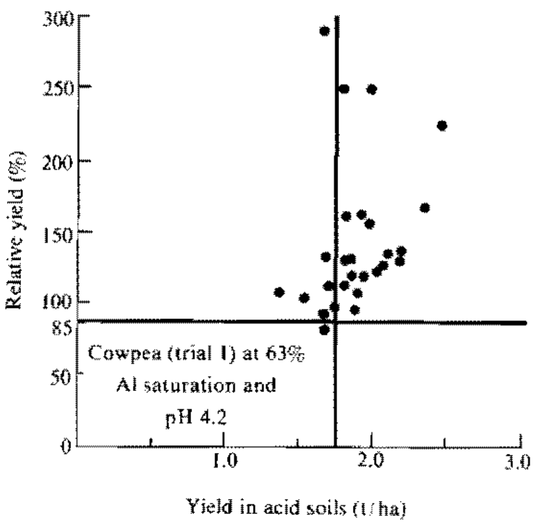

Figure 6. *Use of the model to indicate cowpea cultivars tolerant to Al and with high yield potential under Al toxicity stress (trial 1).*

Table 6. **Some measurements of various cowpea cultivars grown in soils with 63% and 28% Al saturation (trial 1) near Yurimaguas, Peru.**

Line or variety	Yield[a] (t/ha) Unlimed soil	Yield[a] (t/ha) Limed soil	Relative grain yield (%)	Relative height (%)	Relative number of pods (%)
Tvx 2394-01F	1.68	0.58	290	79	318
3 Mesino[b]	1.79	0.72	250	95	250
Tvx 66-2H	2.47	1.09	226	101	261
Tvx 1999-01F	2.38	1.43	166	99	162
Blackeye 5	1.75	1.90	92	97	88
Vita 5	1.72	2.04	84	91	91

a. Days to first harvest. $\bar{X}$ in acid soils = 66

$\bar{X}$ in limed soils = 68

b. Local variety.

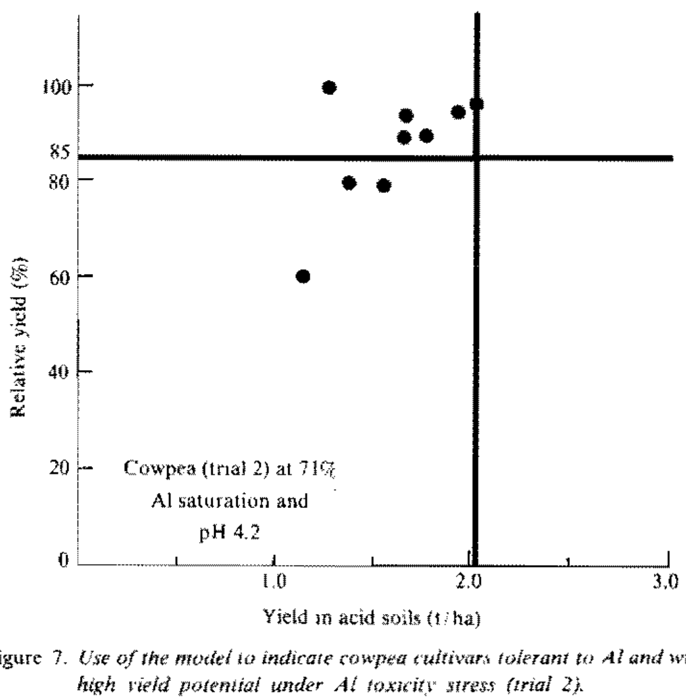

Figure 7. *Use of the model to indicate cowpea cultivars tolerant to Al and with high yield potential under Al toxicity stress (trial 2).*

Table 7. **Some measurements of various cowpea cultivars grown in soils with 71% and 24% Al saturation (trial 2) near Yurimaguas, Peru.**

Line or variety	Yield (t/ha)		Relative grain yield	Relative height	Relative number of pods
	Unlimed soil	Limed soil	(%)		
Tvx 1836-013J	1.30	1.32	99	74	100
Vita 4	2.05	2.12	96	76	94
Tvx 1193-70	1.91	2.01	95	75	86
Tvx 66-2H	1.80	2.03	90	81	89
2 Mesino[a]	1.68	1.94	87	79	89
Vita 5	1.16	1.94	60	56	59

a Local variety.

Summary and conclusions

The proposed method serves well to simultaneously evaluate a number of cultivars for both tolerance to high Al saturation percentages and high yield potential under Al toxic conditions. This method can be adapted to evaluate a number of cultivars for their tolerance to any stress condition. The phrase "tolerant to Al" is a relative phrase and its definition depends on conditions with which a species is evaluated.

A new method is proposed for evaluating a large number of cultivars of any crop species under any soil stress condition, including aluminum toxicity. This method was used to differentiate tolerance to aluminum toxicity of 52 rice, 20 sweet potato, 22 soybean, 11 peanut, and 27 cowpea cultivars in field experiments near Yurimaguas, Peru from 1979 to 1982. Several rice and cowpea cultivars were revealed by the new method to be not only aluminum tolerant, but to possess high yield potential under aluminum toxic soil conditions.

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Calcium and Root Penetration in Highly Weathered Soils

*K. D. Ritchey, D. M. G. Sousa, and J. E. Silva**

Introduction

Detrimental effects of drought can be reduced by a deep root system which draws on subsoil water and nutrient supplies. High aluminum (Al) saturation has been traditionally considered the only chemical limitation to deep root growth in well-drained soils. Calcium (Ca) deficiency is another root growth-limiting factor that needs to be considered in highly weathered soils.

Low levels of calcium limit subsoil root growth

The extent of Ca deficiency in subsoil is probably greater than presently realized. Atomic absorption spectrophotometry allows measurement of small quantities of Ca and has shown that many subsoils have less than 0.02 milliequivalents (meq)/100 g of soil (4 ppm) of this essential element (Table 1).

Table 1. **Exchangeable calcium values in subsoils of selected highly weathered profiles.**

Location	Depth (cm)	Exchangeable calcium (meq/100 g)	Reference
Carimagua, Colombia	114-137	0.0190	Rodriguez, 1975
El Piñal, Colombia	18-30	0.0110	Rodriguez, 1975
Planaltina, Brazil	15-30	0.0090	EMBRAPA-CPAC
Bahia, Brazil	20-40	0.0125	EMBRAPA-CPAC
Virginia, United States	68-84	0.0200	Daniels et al., 1983

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Simple biological test for calcium-deficient soil

Because Ca does not move downward in the plant toward the root tip, the supply that the plant root needs for elongation and growth must come from the root environment. The relatively large seeds of the grain crops are able to supply the other nutrients necessary for several days of root growth.

This fact was used by researchers of the Cerrado Agricultural Research Center (CPAC-EMBRAPA) at Planaltina, D.F. in central Brazil for development of a simple biological test for the detection of Ca-deficient soils (Ritchey et al., 1982 and 1983a). A carefully collected sample of subsoil at field capacity is planted with three to seven pregerminated seeds, preferably of the variety which will be grown on the field being tested. For routine testing of large numbers of subsoils, we have used five wheat seedlings in ordinary disposable plastic drinking cups.

The seedlings are grown in a box covered with a thin sheet of polyethylene film to reduce evaporation and eliminate the need for watering. The ambient light in the laboratory is sufficient for the 4 days of growth. After 4 days, the plants are removed and the longest root on each plant is measured with a ruler.

The addition of as little as 0.002 meq/100 g of Ca resulted in increased growth in a sample of the 90- to 105-cm layer of a clayey red-yellow Latosol (Typic Acrustox) free of exchangeable Al (Figure 1). Adding calcium chloride, calcium phosphate, or calcium carbonate was equally effective in increasing root growth in wheat, maize, and soybeans (Table 2), while magnesium carbonate ($MgCO_3$) was ineffective in increasing growth although it increased the soil pH.

Tests of a number of highly weathered profiles from central Brazil have shown that at exchangeable Ca levels of less than 0.02 to 0.05 meq/100 g, there is a marked reduction in 4-day root growth (Figure 2).

In tests conducted on a collection of samples from seven dark-red and red-yellow Latosol profiles using an apparently Al-tolerant wheat cultivar (Moncho BSB), there was little reduction in 4-day root growth associated with exchangeable Al levels of 1 to 3 meq/100 g and very high Al saturations (Figure 3).

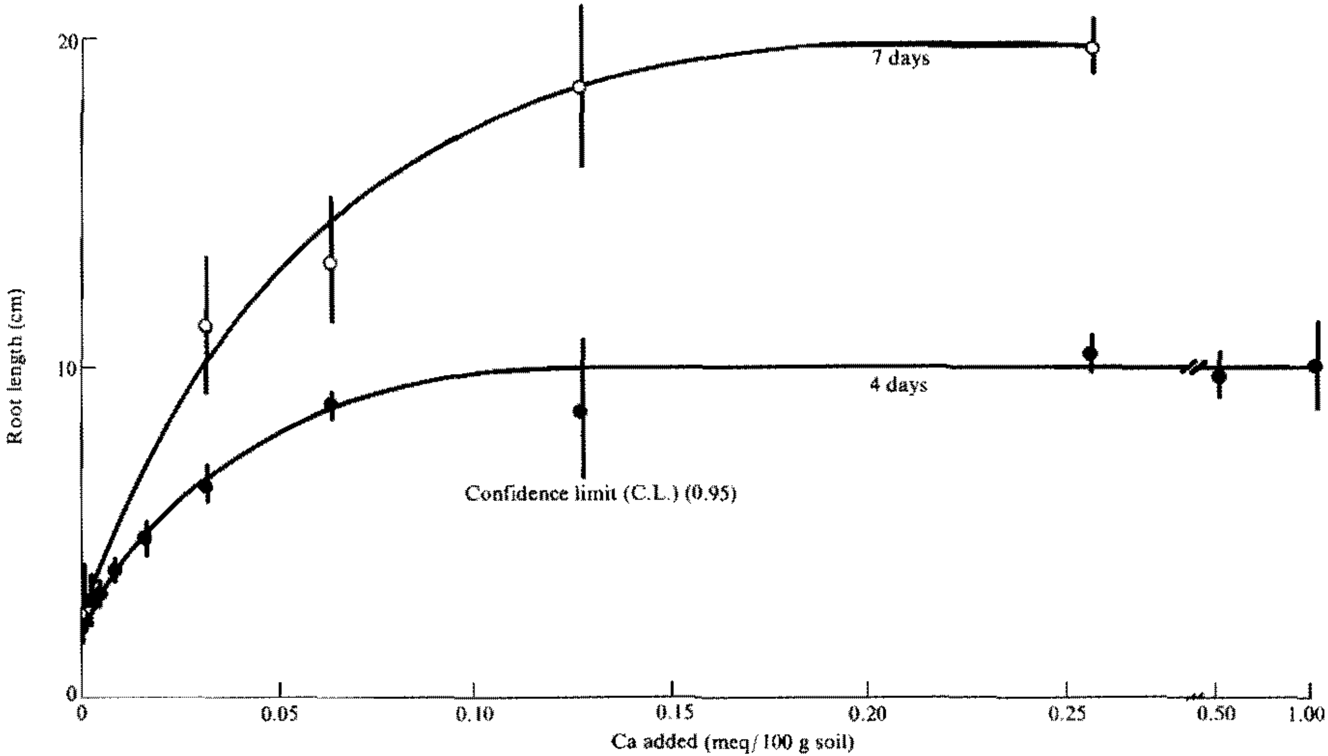


Figure 1. *Wheat seedling root growth as a function of added Ca in a deficient Typic Acrustox subsoil. (Adapted from K. D. Ritchey et al. 1982.)*

Table 2. **Root growth (cm) and soil pH resulting from calcium additions to soil from the 90- to 105-cm depth of a Typic Acrustox profile.**

Calcium added (meq/100g)	Source	pH	Root growth in 4 days Wheat (Moncho BSB)	Maize (Cargill 111)	Soybean (IAC-2)
0	-	5.7	2.7	3.0	1.8
0.21	$CaCl_2$	5.0	8.5	15.1	6.8
0.21	$Ca(H_2PO_4).H_2O$	5.9	8.3	16.3	8.9
0.42	$CaCl_2$	4.9	9.5	17.5	8.5
0.42	$CaCO_3$	6.0	8.7	14.5	8.1

SOURCE: Ritchey, K. D.; Silva, J. E.; and Costa, U. F. 1982.

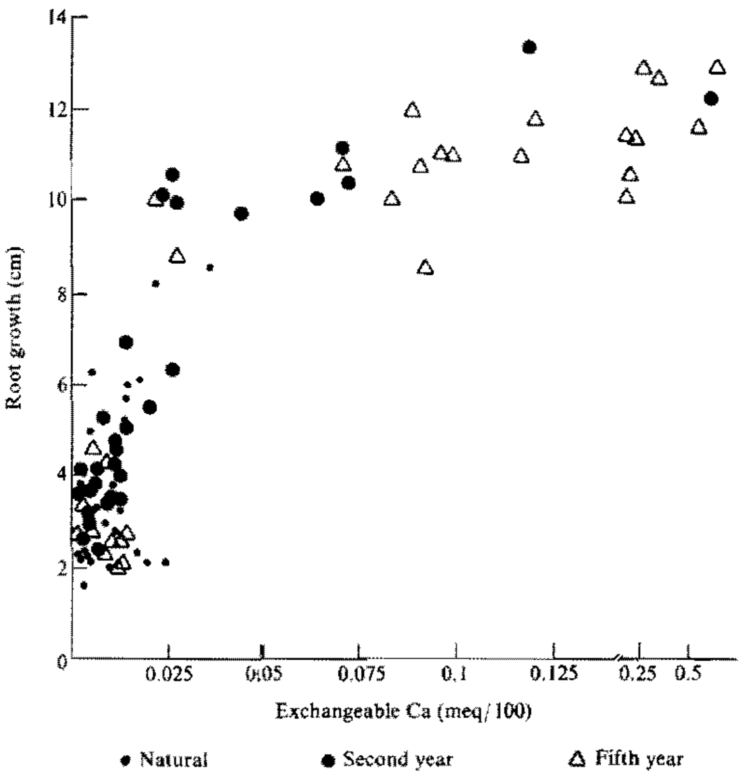


Figure 2. *Wheat seedling root growth as a function of exchangeable Ca content present in soil samples taken at various depths from three fields cultivated for various lengths of time. (Adapted from K. D. Ritchey et al., 1983.)*

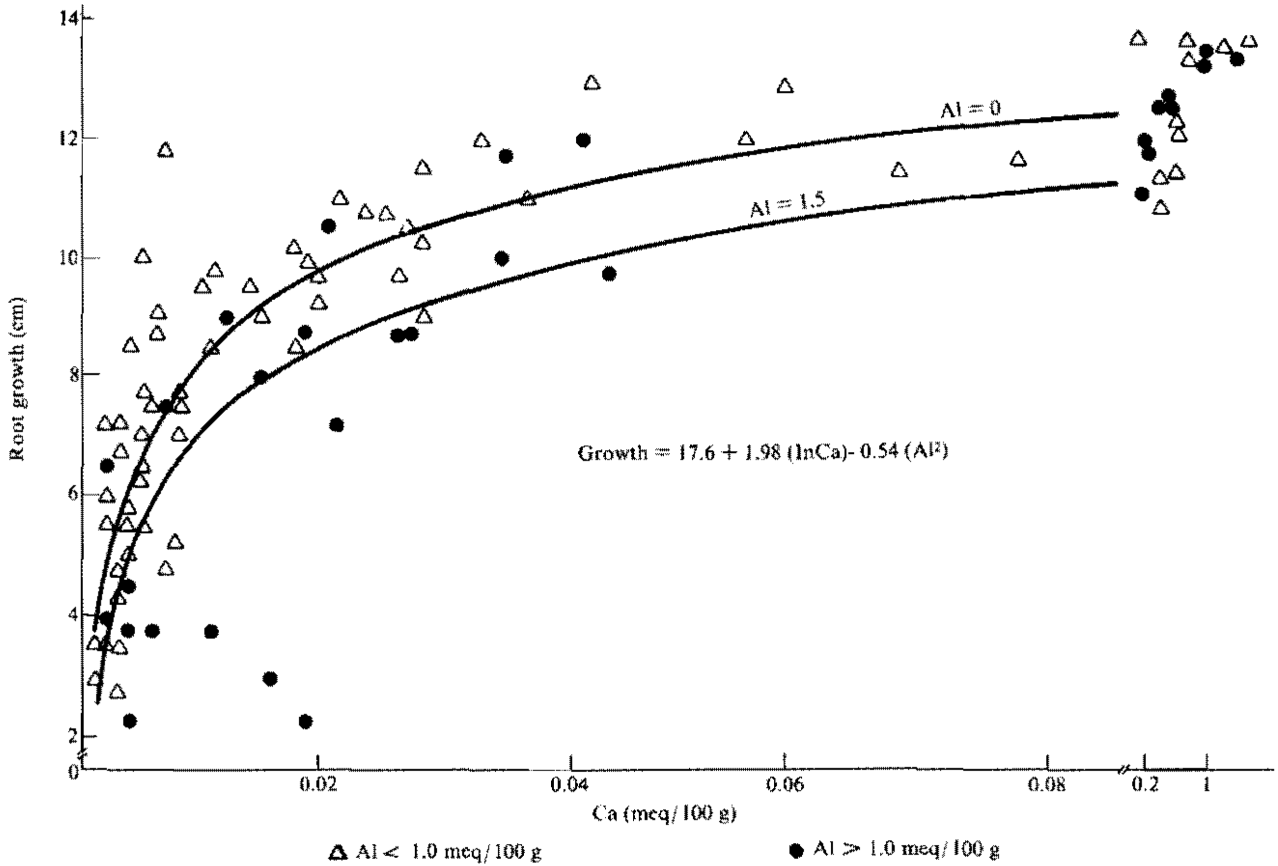


Figure 3. *Wheat seedling root growth as a function of exchangeable Ca content present in soil samples taken at various depths from eight dark-red and red-yellow Latosol profiles at CPAC. Predicted root growth as a function of Ca for soil exchangeable Al values of 0 and 1.5 meq/100 g are shown (unpublished results).*

Aluminum effects detectable by this method would be those directly or indirectly causing immediate problems in root cell division and elongation, because a 4-day seedling root test would not be expected to be sensitive to all aspects of Al toxicity, particularly those related to impairments of phosphorus (P) uptake and other nutrients, which, except for Ca, are supplied by the seed.

Field effects of calcium-deficient subsoils

Field calibrations of the biological Ca-deficiency test have been carried out on clayey soils where low Ca was the principal problem. These are the situations where the detection of Ca deficiency would be most useful, because the correction of Ca deficiency is much easier than the correction of Al toxicity.

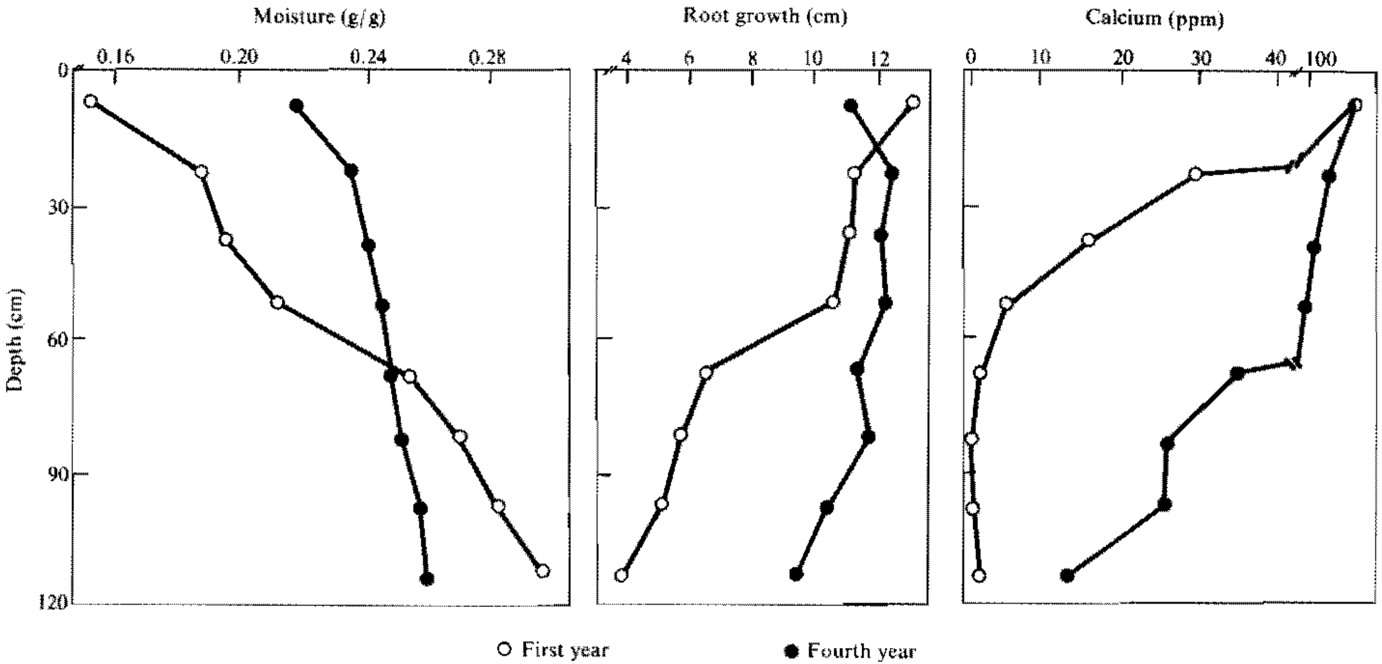
After 17 days of drought, "Cristalina" soybeans growing on a newly cleared virgin site were seriously wilted, while those growing on a 5-year-old site nearby were not (Ritchey et al., 1983a). The soybean plants in the recently cleared site had exploited the water in the top 60 cm of the profile, but their roots had not penetrated much below that (Figure 4). In the older site, water uptake was more uniform throughout the profile.

The biological test results using wheat seedlings showed that conditions below 60 cm in the new site were inadequate for root growth, and Ca at this depth was less than 5 ppm (0.025 meq/100 g).

Amelioration of subsoil calcium deficiency

For highly weathered soils with extensive iron and aluminum oxide coatings, farmer use of calcium sulfate ($CaSO_3$) and lime promote a long-lasting increase in subsoil Ca.

A comparison was made among three sites in a clayey red-yellow Latosol (Silva and Ritchey, 1982). The virgin cerrado had extremely low exchangeable Ca levels throughout the profile (Figure 5), and biologically tested root growth results were correspondingly low (Figure 2). The farmer on one side of the road had fertilized using triple superphosphate (which contains little or no calcium sulfate), while the field on the other side of the



○ First year ● Fourth year

Figure 4. *Moisture content, biologically tested wheat seedling root growth, and exchangeable Ca content as a function of depth for soybean fields in the first and fourth years of cultivation. (Adapted from K. D. Ritchey et al., 1983.)*

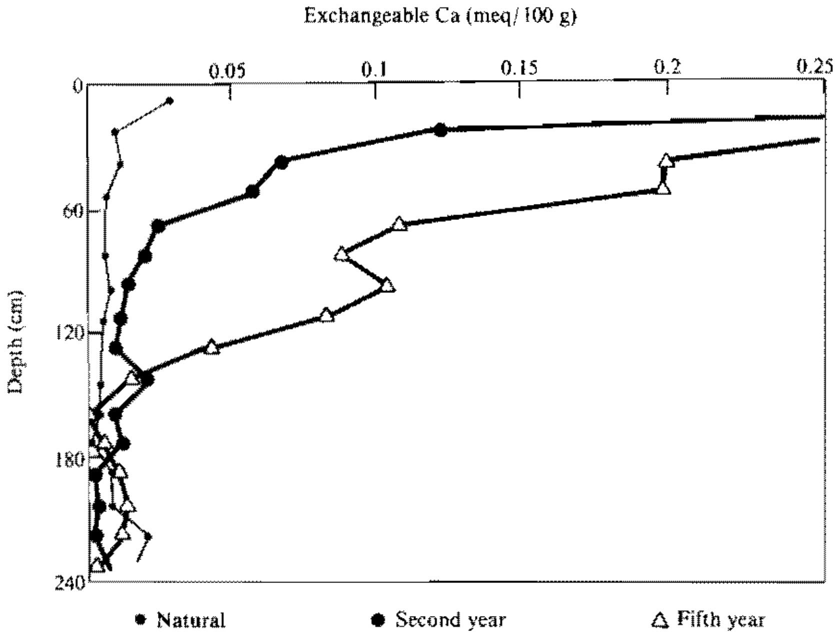


Figure 5. *Exchangeable Ca contents as a function of depth in three red-yellow Latosol profiles, located in areas cultivated for various lengths of time. (Adapted from J. E. Silva and K. D. Ritchey, 1982.)*

Table 3. **Fertilizer nutrients added, yield obtained, and condition of soybean plants during stress in farmer's fields in the second and fifth year after clearing.**

	Time of cultivation	
	2 years	5 years
	(kg/ha)	
Total nutrients added		
SO_4	8	583
P	118	334
Results		
Soybean yield	1020	2760
Appearance during 30-day drought	Wilted	Normal

SOURCE: Silva, J. E. and Ritchey, K. D. 1982.

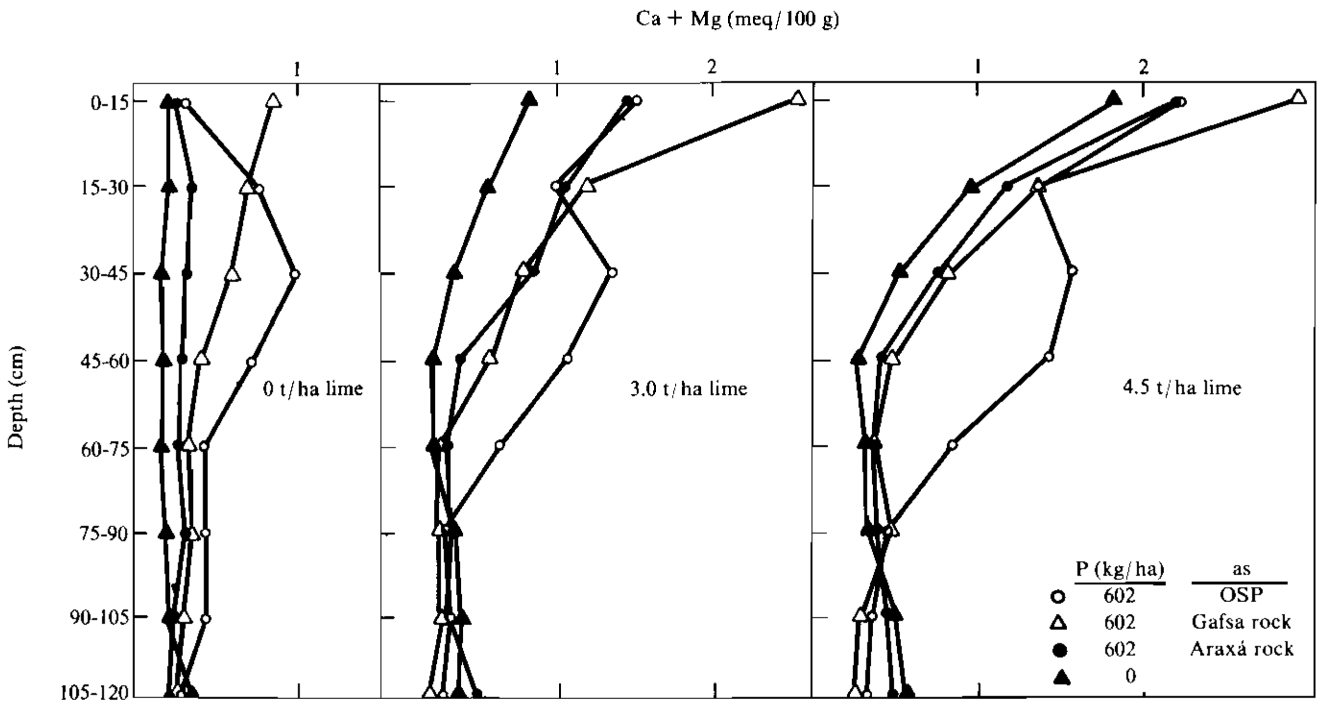


Figure 6. *Exchangeable bases as a function of depth in a dark-red Latosol which received approximately 2100 kg/ha SO_4 as ordinary superphosphate (OSP) compared with nonsulfur-supplying sources at three lime rates. (Adapted from K. D. Ritchey, 1980.)*

road had received 583 kg/ha of sulfate as ordinary superphosphate fertilizer (OSP) over a five-year period. In the sulfate-treated field, Ca leaching, biologically tested wheat root growth, and soybean root growth observed in the field pits were all better. After 30 days of drought, the soybeans in the field which received gypsum as OSP were much less wilted than in the other field, and yields were higher (Table 3).

When large amounts of gypsum are applied, it is necessary to use adequate amounts of dolomitic limestone (Figure 6). The use of these amendments together promotes a better distribution of Ca throughout the profile (Ritchey et al., 1980), and also reduces leaching losses of potassium (K) and magnesium (Mg) which can be serious if large quantities (3-6 t/ha) of calcium sulfate are applied without lime (Ritchey et al., 1983b).

Species and genotype response to aluminum and calcium

In order to routinely examine species and cultivar responses to varying Ca levels, an exchangeable Al-free red-yellow Latosol subsoil and a dark-red Latosol subsoil with about 1.5 meq/100 g exchangeable Al were treated with varying quantities of $CaSO_3$ (K. D. Ritchey, D. M. G. Sousa, and C. Sanzonowicz, unpublished data). Commercial hybrids and lines of sorghum supplied by Renato Borgonovi, Gilson Pitta, and Robert Schaffert of EMBRAPA's National Corn and Sorghum Research Center (CNPMS) at Sete Lagoas, Minas Gerais, Brazil, showed varied responses to Al levels in soil. Root lengths relative to the length of the best replicate in each trial were plotted against added Ca. The hybrid AG 1002, which yielded well at CPAC on soils farmed for a number of years, showed seriously reduced root growth under conditions of high Al saturation and/or low soil Ca (Figure 7). Similar results were observed with TX 399B and BR 007B (Figures 8 and 9). SC 283, on the other hand, showed a much smaller reduction with Al (Figure 10) as did SC 112-14 (Figure 11).

Plotting the "relative length with Al" obtained by dividing the length obtained in the high Al soil by the root length obtained in the exchangeable Al-free soil shows a clear separation of the lines and hybrids tested (Figure 12). The SC 283 and SC 112-14 lines, which seemed least affected by Al in the 4-day test, were found to

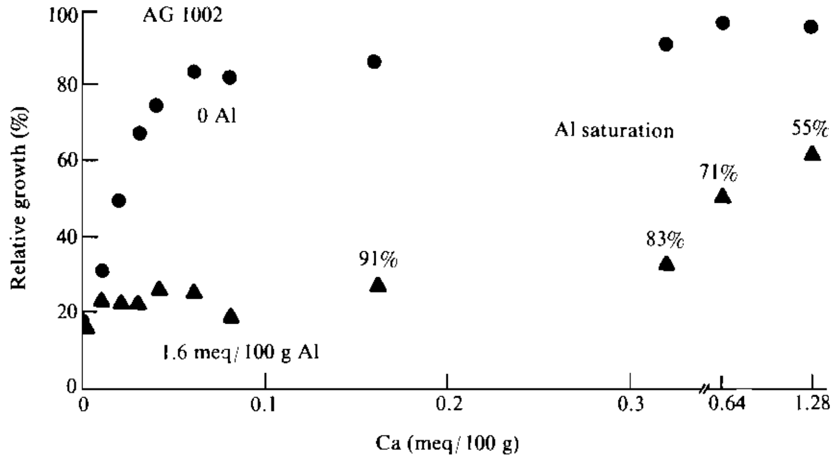


Figure 7. *Relative root length of AG1002 sorghum hybrid grown 4 days on an exchangeable Al-free red-yellow Latosol subsoil and on a dark-red Latosol with high Al saturation, as a function of levels of added calcium sulfate (unpublished results).*

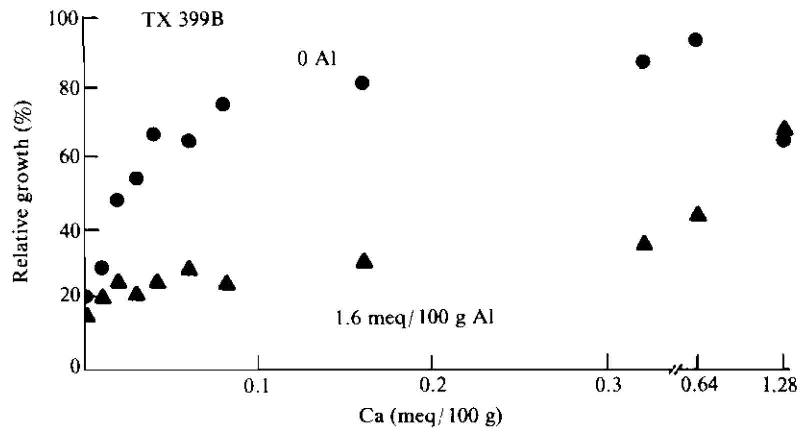


Figure 8. *Relative root length of TX 399B sorghum grown 4 days on an exchangeable Al-free red-yellow Latosol subsoil and on a dark-red Latosol with high Al saturation, as a function of levels of added calcium sulfate (unpublished results).*

be tolerant to Al by Borgonovi, Pitta, and Schaffert (this volume). This agreement is encouraging; it must be remembered, however, that tolerance to high Al in the field would include many additional traits not tested in a four-day seedling assay. For the sensitive lines grown in subsoils with high Al, Al toxicity seriously restricted root growth at soil Ca levels well above the critical range. Four-day root length began to increase only when the quantity of added calcium sulfate was sufficient to markedly reduce estimated Al saturation (Figure 7).

For the Al-tolerant lines and in the Al-free subsoil, the seriousness of inadequate Ca is clearly shown (Figures 7-11). In the untreated subsoil, length was only one-fourth that obtained when 0.08 meq/100 g Ca was added (Figure 13).

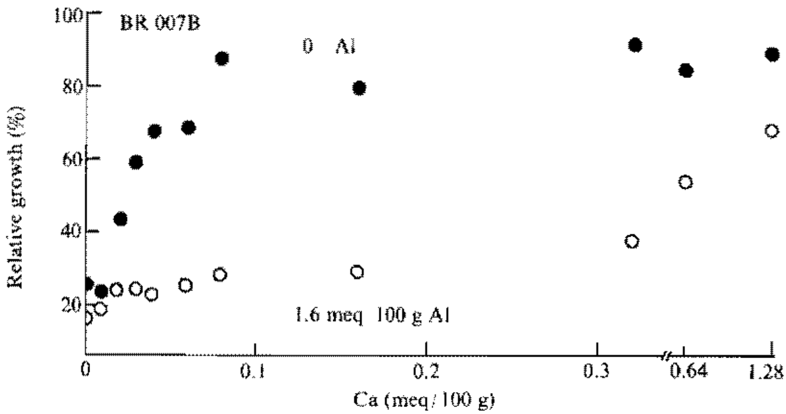


Figure 9. *Relative root length of BR 007B sorghum grown 4 days on an exchangeable Al-free red-yellow Latosol subsoil and on a dark-red Latosol with high Al saturation, as a function of levels of added calcium sulfate (unpublished results).*

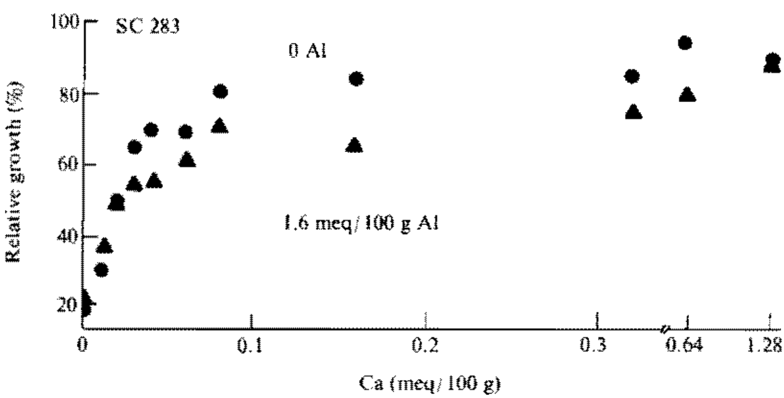


Figure 10. *Relative root length of SC 283 sorghum grown 4 days on an exchangeable Al-free red-yellow Latosol subsoil and on a dark-red Latosol with high Al saturation, as a function of levels of added calcium sulfate (unpublished results).*

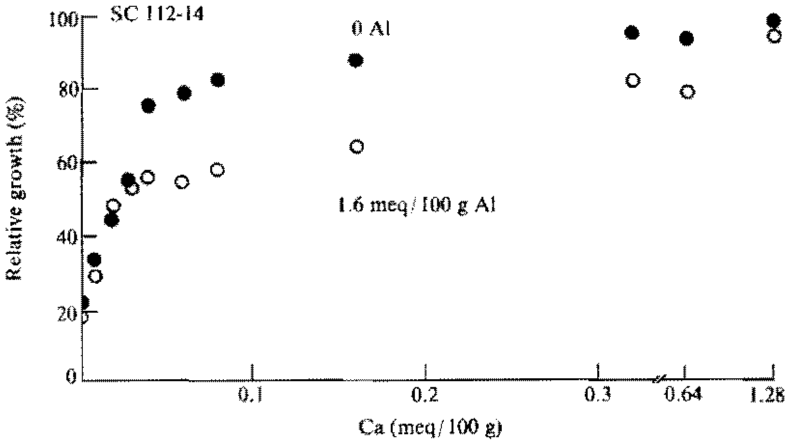


Figure 11. *Relative root length of SC 112-14 sorghum grown 4 days on an exchangeable Al-free red-yellow Latosol subsoil and on a dark-red Latosol with high Al saturation, as a function of levels of added calcium sulfate (unpublished results).*

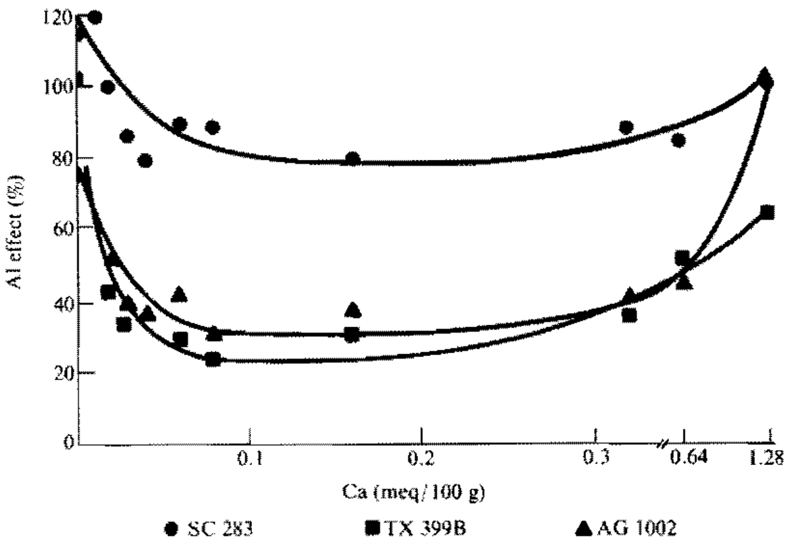


Figure 12. *Four-day sorghum seedling root growth in a high Al saturation subsoil in relation to growth in an exchangeable Al-free subsoil as a function of levels of added calcium sulfate (unpublished results).*

In the exchangeable Al-free soil, the five sorghum genotypes tested did not show much difference among themselves in relation to growth as a function of added Ca (Figure 13). Note that the Ca values are presented on a log scale. The break in slope on the log scale at about 0.08 meq/100 g may reflect satisfaction of the nutritional Ca requirements of the plant.

Preliminary comparisons among six species on a group of soil samples from Goiânia with varying Ca and Al contents (Figure 14) showed that IRAT-4 rice and Brasisul NK 233 sorghum apparently were able to maintain near maximum root lengths at slightly lower exchangeable Ca values than *Leucaena leucocephala* cv. Cunningham, *Mucuna aterrimum* (mucuna preta, a rustic-green manure crop), Moncho BSB wheat, and a cowpea cultivar (unpublished data of K. D. Ritchey, Claudio Sanzonowicz, and D. M. G. Sousa). There was much less difference among species for the Ca value at which root growth was one-half maximum. In this trial, only the sorghum showed a detrimental effect of exchangeable Al.

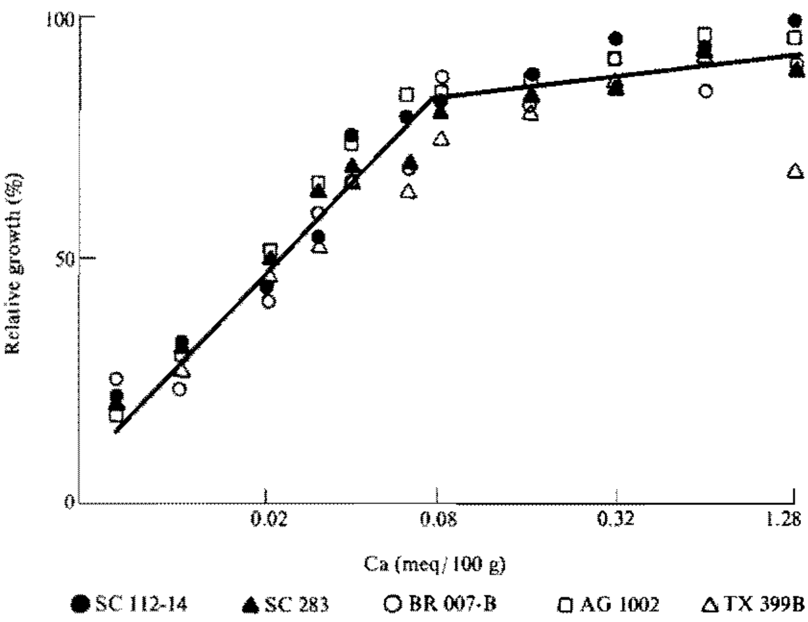


Figure 13. *Relative root growth of five sorghum genotypes as a function of levels of added calcium sulfate in an exchangeable Al-free red-yellow Latosol subsoil. Note that the horizontal (Ca) axis has a log scale. Relative root length was based on maximum root length attained by each genotype (unpublished results).*

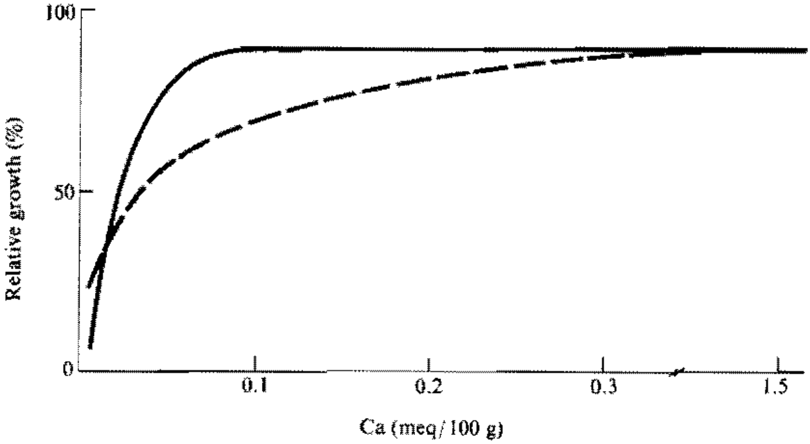


Figure 14. *Relative root growth as a function of exchangeable Ca in soil samples collected from various depths of an experimental site in Goiânia for six species. Relative growth was based on maximum root length attained by each species (unpublished results).*

Summary

Calcium deficiencies in subsoils of highly weathered profiles are probably more common than presently believed. Subsoils with less than 0.02 to 0.05 meq/100 g exchangeable Ca have been reported in Colombia, Brazil, and the United States. A simple biological test based on four-day seedling root growth, developed for identifying Ca deficiency in soil samples, showed that root growth of common large-grained annual field crops is seriously reduced at these levels. Such identification is important because correction of Ca deficiency is easier than correction of Al toxicity. In field situations, where subsoil Ca levels had been increased with the use of lime and calcium sulfate (contained in ordinary superphosphate), soybean roots were able to grow deeper and better utilize subsoil moisture to withstand droughts. The biological test carried out in soils with and without exchangeable Al clearly separated previously identified Al-tolerant and non-tolerant sorghum lines. No differences between the sorghum lines were evident in relation to Ca requirement, although there seemed to be some differences between species.

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Sorghum Evaluation in the Llanos of Venezuela

*Héctor Mena T.**

Introduction

In a relatively short time Venezuela has increased consumption and area planted to grain sorghum, which has become the most important crop planted after maize. In 1970, only 2954 ha were planted to sorghum while 264,929 ha were planted in 1980. In Venezuela, the crop has a dual purpose and the grain is used mainly in the preparation of foodstuffs. To date, only 40% of total grain demand is satisfied with approximately 350,000 t produced nationally. As a consequence of vast areas planted, large amounts of seed are needed. These are mainly imported, due to serious problems not yet solved in the production of seed of national hybrids. In view of this, a national program was established in 1977 to evaluate imported sorghums for their adaptation to the country's varied agroecological areas (Table 6, appendix). Since then, 350 sorghum hybrids have been evaluated. However, most of these have been discarded due to the crop's phytosanitary characteristics, and some have failed because of their low adaptation levels. Only about 23 accessions are maintained as commercial hybrids in Venezuela.

Venezuela has high edaphic variability and consequently a wide range of genetic materials suitable to each soil must be kept. Soils planted to sorghum generally have very low natural fertility, thus requiring liming and high fertilization levels to obtain good yields.

Soil constraints in Venezuela

According to Comerma (1976), Venezuela has few soils with no agrophysical constraints (2%). The main soil limitations are:

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1. Forty-four percent (44%) have excessive relief; these are in the mountainous regions with associated hills.

2. Thirty-two percent (32%) have low natural fertility; these are in the central, eastern, and southern *llanos* of the country. Of these, more than 87% have very low fertility (Ultisols and Oxisols), which leads to frequent use of soil amendments and fertilizers. The other 13% have constraints, but to a lesser extent than the ones previously mentioned. Acidity and exchangeable aluminum toxicity in these soils hinder sorghum production.

3. Eighteen percent (18%) have drainage problems, including the alluvial plains south of Lake Maracaibo, the central and eastern plains, and the Orinoco Delta. These flat zones have poor drainage and mechanization is difficult.

4. Four percent (4%) are acid soils, and are in the northern part of the country. Approximately 30% of the Ultisols and Oxisols of Venezuela show acidity and exchangeable aluminum problems that can affect sorghum yields.

Table 1 presents the typical soils of the Plateau of La Mesa de Guanipa, located in the Eastern Plains, where Oxisols predominate. This area constitutes more than 500,000 hectares and is where the highest contents of exchangeable aluminum are found. This region is characterized by a flat relief with grass vegetation

Table 1. **Ultisols and Oxisols of the La Mesa Plateau and their great group distribution (ha).**

Classification	Area (ha)
Ultisols	
Paleustults, medium texture, well-drained	162,000
Plinthustults, medium texture	124,000
Plinthustults, not very deep	56,000
Plinthaquults, heavy	32,000
Total Ultisols	374,000
Oxisols	
Haplustox, medium texture, well-drained	429,000
Haplustox, fine texture	68,000
Haplustox, severely eroded	16,000
Haplustox, gravel soils with mounds	2,000
Total Oxisols	515,000
Total area	2,797,015

interrupted by gallery forests. The soils are weathered (lixivial), have a sandy texture, and are poor in nutrients. More than 50% of the soils are acid and retain moisture poorly. Under these conditions, it is necessary to apply 1 or 1.5 t/ha lime to obtain acceptable sorghum yields.

Regional trials in the Venezuelan Llanos

According to the results obtained in various trials over the years, a total of 28 cultivars with good performance predominate in Venezuela. This group includes some national materials that substantially surpass yields of imported hybrids (Table 2 and Table 7, appendix), Chaguaramas-3 and Prosevenca-5 hybrids. A large number of these trials are conducted in the central, midwestern, and eastern Plains of Venezuela where Ultisols and Oxisols predominate. It is worth mentioning that national cultivars are in general late followering, taller, have more foliage, and stand stress conditions better than the imported hybrids. They are also more tolerant to acid soil conditions typical of almost all of the plains in Venezuela, indicating that these cultivars also have a good degree of tolerance to the exchangeable aluminum found in these soils. This advantage can also be observed in Table 3, showing yield results at the national level.

Among the imported hybrids, NK Savanna 5, Pioneer 815-B, Pioneer 816-B, DeKalb D-59+, and DeKalb DK-64 show the best performance. National hybrids, in general, are crosses of the "temperate x tropical" type where the tropical line provides a series of dominant genes adapted to tropical conditions, such as infertile acid soils, tolerance to aluminum, severe temperature and moisture changes, etc. These hybrids are also tolerant to the phytotoxic effects of insecticides and herbicides. It is worth pointing out that the best hybrids in Venezuela, both national and imported, have brown grain color with a high tannin content, suggesting a relation between high tannin content and good adaptation to tropical conditions (Chaguaramas-3, NK Savanna 5, Pioneer 815-B, Pioneer 816-B, and Prosevenca-5). This can be explained by the fact that sorghum is of tropical origin and has undergone natural selection. However, some white grain varieties having good performance have been recently evaluated.

Table. 2. **Average yield (kg/ha, 12% moisture content) of grain sorghum cultivars in regional trials in Venezuela.**

1980 (16 trials)		1981 (14 trials)		1982 (12 trials)	
Cultivar	Yield	Cultivar	Yield	Cultivar	Yield
Chaguaramas-3	4179	Chaguaramas-3	4529	Prosevenca-5	4290
NK Savanna 5	3977	Funk's GHW 1758	4297	Pioneer 816-B	3952
DeKalb D-59 +	3698	Prosevenca-5	4289	Asgrow 8101	3882
Pioneer 816-B	3633	Pioneer 816-B	4103	Pioneer 815-B	3828
Pioneer 8225	3480	Pioneer 815-B	3880	DeKalb D-59+	3750
Pioneer 815-B	3480	WAC 5005	3859	PW 861 DR	3691
Pioneer 8199	3375	DeKalb DK-64	3819	PW 860 DR	3506
Oro DR II	3338	NK-Savanna-5	3716	DeKalb DK-64	3473
Acco DR 1095	3301	Acco DR 1095	3708	WAC 5005	3408
Warner 832 DR	3291	Pioneer 8225	3565	Penta 5580	3373
WAC 5018	3275	DeKalb D-59+	3511	WX 832 DR	3343
WAC 5005	3238	PW 861 DR	3488	GHW 2554	3327
Warner 641	3224	Pioneer 8199	3418	Acco DR 1095	3320
TE Hondo	3190	DeKalb D-55	3393	Llanero-1	3262
PW 860	3104	H-791 A	3354	PAG 6658	3233
DeKalb D-55	3096	WX 832 DR	3338	TE Hondo	3114
NK Savanna-3	2912	PW 860	3311	Bravo E	3052
TE 7842	2888	DeKalb DK-063	3310	Pioneer YB 817	2883
Pioneer 8501	2821	DeKalb DK-045	3300	J 404	2869
WAC 5008	2773	Acco DR 1075	3276	G 499 BR	2428
Master DMT	2767	Texas Triumph 68-D	3183		
Funk's G-577	2662	TE Hondo	3112		
NK 266	2581	Monagas-1	3051		
NK 180 DMR	2286	Funk's G-589	2819		
Pioneer 8311	2546	Guárico-2	2678		

Table 3. **Comparison of yields (kg/ha, 12% moisture content) among imported and national hybrids.**

Hybrid	Location: Samán Mocho Carabobo	Coro	Chaguaramas Guárico 1972	Chaguaramas Guárico 1973
Best-yielding imported hybrid	5624	5968	3354	3377
Best-yielding national experimental hybrid	9230	8581	6413	6449

Experiences with aluminum-tolerant sorghum

Solórzano (1971) and Sánchez (1978, data in Table 8, appendix) conducted field and greenhouse trials in Venezuela to measure the tolerance of various national hybrids to exchangeble aluminum toxicity and to compare the tolerance levels of the Charaguamas series of hybrids with other national hybrids (Table 4). The Chaguaramas hybrids in the control plots (without lime applications) produced average yields over 3000 kg/ha, While the other hybrids had lower yields. On the other hand, with successive increases in applied lime, yields tended to increase for susceptible materials, while the Chaguaramas hybrids maintained a relatively stable high yield level.

Soil without lime application had a pH of 4.4 and 0.80 meq Al/100 g in the 0-10 cm depth of soil and a pH of 4.1 and 1.30 meq Al/100 g in the subsoil (Table 5). When lime was applied to

Table 4. **Average grain yield (kg/ha, 10% moisture content) for the Barinas and Chaguaramas series at different levels of applied lime.**

Series	Applied lime[a] (kg/ha): 0(0)	650(0.5)	1300(1.0)	2600(2.0)	3250(2.5)	3900(3.0)	Average
Barinas	732	1447	2128	1585	2123	1892	1651
Chaguaramas	3050	3617	4747	5053	3957	4747	4195

a. Amount of exchangeable Al that is neutralized in the soil.

Table 5. **Soil pH and exchangeable Al values at different applications of lime 80 days after application.**

Lime applied (kg/ha)	Soil depth (cm)	pH	meq Al/100 g
0	0-10	4.4	0.80
	10-25	4.1	1.30
650	0-10	4.4	0.61
	10-25	4.2	1.15
1300	0-10	4.5	0.46
	10-25	4.0	0.94
2600	0-10	5.7	0.04
	10-25	5.1	0.06
3250	0-10	6.1	0.04
	10-25	5.1	0.12
3900	0-10	6.0	0.03
	10-25	5.1	0.04

SOURCE: Solórzano, P. R. 1971.

neutralize 50% of the exchangeable Al, the value for meq Al/100 g decreased 25% in the upper strata and slightly in the lower strata while pH remained at the same level as the control. When enough lime was applied to neutralize all of the Al, the value for meq Al/100 g decreased 45% in the upper strata and 30% in the lower strata; however, the pH still remained at the same level as the control. Beyond this level, with successively higher lime rates, yields tended to be stable and then fell progressively. This may be due to the fact that at this point the level of exchangeable Al in solution is lowered to nontoxic levels. At higher rates, the soil acidity rises to approximately pH 6 and exchangeable Al practically disappears.

Clemente and Sánchez (1970) increased sorghum yields and protein content by 42% and 32%, respectively, with applications of 1 t lime/ha, to the acid (pH 4.2), infertile soils in the western plains.

Conclusions

The following conclusions can be made:

There is a selected group of national and imported sorghum hybrids that are adapted and produce good yields in Venezuela.

National hybrids are better adapted than the imported ones because of their tolerance to Al and acid soils.

In Venezuela, the adaptation factors of tolerance to Al and acid soils are tested because the cultivars are grown on Oxisols and Ultisols.

Tropically adapted hybrids are basically the result of crosses between temperate and tropical lines.

Summary

The demand for seed of sorghum hybrids has increased in recent years in Venezuela and much of the seed is presently imported (90%). For this reason, the regional sorghum program had a very low adaptation level to the Venezuelan plains. Soils in this area are very poor in nutrient content and generally have aluminum and low pH (Ultisols and Oxisols). Presently, there are 23 imported hybrids approved for the Venezuelan market along with some national hybrids. The national hybrids perform better than the imported ones, from the total adaptation point of view. NK Savanna 5, Pioneer 815-B, Pioneer 816-B, DeKalb DK-64, and DeKalb D-59+ are the best imported hybrids in Venezuela. Chaguaramas-3 and Prosevenca-5 produce better average yields and are more tolerant to acid soils and exchangeable aluminum than imported sorghum hybrids. Furthermore, they perform very well under climate stresses.

These tropically adapted sorghum hybrids result from temperate-tropical crosses and have very good performance in the tropical areas of Venezuela and Colombia. From experience with evaluation trials on acid soils, these hybrids are superior because they tolerate the environmental factors found there.

Appendix

Table 6. **Sites, location, soils, precipitation, and temperatures of sorghum regional trials, Venezuela.**

1. Gonzalito-Turmero, Aragua: Soils of medium texture, Class II, moderately deficient in P and K. Mean temperature 25.2ºC. Precipitation 1400 mm/year.
2. Villa de Cura, Aragua: Semiheavy soils, Class III and II. Mean temperature 24.5ºC. Precipitation 1200 mm/year.
3. El Sombrero, Guárico: Poor savanna soils, laterite, acid, low P and N, Class III. Mean temperature 26.5ºC. Precipitation 850 mm/year.
4. Chaguaramas, Guárico: Hilly soils, sandy, infertile, Class II with erosion and acidity problems. Mean temperature 26.8ºC. Precipitation 700 mm/year.
5. Las Mercedes, Guárico: Intermediate savanna soils, medium and heavy texture, low natural fertility. Mean temperature 26.7º C. Precipitation 800 mm/year.
6. Valle de la Pascua, Guárico: Hilly soils, Class II, poor in N and P, acid. Mean temperature 26.5ºC. Precipitation 900 mm/year.
7. Calabozo, Guárico: Heavy savanna soils, low fertility, Class II and IV. Mean temperature 27.3ºC. Precipitation 790 mm/year.
8. Aruare, Portuguesa: Soils of medium texture, poor in P and K. Mean temperature 26.5ºC. Precipitation 1680 mm year.
9. Barinas, Estado Barinas: Soils of medium and heavy texture. Relatively fertile. Mean temperature 26.5ºC. Precipitation 1780 mm/year.
10. Monagas, Maturín: Poor soils medium sandy texture, acid, low in P and K. Mean temperature 27.5ºC. Precipitation 1000 mm/year.

Table 7. **Summary of the sorghum regional trial carried out at El Sombrero, Guárico, Venezuela, 1981.**

Cultivar	Peduncle length (cm)	Plant height (cm)	Panicle length (cm)	Lodging (%)	Deterio-ration[a]	Damage[a] by midge	Damage[a] by birds	Percent with respect to $\overline{X}$ of trial[b]	Yield (kg/ha, 12% moisture)
Chaguaramas-3	26	160	22	1	1	1	2	274.9	3420
Prosevenca-5	23	162	21	1	1	1	2	222.4	2767
NK Savanna 5	34	138	22	5	1	1	2	188.7	2374
Guárico-2	6	123	21	1	1	1	2	145.8	1814
Pioneer 816-B	19	110	16	10	6	2	1	126.7	1576
Monagas-1	14	146	20	1	1	1	4	108.1	1345
DeKalb DK-64	26	126	23	1	1	1	4	106.8	1329
PW 860	12	103	19	2	2	2	3	101.7	1265
Pioneer 815-B	15	95	16	8	1	2	2	73.9	919
DeKalb DK-045	12	85	17	1	2	2	2	72.4	901
Pioneer 8225	10	115	18	9	6	1	1	71.5	889
Pioneer 8199	23	108	22	5	4	5	3	65.4	814
Texas Triumph 68-D	19	112	17	5	2	1	3	62.9	783
Funk's G-589	18	102	17	2	4	2	4	62.2	774
Warner 832 DR.	15	104	17	3	3	2	3	61.3	763
TE Hondo	20	100	16	3	2	1	2	60.5	753
DeKalb D-59+	19	112	19	5	4	2	3	60.5	752
DeKalb DK-063	18	110	17	1	5	1	2	48.9	609
DeKalb D-55	10	124	24	5	2	1	3	43.0	535
H-791 A	16	105	21	8	5	2	6	42.3	526

a. Ratings based on a visual scale with 1 being minimum and 6 maximum.

b. $\overline{X}$ = 1244.1 kg/ha
CV = 22.7%
LSD = (0.05) 481.3 kg/ha
LSD = (0.01) 654.3 kg/ha

Table 8. **Effect of lime applications required to obtain maximum yields under acid conditions present in nine areas of northeastern Venezuela, Experiment 7.**

Area	Lime rates for maximum yield (t $CaCO_3$/ha)	pH at planting date	Maximum sorghum yield (g dry weight/pot)	Maximum yield increase with lime application (%)	Exchangeable Al		Exchangeable acidity	
					meq/100 g	neutralized	meq/100 g	neutralized
San Tomé	0.5	5.9	4.2	90.48		100.00	0.90	77.50
Guanipa	0.5	5.4	6.6	19.70	0.20	62.26	0.40	50.00
Sabaneta	1.0	5.3	13.2	36.36	0.30	67.39	0.57	56.82
Uracoa	1.5	5.2	13.8	31.88	0.62	65.93	0.90	60.53
Mánamo	1.0	5.7	23.6	91.02		100.00	0.15	40.00
B. Guarapiche	1.0	5.3	16.4	92.13	0.14	85.11	0.32	73.55
Guarataro	6.5	5.3	29.2	94.08	1.20	80.42	1.60	76.81
San Agustín	2.0	5.3	29.6	91.99	1.25	39.90	1.70	37.73
Delta	8.0	4.5	37.9	96.17	0.77	74.59	1.33	68.54

SOURCE: Sánchez, C. 1978.

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Potential Role of Grain Sorghum in the Agricultural Systems of Regions with Acid Soils in Tropical Latin America

Carlos Seré and *Ruben Dario Estrada**

Introduction

During recent decades there has been a rapid expansion in the consumption of poultry in Latin America induced by the growth of per capita income and technological changes in the poultry industry which have increased supply at decreasing real prices. This has caused a marked increase in demand for animal feed grains, mainly maize and sorghum. A large proportion of this additional demand has been covered by increasing imports, encouraged by policies over-evaluating exchange rates and by the ample availability of international credit.

The recent recession has reversed these macroeconomic tendencies and has led to the design of more adequate policies to expand internal supply. Given the land resources available in Latin America, 300 million hectares of savanna with soils having good physical characteristics but marked acidity and aluminum constraints, breeding programs have been established to adapt grain sorghum to these conditions. Initial results seem to indicate that there exists a good potential in biological terms. This paper is an economic analysis of the potential for sorghum production in the savanna conditions of the Eastern Plains of Colombia. Particular emphasis is given to possible interactions between sorghum production and predominant existing production systems, basically cattle production.

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Importance of sorghum in tropical Latin America

Production, area, and yield

Tables 1, 2, and 3 present data on sorghum production, area, and yield in Latin American countries. Even though tropical South America has had an extraordinary growth in cultivated area and production in the last 20 years, it is still behind both Central America and temperate South America. All countries have increased their yields but differences existing in 1960 (300 kg/ha) have increased (1000 kg/ha) in favor of those countries located in more fertile regions, with the last place held by tropical countries with acid soils. These results reflect sorghum research policies, where high priority has been given to high-yielding materials in dry and fertile lands and very low priority given to materials adapted to rainy climates. Aside from Venezuela, little sorghum is sown in Oxisols or Ultisols of Latin America.

Table 1. **Area (thousand hectares) planted in sorghum in Latin America and the Caribbean.**

Region	1960/62	1970/72	1979/81
Tropical South America	28.7	105.6	634.0
Central America and the Caribbean	334.0	1490.3	2072.4
Total tropical Latin America	362.7	1595.9	2706.4
Temperate South America	774.7	2062.8	1862.5
Total Latin America	1137.4	3658.7	4568.9

SOURCE: CIAT (Centro Internacional de Agricultura Tropical). 1983.

Table 2. **Production (thousand tons) of sorghum in Latin America and the Caribbean.**

Region	1960/62	1970/72	1979/81
Tropical South America	41	238	1301
Central America and the Caribbean	470	3138	5500
Total tropical Latin America	511	3376	6801
Temperate South America	1317	3835	5680
Total Latin America	1828	7211	12481

SOURCE: CIAT (Centro Internacional de Agricultura Tropical). 1983.

Table 3. **Average sorghum yields (kg/ha) in Latin America and the Caribbean.**

Region	1960/62	1970/72	1979/81
Tropical South America	1429	2254	2052
Central America and the Caribbean	1407	2105	2653
Total tropical Latin America	1408	2115	2512
Temperate South America	1700	1859	3049
Total Latin America	1607	1971	2732

SOURCE: CIAT (Centro Internacional de Agricultura Tropical). 1983.

Demand and international commerce

Information on international commerce of maize and sorghum and an estimate of sorghum demand under different consumption alternatives and maize substitution are shown in Tables 4 and 5. As a whole, Latin America is self-sufficient in the production of grains, but there are large differences among countries, especially in tropical America. In spite of large increases in area and production, Central America and the Caribbean have the largest commercial deficit; 3 million tons of maize and 2 million tons of sorghum annually. Tropical South America imports small amounts of sorghum (686,000 tons) but imports more than 3 million tons of maize per year, primarily for the manufacture of foodstuffs. Brazil, Bolivia, Colombia, and Venezuela, which have large areas located in well-drained savannas with acid soils, would need to plant approximately 5 million hectares to produce the 10 million tons of sorghum required to substitute for maize and sorghum imports and for maize consumption in foodstuffs (Table 5).

It must be pointed out that these figures correspond to current demand. An additional marked increase in potential demand is expected due to the high income elasticity of poultry meat, to population growth, and to the increase in per capita income. In spite of internal prices being substantially higher than international prices (Table 6), this region is a net importer of grains. International recession and critical problems in the balance of payments create additional incentives for the growth of internal supply. Agricultural frontier areas such as savannas would seem to have appropriate conditions to substantially contribute to domestic supply, if technically and economically viable.

Table 4. **Availability (thousand tons) of maize and sorghum in Latin America and the Caribbean, 1979-1981.**

Region	Maize		Sorghum	
	Production	International commerce[a]	Production	International commerce[a]
Tropical South America	22635	3123	1301	686
Central America and the Caribbean	14178	2968	5500	2120
Total tropical Latin America	36813	6091	6801	2806
Temperate South America	10133	-5848	5680	-3604
Total Latin America	46946	243	12481	-798

a. Exports.

SOURCE: CIAT (Centro Internacional de Agricultura Tropical). 1983.

Table 5. **Expansion potential[a] of sorghum production (thousand tons) and area (thousand hectares) in countries with important acid soil regions, 1979-1981.**

Region	Alternative 1[b]		Alternative 2[c]		Alternative 3[d]	
	Production	Area	Production	Area	Production	Area
Brazil	174	87	1468	734	6969	3484
Bolivia	17	9	0	0	124	62
Colombia	488	244	189	95	884	442
Venezuela	530	265	1464	732	1591	795
Total	1209	605	3121	1561	9568	4783

a. Assuming sorghum yields in acid soils to be 2 t/ha.
b. Alternative 1: Move present production areas to acid soil regions.
c. Alternative 2: Requirements to substitute maize and sorghum imports. Maize/sorghum equivalent = 1:1.
d. Alternative 3: Move present sorghum production areas and substitute sorghum and maize imports and 30% of the maize used in foodstuffs.

Production systems in acid soil regions

Figure 1 shows the main regions in tropical South America and their agroecological characteristics. Countries with potential area for the production of new sorghum varieties have 655 million hectares under Oxisols and Ultisols, of which only 16% can be used for sorghum production and correspond to the well-drained savannas with well-defined dry seasons (Table 7). Between 1978 and 1982, the CIAT Tropical Pastures Program carried out a characterization study of the main production systems existing in the well-drained savannas of Brazil, Colombia, and Venezuela (Vera and Seré, 1985). Forty-one farms were selected in these regions to be supervised during a two-year period. A multidisciplinary team characterized the cattle farms in terms of:

Natural resources: physiographic characteristics, soils and their uses, native pasture species;

Technological level: use of mineral salts, division of the herd by categories, weaning, etc.;

Production: birth rates and weight gains; and

Economics: flow of income and expenditures, profitability, etc.

Table 6. **Maize prices (US$/t)[a] to producers and foodstuff manufactures, and import prices, 1978-1980.**

Country	1978			1979			1980		
	Price to producer	Price to foodstuff manufacturer[b]	Import price[c]	Price to producer	Price to foodstuff manufacturer[b]	Import price[c]	Price to producer	Price to foodstuff manufacturer[b]	Import price[c]
Brazil	128	108	128	120	126	152	n.a.	209	106
Colombia	174	180	99	211	211	145	315	309	160
Venezuela	214	214	176	268	268	186	326	326	218

a. Exchange rate taken from IMF (International Monetary Fund), (1978, 1979, 1980).

b. Maize price in October, 1978, 1979, and 1980 taken from USDA (United States Department of Agriculture).

c. Prices taken from FAO (Food and Agriculture Organization of the United Nations), (1978, 1979, 1980).

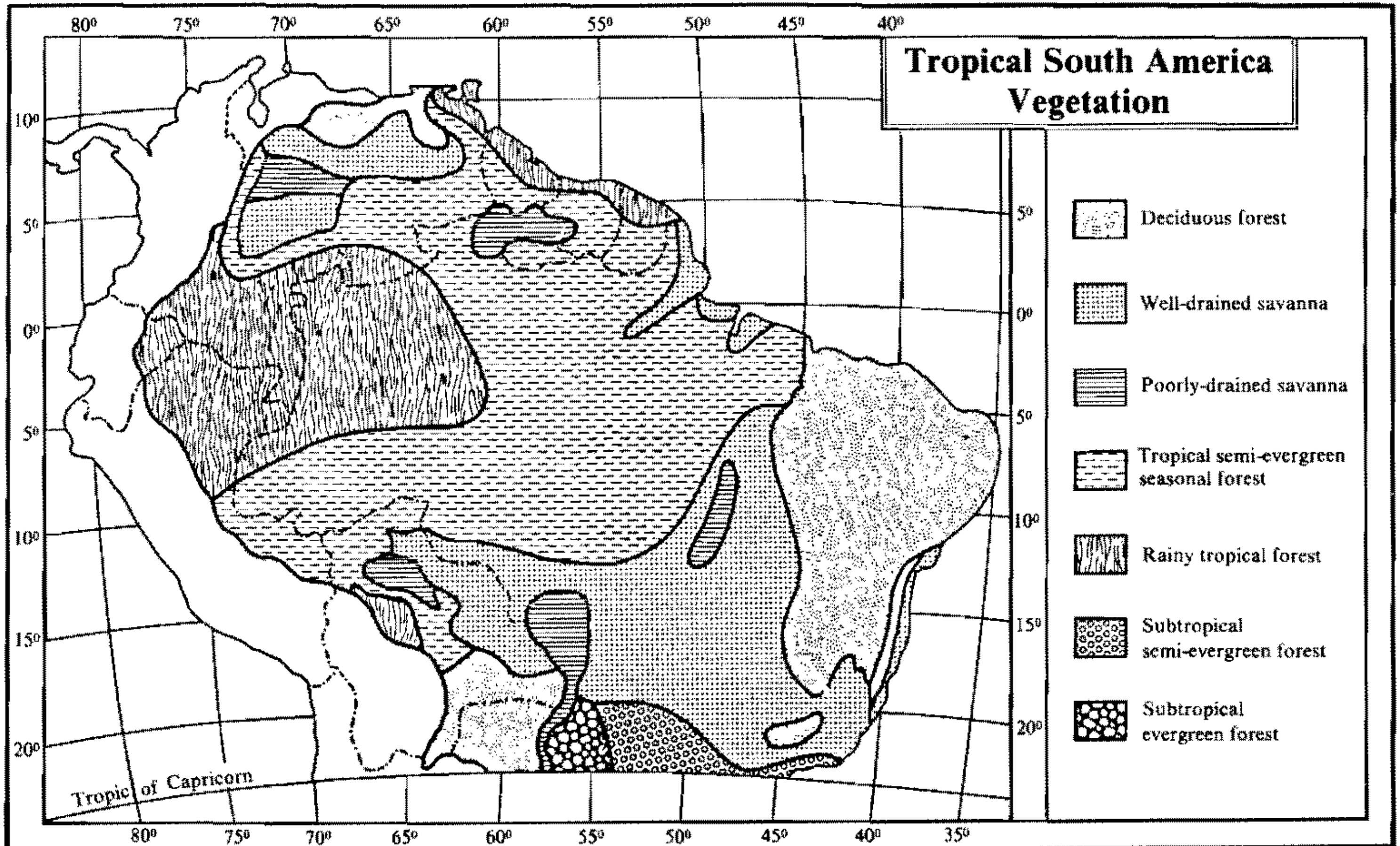


Figure 1. *Agroecologic classification for tropical South America. (Adapted from T. T. Cochrane et. al., 1985.)*

Table 7. **Agroecologic formations (million ha) in major countries of Latin America with acid soils.**

Country	Oxisols and Ultisols	Tropical forests	Other formations	Poorly-drained savannas	Well-drained savannas[a]
Brazil	502	328	84	10	80
Bolivia	23	19	1	3	0
Colombia	73	58	4	3	8
Venezuela	57	38	1	4	14
Total	655	443	90	20	102

a. Potential area for sorghum varieties adapted to acid soils.

SOURCE: CIAT (Centro Internacional de Agricultura Tropical) estimates based on Cochrane. FAO (Food and Agriculture Organization of the United Nations). FAO-UNESCO (United Nations Education, Science, and Culture Organization). 1975.

The regions studied had two well-defined rainy and dry seasons, but differed in their precipitation level and length of dry season. The Venezuelan savannas are drier (1000 mm/year) compared to the Brazilian (1800 mm/year) and Colombian (2000 mm/year) savannas. The dry season is shorter in Colombia and Venezuela (four months) than in the Brazilian Cerrado (five months) where, in addition, discontinued rainfall during the wet season (*veranicos*) require that material introduced be well adapted to these soil conditions in order to survive by extracting water from deeper levels.

The physiographic characteristics of the farms showed that the well-drained savannas make up most of the area, followed by the lowlands and gallery forests. Although the well-drained savanna ecosystem was very uniform, there were large variations in terms of soils from one country to the other and even within the same farm. Table 8 presents the main chemical characteristics of the soil (pH, P and K content, and aluminum saturation). Colombia has the most acid soils and the highest levels of aluminum saturation, requiring applications of at least 1.7 t/ha of lime to establish sorghum varieties adapted to acid soils. No serious soil constraint to the new varieties was found in Brazil; and overall, the low fertility level was more important than the degree of acidity or of aluminum saturation. Venezuela has aluminum saturation problems where production would be carried out permanently. The average fertility level is a little higher than that of Brazil and Colombia, but throughout the well-drained savanna ecosystem applications of nitrogen, phosphorus, and potassium are required for each harvest (Table 8).

Table 9 shows a comparison among the production systems of the different regions studied. In general, they are extensive systems with more than 1500 ha of total area located in frontier zones dedicated to animal breeding. The average herd size is 550 animals with 0.59 ha of planted grass available per animal and with beef production varying from 12 to 36 kg/yr and from 54 to 65 kg per AU per year. Native vegetation is the most important forage resource for animal feed but its importance varies between regions and with farm size. The rapid expansion of rice production in Brazil enhanced planting of grasses at a faster rate than herd growth.

The more commercial orientation of the Venezuelan (marketing milk) and Brazilian (marketing of weaned male calves) livestock is

Table 8. **Main soil characteristics of farms studied.**

Characteristic	Brazil			Colombia			Venezuela		
	Average	(1)[a]	(2)[b]	Average	(1)[a]	(2)[b]	Average	(1)[a]	(2)[b]
pH	5.43	5.84	4.99	4.50	4.70	4.30	4.90	5.35	4.82
P (ppm)	3.31	5.87	0.38	2.10	1.30	2.70	6.34	9.61	1.53
K (meq/100 g)	0.14	0.14	0.09	0.05	0.03	0.04		--	-
Aluminum saturation (%)	13.96	0.30	46.70	88.00	72.00	90.00	30.00	0.00	86.00

a. Farm with lowest degree of aluminum saturation.
b. Farm with highest degree of aluminum saturation.

Table 9. **Principal physical characteristics of production systems studied in three different regions.**

Characteristic	Brazil (1980)	Colombia (1978)	Venezuela (1980)
Number of farms	12	16	13
Distance to market[a] (km)	147	300	50
Average size of farm (ha)	2578	2901	1533
Labor (man-hours)	7.0	3.2	4.1
Size of herd (AU)	538	526	685
Proportion of cows (%)	40	41	39
Grass sown (ha)	774	181	195
Crops			
Sorghum			
Area (ha)	..	0	18[b]
Percent of farm size	—	—	2
Rice			
Area (ha)	126	0	—
Percent of farm size	5	—	—
Cattle production			
kg/ha/year	15	12	36
kg/AU/year	65	54	55
Crop production			
kg/ha harvested	2138	—	—

a. Distance from farm to closest population center with more than 200,000 inhabitants.
b. Stubbles of crops planted in 1979.
SOURCE: Vera and Seré, 1985.

associated with a more advanced infrastructure development that positively affects the adoption of new crop-integrated systems.

Colombian farms studied had no commercial plantings of any crop and pasture introduction was carried out without intercropping. During the year studied, the average Brazilian farm had 126 ha planted to rice, which represented 5% of the total farm area. In these farms, crops were used for pasture establishment and no farms grew crops in a permanent way in the same field for more than two years. During this same period, fertilizers were not subsidized in Venezuela and farmers quit planting sorghum which was the traditional crop in the area. During the initial year of the study there was an average of 18 ha of sorghum stuble.

The use of crops in a permanent way or for the introduction of pastures requires a substantial modification in the administration structure and considerably affects economic parameters particularly the flow of the farm's income and expenditures. This is evident in the difference between Brazilian parameters with abundant crops, and Colombian and Venezuelan parameters without crops (Table 10).

The relative importance within the country of the zone under study is determined by the availability of roads and the distance to the closest markets. Less than 1% of the total national population lives in the Colombian Llanos, while 18% live in the Brazilian Cerrados and Venezuelan Llanos. The availability of fertile land in other regions of the country determines to a great extent the efforts to develop this region; the mentioned policy is clear in Venezuela and Brazil and very limited in Colombia.

Table 10. **Principal economic characteristics (US$/ha) of the systems studied.**

Characteristic	Brazil	Colombia	Venezuela
Investment			
Total	391.00	72.00	602.00
Equipment	24.00	3.00	66.00
Gross income			
Cattle	20.00	7.00	40.00
Crops	45.00	—	—
Inputs			
Salts and animal health drugs	0.97	0.87	1.18
Fertilizers	8.58	0.02	1.02
Fuel	3.38	0.00	0.00
Other	9.32	0.11	0.75
Total	22.25	1.00	2.95
Labor	6.95	1.25	9.65
Depreciation	5.56	0.97	14.21
Total costs	34.76	3.22	26.81

SOURCE: Vera and Seré, 1985.

Sorghum potencial under these production systems

To determine sorghum potential, commercial production is estimated at 2 t/ha which is the productivity normally achieved with the new varieties in field performance trials. Economic efficiency is determined based on 1984 prices of inputs and existing products in the Eastern Plains of Colombia, assuming that if this alternative is attractive in Colombia it will be more advantageous in Brazil and Venezuela, which have a comparative advantage for sorghum production in acid soils. This comparative advantage is due to the greater infrastructure development in acid soil regions, lower precipitation levels, little availability of fertile zones, and a great demand for grain to supply an expanding poultry industry.

Peanuts, cassava, and rice are well-adapted crops to acid soil conditions, but the first two are less commercial in frontier areas and rice adapts better to zones dominated by "favored upland" where rainfall surpasses 2000 mm/yr. Productivity obtained with rice would allow this crop to compete with sorghum in well-drained savanna ecosystems, but the presence of diseases attacking leaves during the vegetative period restricts these possibilities.

The economic feasibility of sorghum production will be analyzed under two conditions: as a semestral crop; and as a complement for the introduction of pastures and for cattle feed as a stubble crop during critical periods.

Given the availability of lime in various regions, it seems pertinent to consider the economic feasibility of using better-adapted but lower-yielding germplasm when reasonable productivity can be achieved by applying higher levels of lime to already existing varieties normally used in fertile lands. Trials carried out (Salinas, 1975) at the Centro de Investigaciones de Maiz y Sorgo at Sete Lagoas (Brazil) demonstrated that adapted germplasm yielded the same with lime applications of more than 4 t/ha, and that its root system reached only 40 cm/100 cm^3 of soil. As the level of applied lime decreased and was incorporated more superficially, the varieties adapted were capable of developing a root system up to 2 meters deep, making the extraction of water and nutrients more efficient in a larger subsoil profile.

The main characteristic of the germplasm adapted is its efficiency to extract water from subsoil during periods of *veranicos* and not so much its tolerance to saturation during a uniform rainy period. This characteristic is very important since:

It allows the use of lower lime levels.

It allows planting with simple soil preparation, incorporating lime to a depth of 15 cm. This land preparation is sufficient for pasture establishment in savannas.

Lower harvest yields are obtained, but at a lesser risk.

It could be more efficient in extracting nutrients such as P, K, and Mg which are important in production and are more expensive.

In regions such as the Eastern Plains lime is expensive.

Sorghum as a semestral crop

In order to evaluate sorghum competitiveness as a biannual crop in the llanos, comparative budgets for the production of sorghum in fertile versus acid lands were prepared (Table 11). The budget for fertile lands was based on prices and inputs used in the Cauca Valley and that for acid lands was based on input requirements and prices of a farm located 40 km east of Puerto López in the Eastern Plains of Colombia.

The main differences between the budgets are:

Fertilizers

Sorghum varieties adapted to acid soils perform well up to 60% aluminum saturation. Farms in the Eastern Plains of Colombia had average saturations of 88%, making it necessary to apply 1740 kg lime/ha to reduce aluminum saturation to the percentage required. The following formula was used to determine the amount of lime:

$$RL = 1.8\,[Al - RAS\,(Al + Ca + Mg)/100]$$

where: RL = required lime (t/ha)

RAS = required aluminum saturation (%)

Al, Ca, Mg = milliequivalent (meq) of each element per 100 g soil

This formula was used by Cochrane (1980) for the Colombian Llanos. It was assumed that with one application, three continuous sorghum harvests could be obtained without further amendments.

The level of nitrogen applied in the Cauca Valley was

Table 11. **Comparative budget (US$/ha) for sorghum production in fertile lands and in acid soils.**

Expense	Soil: Fertile yield[a] (3 t)	Soil: Acid yield (2 t)
Labor		
Equipment (8.5 h x US$10/hour)	85.0	—
(8.5 h x US$11/hour)	—	93.5
Manual labor (20 day wages x US$5/wage)	100.0	100.0
Inputs:		
Seeds (16 kg x US$0.40/kg)	6.4	—
(8 kg x US$0.80/kg)	—	6.4
Fertilizers		
Lime (580 kg x US$0.03/kg)	-	17.4
N (46 kg x US$0.65/kg)	29.9	29.9
P_2O_5 (13 kg x US$0.38/kg)	—	4.9
K_2O (40 kg x US$0.40/kg)	—	16.0
Weed control (3.5 l.t. x US$3.50/l.t.)	12.2	12.2
Insect control (1.0 l.t. x US$4.71/l.t.)	4.7	4.7
Harvest (1 hour x US$40/hour)	40.0	40.0
Services (administration and technical assistance)	23.0	23.0
Rental	120.0	12.0
Packing (US$0.50/unit of 60 kg)	25.0	17.0
Transportation (US$5/t/100 km)[b]	15.0	30.0
Interest (3 months on total expenditure)	27.7	24.4
Total (US$/ha)	488.9	431.4

a. Information from CVC (Corporación Autónoma Regional del Valle del Cauca), 1982, and author's estimates.

b. Acid soil area is 300 km from market.

considered adequate for the llanos, whose natural fertility was made similar to that of the Cauca Valley by applying 13 kg/ha of phosphorus and 40 kg/ha of potassium in addition to the nitrogen.

Rental

Rental cost is an estimate of the availability of good land; the initial budget considered US$120/semester as the rental for fertile lands and US$12/semester for acid lands. The first price is the normal rate charged in the Cauca Valley and the second corresponds to the opportunity cost of land exploited in an extensive way in the Colombian Llanos, with a stocking rate of 0.2 AU/ha. In spite of the large difference existing between the two prices, this difference would be reduced to less than 50% if cost of amendments and of transportation of products to the centers of consumption located in fertile lands were considered. The proximity to consumption centers in Venezuela and Brazil as well as the lack of underutilized fertile lands make sorghum production in acid soils more attractive in these two countries.

Transportation costs

In fertile lands, the centers of consumption are, on average, 100 km from production areas; this distance reaches 300 km in the case of the Colombian Llanos and represents an additional US$10.00/t which, together with the cost of transportation of fuel and inputs, increases production costs in frontier areas.

Mechanization, hand labor, seed, weed and insect control costs, as well as harvests, do not vary substantially from one region to another because we consider them to be values which depend more on the land (type of soil, weed population, etc.) after various production cycles and not on the area in general nor on the adoption of a determined variety.

Based on comparative budgets, the "equivalent yield" was estimated and defined as the yield of sorghum per hectare of acid soil requiring the same cost per ton produced in fertile land.

Figure 2 presents results obtained when carrying out a sensibility analysis on the availability of fertile land (cost of rental) and on its productivity.

If yields of only 2 t/ha can be obtained in acid soils, this activity would only be competitive if the availability of fertile land is low (more than US$100/semester), and its productivity very poor (less than 2.5 t/ha). With the rental costs normally charged in the Cauca Valley (US$120/semester) and with the 3 t/ha production normally obtained, it would be impossible to compete unless 3000 kg were produced in acid frontier lands. This yield would cover costs of transportation and fertilizers and cancel land rental cost in acid soil areas. Under these conditions the Eastern Plains would compete only for a few years after plowing the savanna, while the costs of land preparation and weed and insect control remain low.

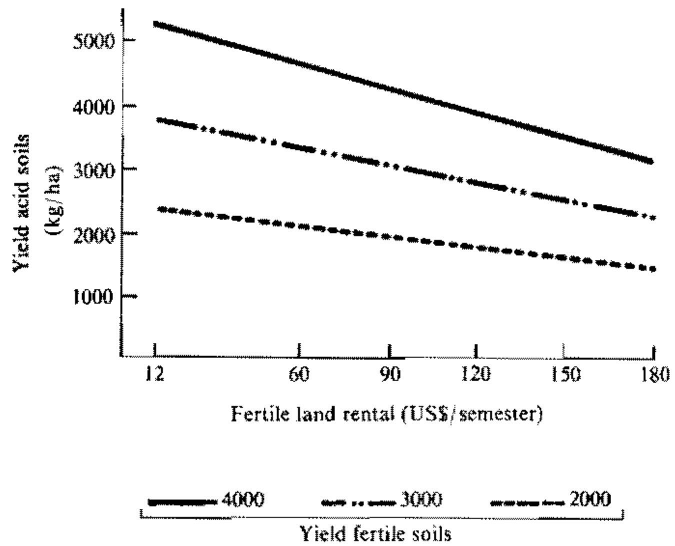


Figure 2. *Equivalent sorghum yields on fertile and acid soils. Yields required to make sorghum production competitive in acid soils according to opportunity cost of land presently cultivated and yields obtained. Opportunity cost of acid land: US$12/semester.*

Observing the comparative budgets, we can see that in the fertile land more than 85% of the total costs (land preparation, manual labor, seed, fertilizers, weed and insect control, services, and rental) are independent from the yield level, stimulating producers to increase yields as the only mechanism to reduce costs per ton (Figure 3), thus increasing demand due to scarcity of fertile land and the availability of high-yielding varieties.

At the international level, prices for grains have decreased in real terms from US$240 in 1950 to US$126 in 1980 (IBRD, 1982) and the Latin American countries which have been able to compete are those which have increased their yields over the 3-ton national average. The increase in real prices for fuel reduces the incentive to produce in frontier areas and to intensify already utilized fertile lands close to market places. The new technology could be applied in acid lands near inhabited centers, as is the case with Venezuela and Brazil, and with some small areas in Colombia.

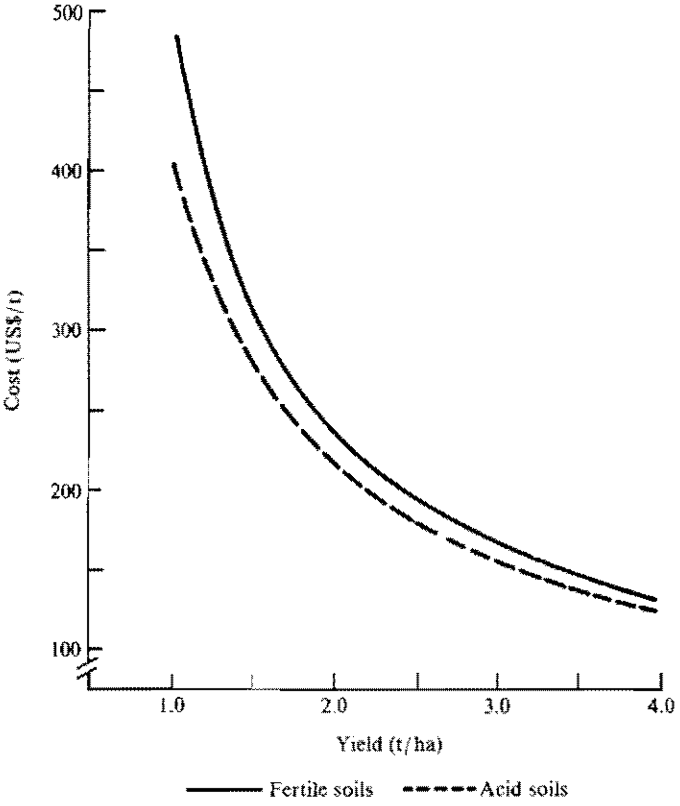


Figure 3. *Production costs depending on yield levels obtained in both acid and fertile soils.*

Sorghum production as a complement to pasture establishment

With current yields (2 t/ha), it does not seem feasible to introduce large-scale sorghum production to the well-drained Colombian savannas unless it complements or utilizes existing inputs in the present production systems, increasing the system's overall profitability. This section will discuss the economic feasibility of introducing sorghum by using fertilizers applied to pastures without weed control, and complementing forage production in the farm with sorghum stubble in a strategic use of this forage. To this end, the study uses results of experiments obtained in follow-up activities during six years on a farm in the Eastern Plains, where improved pastures were introduced in 5% of the area to be used strategically by the breeding herd. Through the supplementation of the herd during the critical period after conception, breeding cows were expected to advance their reconception phase. Afterwards the herd was fed on savanna. Thus, with only 5% of the area in improved pastures, in a 4-year period, the birth rate went from 50% to 57%, the weight of weaned calves increased from 109 to 162 kg, and the total stocking rate of the farm increased from 0.13 AU/ha to 0.24 AU/ha. In economic terms, the investment in pastures and additional cattle generated an annual return of 35%, assuming 12 years of pasture persistence with refertilizations every 3 years.

To evaluate the possible contribution of intercropping with sorghum, the additional cost per hectare applied to produce sorghum was budgeted (Table 12) and included in the cash flow of the investment, assuming a 2 t/ha sorghum yield and a price of US$160 per ton at the farm. The impact of this, in terms of cash flow, is presented in Figure 4.

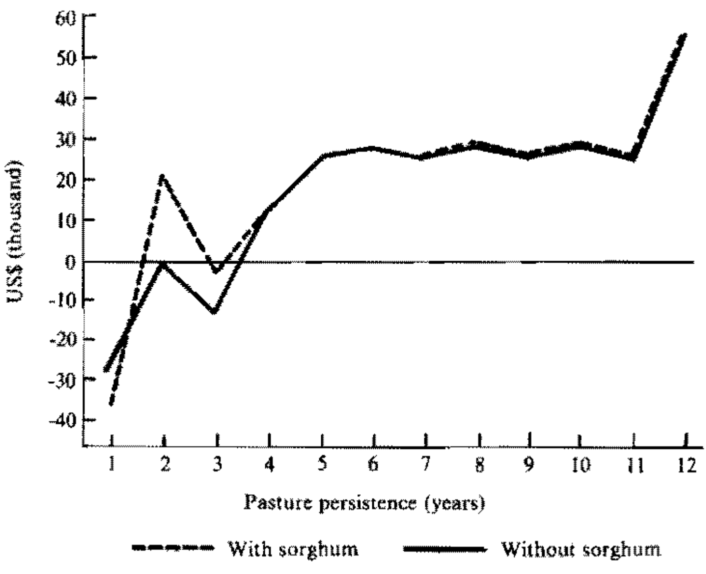


Figure 4. *Marginal cash flow in the establishment of improved pastures. Case study farm with 154 hectares of sown grass; 144 hectares were planted during the first year and 40 hectares during the second year.*

Table 12. **Comparative budget (US$/ha) for planting grass, and sorghum and grass.**

Expense	Grass	Sorghum and grass	Additional investment
Labor			
Equipment (8.5 hr x US$11/hr)	93.5	93.5	0.0
Manual labor (10 day wages x US$5/day)	50.0	50.0	0.0
Inputs			
Seed			
Sorghum (8 kg x US$0.80/kg)	—	6.4	6.4
Andropogon gayanus (5 kg x US$6.00/kg)	30.0	30.0	0.0
Stylosanthes capitata (2 kg x US$7.00/kg)	14.0	14.0	0.0
Fertilizers			
Lime (1400 kg x US$0.03/kg)	—	42.0	42.0
N (46 kg x US$0.65/kg)	—	29.9	29.9
P_2O_5 (50 kg x US$0.38/kg)	19.0	19.0	0.0
K_2O (22 kg x US$0.40/kg)	8.8	8.8	0.0
Pest and disease control (1.0 l.t. x US$4.7/l.t.)	—	4.7	4.7
Harvest (1 hr of equipment x US$40/hr)	—	40.0	40.0
Services (administration and technical assistance)	—	23.0	23.0
Packaging (US$0.5/60 kg units)	—	17.0	17.0
Transportation (US$5.0/t x 100 km)	—	30.0	30.0
Interest (% over average capital)	13.0	25.0	12.0
Total	228.3	433.3	205.0

The main advantages of using sorghum as a pioneer crop are:

1. Sorghum production uses 90% of the inputs used in pasture production; additional costs (US$205/ha) correspond to lime, fertilization, harvest costs, packaging, transportation, and administration (Table 12). These costs are recovered to a great extent when yields are good. There is low risk in the operation since the main costs come during harvest. If the yield is very low, these costs are avoided by grazing sorghum instead of harvesting it.

2. During the first years, sorghum production substantially improves the cash flow of the investment in pastures.

3. Marginal profitability of the pastures grown in association with sorghum increases from 34% to 52% per year, for yields ranging from 1.3 to 2.5 t of grain/ha (Figure 5).

4. During initial soil preparation, mineralization of nutrients takes place, providing nitrogen and potassium. If this contribution is sufficient for sorghum production, profitability would increase from 34% to 60%, with 1.0 and 2.5 t/ha yields (Figure 5).

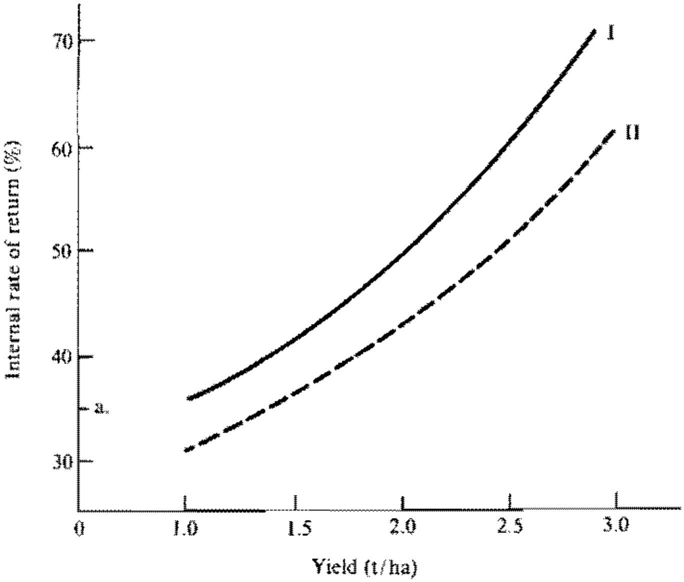
5. Depending on the variety planted, sorghum stubble can provide approximately 5 t DM/ha with an energy content superior to that of native savanna. Farm cows with initial low weight can graze on stubble as an energy bank for the savanna and achieve weight gains of more than 250 g/day, reducing the time required to reach adequate weights and allowing a strategic rather than a continuous use of the pasture.

6. Pasture establishment is financed by short-term loans, the same as are made for commercial crops with a growth cycle of less than one year. This possibility would enhance the establishment of improved pastures, not only because of the availability of more agile financial resources, but also because of the substantial improvement in the cash flow generated by sorghum production.

7. Simulations indicated that with grass and legume pastures with persistence of less than six years it was not feasible to obtain adequate profitability, especially because of the negative flow during the first years. The introduction of pasture/crop associations would result in a profitable return if improved pastures persisted during at least four years and sorghum yields reached 2 t/ha. This alternative would broaden the possibilities of introducing more productive though less persistent grass/legume mixtures or of substituting pastures as soon as their potential decreases when the legume disappears.

Once sorghum materials adapted to acid soils have been obtained, the main constraints for establishment of this association would be:

Regional infrastructure for sorghum planting (harvesters, transportation, and warehousing);



I. Profitability of sown pastures and sorghum considering that mineralization provides all N + K required.
II. Profitability of sown pastures and sorghum without considering mineralization.
a. Project profitability without planting sorghum.

Figure 5. *Marginal profitability of sown pastures, excluding sorghum as a pioneer crop.*

problems of damage caused by birds due to limited area of these plots in relation to the region; and

lack of agronomic research data in relation to planting densities and dates and levels of fertilization to efficiently manage the competition between sorghum, grasses, and forage legumes.

Conclusions

The following conclusions can be derived from the discussed material:

1. With yields of 2 t/ha, it does not seem feasible to plant sorghum as a permanent crop in acid soils of the well-drained savanna areas of the Eastern Plains of Colombia.

2. The use of sorghum as a pioneer complementary crop in

the establishment of improved pastures is very attractive. It solves biological problems and reduces economic disadvantages (negative cash flow during various years and medium profitability) of the pasture introduction system used until now.

3. In this combined agropastoral system, sorghum yields above 1.5 t/ha make the investment in improved pastures attractive and enables the use of germplasm less adapted to acid soils.

4. The economic feasibility of planting sorghum every four years enables the use of less persistent but more productive legume associations.

5. Brazil and Venezuela have a comparative advantage over Colombia in production of sorghum in acid soils. This advantage is determined by: the location of the acid-soil region in relation to population centers, lower degree of aluminum saturation, less availability of fertile land, and higher internal prices.

6. These results are consistent with the process of pasture introduction observed in tropical as well as in temperate countries. Massive planting of pastures is always associated with the existence of a profitable crop, e.g., rice in the Brazilian Cerrados, wheat in the Argentinean Pampa.

7. This *ex ante* analysis indicates a considerable potential for sorghum adapted to acid soils to make more dynamic the extensive systems currently predominant. To make this potential become effective, basic and applied research efforts are needed.

8. Given the relation of prices between the fixed costs per hectare in sorghum production for land preparation, planting, and particularly for harvesting, and the price of lime as well as the price of sorghum in the region, it seems more important to increase yields than to achieve adaptation at higher levels of aluminum saturation. Preliminary evidence seems to indicate that it is convenient to focus research on increasing yields at levels of 50% aluminum saturation. Brazil and Venezuela have large areas with these characteristics for potential sorghum production. Due to the low buffering power of Oxisols predominating in the Eastern Plains of Colombia, limited amounts of

applied lime are required to reduce aluminum saturation to this level. Given the extension of available land in relation to the amount of area planted to sorghum required to supply the internal market, it seems logical to wait until lands with lower aluminum saturation levels are destined to this crop.

9. Varieties highly tolerant to aluminum toxicity can play an important role in pasture establishment in association with sorghum. In the case of pastures adapted to high aluminum saturation levels, it is more important to reduce initial investment in liming. Applied agronomic research is necessary to evaluate at the field level the viability of this promising strategy.

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BREEDING AND SCREENING

Effective Screening Techniques for Tolerance to Aluminum Toxicity

*R. H. Howeler**

Introduction

It has been estimated (Sánchez, 1981) that in the tropics there are 2050 million hectares, or 42% of the land area, occupied by Oxisols, Ultisols, or Inceptisols. In tropical America these soil orders occupy 1019 million hectares or 72.6% of the land area. These soils are generally characterized by extreme acidity and low levels of available nutrients. For that reason they are subutilized and form one of the last land resources into which agricultural production could expand.

However, most crop species are susceptible to high concentrations of aluminum (Al), which is one of the major limiting factors of these soils. This can be overcome either by liming the soils to neutralize the exchangeable Al, or by selection of species and varieties tolerant to high levels of Al. The second alternative is more practical, since application of large amounts of lime is very expensive and can alter only the Al content of the topsoil, resulting in shallow root systems of Al-sensitive crops. By selection of Al-tolerant crops and varieties it is often possible to obtain good yields with a minimum input of lime, the latter serving mainly as a source of calcium (Ca) and magnesium (Mg).

Figure 1 shows the response of various crops to lime application in Carimagua, Colombia. While cowpea and cassava were both very tolerant to soil acidity, producing 40% of maximum yield without lime application, cowpea produced near-maximum yield at 0.5 t lime/ha, while cassava required 2 t/ha. Sorghum and rice (dwarf varieties) were both highly susceptible to soil acidity, while beans and corn were intermediately susceptible.

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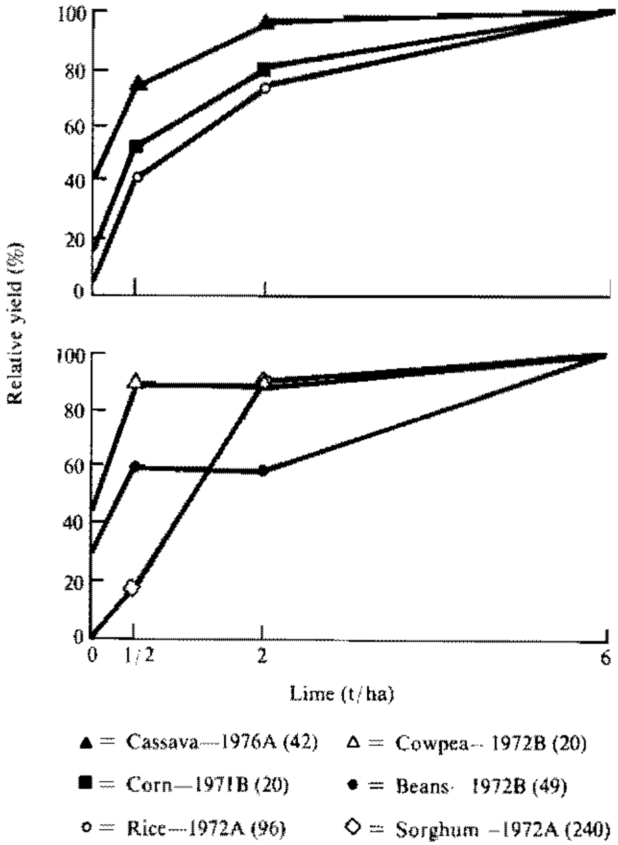

Figure 1. *Response of six crops to lime application in Carimagua. Numbers in parentheses indicate the number of varieties or breeding lines tested.*

With expansion during the past decade of the international agricultural research centers, each with large germplasm collections, interest in evaluating this germplasm for Al tolerance has markedly increased, especially in Latin America with its large percentage of acid soils. In addition, in North America, several breeders of temperate-climate crops have started to incorporate Al tolerance into high-yielding varieties for acid-soil areas. Thus, both in the tropics and in temperate climates, several screening techniques have been developed for evaluating the Al tolerance of large numbers of varieties or breeding lines. Some of the more effective techniques will be described in this paper with some indication of their advantages and disadvantages.

Nutrient solution techniques

For plant breeders, who have to evaluate large numbers of materials, often with very limited amount of available seed, the nutrient solution technique has many advantages. It is rapid, requires little seed, and often is nondestructive. The best materials can later be transplanted to the field to test for disease and insect tolerance as well as for yield potential. The main drawback is that nutrient solutions are time consuming and difficult to manage, since the toxic effect of Al is greatly influenced by temperature, pH, and the concentration of Al, phosphorus (P), Ca, Mg, and potassium (K). As plants absorb nutrients from the solution, the concentration of these nutrients as well as the pH of the solution change. Thus, a careful control of all factors is essential to obtain reproducible results. The technique is most suitable for species grown from sexual seed with small nutrient reserves and rapid initial growth. It is not well suited for species such as cassava, which are vegetatively reproduced and grown from stakes or rooted tip-cuttings with large plant-to-plant variability.

Among the nutrient solution techniques there are essentially two approaches, each with variations. The first approach is to subject uniformly-selected seeds to a range of Al concentrations during a relatively short period (20-48 hours). This Al "pulse" is then followed by either a recovery period in normal nutrient solution or by a staining procedure with hematoxylin, in order to determine at which Al concentration there is irreversible and permanent damage of the root meristem inhibiting further growth. The second approach is to grow young plants at a high and low Al concentration of the solution for several weeks and determine the relative root or shoot growth as a measure of Al tolerance.

Aluminum-pulse technique

The Al-pulse technique has been employed by Moore et al. (1976) for screening wheat varieties. They subjected each variety to several Al concentrations during 48 hours, followed by a recovery period of 72 hours in non-Al toxic nutrient solution. After this period, roots were observed to determine the lowest Al concentration which caused irreversible inhibition of cell division and thus regrowth of the root tip during the recovery period. In this case, the root tip is misshapen, often swollen, and discolored. During

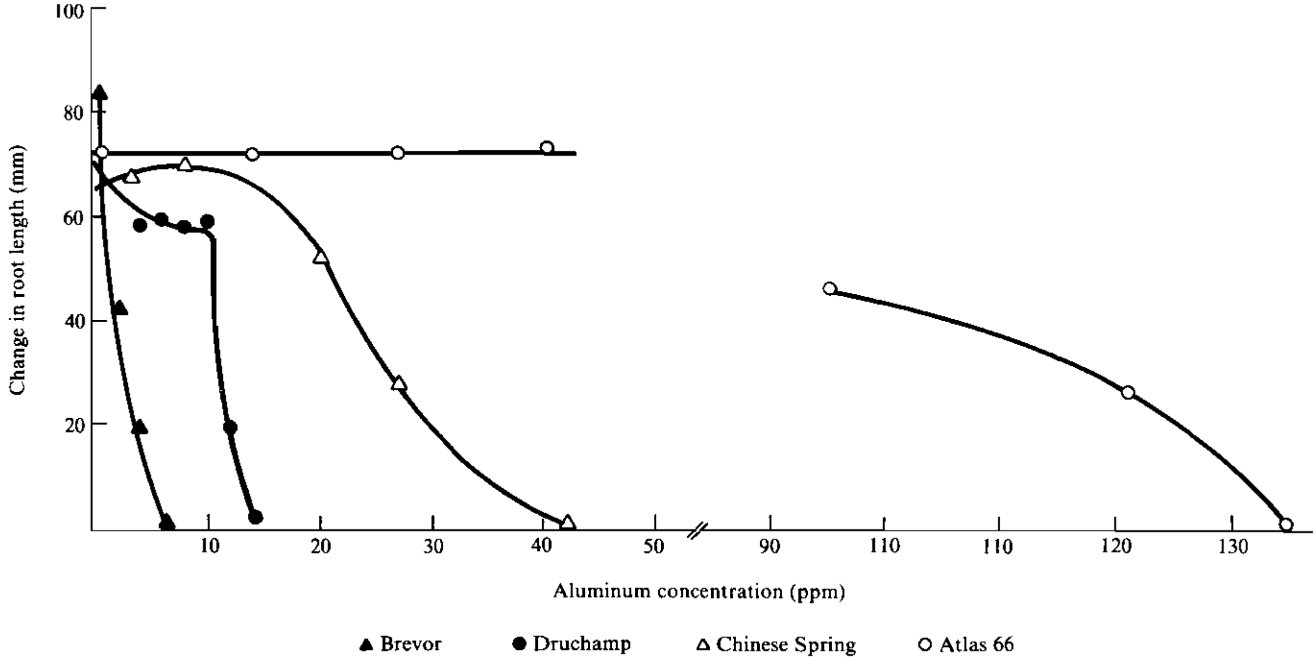

Figure 2. *Change in primary root length in the 72-hour recovery period following a 48-hour pulse treatment of Al for four reference wheat cultivars. (Adapted from D. P. Moore et al., 1976.)*

the recovery period, the root tip does not reinitiate growth, but instead, lateral roots develop at some distance from the root tip. Figure 2 shows that very Al-susceptible wheat varieties have irreversibly damaged root tips at low Al concentrations of 6-10 ppm; for moderately sensitive varieties this occurs at about 14 ppm, for moderately tolerant varieties at 40 ppm, and for very tolerant varieties at 130 ppm. Thus, wheat varieties are separated into four, clearly distinct categories of Al sensitivity, each represented by a standard variety, which is included in each test.

A variation of the Al-pulse technique was developed by Polle, Konsak, and Kittrick (1978a and 1978b) using a hematoxylin staining technique to determine visually the damage to root tips caused by a 20-hour pulse of various Al concentrations in solution. For screening of wheat varieties, they used nutrient solutions of 5, 10, and 20 ppm Al; while for corn they recommended solutions of 4.0, 6.7, 9.5, 12.1, 14.8, and 17.5 ppm. After germination, seeds of each variety are selected for uniformity and three seeds are placed in holes in each of six styrofoam strips. After 24 hours in normal nutrient solution, the strips are transferred to solutions of different Al concentrations for 20 hours, followed by washing in distilled water and staining for 15 minutes in 0.2% hematoxylin. After washing off the excess hematoxylin, root tips are separated from the plant and placed on filter paper in order of increasing Al-concentration. The degree of Al tolerance is determined by observing at which Al concentration the area behind the root tip becomes stained by the hematoxylin. With Al sensitive Brevor wheat this occurred at 5.4 ppm Al, while with the tolerant Atlas variety this occurred at 32.4 ppm. By including 3-4 standard varieties in each test the breeding lines can be accurately scored for Al tolerance.

Relative growth at two aluminum concentrations

Aluminum tolerance can also be evaluated by growing each variety at two Al concentrations, one low or zero concentration at which plant growth is optimal, and one high concentration at which growth, especially of roots, is affected by Al toxicity. After several weeks of growth in these two nutrient solutions, Al tolerance of each variety is then determined from the relative root weight or length at high and low Al in solution. While most species show optimal growth without Al in the nutrient solution, some species actually grow better at low Al concentrations in solution. For rice and cassava, Howeler and Cadavid (1976) and the Centro Internacional de Agricultura Tropical (CIAT) (1978) recommended a concentration of 3 ppm Al for optimum growth. The high concentration should be selected so the Al-tolerant varieties are little affected while the Al susceptible varieties show a markedly reduced root growth. The selection of this high Al concentration depends on the general Al tolerance of the plant species to be screened as well as on the concentration of P, Ca, Mg, K, and the pH and temperature of the nutrient solution. Rhue and Grogan (1976) recommended for corn a pH of 4.6 and a freshly prepared nutrient solution since a higher pH or aging of the solution decreased the toxic effect of the Al. At pH above 4.5, especially with high concentrations of Al, P, and Ca, the Al precipitates in the nutrient solution and its toxic effect decreases. Since the pH of the nutrient solution either increases or decreases, due to differential absorption of NO_3 or NH_4 from the solution, it is very important to adjust the solution pH daily to its original level using dilute solutions of HCl and NaOH. The P and Ca concentration of the solution should be low enough to prevent the precipitation of Al, but high enough to supply adequate amounts of these nutrients to the plants. To prevent the complete exhaustion of these nutrients, the solutions should be completely replaced at frequent intervals, depending on the rate of plant growth and nutrient extraction from the solution.

After 2-3 weeks of continuous growth in these two Al-nutrient solutions, plants of each variety are harvested, and their Al tolerance evaluated either by determination of total plant or root weight, or by measuring maximum root length at each concentration. An Al-tolerance index is calculated from the relative root length (or weight) at high and low Al. Standard varieties are included in each test to adjust for slight changes in the experimental conditions between tests. Typical values of relative root length, using 43 ppm Al as the high-Al concentration, were 0.14 for Brevor, 0.38 for Druchamp, 0.54 for Chinese Spring, and 0.83 for the Al-tolerant Atlas wheat varieties (Polle et al., 1978a). If large numbers of breeding lines have to be evaluated and their root length (or weight) is nearly the same without Al stress it is often convenient to screen at only the high level of Al thus doubling the number of lines that can be screened at one time. In this case, root growth of each line is compared with those of a number of standard varieties, from which an Al-tolerance index is calculated.

Both the experimental conditions and the method of calculation of the tolerance index varies among researchers and crops. Some workers (Howeler and Cadavid, 1976) used germinated seed suspended over a nutrient solution so that the roots grew directly in the aerated solution; others (Polle et al., 1978a; 1978b) had the root system growing between a lucite plate and filter paper partially submerged in the nutrient solution. With the latter system, aeration is not necessary. Hutton (1980) used a sand culture system, periodically flooded with nutrient solution of 5 ppm Al concentration, to screen *Leucaena* species and breeding lines for Al tolerance. This system obviates the need for aeration or for a special plant support system, but is fairly costly in terms of pumps and timers and requires a dependable source of energy, which is not always available in the tropics. The system of periodic misting of the roots with nutrient solution is not recommended unless a dependable energy source is available; one is likely to lose all plants when the power supply is interrupted even for short periods of time.

For calculation of the tolerance index, many workers use the relative root length or weight, i.e., root length at high Al over root length at low Al. Others use the relative total plant weight, or the length of the adventitious roots. Another variation is to grow each variety first about one week in normal nutrient solution, measure root length, then transfer to nutrient solution of high Al, and after another 1-2 weeks measure root length again. The root length increase in the Al solution divided by the original root length obtained without Al is another effective method for calculating an Al-tolerance index. The latter system is less time consuming and reduces the problem of plant-to-plant variability since measurements are made twice on the same plants.

Field-screening techniques

Field-screening techniques are similar to nutrient-screening techniques at two Al concentrations in that the same varieties or lines are grown at two or more Al levels in the field. Generally, an Al-tolerance index is calculated from the yield obtained under high and low Al stress. The different levels of Al stress are obtained by application of different amounts of lime, often applying no lime in the high-stress plot and enough lime to neutralize all exchangeable Al in the low-stress plot. The lime levels to be used have to be determined from preliminary trials in which lime response curves are determined for standard varieties having a large range in Al tolerance. Under the high-stress conditions, the susceptible varieties must be markedly affected by Al toxicity while the tolerant varieties are little affected; under the no-stress conditions, all varieties must grow well without Al stress and without the induction of nutrient deficiencies. Thus, care must be taken not to induce K, Mg, or minor element deficiencies by application of high levels of calcitic lime. Spain et al. (1975) reported a negative response to liming in many cassava varieties due to induction of zinc (Zn) deficiency, making the determination of Al-tolerance indices meaningless. Once enough Zn was applied in both high and low Al-stress plots varieties could be screened for Al tolerance.

The Al-tolerance index is often calculated by dividing the yield at high Al stress by that obtained at low stress. While this tends to separate out all varieties highly affected by Al toxicity, it also tends to include with the truly Al-tolerant germplasm those Al-susceptible varieties having a low yield potential without stress. Thus, those varieties selected as having the highest Al-tolerance index often have low yields under both high and low stress. CIAT (1978) has tried to correct this discrepancy by multiplying the relative yield at high and low Al by the relative yield at high Al, i.e., the yield of the particular variety at high Al divided by the highest yield obtained at high Al. This gives additional weight to the variety's performance under high Al stress (the real objective of the screening), while partially correcting for year-to-year or site-to-site variations in experimental conditions. Instead of the highest yield obtained at high Al stress, it would be better to use the average yield of a number of standard varieties at high Al. This gives a more consistent correction factor for variations in experimental conditions.

If the objective of the screening is mainly to select varieties that in a specific location produce well under both low and high Al stress, i.e., produce well under high stress, but even much better when enough lime is applied to eliminate the stress, then the third formula for an Al-adaptation index in Table 1 is more suitable. In this case, yields at high stress are multiplied by those obtained at low stress, and divided by the same product of the average yields of all varieties at low and high stress. Thus, varieties with an adaptation index above 1 had an above-average product of yields under low and high stress. When yields of each variety are plotted on a graph with yield at low Al on the Y axis and yield at high Al on

Table 1. **Three formulas used to calculate acidity tolerance indices of varieties or breeding lines of various crops.**

1) $\frac{\text{Yield without lime}}{\text{Yield with lime}}$

2) $\frac{\text{Yield without lime}}{\text{Yield with lime}} \times \frac{\text{Yield without lime}}{\text{Highest yield without lime}}$

3) $\frac{\text{Yield without lime x Yield with lime}}{\text{Average yield without lime x Average yield with lime}}$

the X axis, these varieties fall above the line $Y = \frac{C}{X}$ where C is the product of the average yields at high and low Al (Figure 3). Again, C is used as a correction factor to reduce the effect of year-to-year or site-to-site variability. The average yield of a set of standard varieties would be a better correction factor, since the average yield of the trial (C) is not only affected by the experimental conditions but also by the general Al tolerance and yield potential of the germplasm to be screened.

Another alternative is to plot the yields at high and low Al as in Figure 3, but divide the graph into various fields, using lines of average X and Y values to divide the graph into four fields, or the line of average and twice-average X and Y values to divide the graph into nine fields (Figure 4). Each field can be assigned a number or letter and varieties are grouped into four or nine categories. Each category can be interpreted as a certain combination of Al tolerance and lime responsiveness. Generally, varieties are selected that are highly Al tolerant but also lime responsive, i.e., they yield well at high and at low lime. These would be approximately the same varieties selected as highly adapted in Figure 3.

When varieties are screened for both Al and low P tolerance, space and work can be reduced by combining the low-stress plots for both factors. In this case one can use three plots: the no-stress plot with high lime and high P; the P-stress plot with high lime and low P; and the Al-stress plot with low lime and high P. Yields at both low lime and low P are compared with those of the no-stress plot to calculate Al and low P tolerance or adaptation indices, respectively. Since the yield in the no-stress plot is used to calculate both indices, the same variety is often found to be adapted to both low P and high Al. Because Al tolerance may have resulted from a better ability to absorb P, a high tolerance to both factors is also physiologically compatible.

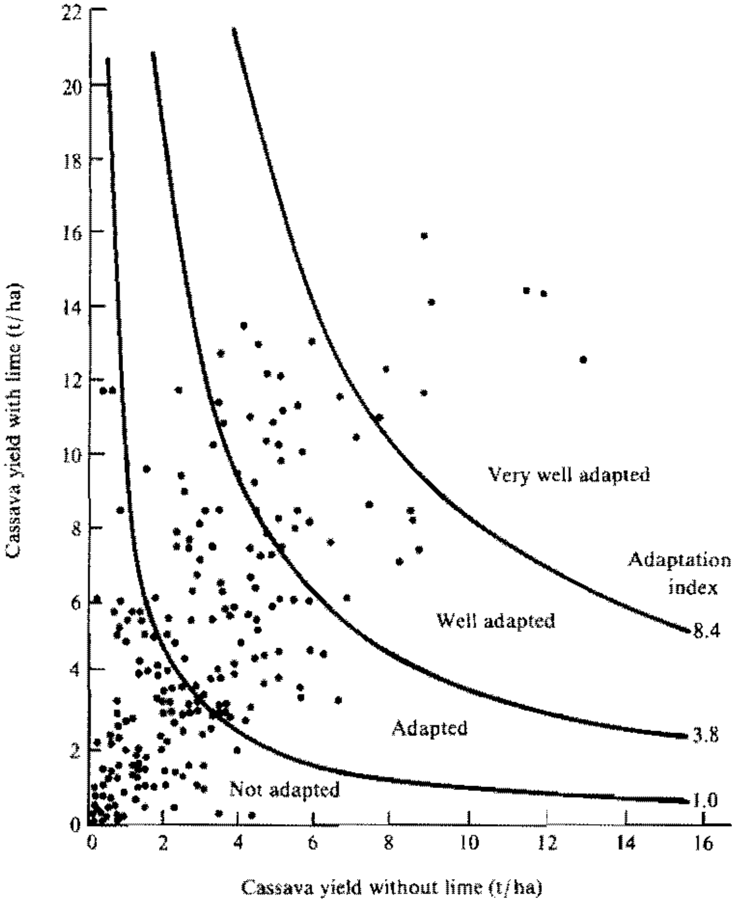

Figure 3. *Relation between cassava yields obtained with and without application of 4 t/ha of lime in a field-screening of 275 varieties and breeding lines in Carimagua. Lines dividing the four adaptation categories were calculated by:*

$$Y = \frac{1}{X}, \quad Y = \frac{C_1/C}{X} \quad \text{and} \quad Y = \frac{C_2/C}{X} \quad \text{where} \quad C = \overline{X}.\overline{Y}$$

$$C_1 = (\overline{X} + 1\ SD)\ (\overline{Y} + 1\ SD) \text{ and } C_2 = (\overline{X} + 2\ SD)(\overline{Y} + 2\ SD)$$

where $\overline{X}$ and $\overline{Y}$ are the average yields without lime, and SD is the standard deviation.

The ability of certain varieties to benefit from an effective association with VA-mycorrhizae will definitely affect their low P tolerance since it reduces their external P requirements (Howeler and Sieverding, 1982). Whether or not it affects their Al tolerance has yet to be determined. If it does, it would militate against the

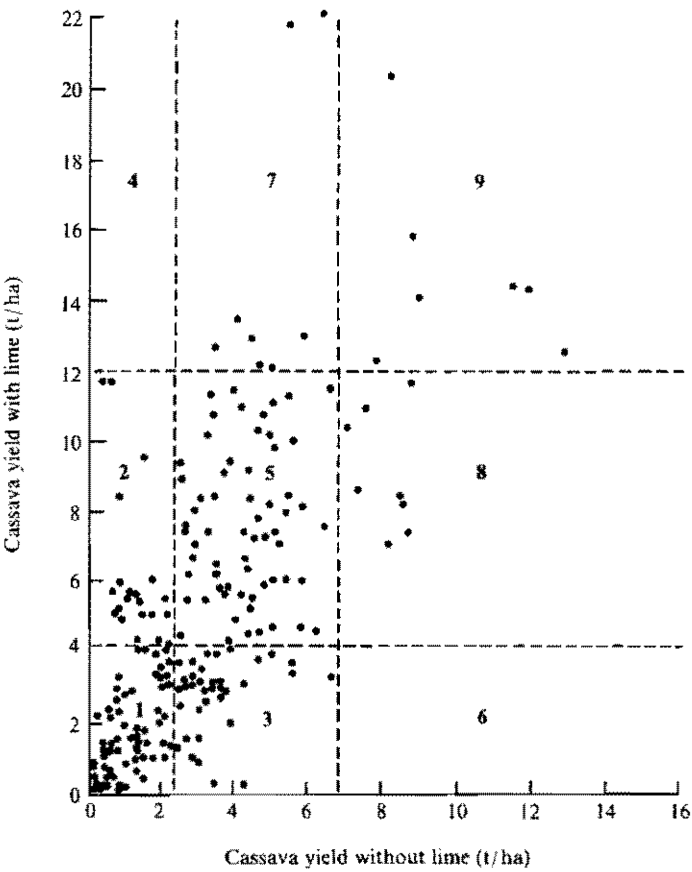

Figure 4. *Relation between cassava yields obtained with and without application of 4 t/ha of lime in a field-screening of 275 varieties and breeding lines in Carimagua. Vertical lines correspond with $\overline{X}$ and $\overline{X}$ + 2 SD and horizontal lines with $\overline{Y}$ and $\overline{Y}$ + 2 SD where $\overline{X}$ and $\overline{Y}$ are average yields without and with lime, and SD is the standard deviation.*

use of nutrient solutions to screen varieties for Al tolerance since the root systems in nutrient solutions are seldom infected with mycorrhizae while those in soils are. For highly mycorrhizae-dependent crops like cassava and *Stylosanthes* species the physiology of P (and possibly Al) absorption from nutrient solution is quite different from that in a mycorrhizae-infected soil. The fact that some of these highly mycorrhizae-dependent crops are also highly Al tolerant may suggest an interrelation between these characteristics. Moreover, highly mycorrhizae-dependent crops such as cassava tend to have a high P requirement in non-mycorrhizal nutrient solution (Howeler et al., 1982); thus in high

Al-nutrient solutions, which must have low P concentrations to prevent precipitation of Al-phosphate, these plants may suffer from P deficiency.

Comparison of techniques

Field-screening techniques have the advantage over nutrient solutions in that large numbers of lines can be screened at the same time, being subjected to the same climatic conditions, and often at a greatly reduced cost. Moreover, the Al-tolerance index is based on actual yields of harvestable products instead of on root length or weight, which are not necessarily well correlated with yield. The relative cost of each technique depends on the crop. Rice is easy to screen in nutrient solutions because it does not require aeration, grows in a minimum of space, and has enough of a range in Al tolerance that varieties can be easily and accurately screened in solution; in the field it requires a considerable amount of attention and the data may be affected by disease or pest attack as well as by bird damage (Howeler and Cadavid, 1976). Cassava, on the other hand, is difficult to screen in solution because of its vegetative propagation, high mycorrhizal dependence, aeration and large space requirement, and excessive plant-to-plant variability. This crop can be fairly easily screened in the field, because once planted, it requires little attention for about a year when the swollen roots are harvested. In the field, nearly 700 varieties could be screened in one year, and the same field could be reused for several years with a minimum amount of additional inputs.

However, the field-screening techniques have two major drawbacks. The soil has to be carefully selected to be uniformly high in Al, low in Ca and P, and without excess Mn. Also, in some soils high in organic matter (OM), the toxic effect of Al is partly neutralized by the formation of organic complexes with Al (Munévar and Wollum, 1983). Thus, in two soils of similar exchangeable Al content and Al saturation, cassava showed little response to liming in the high OM soil of Quilichao, but a marked response in the low-medium OM soil of Carimagua. For that reason, varieties could not be evaluated for Al tolerance in Quilichao. Thus, uniform and sufficiently high stress conditions are sometimes difficult to find for Al-tolerant crops. On the other hand, for Al-susceptible crops like beans and sorghum stress conditions may be too high for any variety to survive and in that case some lime has to be applied even in the high stress plot. To maintain the same levels of stress over several planting seasons is often impossible to achieve, and screening results of one season are not necessarily comparable with those of another season.

The second major drawback is that plants in the field are subjected to diseases and insect pests, which are often impossible to control entirely. Thus, varieties susceptible to the insect-disease complex in a certain location may show little Al tolerance in that location, but much better tolerance in locations where these insects and diseases do not occur. For example, due to the high disease and pest pressure in Carimagua, only a small percentage of the cassava, rice or bean germplasm can be screened for Al tolerance at that location; the other varieties are killed by diseases or insects, or their performance is seriously affected by these other stress factors.

Summary

Results obtained with nutrient solution techniques have to be well correlated with those of field screenings. So far, the nutrient solution screening methods developed by most researchers have not yet been correlated with field results. Campbell and Lafever (1976) found a high correlation between results of wheat screenings in nutrient solution and those in the field. The correlation was slightly better when relative root length (RRL) values were used as the tolerance index in solution instead of a tolerance index based on averages of standard varieties. Howeler and Cadavid (1976) found that grain yields of 240 rice cultivars at 0.5 t/ha lime level were well correlated ($r = 0.64$) with RRL values of the same varieties determined in nutrient solutions of 3 and 30 ppm Al. Thus, for rice and wheat, which both show a wide range of Al tolerance, nutrient solution techniques are fast and quite accurate for selection of highly Al-tolerant varieties. In species like cassava, with a high mycorrhizal dependency and a much smaller range of Al tolerance, field screenings based on actual yield seem more reliable and in many cases more efficient in selecting high-yielding germplasm with good tolerance to extreme soil acidity.

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Tolerance to Aluminum Toxicity in Upland Rice for Acid Soils

*César P. Martínez and Surapong Sarkarung**

Introduction

In Latin America, approximately 8.2 million hectares of land are planted to rice, of which 74% is upland rice. Total production is estimated to be 16.3 million tons with 47% being contributed by the upland rice sector.

It is not true that upland rice culture in Latin America represents a uniform system where agronomic practices, climatic conditions, and production constraints are similar. On the contrary, it is characterized by continuous changes in ecosystems with productivity levels that range from the lowest to the highest. Cultivated soils, rainfall, and rainfall distribution vary considerably.

The savannas of Colombia, Venezuela, and Guyana; the Amazon region; the Brazilian Cerrado; the Bolivian savanna; and other minor areas constitute one of the largest unexploited land areas of the world and represent an important resource for the production of crops such as rice. A large proportion of this area combines abundant and well-distributed rainfall with acid, low fertility soils, but with good physical properties. Other climatic factors such as temperature, relative humidity, and sunlight are favorable for rice production (CIAT, 1983; Sánchez and Salinas, 1981).

The objective of this paper is to discuss some of the effects produced by aluminum (Al) on the rice plant and to point out methods used by the CIAT Rice Program in developing varieties tolerant to Al toxicity and low fertility for savanna soils of Latin America.

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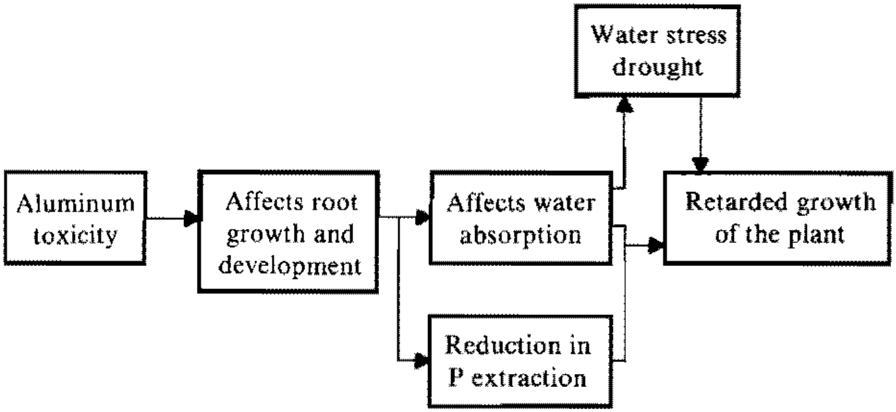
Aluminum tolerance research with rice

Varietal differences

Toxicity produced by aluminum represents an important constraint for rice production in acid soils. Aluminum levels of 2-3 meq/100 g of soil are frequent in the savannas of Colombia, Venezuela, Guyana, and in the Brazilian Cerrado. Soils with aluminum saturation higher than 60% have aluminum toxicity problems (Cochrane and Sánchez, 1982; Sánchez and Salinas, 1981; Camargo, 1982; Howeler and Cadavid, 1976; IRRI, 1978; IRRI, 1980; Martínez, 1976; Sarkarung, 1984).

Studies carried out under field conditions or using nutrient solutions in the greenhouse have found varietal differences in the response of rice to aluminum toxicity. Varieties such as Monolaya, Colombia 1, Bluebonnet 50, IAC 165, IAC 1246, IAC 25, TOX 1010-49-1, TOX 1781-15-1, IRAT 112, and NGOVIE were classified as tolerant, while cultivars such as IR8, IR665-23-3-1, CICA 4, and Metica 1 were considered to be susceptible to aluminum toxicity.

Toxicity caused by aluminum is manifested in susceptible varieties as severe yellowing of young leaves and death of older leaves, and as the symptoms intensify, the plants are damaged and develop few roots. Indirect effects caused by toxicity are also sometimes observed, such as magnesium and phosphorus deficiencies (Martínez, 1976; Sarkarung, 1984). According to De Datta (1981), the effect of aluminum toxicity on the rice plant can be represented as follows:



Martínez (1976) studied the performance of seven rice varieties at various aluminum-concentrations in nutrient solutions (Table 1). The length of the main root was measured immediately after treatment with aluminum and then the plantlets were placed in a nutrient solution free of aluminum for 48 hours. At the end of that period, the root was measured again, and differences between measurements recorded (Table 1). As the content of aluminum was increased, root length decreased in all of the varieties. However, there were significant differences among varieties.

Table 1. **Influence of aluminum on root length (mm) of some rice cultivars.**

Cultivar	Aluminum concentration[a] (ppm) 0	20	25	30
Monolaya	26.1 a	20.4 a	13.7 ab	2.8 a
Bluebonnet 50	25.4 ab	20.0 ab	14.7 a	7.5 a
IR665-23-3-1	21.4 abc	1.3 d	1.4 d	0.4 a
IR8	20.5 abc	3.8 cd	3.3 cd	1.8 a
CICA 4	19.1 c	2.9 cd	1.4 d	0.6 a
IR5-64-2-2	16.9 c	6.3 cd	2.8 cd	2.3 a
Colombia 1	15.4 c	7.9 c	4.4 cd	0.7 a

a. Standard error = 0.8314. Means followed by the same letter in each column are not significantly different at 5% level of probability in Duncan's Multiple Range Test

SOURCE: Martínez, C. P. 1976.

Effect of aluminum on cellular division

The effect of aluminum on the mitotic process or mitosis was studied in meristems of rice roots (Martínez, 1976). Samples were taken from root tips of plantlets grown in nutrient solutions with and without aluminum. The samples were taken at regular intervals and in each case the number of cells undergoing the process of division were counted (Table 2). The data indicate that less mitotic activity occurred in the root meristems of varieties susceptible to aluminum toxicity, such as CICA 4 and IR665-23-3-1, than in tolerant varieties, such as Monolaya and Bluebonnet 50, even with only 6 hours in the solution with aluminum. The number of cells undergoing cellular division is very low at 72 and 95 hours and, in the case of IR665-23-3-1 and CICA 4, the values differ significantly from those of Monolaya and Bluebonnet 50.

Furthermore, the number of cells found in each phase of the mitotic process (prophase, metaphase, anaphase, and telophase) were counted and it was found that aluminum affected each mitotic process and not one phase in particular (Martínez, 1976).

Table 2. **Effect of aluminum (20 ppm) on the number of cells in process of mytotic division in a sample[a] of 500 cells of the root meristem.**

Treatment	Monolaya	CICA 4	Bluebonnet 50	IR665
Control at 6 hours	17.5	14.0	17.0	16.0
20 ppm Al	13.0	9.5	14.3	6.8[bc]
Control at 24 hours	17.5	20.3	17.3	17.5
20 ppm Al	14.3	6.5[bc]	13.3	4.8[bc]
Control at 48 hours	21.3	16.8	16.0	17.0
20 ppm Al	11.3[b]	7.5[b]	11.8	4.0[bd]
Control at 72 hours	16.8	15.8	17.8	18.0
20 ppm Al	10.0	1.5[bd]	10.5[b]	2.0[bd]
Control at 96 hours	14.8	14.8	17.3	15.0
20 ppm Al	11.5	3.0[bd]	10.5	2.3[bd]
Control at more than 48 hours	13.8	14.8	15.3	15.3
20 ppm Al	14.5	3.0[bd]	11.8	3.0[bd]

a. Standard error: 1.034; L.S.D. (5%) = 7.0

b. Differ significantly from the respective control.

c. Differ significantly from Monolaya or Bluebonnet 50.

d. Differ significantly from Monolaya and Bluebonnet 50.

SOURCE: Martínez, C. P. 1976.

Inheritance of tolerance to aluminum toxicity

Martínez (1976) made crosses between varieties tolerant and susceptible to aluminum toxicity and evaluated F_1, F_2, and BC_1 generations in nutrient solutions using 20 ppm of aluminum. It was found that in the Monolaya and Bluebonnet 50 varieties, tolerance to aluminum toxicity was recessive and was controlled by two pairs of genes. The genes in these two varieties are possibly allelic, but have different degrees of expression or incomplete penetrance. Camargo (1982) used a similar technique and found that tolerance to aluminum toxicity was under genetic control in the varieties IAC-165, IAC-47, IAC-25, and IAC-1246. Moreover, susceptibility was partially dominant over tolerance.

The discrepancy between the two previous studies may be due to differences in the methods used, since the length of time the materials were exposed to solutions with aluminum was not the same. Nonetheless, both studies indicated that the genetic variance varied depending on the amount of aluminum used in the evaluation of segregating populations. There were no maternal effects in the expression of tolerance to aluminum toxicity.

Varietal improvement for acid savanna soils

Location and characteristics of the ecosystem

Evaluation and selection of materials tolerant to acid savanna soils are being conducted at Villavicencio, Colombia, at the Centro Regional de Investigacion La Libertad, an experimental station that belongs to the Instituto Colombiano Agropecuario (ICA). This region is characterized by abundant (3477 mm/year) and well-distributed precipitation (Owen, 1982). The soils used are known as Oxisols, are acidic (pH 4.4), have an aluminum content of 3 meq/100 g of soil and 83% aluminum saturation, and have very low contents of phosphorus, potassium, calcium, magnesium, sulphur, and boron. Water retention capacity in the soil is very low.

Objectives and strategies

The general strategy focuses on obtaining adequate varieties for a technology of low inputs. These varieties must be tolerant to various soil problems, especially aluminum toxicity, and to the main diseases and pests (pyricularia, leaf scald, blast, grain stain, brown leaf spot, nematodes, and stemborer) present in this ecosystem. These varieties must also have good grain quality and be able to efficiently use the scarce nutrients available in the soil.

The breeding program initially covers two main aspects:

Introduction and evaluation of germplasm for its tolerance to aluminum toxicity.

A hybridization and selection program to incorporate into the aluminum-tolerant materials other desirable characteristics such as pest and disease resistance, good grain quality, and high yield potential.

The selection criteria followed in the development of an ideal plant type for this savanna ecosystem are:

Long, thick, and deep roots;

good initial vigor;

low or intermediate plant height (90-120 cm);

superior erect leaves, slow senescence;

large, thin, heavy grains;

intermediate tillering and strong stems; and

low percentage of sterility.

Materials and methods

Approximately 1360 cultivars including breeding lines, native varieties, and traditional materials coming from different institutions such as the International Institute of Tropical Agriculture (IITA), Institut de Recherches Agronomiques Tropicales et de Cultives Vivriéres (IRAT), International Rice Research Institute (IRRI), Centro Internacional de Agricultura Tropical (CIAT), and the Instituto Agronomico de Campinas (IAC), (CIAT, 1985; Sarkarung, 1984) were evaluated in 1984. A field design consisting of "acid strips" formed by two bands of high and low acidity were used. The latter was obtained by applying 3 t/ha of dolomitic lime 15 days before planting with the objective of increasing soil pH and neutralizing aluminum. No lime was applied to the highly acid band.

The materials under evaluation were in blocks covering both high and low acidity bands. The varieties Metica 1 (susceptible), IRAT 122, and IAC 165 (tolerant) were planted as controls every 12 cultivars. All plots received a minimum fertilization at the time of planting with 50 kg N (urea), 60 kg P_2O_5 (triple superphosphate), and 40 kg K_2O (potassium muriate) per hectare. To avoid confusing effects due to possible damages caused by diseases and insects, insecticides and fungicides were applied regularly. Aluminum toxicity was evaluated at 40 and 70 days after planting, using a rating scale of 1 to 5 (Table 3).

Table 3. Scale to evaluate aluminum toxicity symptoms.

Scale	Symptoms
1	No difference in development at high and low acidity conditions.
2	Slight yellowing of a few plants at high acidity conditions; plant development is scarcely affected.
3	Certain yellowing in the plants; slight decrease in height.
4	Uniform yellowing and marked decrease in height; no dead leaves.
5	Severe yellowing, marked decrease in height and death of inferior leaves.

SOURCE: Sarkarung, S. 1984.

Results and discussion

The cultivars most susceptible to aluminum toxicity had very intense yellowing, and plant and root growth were affected considerably. Tolerant cultivars (Table 4) grew well under both conditions (high and low acidity) and were classified in categories 1 and 2 of the rating scale (Table 3). Of the 1360 cultivars evaluated, only 180 showed good adaptation to savanna conditions and will be used as progenitors in the crossing program (CIAT, 1985; Sarkarung, 1984). Aluminum tolerance was found in cultivars of different geographic origin. Improved lines coming from the breeding programs at IITA, IRAT, and IAC-Campinas, showed good adaptation and seemed to have a higher degree of aluminum tolerance than the local varieties, Monolaya and Colombia 1.

Table 4. **Cultivars highly tolerant to aluminum toxicity and their origin, Centro Regional de Investigación (CRI), La Libertad, Colombia, 1984.**

Cultivar	Origin[a]
Advanced breeding lines	
TOX 891-212-2-102	IITA, Nigeria
TOX 1010-22-7-16	IITA, Nigeria
TOX 1010-49-1	IITA, Nigeria
TOX 1815-34-201-201-1	IITA, Nigeria
TOX 1781-15-1	IITA, Nigeria
TOX 1780-5-7	IITA, Nigeria
IRAT 194-1-2-B	IRAT, Ivory Coast
IRAT 112	IRAT, Ivory Coast
IRAT 122	IRAT, Ivory Coast
IRAT 146	IRAT, Ivory Coast
IAC 164	IAC, Brazil
IAC 5032	IAC, Brazil
IAC 25/PJ-110-99-1-4-1	INIA, Mexico
OS6/IRAT 13-Al-ICM-1JM	INIA, Mexico
Traditional and native varieties	
Ngovie	Sierra Leone, Africa
Lac 23	Liberia, Africa
Ku 28	Thailand, Asia
Padi Bokokut	Indonesia, Asia
OS6	Zaire, Africa
Zebu	Philippines, Asia
Monolaya	Colombia, South America
TOS 5806	Africa
63-83	Ivory Coast and Asia

a. IITA — International Institute of Tropical Agriculture
IRAT — Institut de Recherches Agronomiques Tropicales et de Cultives Vivriéres
IAC — Instituto Agronómico de Campinas
INIA — Instituto Nacional de Investigaciones Agrícolas

In general, it was observed that all aluminum tolerant cultivars have deep roots, but not all genotypes with deep roots are tolerant to aluminum toxicity.

Among the materials evaluated, some high-yielding dwarf genotypes were included. It was observed that these genotypes adapt poorly to this ecosystem. These irrigated genotypes are characterized for their superficial rooting system and excessive tillering and probably because of this they are predetermined to upland stress, to nutritional unbalances, and to water deficiency in the soil.

There was no correlation between plant height and tolerance to aluminum toxicity (Table 5). Many upland dwarf genotypes had high aluminum tolerance and good adaptation to savanna conditions. These upland dwarf lines have thick and deep roots (CIAT, 1985).

Loss in yield due to aluminum toxicity was estimated (Table 6). Relative yields of the tolerant, moderately tolerant, and susceptible cultivars were 92%, 70%, and 48%, respectively, relative to the yield obtained in the low acidity strips.

A group of rice cultivars previously classified as tolerant in aluminum nutrient culture were also included. Less than 10% of 258 cultivars were rated as tolerant in the field. The majority exhibited severe yellowing in the high acid strips 40 days after planting, although some recovered at maturity. This type of tolerance is undesirable because it would cause yield reduction.

Table 5. **Relation between height and aluminum toxicity of some varieties evaluated in the acid strips, Centro Regional de Investigación (CRI), La Libertad, Colombia, 1984.**

Cultivar	Height (cm)	Reaction to aluminum[a]	Ecosystem
TOX 891-212-2-102	55	1	Upland
TOX 1815-34-201-201-1	75	1	Upland
TOX 1010-24-6-1-1-1B	61	2	Upland
IRAT 146	55	2	Upland
IRAT 122	77	2	Upland
IRAT 194-1-2-3	66	2	Upland
IAC 25/PJ-110-99-1-4-1	63	1	Upland
Colombia 1/M312A	67	1	Upland
CICA 8	52	5	Irrigated
IAC 165 (Resistant control)	96	2	Upland
Metica 1 (Susceptible control)	55	4	Irrigated

a. Based on the scale presented in Table 3 to evaluate aluminum toxicity symptoms.

Table 6. **Relative yield[a] of varieties with different reactions to aluminum toxicity.**

Class[b]	Scale[c]	Relative yield (%)
Tolerant	1-2	92
Moderately tolerant	3	70
Susceptible	4-5	48

a. Relative yield = $\frac{\text{Yield in high acidity bands}}{\text{Yield in lime bands}}$

b. In each class a sample of 50 cultivars was taken.

c. Based on the scale presented in Table 3 to evaluate aluminum toxicity symptoms.

Summary

The Rice Program at CIAT is intensifying breeding for tolerance to the acid savanna soils. Major production constraints for rice in this ecosystem are: the lack of adapted rice varieties for acid, infertile soils; biological (disease and insect) constraints; and inadequate information on agronomic practices. The approach in varietal improvement is directed toward development of rice varieties suitable for a minimum input system. A field-screening procedure is described. Donor cultivars having high tolerance to aluminum toxicity were identified.

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Breeding Methodology for Phosphorus Efficiency and Tolerance to Aluminum and Manganese Toxicities for Beans (*Phaseolus vulgaris* L.)

*M. Thung, J. Ortega, and O. Erazo**

Introduction

Bean yields in Latin America are generally very low. The largest producers, Brazil (FAO, 1976) and Mexico (Lepiz, 1977), with more than 70% of the area, report yields under 700 kg/ha. These low yields are caused by, among other things, adverse soil conditions such as acidity, low phosphorus (P), and high aluminum (Al) and manganese (Mn) toxicity problems.

Phosphorus deficiency is the most common nutritional problem of beans in Latin America. Either Al alone or Al and Mn toxicities are almost always present in acid soils with low base saturation. Muller et al. (1968) showed that 20% of 110 soil samples from Central America had pH values under 6.0. Beans are known to perform better in soils with pH values between 6.0 and 7.15 (Jacob and Vexkuell, 1963).

Unfortunately, beans are cultivated in areas with pH values under 6.0 (Muller et al., 1968) and where P deficiency is common. Small applications of $CaCO_3$ reduce exchangeable Al below toxic limits without increasing the soil pH. Beans are more sensitive to Al and Mn toxicity and need higher Ca levels than other crops, including Poaceous species. Limited liming is necessary to overcome the Al and Mn complex without inducing zinc (Zn) and boron (B) deficiencies when breeding beans for their efficiency to low phosphorus levels.

Application of P fertilizers is too expensive for the common

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farmer and its efficiency is low. Kick and Minhas (1972) estimated that the bean plant utilizes between 10% and 30% of the fertilizer applied. Cobra Neto (1976) found that beans absorb only 9.1 kg P/ha and remove only 3.6 kg P/ha through 1000 kg of seed. As a general rule, the higher the soil P deficiency, the less efficient the plant to absorb P added as fertilizer. For this reason, it is better to look for a plant efficient in the use of P and moderately tolerant to Al toxicity, rather than trying to improve the soil conditions.

The objectives of this research were:

1. To evaluate bean efficiency in the use of low P levels in the soil and its response to additional P applications.
2. To evaluate bean tolerance to Al and Mn toxicities and its response to additional liming.
3. To identify good material resulting from evaluations in steps 1 and 2.
4. To recommend promising material identified in step 3 as efficient and tolerance-breeding sources to improve architecture, and resistance to drought, diseases, and pests.

Phosphorus in the soil and its deficiency in the bean plant

Phosphorus is always changing in the soil and can be found in three different forms:

Directly available to the plant through the soil solution;

unstable but with possibilities to be transformed into a form available to the plant; and

completely fixed and not available to the plant.

In general, P availability decreases with soil acidity. Phosphorus deficiency in the bean plant is shown by leaf color changes, necrotic borders, early defoliation, reduced growth with very thin stems, and short internodes. The flowering stage is delayed and the period to physiological maturity is shortened. The principal root is very short and sometimes the tap root is replaced by adventitious roots.

Aluminum in the soil and its toxicity in the bean plant

Aluminum is the second most common of the major elements present in the soil (Scheffer and Schachtschabl, 1970), but it is generally not a threat provided it is not assimilated by susceptible plants.

Aluminum toxicity affects mainly the roots, inhibiting cell division, reducing root system development (MacLeod and Jackson, 1967; Fleming and Foy, 1968; Foy, 1974), and reducing growth of the plant in general as a secondary effect. Susceptible plants absorb Al and accumulate it within or around the roots. Aluminum also reduces P intake due to a reaction between the two elements forming aluminum phosphates. Aluminum toxicity is evident when the plants are stunted and loosely rooted in the soil. Young leaves become yellow and, if toxicity is very severe, some necrotic spots become visible along the borders. Roots are the most affected organs and are used as a parameter to evaluate tolerance (Armiger et al., 1968; Reid et al., 1971).

Manganese in the soil and its toxicity in the bean plant

Manganese is present in the soil in three different forms: Mn^{++}, Mn^{+++}, and Mn^{++++}. Only the Mn^{++} form is readily assimilated by the plant and can be found in the absorption complex or free in the soil solution. High organic soils which are acid, such as the Andosols, have a high Mn content and can cause severe damage to the bean plant.

Manganese absorption and movement within the plant is in the Mn^{++} form. This form is not very mobile and cannot pass into the phloem (van Goor and Wiersna, 1974). High amounts of Mn can be accumulated in the leaves without producing toxicity symptoms or affecting the yield; it is common to find leaves with a Mn content of 1000 ppm.

When the tolerance level is exceeded, Mn toxicity causes yellowing between the leaf veins, deformation and shrinkage of leaves and buds, and necrosis of old leaves when toxicity is very serious.

Genetic variation of beans under adverse conditions

There is strong evidence about bean genetic variation regarding its efficiency in the use of P and its tolerance to Al and Mn toxicities. Some commercial varieties from Brazil (Carioca and Mulatinho 349 (G5059)) are not only P efficient, but also tolerant to moderately high levels of Al and Mn. Commercial varieties from Central America and Colombia are susceptible to such soil conditions. Recent data show that grain color does not affect P efficiency or tolerance to Al or Mn problems.

Screening methodology

Several investigators have looked for a methodology that allows easy management of large numbers of lines in a relatively short period of time, at low cost, and with good correlation to final yields. In the case of tolerance to high levels of Al in the soil, most researchers agree that the roots, the most affected part of the plant, are a good indicator of the tolerance index. Foy (1974) used the growth rate index; Reid et al. (1971) used the intensity of the root color; and Hanson and Kamprath, (1979) used the activity of the adenosine triphosphate (ATP) enzyme in the roots. All of them obtained good correlations with yield.

Plant parts used to study Al and P effects are destroyed during the evaluation process. It is then impossible to use the same plant for seed production except with the Polle et al. (1978) method in which the plant can be recovered after using hematoxylin. Plant destruction slows the breeding process in early generations and makes it difficult to assure the genetic identity of the materials selected, except in the case of genetically identical plants.

Another factor that must be considered is that when selection occurs during the vegetative stage it is assumed that the plant has the same P absorption capacity during the remainder of the growing period ignoring the highest P mobilization activity during the pod formation stage. Haag et al. (1967) showed that P absorption reaches a maximum by the pod formation stage and is maintained at this level until physiological maturity. Absorption of P is very low between the germination and the flowering stages.

Grain yield was used as an evaluation parameter to facilitate breeding of materials according to their efficiency or tolerance. Crop growth vigor was also observed during all stages without any correlation to the final yield. Plants can grow perfectly well in low P levels up to the pod formation stage. At this stage, pods in no-stress plots filled normally while pods in stress plots did not fill well.

Field technique

Site

Aluminum and/or Mn toxicities vary, the same as fertility, according to the zone. For this reason it was necessary to conduct preliminary field studies to determine Al, Mn, and P stresses.

Determination of Al and Mn stress levels

To determine Al and Mn stress levels, a liming trial, applying different levels of dolomitic or calcitic lime, was conducted by planting different bean varieties, including tolerant and susceptible types. Aluminum toxicity was calculated according to its saturation level in the soil using the Pearson (1975) formula:

$$\text{Al saturation (\%)} = \frac{\text{Al}}{(\text{Al} + \text{Ca} + \text{Mg} + \text{K})} \times 100$$

where the units for cations were given as milliequivalents in 100 grams of soil.

Figure 1 shows the results of such a study at the Centro Internacional de Agricultura Tropical (CIAT)-Quilichao (1979A). In this case, application of 800 kg $CaCO_3$ equivalent was enough to achieve 65% Al saturation under the CIAT-Quilichao conditions. With a lower rate of lime, Al saturation percentages vary erratically. This level of Al saturation may appear too high, but the presence of a high organic matter content (7%) helps reduce Al toxicity through its absorption complex. With higher rates of lime, both susceptible and tolerant varieties grow well and produce good yields.

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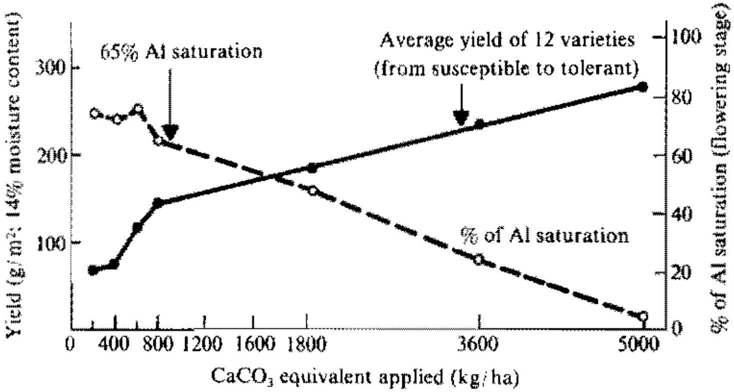

Figure 1. *Effect of Al saturation during the flowering stage on the yield of 12 bean varieties at CIAT-Quilichao, 1979A, where the coefficient of variation (C.V.) equals 22% and the standard deviation (SD) at 0.05 equals 40.*

The amount of $CaCO_3$ needed to reduce Al stress can also be determined using the same trial. According to Figure 1, more than 4000 kg of $CaCO_3$ equivalent were required to reduce (without eliminating) the Al toxicity effect. Application of more than 6000 kg of $CaCO_3$ equivalent causes other problems such as mobilization or fixation of microelements, P fixation, and the promotion of some plant diseases.

Determination of P stress level

The same system used to determine Al stress was used to determine P stress levels using different bean varieties.

Phosphorus application levels should be carefully analyzed. Under CIAT-Quilichao conditions, beans can grow well with P levels around 4 ppm (Bray II) and applications of 2000 kg of $CaCO_3$ equivalent, while at other sites this concentration is not enough.

To determine the P stress level, a graph is constructed, such as Figure 2, where the points represent data from each variety and the dispersion is maximum; that is, differentiation of varieties is the most visible. This rate is used as the P stress level.

The no-stress level is determined by observing the closer points. The difference between them is assumed to be the difference between the levels of maximum yield of the varieties. The no-P-stress level has a limit; if applied in excess, P becomes expensive and can change the relationship between elements.

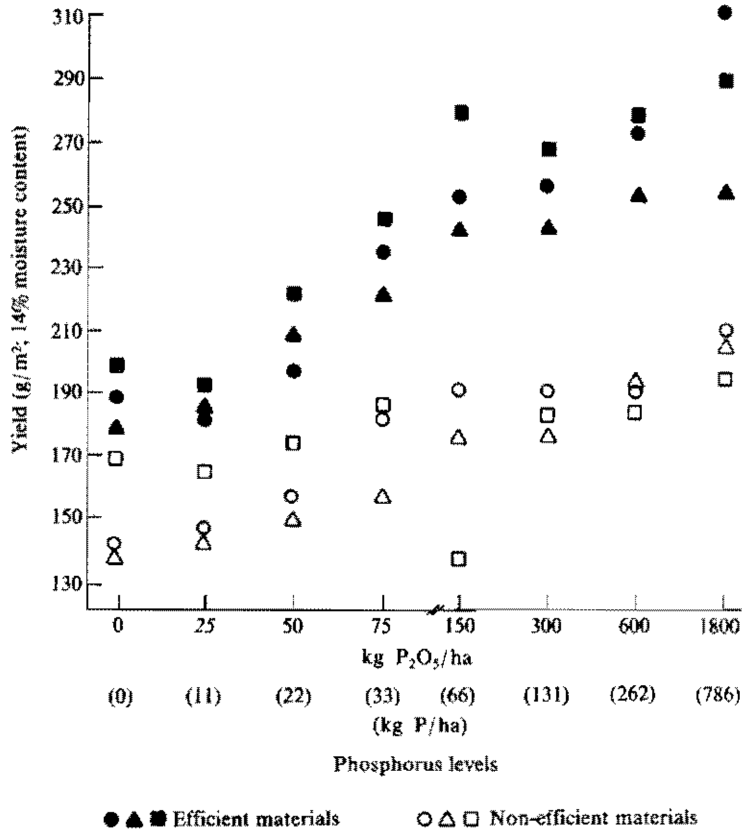

Figure 2. *Phosphorus effects on bean production at CIAT-Quilichao, 1979.*

Simultaneous breeding treatment

Once the different levels (stress and no stress) are known, they can be used in combination for a simultaneous breeding process. Each plot represents a treatment with at least three replications.

Treatment I: Al stress plots with no P stress.
Treatment II: P stress plots with no Al stress.
Treatment III: No Al or P stress (optimum levels).

Soil preparation for large-scale screening and breeding plots

Once the Al and P stress and no-stress levels are known, the field is prepared for liming. Half of the $CaCO_3$ is broadcast and incorporated as deep as possible (about 20 cm), the other half is broadcast before planting. Seeds are over planted (20% more) in 3.0-metre-long rows with 0.6 m between rows, and stands are thinned two weeks after germination to obtain stands of 25 plants/m^2. Bean germplasm should be separated according to growth habit. Growth habits I and II (bush type) can be planted separately, while growth habit III (prostrate) lines should be planted together to achieve a certain degree of competition among lines and not between growth habits. Half a metre is left at each end of the row and only the 2.0 m sections in the center are harvested.

Modifications to the breeding methodology

Based on field results, some modifications were made and the methodology was divided into three stages which included the following aspects:

Stage I. This stage was integrated by bean lines (200-300) from the Preliminary Uniform Yield Trials, plus seven controls tolerant to acid soil conditions. Advanced breeder lines and/or lines from adaptation nurseries can be evaluated at the same time. Each variety or line is planted in four-row plots grouped by growth habit and grain color. Treatments included in this stage are Al and P stresses. For the P stress treatment, 1 ton $CaCO_3$ equivalent/ha was broadcast and incorporated; 75 kg P_2O_5/ha as triple superphosphate (TSP,46%), 60 kg N/ha as urea (46%), and 60 kg K_2O/ha as KCl (60%) were applied in bands; B and Zn (0.5%) were applied to the leaves if deficiency symptoms were present.

For the Al stress treatment, 500 kg $CaCO_3$ equivalent/ha, 220 kg P_2O_5/ha as TSP (46%), 70 kg N/ha as urea (46%), 60 kg K_2O/ha as KCl (60%), and micronutrients were applied in the same way as for the P stress treatment. No replications were made, and data were taken on adaptation on a scale of 1 (good) to 5 (poor). Central rows were harvested for yield evaluation when moisture content of the seed was 14%. The plot was protected against insects and/or diseases and complete soil analyses were carried out at 0-20 and 20-40 cm before planting and after harvesting.

Stage II. This stage contained those lines (50-80) that showed good yield and adaptation in Stage I and the same lines used as controls in the first stage. Three treatments were included in this stage : one with P stress; another with Al stress; and the third with no P or Al stresses, distributed in a random plot design with three replications. Each line was planted in four rows 3.0 metres long with 0.6 m between rows. Phenological data were taken from the two central rows (days-to-germination, flowering, physiological maturity) and yield components (number of plants per plot, number of pods per five plants, number of seed per five plants, total weight in grams/plot at 14% moisture content) for the corresponding variance analysis.

For the no-stress treatment, 2500 kg $CaCO_3$ equivalent per hectare per semester, 300 kg P_2O_5 as TSP (46%), 100 kg N/ha as urea (46%), 100 kg K_2O/ha as KCl (60%), 20 kg S/ha, 1 kg Mg/ha (20 kg $MgSO_4$/ha), 1 kg B/ha (10 kg borax/ha), 5 kg Zn/ha (25 kg $ZnSO_4$), and 1 kg Mo/ha (1 kg NaMo) were applied.

For the P stress treatment, 1000 kg $CaCO_3$ equivalent/ha and 50 kg P_2O_5/ha as TSP (46%) were applied per semester. Other nutrients were applied the same way. as for the P stress treatment in Stage 1.

For the Al stress treatment, 500 kg $CaCO_3$ equivalent/ha and 200 kg P_2O_5/ha as TSP (46%) were applied per semester. Other nutrients were applied in the same way as for the P stress treatment in Stage 1.

Stage III. Included in this stage were outstanding lines from Stage II (around 15 plus 7 controls from Stages I and II). The same treatments used in Stage II were applied here. The plot size per line was five rows, 4.0 metres long and 0.6 m between rows. Agronomic management was the same as for Stages I and II; the three central rows were harvested and the same data evaluated on Stage II are also evaluated in Stage III. The no stress treatment was the same as for Stage II.

The P stress treatment received 1000 kg $CaCO_3$ equivalent/ha, 30 kg P_3O_5/ha as TSP (46%), and the other nutrients were applied in the same manner as for Stages I and II per semester.

The Al stress treatment received 400 kg $CaCO_3$ equivalent/ha, 180 kg P_2O_5/ha as TSP (46%), and the other nutrients were applied in the same manner as for Stages I and II per semester.

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It is important to note that P and Al stress levels were established for the Ultisol conditions of Quilichao. For this reason, it is neccesary to carry out complete soil analyses before planting and after harvesting for each particular situation.

Data collection

a. Phenological

1. Days-to-germination (when 50% of the plants have emerged)
2. Germination rate
3. Days-to-flower
4. Days-to-physiological maturity

b. Yield analysis

1. Number of plants harvested
2. Number of filled pods per plant (sample of 5 plants per row)
3. Number of pods/plant
4. Yield (g/m^2) at 14% moisture content

Data evaluation

Statistical evaluations did not give satisfactory results because yield differences were large among lines. The main objective was to observe yield stability in the three or four replications within a growth habit.

The same control lines were always planted in each screening. They were used to measure the relative importance of differences between lines, because yield is affected by a range of climatic conditions, and the standard materials can be used as a correction factor.

Before selecting lines according to their characteristics, it is necessary to select two additional parameters derived from the yield and the treatment to measure their response:

$$\frac{\text{(yield in no-stress plots) - (yield in stress plots)}}{(P_2O_5 \text{ kg/ha no stress}) - (P_2O_5\text{/ha with stress})}$$

The amount of P in ppm was not used because chemical analysis data greatly depend upon water conditions and time elapsing after application.

$$\frac{\text{(yield in no-stress plots) - (yield in stress plots)}}{\text{(\% Al saturation with stress) - (\% Al saturation without stress)}}$$

Lines within a group (grain color or growth habit), can be classified according to the average yield for the plots with stress in the same group.

Figure 3 shows a classification of lines according to efficiency and their response to the application of P fertilizers. The yield of the lines under P stress is on the X axis and the response to P fertilizer is on the Y axis.

The average yield (in this case 99 g/m²) divides the bean lines into two groups. Those on the left are inefficient, while those on the right are efficient. The average Alpha line (in this case 2.2 kg/kg P_2O_5) divides the bean lines with response above the line

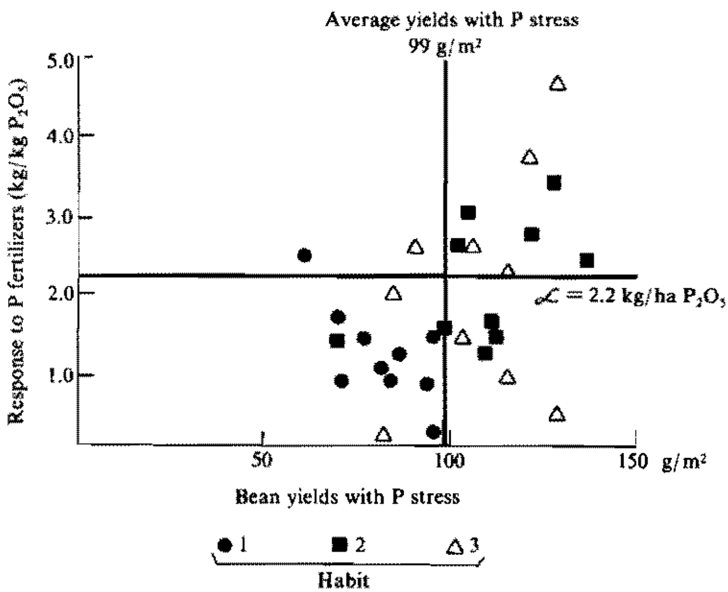

Figure 3. *Evaluation of materials according to their efficiency and response to the application of phosphoric fertilizers at CIAT-Quilichao.*

and without response below the line. We can then classify the breeding lines into four categories :

1. Efficient line with good response. This is a line which produces good yield both with P stress as well as with adequate P.

2. Efficient line without response. This line will yield well under P stress, but will not produce the same as other plants with optimum P.

3. Inefficient line without response. This is a genetically poor line which will not produce good yield either under adequate or inadequate P conditions.

4. Inefficient line with good response. This is a line which produces less under P stress levels but which will produce the same or better yields than an efficient line with adequate P.

Lines in category 3 are rejected or discarded immediately and those in category 2 can be used directly by small farmers who do not apply fertilizer. Lines in category 4 can be released to farmers who use fertilizer if the economic value of the lines is acceptable. Lines in category 1 can be used directly by small farmers. These lines are used as tolerant or efficient breeding sources to improve other lines with resistance to some important diseases.

It is interesting that the results obtained confirm the Lyness (1936) postulate, "The most efficient materials under adverse conditions are not necessarily the best under optimum conditions."

Nitrogen effect on selection is also very important. If the selection process is conducted with an inadequate N supply, the variety response to P fertilizer is masked by the negative effect produced by N deficiency (Figure 4).

In this evaluation, lines were selected only if they showed good efficiency characteristics under P stress conditions, a good response to P fertilizer, or good characteristics for tolerating moderate Al and Mn toxicity levels. There is a positive correlation with their potential yield between lines conditioned to P stress and lines tolerant to Al and Mn toxicities.

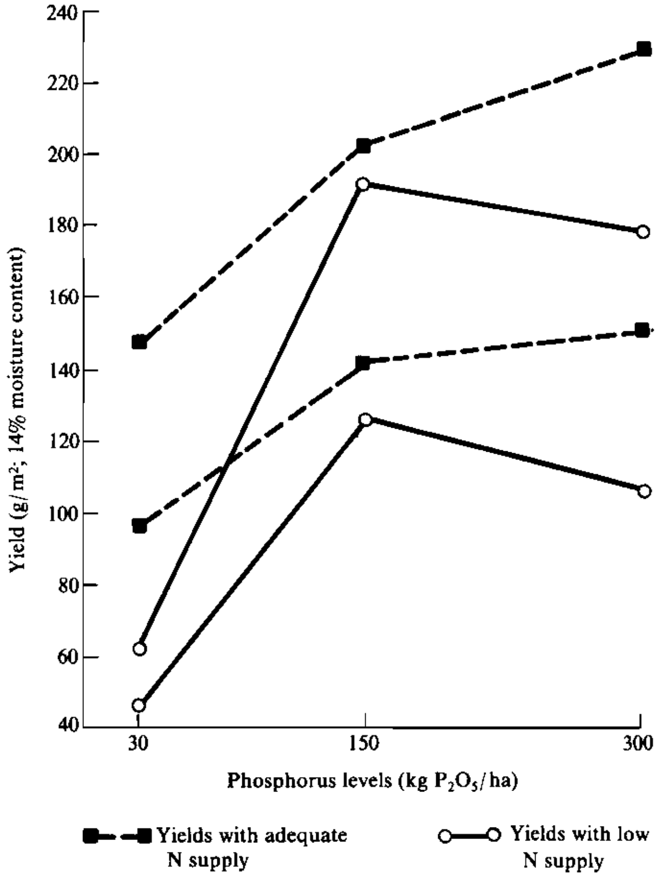

Figure 4. *Range of bean response to different P levels, as affected by different N levels.*

Joint evaluation to obtain tolerant materials to adverse soil conditions

These lines should have all desirable characteristics: efficiency in the use of the P present in the soil, response to the application of P fertilizer, tolerance to moderate Al toxicity, and response to lime applications.

Lines with desirable characteristics can be evaluated and identified using Figure 5. Lines in category 1 are identified as tolerant to acid soil conditions. Most of the lines identified until now as tolerant come from Brazil where they have adapted to adverse soil conditions.

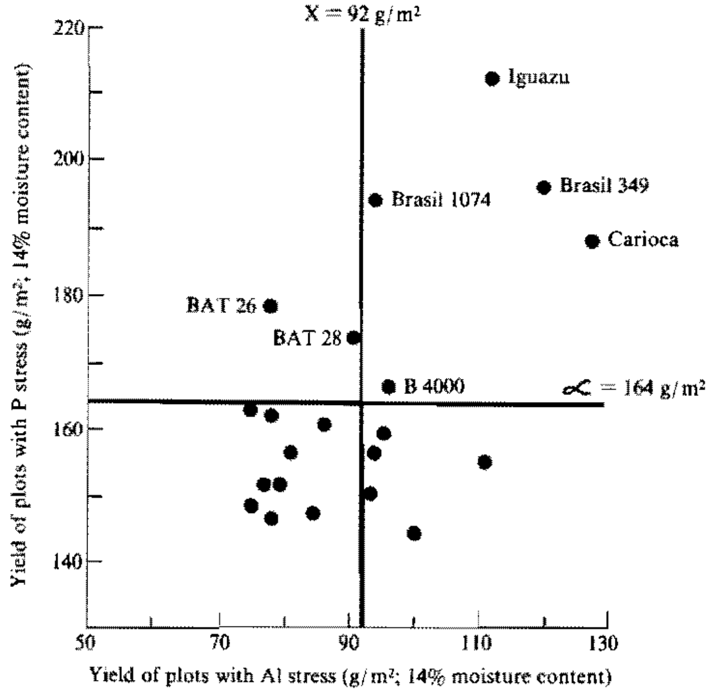

Figure 5. *Evaluation for obtaining tolerant materials to adverse soil conditions.*

These results show the efficiency of this breeding system at CIAT-Quilichao, where Al and Mn also affect production.

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World Sorghum Germplasm Collection and Conservation

*Vartan Guiragossian and Melak H. Mengesha**

Introduction

The importance of germplasm in any crop improvement work is a well established fact. The main purpose and responsibility of the Genetic Resources Unit (GRU) at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is to collect and preserve the vanishing germplasm and make it readily available for present and future utilization. The germplasm must be maintained, as much as possible, close to its original form and genetic constitution. Systematic evaluation and documentation are very important and necessary tasks to help understand and classify the collected material. They also facilitate identification and retrieval of useful germplasm lines for distribution and proper utilization.

Lately, ICRISAT has attempted, through questionnaires, to assess the value and use of the germplasm that has been supplied to many crop improvement programs throughout the semi-arid tropics. The responses that have been received, so far, are most encouraging. The results of this assessment are being studied and compiled for circulation.

The origin and early domestication of sorghum most probably took place in the northeast quadrant of Africa, from the Ethiopia-Sudan border area extending westward to Chad (Dogget, 1970; Harlan, 1971). Other areas in West Africa and Asia are also important centers of diversity.

Collection

The world sorghum germplasm collection work at ICRISAT is

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currently developing at an accelerated pace. We also continue our search for the missing accessions of the world collection from other gene banks. In addition to the already assembled world collection, 10,688 new accessions were assembled from 79 countries by organizing collection expeditions in priority areas, and by correspondence. With these new additions, the sorghum germplasm collection at ICRISAT has reached a total of 22,466 accessions (Table 1). In addition, 2697 new accessions recently obtained from 12 countries are under plant quarantine for release in 1984. When these lines are released, the collection at ICRISAT will reach 25,163 accessions.

Table 1. **Sorghum germplasm assembled at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), January 1983.**

Source	Number of accessions assembled by		
	Rockefeller Foundation	ICRISAT/IBPGR[a]/ ORSTOM[b]/National Programs	Total
Africa			
Angola	23	6	29
Benin	1	3	4
Botswana	28	162	190
Burkina Faso	160	88	248
Cameroun	1753	82	1835
Central African Republic	37	2	39
Chad	125	13	138
Egypt	15	7	22
Ethiopia	1446	2796	4242
Ghana	11	53	64
Ivory Coast	1	-	1
Kenya	313	448	761
Lesotho	-	8	8
Madagascar	-	1	1
Malawi	58	379	437
Mali	95	16	111
Morocco	-	3	3
Mozambique	-	42	42
Namibia	-	1	1
Niger	25	383	408
Nigeria	897	276	1173
Senegambia	12	282	294
Sierra Leone	-	3	3
Somalia	5	120	125
South Africa	483	243	726
Sudan	855	1401	2256
Swaziland	18	1	19

(Continues)

Table 1. **(Continued).**

Source	Number of accessions assembled by Rockefeller Foundation	ICRISAT/IBPGR[a]/ ORSTOM[b]/National Programs	Total
Tanzania	31	401	432
Uganda	471	141	612
Zaire	24	-	24
Zambia	3	207	210
Zimbabwe	123	63	186
Asia			
Afghanistan	5	1	6
Bangladesh	-	9	9
Burma	2	6	8
China	24	44	68
India	2732	1406	4138
Indonesia	6	26	32
Iran	6	1	7
Iraq	2	2	4
Israel	22	-	22
Japan	106	5	111
Lebanon	-	360	360
Nepal	7	1	8
Pakistan	18	11	29
People's Democratic Republic of Yemen	-	1	1
Philippines	1	4	5
Saudi Arabia	-	1	1
South Korea	2	-	2
Sri Lanka	-	25	25
Syria	-	4	4
Taiwan	12	1	13
Thailand	5	-	5
The Soviet Union	5	64	69
Turkey	1	50	51
Yemen Arab Republic	-	216	216
Europe			
Belgium	-	1	1
Cyprus	1	-	1
France	5	-	5
German Democratic Republic	-	4	4
Greece	1	-	1
Hungary	-	26	26
Italy	8	-	8
Portugal	-	6	6
Spain	-	3	3
United Kingdom	-	1	1

(Continues)

Table 1. **(Continued).**

Source	Number of accessions assembled by Rockefeller Foundation	ICRISAT/IBPGR[a]/ ORSTOM[b]/National Programs	Total
America			
Argentina	2	14	16
Cuba	1	2	3
El Salvador	-	1	1
Guatemala	-	6	6
Honduras	-	1	1
Mexico	207	27	234
Nicaragua	-	1	1
United States of America	1208	671	1879
Uruguay	-	1	1
Venezuela	-	1	1
West Indies	-	3	3
Australia and Oceania			
Australia	6	22	28
Papua New Guinea	-	1	1
Unknown	370	27	397
Total	11,778	10,688	22,466

a. IBPGR — International Board for Plant Genetic Resources, Rome, Italy.
b. ORSTOM - Office de la Recherche Scientifique et Technique d'Outre-Mer, France.

Types of collections maintained at ICRISAT

The various types of collections for maintenance have been identified and described by various individuals, committees, and organizations (House, 1981). The Rockefeller Foundation and the All India Coordinated Sorghum Improvement Project (AICSIP) have played leading roles in the initial stages (Rao, 1972; Rockefeller, 1970). Recently, ICRISAT (Mengesha, 1981) has taken the responsibility of world collection, maintenance, and conservation of sorghum germplasm.

Accession collection. This includes the available world collections. All new accessions will be added to this collection. So far, we have 22,466 accessions, each represented by a sample of 500 g.

Basic collection. A basic collection of 1245 accessions was selected from the world collection with stratification based on taxonomic race, geographical distribution, and ecological adaptation to the Patancheru, India location. Similar basic collections may have to be formed for other areas. The present material is being closely observed and used by sorghum breeders at ICRISAT as well as in Cameroun, Guatemala, India, Japan, Mali, Uganda, Burkina Faso (formerly Upper Volta), and the United States.

Spontaneous collection. This consists of wild relatives and weedy races of sorghum. So far, we have been able to maintain 278 accessions of 13 taxa.

Bulks collection. We are now in the initial stage of making bulks. Lines require careful observation and assessment before merging similar material into a number of bulks. House (1981) suggested that entries in one bulk should be similar in origin, height, maturity, and adaptation. We are now selecting different series of similar material from the conversion program to maintain them as bulks.

Named cultivar collection. This collection presently includes only 237 named and released cultivars.

Genetic stock collection. This material includes germplasm with known genotypes that are of special value as sources for certain desirable characters such as resistance to a specific disease. Each sample is maintained by selfing, to obtain a stock of about 1 kg, except for the male sterile lines that are maintained by hand pollination between corresponding male sterile and maintainer lines.

The genetic stocks maintained by GRU, ICRISAT are listed below:

Promising lines for shoot fly resistance	556
Promising lines for stemborer resistance	212
Promising lines for midge resistance	60
Promising lines for aphid resistance	9
Lines less susceptible to grain molds	515
Lines less susceptible to leaf blight	35
Lines less susceptible to anthracnose	124
Lines less susceptible to rust	43
Lines less susceptible to downy mildew	95
Promising lines for drought resistance	246
Glossy lines	501
Pop-sorghums	36

Sweet-stalk sorghums	41
Scented sorghums	17
Twin-seeded lines	131
Large-glume lines	71
Cytoplasmic A B lines	186

All resistant stocks are maintained as suggested by the entomology, pathology, and breeding disciplines and many of these lines are still being tested.

Conversion collection. Following a 1976 recommendation of the IBPGR Advisory Committee on Sorghum and Millets Germplasm (IBPGR, 1976), we are maintaining 176 converted lines obtained from the Texas A&M University/ United States Department of Agriculture (USDA) Conversion Program. The ICRISAT conversion program will soon produce additional converted lines from tropical germplasm.

Special collections. These collections are being assembled to conserve certain important lines selected and developed for their special qualities by various sorghum workers. So far, we have two such collections maintained at ICRISAT. We know there are many more such valuable collections being kept by various sorghum improvement scientists and we hope to assemble and maintain them at ICRISAT.

Karper's Nursery. This nursery was developed by the late Dr. R. E. Karper in Texas, USA, after the introduction of yellow endosperm "Kaura" germplasm from Northern Nigeria. These lines are short and photoperiod insensitive. They were assigned Indian Selection (IS) numbers and are part of the world collection.

ALAD Nursery. This material was developed and assembled by the Arid Land Agricultural Development (ALAD) Program, formerly based in Lebanon, by Dr. L. R. House and colleagues at Tel Amara Station, Lebanon. Some of the yellow endosperm "Kauras" from Karper's nursery comprised the basic material for this nursery. When Dr. L. R. House left Lebanon, this germplasm was sent to ICRISAT for maintenance. There are 1674 accessions in this nursery.

Future areas of collection

The priority areas for future collection of sorghum germplasm, as listed by Mengesha and Rao (1981), are as follows:

Asia—Nepal, Burma, Indonesia, India, Pakistan;

Eastern Africa—Ethiopia (isolated areas), southern Sudan, Uganda, Kenya, Mozambique, Zimbabwe;

West Africa—Sierra Leone, Ghana, Togo, Ivory Coast, Chad, Benin, Mauritania, Burkina Faso; and

Other Areas—South and North Yemen, China, Turkey, Syria, Central African Republic, Congo, Zaire, Angola, Morocco, Saudi Arabia, and Latin America.

The priority areas were identified in collaboration with the Food and Agriculture Organization of the United Nations (FAO)/International Board for Plant Genetic Resources (IBPGR), ICRISAT, and various other international and national scientists in germplasm resource areas. New and important collection areas are identified annually. Actual collection depends upon several factors, including government clearance, financial resources, collaborating national organizations, environment, and other logistical problems.

Evaluation

ICRISAT. More than 19,000 accessions have been evaluated for important morphoagronomic characters (IBPGR and ICRISAT, 1980). The sorghum descriptors published in the above report will promote a more systematic and uniform evaluation and exchange of information around the world. The variation we have in sorghum germplasm is summarized in Table 2. This diversity, the range of which is still expanding, is considered the most important aspect of germplasm collection and utilization.

Screening sorghum germplasm for insects, disease, *Striga*, drought resistance, grain quality, and other characters is being carried out in collaboration with other disciplines. The results of this sorghum evaluation and screening work are shown in Table 3.

Regional evaluation. Evaluation of sorghum germplasm in the rainy season (Kharif) at Patancheru, India, cannot provide complete information because most of the tropical germplasm is photoperiod sensitive. The problem of evaluating photoperiod sensitive germplasm has been recognized by several workers (Dalton, 1970; Eberhart, 1970; Mengesha and Rao, 1981; Webster, 1975).

Table 2. **Range of variation in the presently assembled world sorghum germplasm.**

Character	Range	
	Minimum	Maximum
Days to 50% flowering	36	199
Plant height (cm)	55	655
Peduncle exsertion (cm)	0	55
Midrib color	White	Brown
Panicle length (cm)	2.5	71
Panicle width (cm)	1	29
Glume color	Straw	Black
Glume covering	Exposed	Covered
Grain color	White	Dark brown
Grain size (mm)	1	7.5
Grain weight (g)/100	0.58	8.56
Tillering (no.)	1	15
Stalk sugar content (%)	12	38

Table 3. **Results of sorghum germplasm evaluation and screening.**

Screened for	Accessions (No.)	Promising lines (No.)	Identified and described by
Insect resistance			
Shoot fly	11,287	556	Sorghum entomology
Stemborer	15,724	212	Sorghum entomology
Midge	5,200	60	Sorghum entomology
Disease resistance			
Grain mold	16,209	515	Sorghum pathology
Leaf diseases			
Leaf blight	8,978	35	Sorghum pathology
Anthracnose	2,317	124	Sorghum pathology
Rust	602	43	Sorghum pathology
Downy mildew	2,459	95	Sorghum pathology
Drought resistance	1,752	246	Sorghum physiology and breeding
Other characters			
Low stimulant production for *Striga* germination	15,754	645	Sorghum breeding
Glossy character	15,260	501	Sorghum physiology and genetic resources unit
Popping character	2,694	36	Sorghum breeding
Sweet-stalk character	7,200	41	Genetic resources unit, biochemistry and sorghum physiology

This is the reason much importance is placed on multilocation evaluation of germplasm at or close to its original habit. This project will be conducted at selected regional centers in collaboration with national programs.

Last year, we successfully evaluated the entire Ethiopian sorghum germplasm of 5155 accessions at Nazareth and Arsinegelle, Ethiopia. The work was done in close collaboration with the Ethiopian Plant Genetic Resources Center (PGRC/E) and the Ethiopian Sorghum Improvement Project, with the financial support of Deutshe Gesellshaft für Technische Zusammernarbeit (GTZ), West Germnay.

Documentation

Data tabulated for 7114 IS numbers were computerized at IS/GR, Colorado, USA, using the EXIR program for easy retrieval. The same data were transferred to the ICRISAT computer through magnetic tape and a computer printout was released in the form of a catalogue. In addition to the data already computerized, evaluation data for important descriptors with passport information from IS 10051 onwards have been tabulated for computerization. By the end of this year, all evaluation data will have been entered in the computer for retrieval and diversity analysis.

Rejuvenation and maintenance

The samples that reach the critical level of quantity and/or fall below 85% viability are rejuvenated, and maximum care is taken to avoid altering the original genotype. However, limited change is unavoidable with every regeneration. The most practical and manageable method of maintaining the genetic purity of sorghum during regeneration is achieved by selfing about 20 representative heads of each line and mixing the selfed seeds. After controlled drying, a bulk sample of 0.5 to 1 kg of the threshed seed is placed in storage. The need for frequent regeneration is minimized with appropriate conservation practices.

Conservation

Germplasm conservation is as important as collection. Once the germplasm is collected, it must be properly preserved by appropriate techniques as detailed by the IBPGR (1979 and 1982). In general, the following points are prerequisites for a sound germplasm conservation system.

1. Seeds must be clean and free of foreign material.

2. Seeds must be dried in a drying room with cool temperature and low relative humidity (RH). The recommended standards for the drying room are 15°C and 15% relative humidity (IBPGR, 1982). The moisture content of sorghum seed reaches equilibrium at 6.4% when the relative humidity is about 15% (Roberts, 1974). The temperature recommendation may be too low to be practical. Justice and Bass (1978) discuss several methods for determining and reducing the moisture content of seeds in storage. The authors state that moisture content of seeds plays a most important role in longevity. Seeds should be thinly spread on trays while drying.

3. Viability or percentage of germination must be recorded initially and systematically monitored during storage. This information is needed to determine the extent and interval of rejuvenation.

4. A temperature of 4°C is regarded safe for medium-term storage and -18°C for long-term storage (Ellis et al., 1980).

5. A sufficient quantity of seed must be stored to ensure genotypic representation, to monitor viability, and for germplasm distribution. At ICRISAT, we keep about 500 g of each accession in medium-term, active storage. The IBPGR (1982) has recommended storing about 12,000 seeds of heterogeneous material and about 4000 seeds of homogeneous material in long-term, base storage.

6. Storage containers should be selected carefully. At ICRISAT, we are ordering aluminum cans with hermetic seals for long-term and with airtight screw caps for medium-term cold storage. Plastic bottles with screw caps presently in use will be replaced in due course.

7. Storage chambers: At ICRISAT, we are constructing modular rooms insulated with 10 cm polyurethane walls, ceilings, and floors. The floor is finished in heavy duty galvanized sheet steel. The chambers are essembled in a

large concrete room. The medium-term cold storage chambers are kept at about 30% RH with the use of a Rotair Model N, 300 dehumidifier. Compressors of 3-hp capacity and air-cooled condensers are mounted outside the storage chamber to supply cold air, which is constantly circulated by means of propeller-type fans. Each chamber is equipped with a control panel for effective and reliable manual or automatic operation.

8. Duplicate conservation: For the sake of safety and ease of distribution, it is advisable to store the world collection in at least two locations. Presently, several sorghum collections are stored in different countries of the world. According to Anishetty et al. (1981), relatively large sorghum collections are maintained at the locations listed in Table 4. Attempts are being made to obtain details of the various collections and to transfer samples of seed to the ICRISAT gene bank.

There is a plan to maintain and conserve world sorghum germplasm in four regions of the world, including those at ICRISAT and Fort Collins, Colorado, USA. The first new regional collection may be maintained in Niger. The second one is proposed for Central America. These regional conservations are justified because it is becoming more difficult to transfer germplasm from one region to another, mainly because of quarantine limitations.

Introgression and conversion

Conversion of photoperiod sensitive, tall sorghum genotypes to insensitive, short types is a useful tool for an effective and easy flow of tropical germplasm into various sorghum improvement programs (Dalton, 1970; Eberhart, 1970; House, 1981; Stephens et al., 1967; Webster, 1975). At present we are in the process of converting "Zera-zera" landraces from Sudan and Ethiopia, which are highly prized for their superior agronomic characters, but are of restricted use because of their photoperiod sensitivity and plant height. The F_3 populations of these partially converted landraces have produced promising segregants, as described below:

The desirable Zera-zera head characteristic was retained;

improvement of grain yield and quality was observed;

Table 4. **Major sorghum germplasm collections.**

Country and organization[a]	Type of collection	Number of accesions	Remarks
Argentina, INTA	active	2,700	
Australia	active	1,000	
China, CAAS	active	3,000	
Colombia, ICA	unspecified	912	
Ethiopia	landraces and cultivars	5,000	duplicate at ICRISAT
France, ORSTOM	landraces, wild, and weedy types	2,626	partly transferred
France, INRA	cultivar, dwarf, forage, and grain	400	
India, NBPGR	landraces	2,000	
India, ICRISAT	world collection	22,466	duplicate at NSSL
Japan	landraces and cultivars	466	
Madagascar	unspecified	300	
Malawi, Chitedze	landraces and wild type	483	
Mexico, INIA	introduced cultivars	3,000	
Romania	landraces, wild, and weedy types	4,900	
Thailand	unspecified	1,500	
The Soviet Union, Vavilov Institute	landraces, cultivars, and wild types	9,615	
The United States, NSSL	landraces, cultivars, and wild types	15,000	duplicate at ICRISAT
The United States, Mississippi	sweet sorghum and others	4,610	
The United States, Puerto Rico	landraces and cultivars	4,000	duplicate at ICRISAT
Venezuela	landraces and cultivars	494	
Yemen Arab Republic	Yemen and introduced	4,000	

a. CAAS — Chinese Academy of Agricultural Sciences
ICA — Instituto Colombiano Agropecuario
ICRISAT — International Crops Research Institute for the Semi-Arid Tropics
INIA — Instituto Nacional de Investigaciones Agricolas
INRA — Institut Nacional de Recherches Agronomiques
INTA — Instituto Nacional de Tecnología Agropecuaria
NBPGR — National Bureau of Plant Genetic Resources
NSSL — National Seed Storage Laboratory
ORSTOM — Office de la Recherche Scientifique et Technique d'Outre-Mer

the tropical, photoperiod sensitive material was successfully converted to insensitive genotypes; and

plant height was reduced to about one-half that of the original landrace.

We have recently initiated an introgression program by crossing *S. propinguum* and a promising sorghum cultivar (IS 18758, commonly known as E 35-1) from Gambella, Ethiopia. Preliminary results of this work are promising.

Summary

Germplasm is the most important raw material for any crop improvement program and yet the possible extinction of this invaluable resource is a reality the world has to face. One of the major objectives of the ICRISAT Genetic Resources Unit is to collect and preserve the vanishing germplasm and make it readily available for present and future utilization. The germplasm must be maintained as close as possible to its original form and genetic constitution. The sorghum germplasm collection at ICRISAT contains a total of 25,163 accessions. Systematic evaluation and documentation of these accessions are very important to understand and classify the collected material. They also facilitate identification and retrieval of useful germplasm lines for distribution and proper utilization.

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Prospects for Sorghum Improvement for Phosphorus Efficiency

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Introduction

Phosphorus (P) deficiency is common in sorghum-growing regions of the semi-arid tropics (SAT) (Sallanpaa, 1982), and ranks second in importance only after nitrogen (N) deficiency. In addition to the deficiencies of these two nutrients, other nutrient disorders may be common. For example, zinc (Zn) deficiency is common in India, potassium (K) and sulphur (S) deficiency in West Africa, and aluminum (Al) toxicity in Latin America (Sánchez and Salinas, 1981). Amelioration of P deficiency by application of P fertilizers is costly. Thus, improved farming practices have the best chance of adoption by the small subsistence farmers with limited financial resources if they involve only moderate amounts of low-cost inputs. To achieve this, we need to determine efficient fertilizer practices in conjunction with the development of P-efficient cultivars.

In this paper we will briefly summarize the relevent research at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), near Hyderabad in India. We will report our results from studies on three aspects of P nutrition, viz., soil, plant, and the associated microorganisms, and will discuss the prospects for crop improvement in P-stress (and related) environments.

Response of sorghum to phosphorus fertilization

Because of the wide variation in response to P fertilizer in farmers' fields reported in SAT India (Pal et al., 1982), much more critical base information is required to predict the occurrence of P deficiency. Both the nutrient demand by crops, and capacity of the

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soils to supply P are not well understood. Plant demand for P by high-yielding sorghum cultivars is high (Table I). For information on the soil supply and its adequacy, we rely on fertilizer response experiments, a number of which have been conducted at ICRISAT.

Table 1. **Mineral concentration[a] in grain and straw, and the total amounts of minerals removed by the crops of sorghum at a yield level of 5 tons of grain and 10 tons of straw per hectare during the 1979 rainy season crop on slightly acidic Alfisol at ICRISAT.**

Mineral	Mineral concentration (mg/g)		Nutrients removed by a crop yielding 5 tons of grain and 10 tons of straw per ha (kg)		
	Grain	Straw	Grain	Straw	Total
N	14.6	8.0	73.0	80.0	153.0
K	5.2	10.3	26.0	103.0	129.0
P	3.7	1.2	18.5	12.0	30.5
Mg	2.2	2.2	11.0	22.0	33.0
Ca	0.3	3.0	1.5	30.0	31.5
S	1.0	0.9	5.0	9.0	14.0
	μg/g				
Al	213	947	1.07	9.47	10.54
Fe	55	269	0.28	2.69	2.97
Mn	21	58	0.11	0.58	0.69
Zn	28	25	0.14	0.25	0.39
Cu	6	8	0.03	0.08	0.11

a. Data on mineral concentration represent average values for 12 cultivars grown at four fertility levels with mean slightly acidic-neutral fertilizer, of 45 kg N, 19 kg P/ha.
SOURCE: Seetharama N. and Clark, R. B. Unpublished.

Comparison of crops for their response to phosphate fertilizer

Most of the sorghum grown in the tropics is intercropped. In order to be able to predict the fertilizer needs of sorghum-based cropping systems, we need to know the response of each of the component crops to P fertilizer. A Neubauer-type pot experiment on a severely P-deficient Alfisol (about 1 μg/g Olsen-P) showed quite clearly the marked difference between sorghum and pigeon pea in their needs for added P. Without added P, pigeon pea growth was satisfactory over a period of 40 days, but both growth and P uptake by sorghum were severely limited (Table 2). These marked differences between sorghum and pigeon pea provided confirmation of results obtained in the field.

The experiment was located on a slightly acidic (pH 6.0-6.5) Alfisol (details in next section). Applications of water-soluble P caused much larger responses in sorghum and millet than in pigeon peas. The response by these cereals exceeded 100%, and the application of as little as 10 kg P/ha was sufficient to achieve much of the maximum possible response (Figure I). The benefit to

Table 2. **Effect of addition of phosphorus on growth of sorghum and pigeon pea 40 days after emergence in a pot experiment on a P-deficient Alfisol, ICRISAT, 1980.**

Characteristic	No added P	P added (μg/g)	Least significant difference (0.05)
Dry-matter production (g/pot)			
Sorghum	0.9	3.5	0.3
Pigeon pea	2.5	2.2	0.5
P uptake (mg/pot)			
Sorghum	0.6	3.7	0.3
Pigeon pea	3.4	4.4	0.7

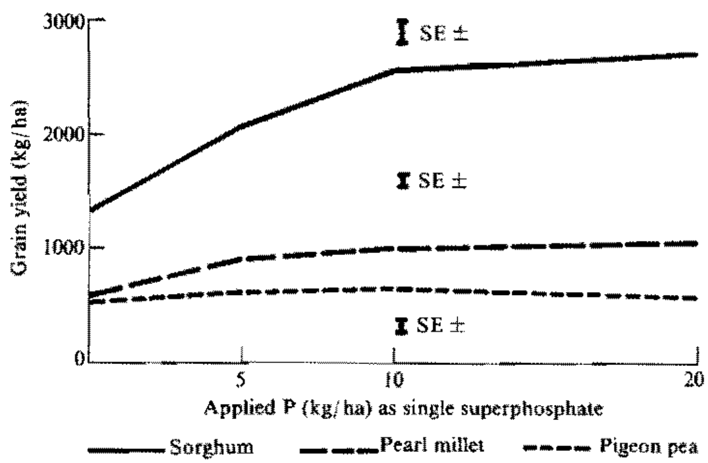

Figure I. *Effect of applied phosphorus on the grain yields of sorghum, millet, and pigeon pea at ICRISAT, 1976 to 1979.*

cost ratios from the first increment (5 kg/ha) of P were very attractive. Even more important, was the consistency of sorghum's response to added P on this Alfisol over the years, independent of seasonal rainfall (Figure 2), in contrast to the variability in N responses (Kanwar et al., 1984). In pigeon pea, the response was consistently small in all years; this crop has a small demand, and appears to be efficient in absorbing P from the soil.

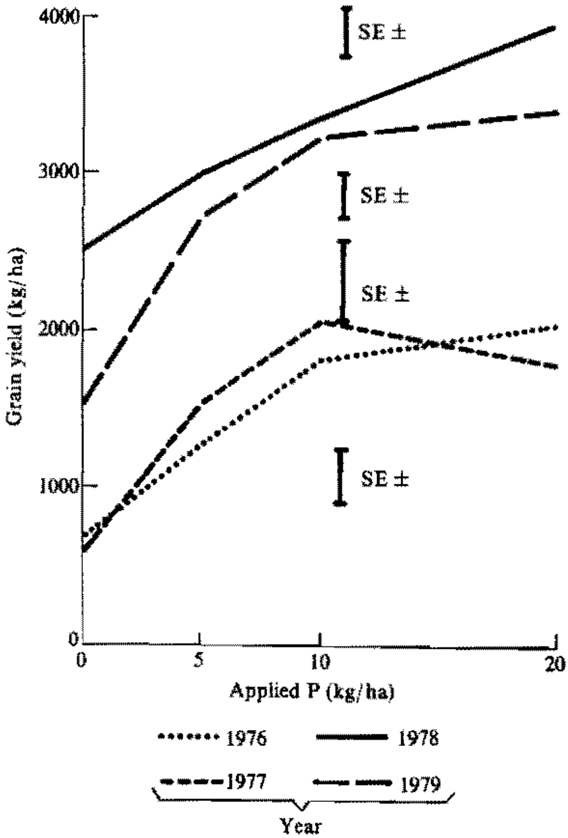

Figure 2. *Seasonal variation in the response of sorghum to single superphosphate at ICRISAT.*

Effect of sources of phosphorus

Studies of different sources of P require carefully designed experiments, because residual effects from a single application may last for several years. Thus, long-term experiments are needed. In such experiments, continuous monocropping is undesirable because of the likelihood of pest and disease buildup. To overcome this problem, we designed a simple two-year rotation of improved cropping systems consisting of an intercrop of millet/ pigeon pea in one year in rotation with a sole crop of sorghum in the next year. Duplicate main plots, one for each cropping system (millet/pigeon pea, and sorghum) ensured that each crop could be examined in each year, with a basal dressing of 40 kg N/ha applied to all treatments of millet, and 60 kg N/ha to sorghum.

Using this general design, we commenced an experiment in 1976 on an Alfisol to determine the extent to which rock phosphate could substitute for water-soluble P source. A major reason for studying the effectiveness of the rock phosphate was the shortage of indigenous sulphur sources in India to convert rock phosphate into soluble superphosphate.

Sorghum responded to rock phosphate but to a much smaller extent than to water-soluble P (Figure 3). Applying all the rock phosphate initially for the whole period of 4 years caused a significantly greater response than annual applications, but only at the highest rate. This experiment has two more years to run before completion of its second 4-year cycle. Thorough soil sampling then will indicate the changes in soil nutrient status.

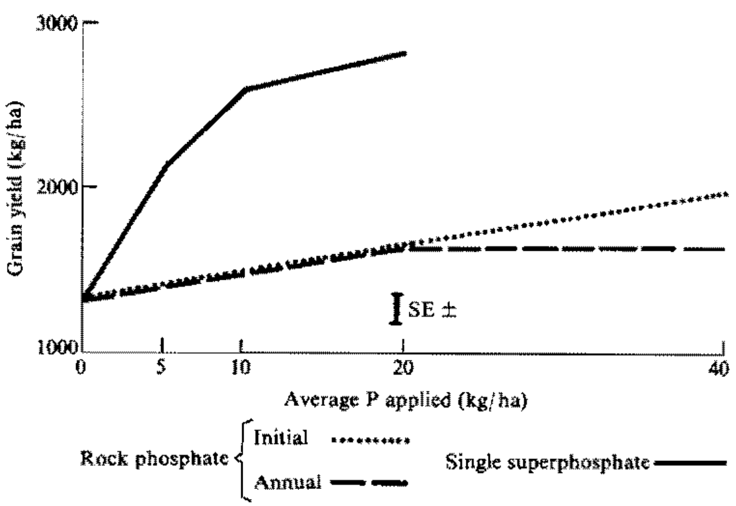

Figure 3. *Effect of source and rate of applied phosphorus on sorghum grain yield at ICRISAT, 1976 to 1979.*

Effect of soil

Preliminary experiments at ICRISAT have also indicated that Vertisols and Alfisols differ markedly in their soil-test/crop-response relationships for P applied to sorghum. In field experiments conducted in the 1981 and 1982 rainy seasons, sorghum responded appreciably to added P only when the available P in the Vertisol was extremely low (less than about 2 µg/g Olsen-P). Larger responses were observed in the long-term experiment on the nearby Alfisol (described above), with an initially higher available P content (3 µg/g). Thus, the two soils appear to have different critical limits. More rigorous testing was attempted in greenhouse experiments, using four sampling sites for each soil to provide a range in available-P status. Relationships based on the Olsen test differed little between the two soil orders, but when other predictive soil tests were used, very substantial differences were observed (Haile, 1983). Further research is in progress at ICRISAT.

Variation in sorghum genotypes for phosphorus nutrition physiology

Genotypic variation in nutritional efficiency can be due to one or more characteristics listed in Table 3. Plants adapted to soils of low fertility appear to have characteristics different from those adapted to optimal nutrient supply (Bieleski and Lauchli, 1983). Hence, we should evaluate sorghum genotypes for their nutrient efficiency under two different conditions:

Performance under moderate to adequate nutrient supply; and

performance when nutrient(s) is severely limiting.

Selection for nitrogen and phosphorus efficiency under adequate nutrient supply

The differential response of sorghum genotypes to the same level of applied nutrients suggests the existence of genotypic differences in the efficiency of nutrient absorption and distribution in the

Table 3. **Possible components of genetic variations for nutrient efficiency.**

I. Acquisition from the environment

1. Efficient root system.
   a) High root to shoot ratio, under nutrient deficiency.
   b) Greater lateral and vertical spread of roots.
   c) High root density or absorbing surface, more root hairs, especially under stress.
2. Physiological efficiency of nutrient uptake per unit root length.
3. Generation of reducing and chelating power (e.g., Fe).
4. "Extension" of the root systems by mycorrhizae.
5. Longevity of roots.
6. Ability of roots to modify rhizosphere to overcome low/toxic levels of minerals.

II. Nutrient movement across roots and delivery to the xylem

1. Lateral transfer through endodermis.
2. Release to xylem.
3. Control of ion uptake distribution by either root or shoot systems, or by both.
   a) Delivery to root or shoot under deficiency.
   b) Overall regulation of nutrient uptake and use at whole plant level.

III. Nutrient distribution within plants

1. Capacity for rapid storage when nutrient is available, for later use.
2. Degree of retranslocation and reutilization under stress.
3. Release of ions from vacuoles under nutrient deficiency.
4. Natural iron chelating compounds in xylem.
5. Rate of leaf abscission and rate of hydrolysis (of organic P, for example).

IV. Growth and metabolic efficiency under nutrient limitations

1. Capacity for normal functioning, even under relatively low tissue nutrient concentration.
2. Element substitution (e.g., Na^+ for K^+).

V. Polyploidy and hybridity levels.

SOURCES: Chaplin, F. S. 1980.
Gerloff, G. C. and Gabelman, W. H. 1983.
Goodwin, D. C. and Wilson, E. J. 1976.
Saric, M. R. 1983.

plant. We have observed considerable variation for different characteristics concerned with both N and P uptake and utilization (Table 4). Our studies also showed that N and P uptake were highly correlated with crop total dry matter production, and the efficiency of translocation (proportion of the total above-ground plant nutrient in the grain) of these minerals was also highly correlated to harvest index (Figure 4). This suggested that: selection for crop growth may automatically include selection for efficient N and P uptake; and that genotypes with reasonable harvest index will also have a reasonable ability to transfer these minerals to the grain.

Several experiments were conducted under different fertility levels and soil types to study the genotypic differences in nutrient uptake and utilization. We found that genotypes with approximately the same biomass and harvest index could vary significantly in N and P uptake as well as in transfer of nutrients to the grain. Such differences are usually masked when the data for the whole set of heterogeneous genotypes are analyzed together. Table 5 shows the variability for such characters in a set of five selected genotypes falling within a comparable maturity class (except IS 6380). Note, for example, that both P 721 and DL 642 have similar

Table 4. **Range of variability for nitrogen and phosphorus and translocation in 14 sorghum genotypes in an Alfisol, postrainy season, 1976.**

Variable	Maximum	Minimum	Mean	Coefficient of variation
Grain yield (g/plant)	54	8	35	30
Dry weight (g/plant)	130	51	79	26
Harvest index (HI) (%)	66	12	42	27
N in grain/plant (g)	1.02	0.16	0.51	33
N/plant (g)	1.25	0.51	0.74	23
N translocation index[a] (NTI) (%)	83	25	69	21
P in grain/plant (g)	0.60	0.07	0.26	44
P/plant (g)	0.65	0.19	0.33	32
P translocation index[a] (PTI) (%)	93	33	79	20

a. Calculated as the percentage of the total above ground N/P in the grain.

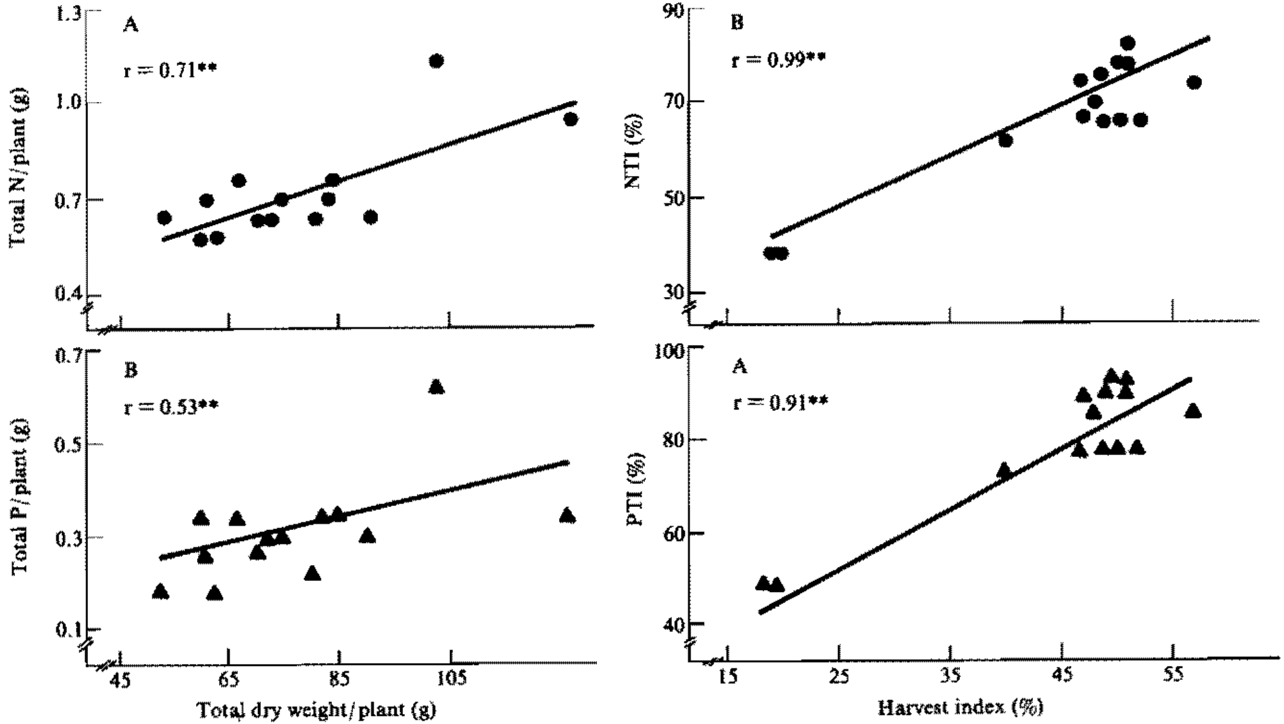

Figure 4. *(A) relationships between plant dry weight and N or P per plant; and (B) relationships between harvest index and N translocation index (NTI), or P translocation index (PTI).*

Table 5. **Nitrogen and phosphorus uptake, translocation, grain and plant dry weights in selected genotypes. Means of three environments with moderate or high N and P fertilization at ICRISAT.**

Attributes	Genotype P 721	IS 858	IS 2223	DL 642	IS 6380	Mean	Standard error of mean (SE) ±
Grain yield (g/plant)	18.3	27.2	21.8	24.1	5.1	19.3	3.8
Total dry weight (g/plant)	60.6	79.1	53.6	61.5	70.2	65.0	4.4
Harvest index (%)	30.2	34.4	40.7	39.2	7.3	32.0	2.6
Total N (g/plant)	0.78	0.77	0.48	0.56	0.67	0.65	0.06
Nitrogen translocation index (%)	44.9	46.8	56.3	42.9	23.9	43.1	4.1
g grain/g N taken up by the plant	23.5	35.3	45.4	43.0	7.6	29.7	13.1
g dry wt/g N in the plant	77.7	102.7	111.7	109.8	104.8	100.0	14.1
Total P (g/plant)	0.19	0.38	0.41	0.43	0.31	0.34	0.05
Phosphorus translocation index (%)	63.2	60.5	41.5	23.3	35.5	44.1	5.8
g grain/g P in the plant	96.3	71.6	53.2	56.0	16.5	56.8	12.9
g dry wt/g P in the plant	318.9	208.2	130.7	143.0	226.5	191.2	31.4
Days to 50% flowering	65	67	67	69	82	70	10

dry weights, but P 721 takes up 39% more nitrogen than DL 642, and has 9% greater nitrogen transfer ability. Similarly, IS 858 and DL 642 have nearly the same harvest index, but the P translocation index for IS 858 is 22% greater than for DL 642.

In order to conclude whether or not the selection for dry weight and harvest index also includes selection for nutrient uptake and translocation to the grain, crosses were made between parents listed in Table 5. F_2 plants were selected for a range of dry weight per plant and harvest index, and in F_3 progenies estimates of dry weight, grain yield, as well as N and P in grain and whole plants, were determined. The correlations between biomass and total nutrient taken up by the different groups of F_3 progenies were again very high ($P > 0.01$). Similar relationships were observed between harvest index and the N and P transfer efficiency.

Thus, the selection for biomass and harvest index under adequate nutrient supply also includes selection for traits concerned with nutrient (N and P) uptake and translocation to the grain. Under moderate to high soil-fertility status, breeding programs specifically aimed at increasing the efficient use of major nutrients are not needed because the inefficient entries will be culled out in the routine process of multilocational trials, or when tested under different fertility levels (Rao et al., 1981; Seetharama et al., 1984; also unpublished data of G. Alagarswamy on pearl millet at ICRISAT: personal communication).

Genotype evaluation under low soil phosphorus and without fertilization

The variability among the few selected genotypes in physiological nutrient use efficiency is shown in Table 5. Dry matter produced per unit P taken up by the plant was more variable than the dry matter production per unit N. In 1977, we selected 140 germplasm entries from a drought-screening nursery consisting of 1200 entries originating from drier regions of the SAT. While most of the lines showed severe P deficiency, these selected lines were free of such symptoms, and have comparatively high grain yields. Later they were repeatedly screened in a field of low soil P status (2 μg/g Olsen-P; an Alfisol, with soil-P further depleted by repeated cropping with maize) for comparing their ability to grow and produce reasonable yields. Table 6 shows the variations in a few selected germplasm and check entries for several characteristics.

Table 6. Genotypic differences in P use efficiency and mycorrhizal colonization in an Alfisol with Olsen P > 0.5 μg/g during the 1983 rainy season at ICRISAT.

Sorghum genotype	Origin	Days to flower	Grain (g/m²)	Biomass (g/m²)	Harvest index (%)	Phosphorus translocation index (PTI) (%)	P uptake (g/plant)	P use efficiency in plant: Grain (g/g P)	P use efficiency in plant: Biomass (g/g P)	Root colonized by mycorrhizae[a]: Field[b] (%)	Root colonized by mycorrhizae[a]: Pot study[a] (%)
Germplasm entries											
IS 10734	Chad	62	145	507	28.5	73.4	0.41	355	1243	34	57(22)[c]
IS 10747	Chad	67	84	337	24.9	68.7	0.62	134	548	64	34(25)
IS 7501	Nigeria	102	35	1264	3.0	19.3	0.84	42	1531	67	16(8)
IS 1320	Nigeria	99	19	676	3.5	18.6	0.54	39	1202	47	65(33)
IS 3860	Mali	95	23	518	4.2	27.3	0.37	60	1392	34	28(23)
Breeding lines											
DL 642	India	80	6	188	2.9	13.4	0.14	43	1358	25	23(10)
CSH 6	India	66	113	531	22.0	73.6	0.58	196	925	43	—(—)
CSV 5	India	84	7	294	2.5	8.3	0.32	21	887	—	—(—)
P 721	USA	80	4	110	3.5	11.5	0.12	32	917	—	—(—)
Mean for 24 entries[d]		78	40.2	415	10.7	35.0	0.42	101	1015	45	31
Standard error of mean (SE) (±)		2.5	14.8	112	2.3	8.6	0.08	23	166	9	15
Coefficient of variation (CV) (%)		4.5	34.4	38	30.2	34.7	28.7	33	23	20	49
Minimum		61	2.7	110	0.41	1.6	0.12	4	548	25	23
Maximum		104	15.7	1264	28.5	73.6	0.89	355	1531	67	65

a. Sampled at 40 days after planting.
b. Sampled at physiological maturity.
c. The figures in parentheses represent percent colonization when the pots are irrigated with 10 μg/g P solutions.
d. Entries studied totaled 24 except for root colonized by mycorrhizae which totaled 7 for field and 6 for pot study.

While differences in maturity and harvest index hinder accurate measurements of efficiency, the superiority of some genotypes (e.g., IS 10734 or IS 10747 over DL 642 and CSV 5) is clear both in grain yield and P uptake (Table 6). Among the released cultivars, the common Indian hybrid CSH 6 showed comparable efficiency to IS 10734 or IS 10747, indicating that the conventional breeding program has also resulted in fairly P-efficient cultivars.

No relationship was observed between concentration of P in plants and either grain or biomass productivity (Figure 5). For identifying the efficient genotypes, we need to consider both high P uptake as well as high efficiency of P utilization in grain and biomass productivity (Table 6). However, utilization quotients can vary widely within a genotype depending upon the quantity and pattern of nutrient supply (Myers and Asher, 1982; also *see* following section).

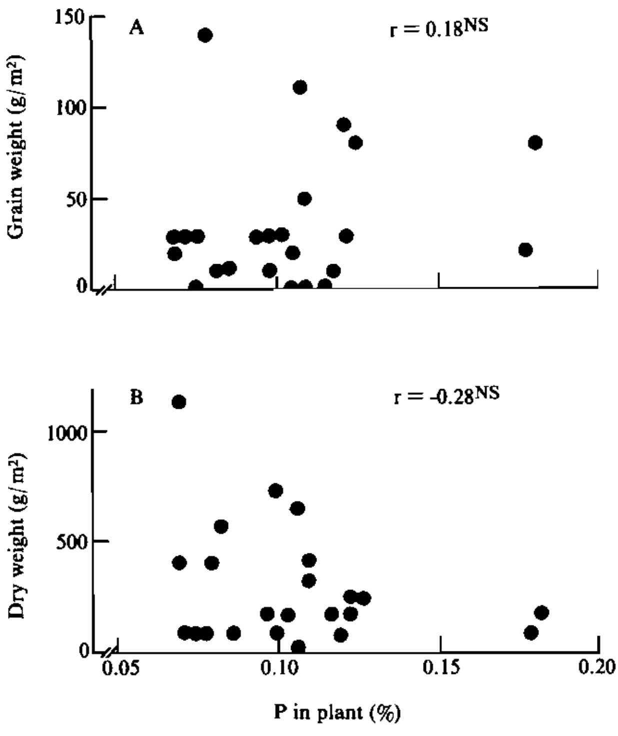

Figure 5. *Relationships between the concentration of P in plant at maturity and grain (A), or dry matter yields (B) at ICRISAT during the 1983 rainy season.*

Mycorrhizae

Differences among host genotypes

A survey of sorghum grown at ICRISAT in Alfisol soils showed extensive colonization of the roots by vesicular-arbuscular mycorrhizae (VAM). We found spore types of the following four major genera of VAM fungi: *Glomus*, *Gigaspora*, *Acaulospora*, and *Sclerocystis*. The extent of root colonization varied with location and plant cultivar, suggesting a possible cause for differences in the amount of benefits that the crop derives from such a symbiotic association under different conditions. The mycorrhizal root colonization, plant growth, and P-uptake response to inoculation vary with isolate of the mycorrhizal fungus used (Krishna and Diart, 1984). The dependence of symbiotic efficiency on the fungal isolate and soil environment is now well known (Abbot and Robson, 1982; Hayman, 1982) but differences between host genotypes are poorly understood.

Differences between host genotypes for percentage root colonization were detected both in field, and in pot culture using low P Alfisol (1 µg/ g soil; extracted with $NaHCO_3$) (Table 6). Addition of P resulted in a decrease in colonization rates, but the "efficient" genotypes such as IS 10734, IS 10747, and IS 1320 still showed higher colonization than "inefficient" hosts such as DL 642. Some interactions between P levels and host genotypes were apparent; the interactions between P levels and isolate efficiency (Howeler and Sieverding, 1983) have not yet been investigated.

Response to mycorrhizal inoculation

In a pot trial, using Alfisol mixed with sand, 1:1 v/v, inoculating sorghum hybrid CSH 5 with five separate species of mycorrhizal fungi increased growth by 15% to 120% (Table 7). Different mycorrhizal cultures varied widely in their ability to stimulate plant growth. The percentage of mycorrhizal colonization and the inorganic P in the xylem exudate correlated significantly, just as the correlation between colonization rate and plant P content (Figure 6). This indicates that P in xylem exudate can be used to select plants and fungus isolates for effectiveness of the symbiosis, in terms of P uptake by the plant.

Table 7. **Influence of mycorrhizal inoculation on shoot dry matter phosphorus concentration in the tissue, and the extent of mycorrhizal colonization[a].**

Fungal culture	Shoot dry matter (g/plant)	P concentration in tissue (mg/g dry wt)	Root colonization by mycorrhizae (%)
Glomus fasciculatum	1.93	5.1	66
Glomus mosseae	2.20	3.5	52
Gigaspora margarita	2.07	4.9	48
Glomus fasciculatum (E3)	1.43	1.8	40
Gigaspora calospora	1.14	3.1	36
Acaulospora laevis	1.33	2.2	32
Control	0.98	1.7	25
Standard error of mean (SE) (+)	0.20	0.2	0.5
Coefficient of variation (CV) (%)	21	13	11

a. 54-day-old plants; all values are means of 5 replicate pots each with one plant grown in 1:1 v/v sand: Alfisol soil mixture steam sterilized before sowing sorghum hybrid CSH 5.

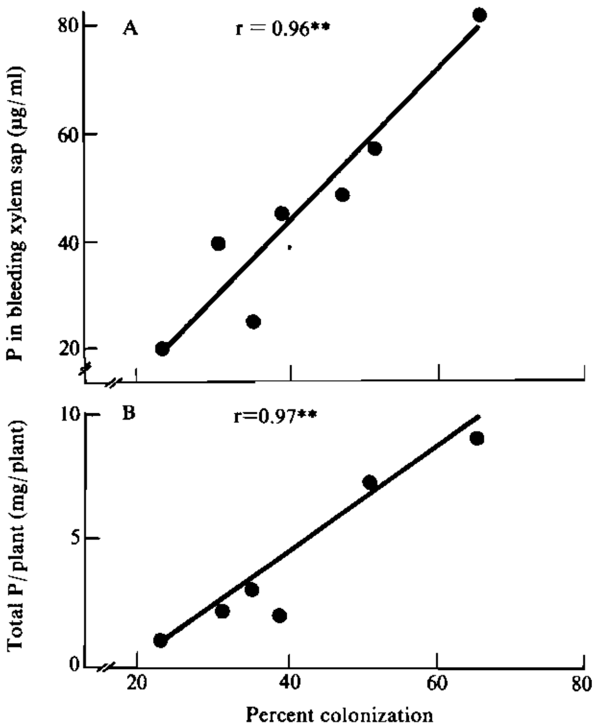

Figure 6. *Relationships between percent root colonization by mycorrhizal fungi and inorganic phosphate (P) determined by vanadium molybdate method in bleeding xylem sap (A), or total P/plant (B) from pot experiments at ICRISAT, 1984.*

Discussion

Our current understanding of the nature of crop adaptation to low levels of natural or added inputs is incomplete. On the one hand, some have unreasonable expectations that crops can be grown continuously without fertilizer; but, on the other hand some have the concern that use of "efficient" genotypes may "mine and squander" limited soil nutrients (Lambert and Arnason, 1982).

Clearly, the problems of P stress cannot be easily resolved, but they can be reduced to manageable proportions if many different aspects—pedological, soil amendment, fertilization, foliar feeding, ecological (e.g., intercropping), and plant breeding—are studied in concert (Fox, 1979). The efficient uptake of the soil P by plants (directly or through mycorrhizae) offers only a temporary solution in the absence of input of external P into the system. In the case of N, at least when high yields are not important, farmers with limited resources can minimize fertilizer N application by introducing legumes into their cropping systems. In the case of P, fertilization can, at best, be only delayed, but its eventual need is unavoidable. Hence, our aim should be to search for more specific combinations of plant genotypes, soils, and soil fertility practices to optimize net returns (Foy, 1983).

Breeding for P stress can be most efficiently carried out in the well-defined target areas, within narrower limits of the theoretical maximum stress and optimum growing conditions (Buddenhagen, 1983). Extremely high levels of efficiency (or stress resistance) may not be a realistic goal, as the different mechanisms involved in adaptation of plants to nutrient stress countervail (trade off) for each other. Plant breeders must be conscious of, and responsive to, both the specific local features of the environment and the possibility of better management techniques. For example, with acid soils of low P status, the soil acidity can be an advantage, in one way: the cheaper rock phosphate may be almost as efficient as the more costly water-soluble P. As P deficiency in crops on acid soils is commonly asssociated with a variety of other stresses (including drought or disease stress), breeders must carefully select and characterize their test locations.

Because the inheritance of traits related to P nutrition in sorghum is more complex than that of resistance to Al toxicity (Clark, 1982), screening and breeding for the former is likely to be more difficult. A nutrient culture system may supplement field evaluations to a much greater extent for screening for mineral toxicity (Duncan et al., 1983), but its usefulness for screening for P uptake, especially with mycorrhizal involvement, has been questioned (Howeler, 1981). However, considering the case with which nutrient stress can be quantified, and the possibility of creating uniform stress for screening, it should be easier to breed for resistance to mineral stress, than for resistance to drought or most other biotic stresses.

In addition to improving P uptake in P deficient or high-P-fixing soils, mycorrhizae are believed to assist plants to absorb other nutrients which may be limiting under acid soil conditions (Hayman, 1982). Mycorrhizae also confer drought resistance by increasing the water uptake, and confer disease resistance either indirectly by preventing predisposition of host plants to weak parasites, such as stalk rots (Jordan et al., 1984), or directly by competing with the soil-borne pathogens (Gerdemann, 1975). Mycorrhizae could also be helpful in overcoming the negative interaction between efficiency of uptake of different minerals (Brown et al., 1977) such as the interaction between the uptake of P and that of iron (Fe) or copper (Cu) (Timmer and Layden, 1980).

The efficiency of mycorrhizal fungi in promoting nutrient or water uptake may depend on a wide variety of factors. Fungus adapted to an alkaline soil may be less effective in acid soils. It is necessary to have an understanding of the effects of environmental stresses (e.g., temperature or waterlogging), and cultural practices (e.g., application of fungicides or lime) on the mycorrhizal association of sorghum plants. Research at ICRISAT is being directed to select sorghum lines showing higher colonization rates under a wide range of environmental conditions (inluding soil P levels), and to quantify the mycorrhizal benefit to the host plant when grown in soils with low P status, especially in lateritic soils.

Research on several aspects of P nutrition of sorghum is urgently needed. Better definition of the efficiency of mycorrhizal colonization, and the efficiency of use of P taken up by the plant for its growth and grain yield are required for practical applications. However, gross agronomic evaluation of genotypes under representative field environments should precede selection based on physiological criteria. Evaluation and improvement of methodologies are needed for characterizing the critical limits of nutrients in different soil types. The role of mycorrhizal colonization in determination of critical levels of P in the soil should also be researched. Critical tissue concentrations in sorghum genotypes, along with the possible interaction with other factors affecting crop growth (Myers and Asher, 1982) and health, also need to be investigated before starting any large-scale breeding efforts to increase nutrient efficiency. Such work on critical concentrations is currently in progress in Australia (C. J. Asher and D. G. Edwards, University of Queensland, personal communication).

As seen in Table 6, the sorghums collected in West Africa seem to be more efficient in P uptake and utilization. Genotypes with the best developed nutritional efficiency traits can be expected to be found in the local cultivars from the most infertile soils, e.g., the leached, Alfisol regions of West Africa (S. W. Buol, North Carolina State University, Raleigh, NC, USA, personal communication). It is worthwhile to screen more sorghum germplasm from the sub-Saharan West Africa, especially from the medium-high rainfall areas, and from similar regions in Tanzania, Thailand, and the hilly areas of eastern India.

Summary

Phosphorus (P) deficiency is common in the tropics. Because the need for added P depends upon characteristics of both the crop and the soil, systematic studies are being made in our experiments at ICRISAT, India. Sorghum and pearl millet on an Alfisol responded substantially to added P fertilizer, but the response of pigeon pea was small. Only 10 kg P/ha was needed to achieve most of the maximum possible response; rock phosphate was much less effective than water-soluble P, as the soil was only slightly acidic. Indications have been obtained that Vertisols differ from Alfisols in their soil test/crop response relationships for P applied to the sorghum.

Where fertility is adequate or nearly so, no special breeding program for increasing the efficiency in uptake or utilization of P appears to be needed; plant performance gives an adequate index of P efficiency. However, because there is significantly more genotypic variation in the efficiency of P uptake and utilization under very low P supply than under a moderate supply, breeding cultivars for low P soils is worth pursuing.

Genotypes adapted to low P conditions showed a greater degree of root colonization by mycorrhizal fungi. Response to inocula-

tion with different mycorrhizal fungi increased dry matter and P content of sorghum plants more than two-fold. Estimation of inorganic P in the bleeding xylem sap can be a quick test for rate of colonization. The significance of the above findings for improvement of sorghum grown on low-nutrient status soils is discussed.

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Evaluation of Mineral Elements in Sorghum Grown on Acid Tropical Soils

*R. B. Clark and L. M. Gourley**

Introduction

Because of its tolerance to drought and many other stress conditions, and its relatively lower requirement for fertilizer, sorghum production has expanded throughout the world, including Latin America. A major constraint limiting sorghum (*Sorghum bicolor* (L.) Moench) and other crop production in Latin America has been mineral element problems associated with acid soils. Since considerable land masses of South America are acid (Figure 1), many mineral deficiency and toxicity problems occur in plants grown on the soils of this continent. Many of the mineral element problems inherent to these soils may be described by noting the effects of pH on the availability of mineral elements essential to plant growth (Figure 2). Deficiencies in calcium (Ca), phosphorus (P), magnesium (Mg), and molybdenum (Mo), and toxicities of aluminum (Al), manganese (Mn), and iron (Fe) might be predicted for plants grown on acid soils. The extensiveness of mineral deficiency and toxicity problems on the acid/infertile tropical soils of Latin America has been reported by Sânchez and Salinas (1981).

A feasible method to enhance production of sorghum and other crops on acid soils is to develop plants that better tolerate mineral deficiency and toxicity stresses associated with these soils. To do this, differences among genotypes to grow, absorb, and use mineral elements need to be identified and evaluated.

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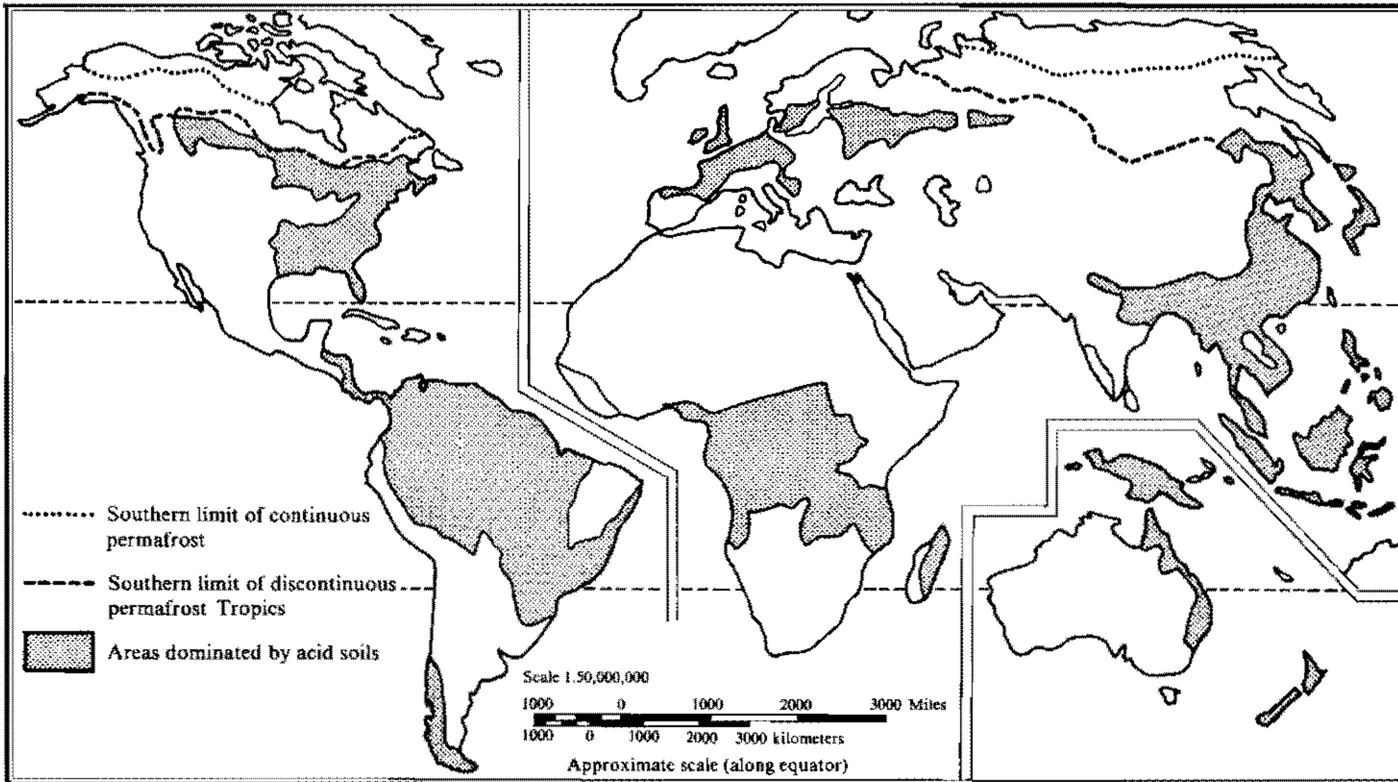

Figure 1. *Distribution of acid soils in climates warmer than cryic (annual soil temperature greater than 8°C).*

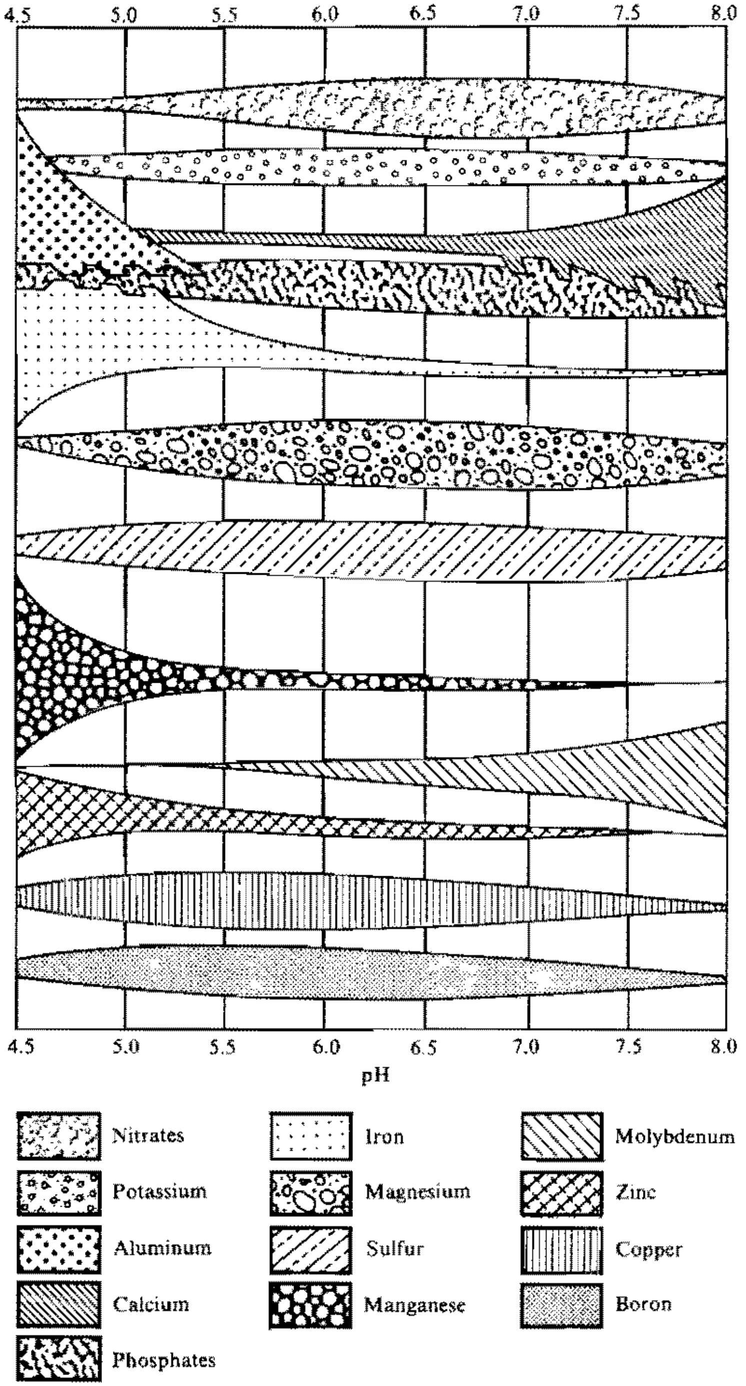

Figure 2. *Effects of pH on the availability of mineral elements in mineral soils.*

The objectives of this study were:

To describe the methodology used to determine mineral elements in plant tissue;

to determine mineral element concentrations and contents in sorghum plants grown on acid tropical soils of Colombia, South America; and

to observe differences and evaluate genotypes for mineral element concentrations and contents.

Determination of mineral elements in plant tissue

Many methods are used to determine mineral elements in plant, water, and soil samples. The various techniques available and their desirable or undesirable characteristics are not discussed here. A method that has been incorporated and used successfully at the University of Nebraska at Lincoln (UNL) for the analysis of mineral elements in plant materials is described.

The method used to determine mineral elements in plant samples at UNL, preparation of samples, and some of the limiting factors have been described by Knudsen et al. (1981). In short, the technique consists essentially of pressing pellets from dried ground plant material (Figure 3, left); putting the pellets into a tray, putting the tray into the instrument chamber (Figure 3, upper right); creating a vacuum in the chamber; answering four questions on a microcomputer terminal (Figure 3, middle right; and Table 1); and waiting for the results (Figure 3, lower; and Table 1). Using the present program, a tray of 40 samples can be analyzed in about 2.5 hours, or about 3.5 minutes per sample. Concentrations of Ca, P, Mg, Mo, Al, Mn, Fe, silicon (Si), sulfur (S), chlorine (Cl), potassium (K), copper (Cu), and zinc (Zn) are obtained for each sample in the general program used. Additional programs have been developed to analyze other elements. The instrument is capable of analyzing elements above number 11 in the periodic table [sodium (Na)] with an atomic weight greater than 23. Sodium can be analyzed if it is in the tissue at about 0.5 mg/g. The only mineral elements required for plant growth that cannot be determined by energy dispersive X-ray fluorescence (EDXRF) are nitrogen (N) and boron (B).

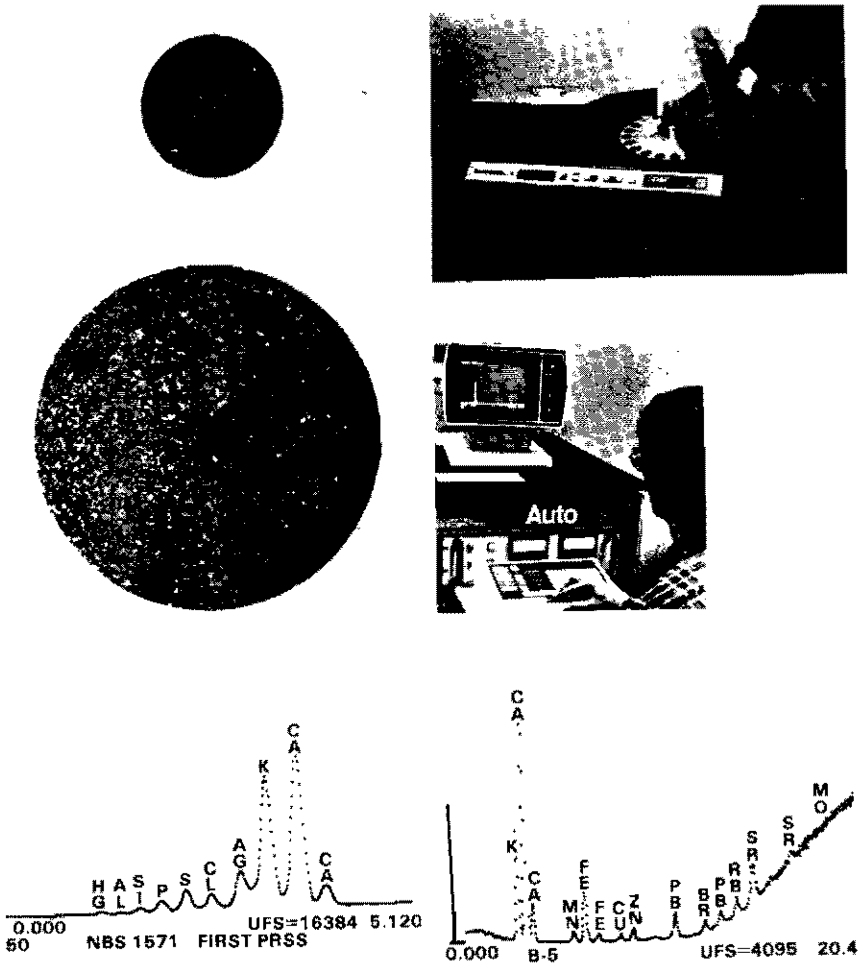

Figure 3. *Energy-dispersive X-ray fluorescence (EDXRF) analysis of plant samples. Small and large pellets (left); putting samples in instrument chamber (upper right); cathode ray tube, X-ray electronic instrument; and instrument keyboard (middle right); graphic peaks of mineral elements analyzed by EDXRF (left and right bottom).*

Table 1. **Printout of mineral element concentrations analyzed by EDXRF.**

RBC/COLOMBIA	5-19-83	1-39
	8:00 AM	1570-10

PROG 2
Plant Analysis: Small Pellets

Samples: How many? 40
First No.? 1
First Position? 1
LABEL: Colombia Mg Al Si P S Cl KE Co:SP Mg-Cl 4/83 101

Fit [0.00 ->10.23] Al
Refit [0.00 ->10.23]

COLOMBIA 1 75SECS ,CHISQD=109.86

Drift Factor 0.900

Mg	K-Ratio=	0.00538	Mg	0.58219
Al	K-Ratio=	0.00000	%Al	-0.00799
Si	K-Ratio=	0.02321	%Si	2.08518
P	K-Ratio=	0.00938	%P	0.39147
S	K-Ratio=	0.01264	%S	0.26916
Cl	K-Ratio=	0.06295	%Cl	0.97619
KE	K-Ratio=	0.15793	%KE	0.00000 Mo K Ca Mn Fe Cu Zn CO:SP

K-Mo 4/83 102
Fit [2.00- >22.46]

COLOMBIA 1 180SECS CHISQD= 2.18

Drift Factor 1.000

Mo	K-Ratio=	0.00217	%Mo	0.00227
K	K-Ratio=	0.20153	%K	4.44660
Ca	K-Ratio=	0.00598	%Ca	0.41789
Mn	K-Ratio=	0.00023	%Mn	0.00555
Fe	K-Ratio=	0.00070	%Fe	0.01102
Cu	K-Ratio=	0.00029	%Cu	0.00195
Zn	K-Ratio=	0.00199	%Zn	0.01310

The low detection limit by the EDXRF procedure is not usually as low as that for many other methods. However, the low detection limits of EDXRF are lower than the concentration of elements in severely deficient tissue, except for Mo in plant materials like the cereals. Molybdenum requirement in sorghum is less than 1.0 μg/g, and at this concentration, Mo is difficult to analyze by most methods. The low detection limits for many mineral elements using a silver X-ray tube are given in Table 2.

Table 2. **Low detection limit (LDL) for mineral elements analyzed in plant materials by EDXRF.**

Element	LDL[a] (μg/g)	Element	LDL[a] (μg/g)
Na	170.0		
Mg	135.0	Cd	9.0
K	40.0	Cr	2.3
Al	32.0	Co	2.0
Ca	30.0	Rb	2.0
Si	28.0	Sr	1.5
P	25.0		
S	19.0	Ni	1.2
Cl	9.3	Pb	1.2
Mn	1.9	Hg	1.0
Fe	1.4	As	1.0
Ca	1.1	Br	0.8
Zn	1.0	Ba	0.5
Mo	1.0	Se	0.5

a. For reliable quantitative values, element concentrations should be about three-fold higher than the LDL.

This procedure has benefited our research program immensely. We can make element analyses with 50 to 100 mg plant tissue (preferably 100 mg), which is not the usual case for many other multielement analysis techniques. This allows us to analyze mineral elements in small amounts of tissue such as individual seedlings, specific plant parts, or segments of plant parts. Sample sizes that must be sent long distances, especially foreign countries, are decreased. The sample is not destroyed in the analysis procedure, so questions that may arise about element concentrations in particular samples can be answered by reanalysis without making new pellets or losing the sample because of its injection as a liquid into the instrument. Accurate weighings of samples for pellets are not needed (weights can be within ±25% of 100 mg without encountering errors). Other time-consuming and labor-intensive procedures such as digestion, ashing, dilution, resuspension and disolution in acids, and decanting are not needed. The need for special glassware and chemicals is also reduced. The cost for specially trained personnel and time involved for analysis have been lowered. This method has allowed the analysis of the large numbers of plant material that must be evaluated in a plant-breeding program at a cost that is usually lower than most procedures.

A major disadvantage of the EDXRF procedure is that so few laboratories use it that some of the normal aids, programs, and repairs have not been developed or are not available for routine use. We have had to develop our own analysis system without the benefit of outside experience.

In the cooperative International Sorghum and Millet Program (INTSORMIL) research program, we have performed the mineral element analyses of plant tissue when these analyses are required or desired. These analyses have enhanced our research ability and have given us needed information that would otherwise be unavailable. The ability of physiologists to better interact with breeders has been facilitated, and reasons why individual plants or genotypes are more tolerant to mineral stress conditions are being better understood, defined, and recognized.

Mineral element variability of sorghum genotypes grown on acid tropical soils

In cooperation with Dr. L. M. Gourley, while assigned at the Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia, mineral element analyses of sorghum genotypes grown on Colombian soils have been performed. The analyses were performed to better understand differences in genotypes for uptake and accumulation of elements in plants grown on acid/infertile tropical soils and how these mineral elements might relate to plant tolerance to these acid soils. Experiments were conducted in which 60 sorghum genotypes were grown on both Carimagua and Palmira soils in a greenhouse (Experiment 1), and 50 sorghum genotypes were grown on a Carimagua soil limed with 2 and 6 tons/ha in the field (Experiment 2). Some of the chemical properties of these soils are listed in Table 3.

Materials and methods

Experiment 1

Plastic pots (16 cm diameter x 18 cm deep) were filled with 2.0 kg soil which had been fertilized with 45 P and 42 K kg/ha. Micronutrients and urea were added to the pots as a liquid at the rate of 15 N, 1.8 B, 1.8 Cu, 1.6 Zn, and 0.3 Mo kg/ha. Two additional liquid N treatments were supplied weekly at the rate of on which sorghum was grown at Carimagua and Palmira, Colombia.

Carimagua				Palmira
2 tons lime/ha		6 tons lime/ha		
0-20 cm[a]	20-40 cm[a]	0-20 cm[a]	20-40 cm[a]	0-40 cm[a]
4.5	4.6	4.8	4.9	7.0
37.0	25.0	38.0	24.0	35.0
7.7	1.7	6.4	1.7	78.0
2.9	2.8	1.6	2.1	ND[b]
1.2	0.6	2.4	1.0	10.3
0.31	0.12	0.42	0.13	5.2
0.25	0.12	0.22	0.10	1.00
4.65	3.65	4.64	3.33	16.50
61.0	76.0	35.0	62.0	-

Table 3. **Chemical properties of soils (limed and unlimed) on which sorghum was grown at Carimagua and Palmira, Colombia.**

	Carimagua					Palmira
	No lime	2 tons lime/ha		6 tons lime/ha		
Parameter	0-40 cm[a]	0-20 cm[a]	20-40 cm[a]	0-20 cm[a]	20-40 cm[a]	0-40 cm[a]

red as needed with
ducted during No-
IAT. The daylength
± 2°C daytime and
ındomized complete

listed in Table 4, TX
At the 2-leaf stage of
pot. Plants were 21
leaf stage when the
plants were visually
l symptoms on the
oil surface, the stalk
d the plants in each
oots from the plants
visual abnormalities
l-air oven for a week
ed (because of soil
pass a 0.5 mm (40-
or mineral element

Experiment 2

ia), seeds of 50 of the
planted during early
2 and 6 tons/ha of
were 75 N, 40 P, and
planting and N was
eaf stage of growth.
u, and 0.3 Mo kg/ha
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200,000 plants/ha.
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, visual ratings were
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types were used as
y susceptible to Al
toxicity). Random

selections of at lea
collected from pla
dried at 60⁰C for or
samples were dried
pass a 0.5 mm scre
analysis.

Table 4. **Name and so**
and Palmira

Pedigree	So
CMSXS154	Br
3DX57/1/1/910	Br
5DX61/1/6/2	Br
ICA NATAIMA	Co
ISR-1	Te
IS 1207C	Te
IS 3625C	Te
IS 5887C	Te
IS 6845C	Te
IS 6964C	Te
IS 7173C	Te
IS 7254C	Te
IS 7273C	Ta
IS 6841C	Te
IS 7542C	Te
IS 7786C	Te
IS 7909C	Te
IS 7994C	Te
IS 22539C	Te
IS 23564C	Te
IS 12610C	Te
IS 12612C	Te
IS 12685C	Te
MN 712	M
MN 1204	M
MN 1388	M
MN 1391	M
MN 1533	M
MN 1557	M
MN 1705	M

d-air oven (70°C) for
ɔellets were pressed.
if less than 100 mg)
d analyzed for P, K,
EDXRF according

:sults and discussion

Experiment 1

had no unusual or
:oms on their leaves,
ver, plants grown on
ıy showed deficiency
ıd some were dead.
l were about 6-fold
soil (Tables 5 and 6).
wer available P, Ca,
ıan the Palmira soil

est dry matter yields
plants grown on the
Tables 5 and 6). The
y matter yields when
ghest and lowest dry
ı soil.

est mineral element
gua soil did not have
trations when grown
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n concentrations of
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Mean S, Cl, and Zn
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s lower in leaves of
es of plants grown on
cted in the leaves of
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n the leaves of plants
Al was reported for

Differences in the r
concentrations were
soil than for plants gr
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are considered to be
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For plants grown c
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Al would interact se
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Clark, unpublished da
ed in roots than in lea
because of soil contam
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levels (R. B. Clark, u
determined in plant
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higher mean concentr
the Carimagua soil. I
concentrations were n
limed Quilichao (Ultis
the same unamended s
association of Si wit
susceptibility to acid
reported to overcome
(Foy et al., 1978; Wer
in leaves of sorghum p
mg/g (Tables 6, 7, ar
unpublished data).

Contents of P, K, C
11.4, 9.8, 7.5, 5.6,
respectively, in leaves
leaves of plants grow
Again, the mineral ele

Cl	0.85	4.57	2.35	0.09	5.4	3.3	352.8	92.9	8.8	106
Si	2.18	12.88	5.30	0.23	5.9	18.0	646	196	17.0	51.5
	μg/g					μg/plant				
Al	< 130[d]	2650	592	42.0	20.4	38	715	189	16	18.6
Mn	38.5	91.8	61.1	1.2	2.4	0.21	5.83	2.33	0.17	27.9
Fe	264	1020	514	17.0	3.8	0.30	4.41	1.87	0.14	14.8
Cu	19.3	54.0	31.2	0.8	2.8	0.08	3.56	1.22	0.11	42.9
Zn	8.4	50.1	32.8	0.8	6.0	0.08	4.12	1.30	0.11	53.5

a. High/low = amount of change noted between the highest and the lowest genotypes.

b. Visual deficiency/toxicity symptom ratings were: 1.0 = none, 2.0 = slight, 3.0 = moderate, and 4.0 = severe.

c. Stages of maturity descriptions were: 1.0 = vegetative, 2.0 = floral initiation, 3.0 = bloom, and 4.0 = grain fill (milk).

d. Low detection limit for the analysis procedure.

Table 8. **Dry matter yield (DMY) and mineral element concentration and content ranges, means, standard error (mean), and high/low values for 50 sorghum genotypes grown on a Carimagua, Colombia, soil limed with 6 t/ha dolomitic limestone in the field (Experiment 2).**

	Element concentration					Element content				
	Range					Range				
Parameter	Low	High	Mean	SE $\bar{X}$	High/low[a]	Low	High	Mean	SE $\bar{X}$	High/low[a]
Visual symptoms[b]	1.0	3.0	1.6	0.1	3.0					
Plant height (cm)	70	192	124	5.0	2.7					
Stage of maturity[c]	1.0	4.0	2.0	0.1	4.0					
DMY (g/plant)	18.2	75.3	40.0	2.0	4.1					
			mg/g					mg/plant		

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ere noted. The range
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Carimagua soil than in
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Experiment 2

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gua soil limed at 2 and
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nts with the highest dry
vith 2 t/ha lime were as
han the plants with the
e soil with 6 t/ha lime.
atter yield when grown
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when grown on the soil
al deficiency/toxicity
own on the soil with 2
with 6 t/ha lime. Plants
were generally shorter
lants grown on the soil

K, Mg, S, Cl, and Cu in
limed Carimagua soil
fferences among these
at the two lime rates,
ments that showed the
because of lime addi-
be expected, the mean
e rate of lime added to
as also higher in leaves
aves of plants grown at
and Al were lower in
l of lime than in plants
e of Al concentrations
ha of lime compared to
oncentrations of Al in
e were similar, but the
otype with the highest

Table 5. **Dry matter yield (DMY) and mineral element concentration and content ranges, means, standard errors (mean), and high/low values for 60 sorghum genotypes grown on a Carimagua, Colombia, soil in a greenhouse (Experiment 1).**

	Element concentration					Element content				
	Range					Range				
Parameter	Low	High	Mean	SE $\overline{X}$	High/low[a]	Low	High	Mean	SE $\overline{X}$	High/low[a]
	mg/plant									
DMY	16.3	79.7	47.8	1.2	4.9					

Breeding Aluminum-Tolerant Sorghums

*R. A. Borgonovi, R. E. Schaffert, and G. V. E. Pitta**

Introduction

The "Cerrado" region of Brazil is the agricultural frontier of the 1980's. This vast region, once thought to be unsuited for crop production, is now receiving the attention that it merits from both policy makers and agricultural researchers. By the end of this century, it is expected that this region will be a principal producer of both food and feed in Brazil. The Cerrado has its peculiarities and problems, and technology must be generated for its agricultural potential to be fully exploited (Alves, 1983).

Distribution and characterization of the Cerrado region

The area under Cerrado vegetation in Brazil occupies approximately 180 million hectares or about 20% of the total area of the country. The Cerrado is distributed in four of the five major regions of Brazil (Figure 1); the Central West, Southeast, Northeast and the North (Ferri, 1977; Goedert et al., 1980).

The climate of the major part of the Cerrado can be classified as a hot and humid climate, with a long, dry season. The average daily temperature ranges from 20°C to 26°C and the average annual rainfall varies between 1000 and 2000 mm (Lopes, 1983).

Water stress is common during the rainy season and frequently reduces the yield of the various crops in this region. Wolf (1977) showed that periods of one to four weeks without rain frequently occur and are complicated with high levels of solar radiation and

* Sorghum breeder (deceased) at the Centro Nacional de Pesquisa de Milho e Sorgo (CNPMS)/Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA); sorghum specialist at the Instituto Interamericano de Cooperación para la Agricultura (IICA)/EMBRAPA; and soil specialist at CNPMS/EMBRAPA, Cx Postal 151, 35700, Sete Lagoas, Minas Gerais, Brazil, respectively.

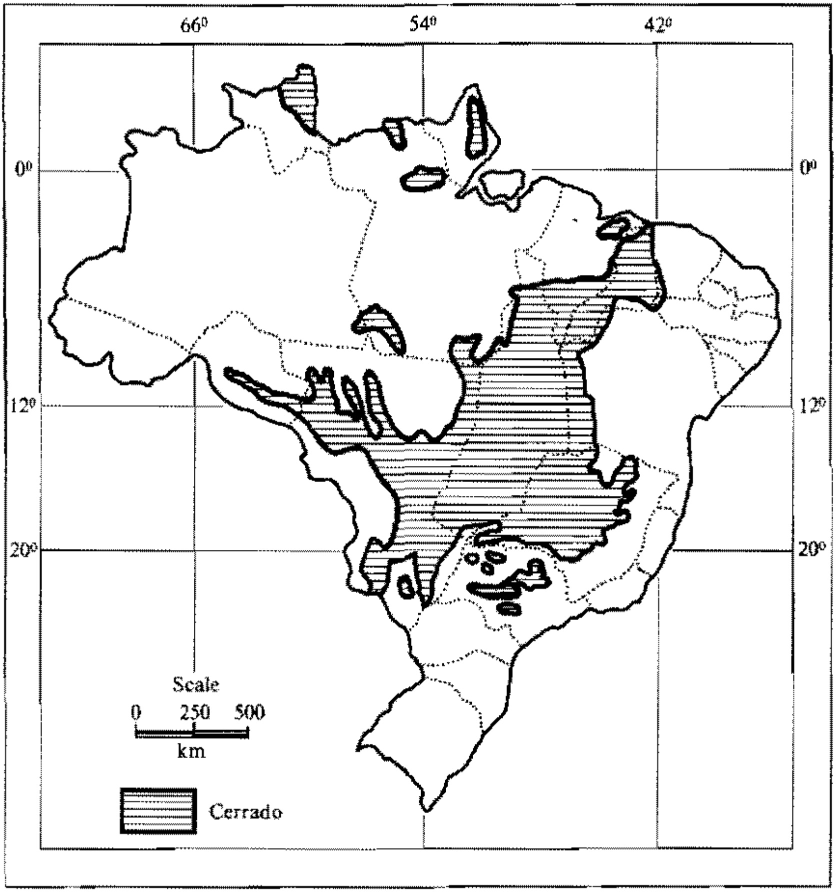

Figure 1. *Distribution of Cerrado and areas in transition in Brazil. (Adapted from EMBRAPA, 1978.)*

high potential evapotranspiration (Figure 2). These periods are called *veranicos* and may cause serious limitations for sensitive annual crops without the use of supplemental irrigation (Lopes, 1983).

The topography of these areas under Cerrado vegetation is generally characterized as plain or slightly rolling, facilitating its mechanization (Goedert et al., 1980).

Fifty-six percent of the area under Cerrado vegetation is classified as red yellow, dark red, and "Roxo" Latosols, according to Sánchez et al. (1974). The great majority of these soils are infertile due to the high phosphorus adsorption capacity, low pH,

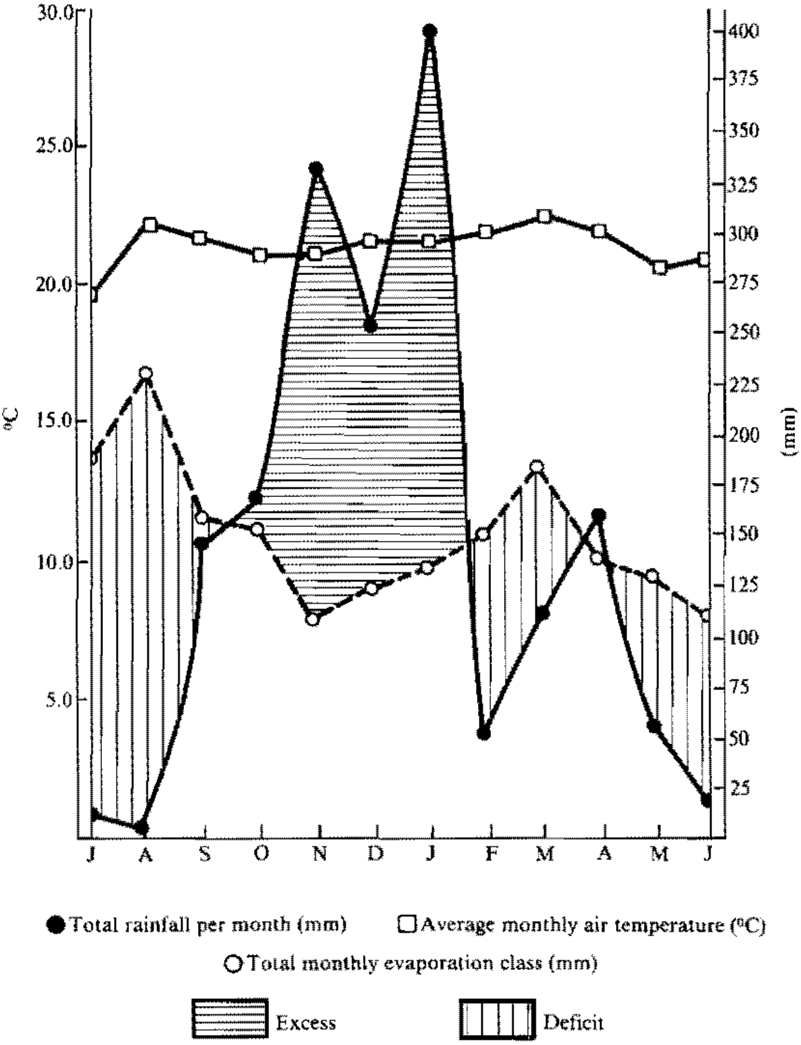

Figure 2. *Principal climate characteristics of Cerrado soils.* *[Adapted from EMBRAPA-CPAC (Centro de Pesquisa Agropecuária dos Cerrados) 1978.]*

high aluminum saturation, low cation exchange capacity (CEC), and a general deficiency of nutrients, principally phosphorus, nitrogen, potassium, calcium, magnesium, and zinc (Lopes and Cox, 1977; EMBRAPA-CPAC, 1978). The Latosols are normally high in clay content but, due to their structure, the water infiltration rate is high and the water-holding capacity is low, thus aggravating the situation of reduced water content in these soils (Lopes, 1983).

The potential of the Cerrado region for grain production

Currently, about 10% of the total grain production (including soybeans) in Brazil is produced in the Cerrado (Goedert et al., 1980). Considering that the exploitation of the Cerrado for grain production has recently been accelerated with special programs such as the "POLOCENTRO," the authors estimate that within 20 years (2 million hectares have been incorporated per annum) 50 million arable hectares of the Cerrado will be in crop production. The principal crops are expected to be beans, corn, soybeans, grain sorghum, and wheat. The area cultivated with sorghum (Table 1) is expected to be 4% of the total area. However, considering that one of the sorghum production systems recommended by research and being adopted by farmers in Southern Goias and the Minas Gerais State (Triangle Region) is the soybean-grain sorghum double-cropping system (EMGOPA, 1978, 1979, 1980, 1981) the area planted with sorghum should be considerably greater than that suggested previously by Goedert et al. (1980). In this case, considering that 20% of the total soybean acreage could be easily double cropped with sorghum, the projected grain sorghum production for the year 2000 is 15 million tons per annum (Table 2).

Table 1. **Projection for the year 2000 of total grain and grain sorghum production in the Cerrado region of Brazil using advanced technology recommended for the region.**

Situation	Area (million ha)	Annual yield (t/ha)	Annual production (million t)
Current (total grain)	5.0	1.5	7.5
Projected (total grain)[a]	50.0	2.5	125.0
Projected (sorghum)	2.0	4.0	8.0

a. Considering rice (15%), beans (4%), corn (20%), soybeans (35%), grain sorghum (4%), wheat (4%), and other crops (18%), after 20 years of development.

SOURCE: Goedert, W. J., Lobato, E., and Wagner, E. 1980.

Table 2. **Projection for the year 2000 of the grain yield, production, and area planted with grain sorghum in two production systems in the Cerrado region of Brazil.**

Production system	Area (million ha)	Annual yield (t/ha)	Annual production (million t)
Principal crop[a]	2.0	4.0	8.0
Soybean-sorghum (double-cropping)[b]	3.5	2.0	7.0
Total	5.5	—	15.0

a. Four percent of total area for grain production.
b. Twenty percent of the area planted with soybeans.
SOURCE: Goedert, W. J.; Lobato, E.; and Wagner, E. 1980.

Assuming that the estimates in Tables 1 and 2 are valid, we should evaluate the available technology for sorghum production for limiting factors that might affect these goals. A complete analysis would involve several factors, such as the application of lime and fertilizers, the use of adapted varieties, types of farming equipment, etc., which are beyond the scope of this paper. Hence, we will discuss the performance of grain sorghum hybrids that are currently available.

Grain sorghum production results from various locations have demonstrated that the commercial varieties generally do not develop satisfactorily without the use of adequate levels of lime and fertilizers (EMBRAPA, 1978, 1979; EPAMIG, 1979).

The use of high rates of lime to correct soil acidity, in many cases, has not been economically feasible because of the elevated costs, i.e., transport, application, and credit. Also, from technical and economic points of view, it is not generally feasible to incorporate lime in the subsoil layer. The acidity found in the subsoil inhibits root growth, principally the root growth of aluminum-sensitive species and cultivars (Foy, 1974), leaving the plants more susceptible to moisture stress during the *veranicos* that occur during the growing season. Hence, the importance of developing cultivars with tolerance to toxic levels of aluminum and other limiting factors of these Cerrado soils or "Cerrado soil complex" is clearly obvious. The species and cultivars better adapted to this Cerrado soil complex are expected to have a greater yield potential, thus a lower production risk factor, due to a lower demand for lime and fertilizers.

The terms "tolerance the Cerrado soil complex," "tolerance to aluminum toxicity," and "aluminum tolerance" are used interchangeably in this paper. It must be kept in mind that aluminum tolerance, in this case, is a complicated topic not well understood.

A review on aluminum tolerance in sorghum for the Cerrado Soil Complex in Brazil

The research program to evaluate sorghum tolerance for the conditions of low pH and high aluminum saturation that predominate in the soils under Cerrado vegetation was initiated at the National Corn and Sorghum Research Center (CNPMS) of Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) in 1974. Since 1975, various papers have been published regarding the range of genetic variability (Schaffert et al., 1975; Pitta et al., 1976, 1979b) of aluminum tolerance in sorghum, methods of screening (Santos et al., 1980; Malavolta et al., 1981), response of sorghum to levels of lime and depth of incorporation (Salinas et al., 1976), genetic control of aluminum tolerance (Schaffert et al., 1975; Pitta et al., 1979a), as well as many related topics. A genetic improvement program was also initiated to develop adapted cultivars and random-mating populations with high levels of tolerance to aluminum toxicity (Borgonovi et al., 1982).

Shaffert et al. (1975) evaluated 30 grain sorghum hybrids under field conditions and showed that the variability to drought tolerance was closely related to the differential root growth that was associated with genetic variability of aluminum tolerance among the hybrids. Later, experiments conducted in the greenhouse using a dark red Latosol soil, Cerrado phase (Table 3), showed that the experimental hybrid Wheatland x TX 2536 and the commercial hybrid Taylor Evans Y 101 had greater root development than the sensitive hybrid RS 610. It was also observed that the tolerant hybrids developed neither discolored roots nor leaves with a bronzing coloration, symptoms frequently associated with aluminum toxicity (Foy et al., 1978). Schaffert et al. (1975) showed that there was genetic variability for root development, indicating that selection for tolerance to aluminum toxicity should be successful.

Table 3. **Some of the chemical characteristics of the dark red Latosol, Cerrado phase, at two lime levels and two soil depths, used to evaluate sorghum germplasm and developing cultivars at CNPMS/EMBRAPA, Sete Lagoas, Minas Gerais, Brazil.**

Lime (t/ha)	Soil depth (cm)	(pH) H_2O	Al (meq/kg)	Ca	Mg	K	P (ppm)	Aluminum saturation[a] (%)
0	0 - 20	4.7	21.0	11.0	3.0	1.9	3	62
	20 - 40	4.6	23.0	8.0	2.5	1.7	2	66
2	0 - 20	4.8	14.0	19.0	2.7	1.5	3	41
	20 - 40	4.6	19.0	9.0	2.2	1.2	2	59

a. $\% \text{ Al} = \frac{\text{Al}}{\text{Al} + \text{Ca} + \text{Mg} + \text{K}} \times 100$

Pitta et al. (1979b) evaluated 1200 sorghum lines of various origins in field conditions with an aluminum saturation ranging between 40% and 60%, and identified a few lines with good aluminum tolerance, principally germplasm that originated from Uganda and Tanzania. These authors also observed that several lines were negatively affected due to the high incidence of foliar diseases. The agronomic characteristics evaluated were: phenotypic Al toxicity symptoms of the plant, grain production, harvest index, and reaction to foliar diseases. The results obtained showed good correlation between the phenotypic evaluation and harvest index with aluminum tolerance.

Various methods of screening sorghum plants in nutrient solutions and in soils under greenhouse conditions have been utilized to identify differences for aluminum tolerance. Salinas and Sánchez (1978) used a nutrient solution with two levels of Al (0 and 8 ppm) and two levels of P (0.05 and 0.20 ppm) to quantify the relative growth rate (RGR) and relative root extension rate (RER) as tools to characterize aluminum tolerance in five sorghum genotypes. Two commercial hybrids (TE Y 101, and RS 610) and three breeding lines (SC 112-14, SC 3349, and TX 7078) were evaluated. Root growth rate and RER responded similarly to that of the best RGR with 8 ppm Al and 0.05 ppm P. The hybrid TE Y 101 was the most efficient cultivar under P, Al, and combined P and Al stress. Dos Santos et al. (1980) obtained significant correlations between greenhouse and field experiments for tolerance to aluminum toxicity. The correlation coefficients between the variables at 64% Al saturation were: dry weight of tops + grain yield (0.72**), and dry weight of roots x grain yield (0.64**). Malavolta et al. (1981) evaluated 30 grain sorghum hybrids in nutrient solution with five levels of Al (0, 3, 6, 12, and 24 ppm) and concluded that total dry weight of the seedlings (shoots and roots), after 3-weeks growth was a better estimate of aluminum tolerance than seedling shoot weight, root weight, seedling height, or root length. The Al concentration that best differentiated the genotypes was 12 ppm. Hybrid TE Y 101 and three experimental hybrids were the most tolerant genotypes.

Salinas et al. (1976) evaluated two grain sorghum hybrids (TE Y 101 and RS 610) that had shown differences in aluminum tolerance in a field experiment with five rates of lime (0, 1, 2, 4 and 8 t/ha) and with two depths of lime incorporation (0 to 15 cm and 0 to 30 cm). The differences between the treatments were directly related to the level of aluminum saturation in the top 15 cm of the soil. The grain yield of the tolerant hybrid TE Y 101, was less affected and responded less to deep lime incorporation than RS 610. The zero, one, and two tons of lime per hectare were the best levels to differentiate aluminum tolerant and susceptible genotypes.

The results of Schaffert et al. (1975), Pitta et al. (1979a), and Furlani and Bastos (1984, personal communication) in field experiments and nutrient solution suggest that the inheritance of tolerance to aluminum toxicity is controlled by a small number of major genes with a dominant effect, probably one partially dominant gene, and a number of modifying genes with minor effects.

Breeding sorghum for tolerance to aluminum toxicity

Program strategy for sorghum production

Three basic alternatives exist for the use of the Cerrado for sorghum production. They are as follows:

1. A **modification** of the soil environment through the neutralization of the soil acidity and application of nutrients until the requirements of the plant are reached. The use of this alternative has serious restrictions because of the high cost of lime and fertilizers as well as high transportation and application costs.

2. An **adaptation** of the plant to the characteristics of the soil by means of genetic manipulation, either by genetic engineering or traditional plant-breeding methods. This alternative has recently received considerable attention by various researchers and several references on ample genetic variance for tolerance to aluminum toxicity have been published (Bastos, 1981; Brown and Jones, 1977; Duncan, 1981a, 1981b; Furlani, 1979, 1981; Pitta et al., 1976, 1979; Sánchez and Salinas, 1976; Schaffert et al., 1975). However, it is doubtful that the genetic variance available is adequate to modify the sorghum plant to an adequate yield potential for production in most Cerrado soils.

3. A **combination** of alternatives one and two (strategy pursued by CNPMS), including a gradual modification of the soil by applying reduced amounts of lime and fertilizers in association with the development of elite sorghum cultivars more tolerant to aluminum and with better nutrient use efficiency. This combination should provide a greater efficiency in the utilization of nutrients by the plants allowing the root system of the aluminum-tolerant plants to absorb water and nutrients from the subsoil layer, thus reducing the effects of the *veranicos* that frequently occur. Several authors have suggested this alternative for the exploration of problem soils (Brown, 1979; Epstein, 1976; Foy and Fleming, 1978; Clark and Brown, 1980; Salinas et al., 1976).

At CNPMS/EMBRAPA at Sete Lagoas, Minas Gerais, Brazil, the objective of the sorghum breeding program for highly acid soils is to develop sorghum cultivars with adequate yield potential in soils with an aluminum saturation between 40%and 50%. This range is based on the impossibility of total substitution of lime in acid soils. This Al saturation generally is reached with 2-3 t/ha of lime. In this breeding program two points should be emphasized: it is necessary to combine adequate levels of aluminum tolerance with good yield potential to obtain genotypes with good and stable yield potential (these types have not been identified in sorghum germplasm screened for aluminum tolerance); and the maintenance of a minimum level of resistance to the principal foliar diseases, principally anthracnose and rust that are widely distributed (Fernandes and Schaffert, 1980) and have the potential of limiting the expansion of sorghum in this region.

Method of screening for aluminum tolerance

Greenhouse screening

Various methods for evaluating sorghum germplasm and segregating breeding material under greenhouse conditions, using either soil or nutrient solutions, have been described in the literature (Konzak et al., 1976; Brown and Jones, 1977; dos Santos et al., 1980; Furlani and Clark, 1981; Malavolta et al., 1981; Furlani, 1981). In general, these methods involve the use of nutrient solutions that facilitate the handling of the plants and the evaluation of the root systems of the seedlings.

The germplasm screening experiments conducted in the greenhouse at CNPMS/EMBRAPA to identify sorghum lines and segregating families with different degrees of aluminum tolerance began with the methodology suggested by Clark (1975), and more recently those techniques proposed by Furlani and Clark (1981), Furlani (1981), and Magnavaca (1982). The seeds are germinated in paper toweling rolled into tubes and placed vertically in water and aerated for seven days. On the eighth day, the seedlings are examined for possible root damage and the initial seminal root length (ISRL) is measured and recorded. The nutrient solution used is that recommended by Magnavaca (1982) except for a small difference in the Al concentration. The source of aluminum is $KAl(SO_4)_2 . 12 H_2O$ and the Al concentration is 180 µM (4.8 ppm). The pH of the solution is initially adjusted to 4.0. The composition of the nutrient solution is presented in Table 4.

Eight and one-half litres of the nutrient solution are placed in each container. A plexiglass top containing 49 holes 20 mm in diameter for the young seedlings, and two holes of 10 mm for aeration and monitoring the system, is suspended in the container. The seedlings are fixed in the holes with pieces of sponge rubber so that the development of the adventitious roots is not impeded. The nutrient solution is constantly aerated during the growth period, normally 10 to 12 days.

At the end of the growth period the seedlings are removed and the roots are visually examined for symptoms of aluminum toxicity. The final seminal root length (FSRL) and adventitious

Table 4. **Composition of nutrient solution used for the growth of sorghum plants, CNPMS/EMBRAPA, Sete Lagoas, Minas Gerais, Brazil.**

Stock solution			Full-strength nutrient solution					
Name	Chemical	Concentration	ml	Cation	Anion	Total composition		
		(g/L)	(stock/L)	(mg element/L)		Element	(mg/L)	(µM)
Ca	$Ca(NO_3)_2 \cdot 4H_2O$	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	3410
						Mg	20.8	855
K	KCl	18.6	2.31	K^+ = 22.5	Cl^- = 20.4	NO_3-N	144.1	10293
	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	581
Mg	$Mg(NO_3)_2 \cdot 6H_2O$	142.4	1.54	Mg^{++} = 20.8	NO_3^--N = 24.0	B	0.27	25
						Cl	21.05	596
P	KH_2PO_4	17.6	0.35	K^+ = 1.7	$H_2PO_4^-$-P = 1.4	Fe	4.3	77
						Mn	0.5	9.1
Fe	$Fe(NO_3)_3 \cdot 9H_2O$	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
Micro	$MnCl_2 \cdot 4H_2O$	2.34	0.77	Mn^{++} = 0.5	Cl^- = 0.65	Na	0.04	1.74
	H_3BO_3	2.04			$BO_3^{\equiv}$-B = 0.27	HEDTA	20.6	75
	$ZnSO_4 \cdot 7H_2O$	0.88		Zn^{++} = 0.15	$SO_4^=$-S = 0.07			
	$CuSO_4 \cdot 5H_2O$	0.20		Cu^{++} = 0.04	$SO_4^=$-S = .02			
	$Na_2MoO_4 \cdot 2H_2O$	0.26		Na^+ = 0.04	$M_0O_4^-$-M_0 = 0.08			

SOURCE: Magnavaca, R. 1982.

root length are recorded for each plant. The relative seminal root growth (RSRG) is calculated as follows (Furlani, 1981):

$$RSRG\ (\%) = \left[\frac{ISRL}{FSRL} - 1\right] \times 100$$

Field screening

The field screening of sorghum germplasm and segregating breeding material for aluminum tolerance are normally restricted because of the lack of uniformity of the experimental area with respect to aluminum saturation, phosphorus and potassium levels etc. With the objective to minimize these problems, the following procedure is being used to prepare an area for better uniformity:

1. Identification of a virgin soil with high aluminum saturation.
2. Determination of a response curve and application of lime to obtain a desired level of aluminum saturation between 40% and 50%.
3. The phosphorus, as simple superphosphate, and potassium, as KCl, are applied broadcast and incorporated into the soil.

This technique not only improves the chemical uniformity of the area, but also tends to minimize the effect of differential availability of nutrients to the plants. Nitrogen is the only banded fertilizer applied.

Soil and plant samples are analyzed and evaluated during the growing season, so that the Al concentration, nutrient status (e.g., P, Mg, Zn), and soil moisture can be monitored. Differences in plant moisture content during the *veranico* probably indicate differential root growth. Agronomic characteristics such as plant height, flowering date, disease reactions, grain production, and harvest index are also recorded.

Sources of tolerance to aluminum toxicity

The methodology described above has allowed CNPMS to identify sources of aluminum tolerance and also confirm results of other researchers (Table 5). The genotypes SC 283, SC 175-14,

Table 5. **Reaction of selected Al-tolerant sorghum lines in nutrient solution grown at 4.8 ppm aluminum at CNPMS/EMBRAPA, Sete Lagoas, Minas Gerais, Brazil.**

Identification	Origin	Group	Restoration reaction[a]	Relative seminal root growth (%)
IS 7254C (SC 566-14)	Nigeria	Caudatum	B	39.5
5 DX 61/6/2	Uganda	—	R	38.6
MN 1204	—	—	—	38.5
IS 7173C (SC 283)	Tanzania	Conspicium	B	34.2
IS 1335C (SC 418)	Tanzania	Caudatum-Kafir	R	28.6
IS 12666C (SC 175-14)	Ethiopia	Zera-Zera	R	26.0
IS 3625C (SC 549)	Nigeria	Conspicium	R	23.4
V 20-1-1-1	Uganda	—	R	20.4
156-P-5-Serere-1	Uganda	—	R	17.2
IS 12564C (SC 048)	Sudan	Zera-Zera	R	15.5
IS 1309C (SC 322)	Tanzania	Nigricans	PR	12.8
IS 7542C (SC 408)	Nigeria	Caudatum-Guineense	R	12.7
3 DX 57/1/1/910	Uganda	—	R	11.9
(TX 2536 x SC 112-14) der	Brazil	—	R	11.8
IS 11612C (SC 112-14)	Ethiopia	Zera-Zera	R	8.7
TX 2536	USA	—	R	5.7
IS 8361 (Wheatland)	USA	—	B	3.3
TX 623 (Al-sensitive)	USA	—	B	4.5

a. B = Nonrestorer
PR = Partially restores (cytoplasmic male-sterile produced) hybrid to male fertility
R = Fully restores (cytoplasmic male-sterile produced) hybrid to male fertility

SOURCE: Borgonovi, R. A.; Guimares, D. V.; Magnavaca, R.; and Schaffert, R. E. (Unpublished data).

SC 418, SC 048 and SC 112-14 were selected in field conditions and can be considered tolerant to the Cerrado soil complex. The other genotypes in Table 5 were selected from greenhouse studies (nutrient solution and/or soil experiments). The genotypes with RSRG less than 20% have been selected because of their performance under field conditions.

The results indicate that screening in nutrient solution should be complemented with field confirmation to select sources of tolerance to the Cerrado soil complex and to identify escapes. The line TX 623 has consistently shown a sensitive reaction in both field and greenhouse studies.

The reaction of the sorghum lines Wheatland and TX 2536 per se do not indicate tolerance to aluminum toxicity. However, the hybrid of these two lines has shown tolerance in several studies (Schaffert et al., 1975; Salinas et al., 1976; dos Santos et al., 1980). These results suggest the existence of genes with complementary effects. The roots of Wheatland form a massive fibrous system under normal conditions and the roots of TX 2536 remain white and do not form the typical dark brown coloration of susceptible genotypes under high levels of aluminum.

The performance (Table 6) of the hybrids currently available, made with the best sources of tolerance to aluminum toxicity,

Table 6. **Average performance of the hybrids of three female lines[a] and seven male lines tolerant to aluminum, in a dark red Latosol, Cerrado phase, CNPMS/EMBRAPA, Sete Lagoas, Minas Gerais, Brazil.**

Male parent of hybrid and checks	Days to flower	Plant height (cm)	Grain yield (t/ha)
SC 048	69.3	137	1.80
SC 418	69.3	137	1.81
SC 112-14	69.0	141	1.94
3 DX 57/1/1/910[b]	84.6	186	3.19
V 20-1-1-1[b]	87.3	189	2.98
156 P-5-Serere-1[b]	86.3	184	2.67
5 DX 61/6/2[b]	85.7	186	2.66
Al-sensitive check hybrids[c]	72.3	106	1.06
Line SC 283	68.0	119	2.03
Line SC 112-14	82.0	72	0.78

a. BR 007A (Redbine derivative), Wheatland A and Redlan A.

b. Susceptible to lodging.

c. EMBRAPA BR 300, Agroceres AG 1003, and Pioneer B 815.

SOURCE: Borgonovi, R. A.; Santos, F. G.; and Schaffert, R. E. (Unpublished).

demonstrate that it is not possible to use these sources per se in a plant breeding program. In general, these hybrids are late-maturing, tall, lodging-susceptible, and relatively unproductive.

Preliminary results of aluminum tolerance inheritance studies

Only a few studies dealing with inheritance of aluminum tolerance in sorghum have been reported in the literature (Pitta et al., 1979a; Furlani, 1981; Bastos, 1981; Bastos, 1982). Preliminary results of Pitta et al. (1979a) relative to the evaluation of two female lines, (BR007 and Wheatland), three male lines (TX 2536, SC 112-14, and TAM 428), and their hybrids under field conditions suggested the presence of a small number of genes with a dominant effect for the control of aluminum tolerance. According to Furlani (1981), the type of genetic behavior involved in aluminum tolerance varied depending upon the germplasm used as well as the aluminum concentration in the nutrient solution. The author also showed that with an aluminum concentration of 43 µmol/L (1.2 ppm) very few genotypes were identified as Al sensitive. However, at a concentration of 96 µmol/L aluminum, the genotypes previously classified as Al tolerant, SC 283 and SC 112-14, firmed their behavior. The author considered the inheritance of aluminum tolerance in sorghum to be complex.

Bastos (1981) evaluated the relative root length of lines and their F_1 hybrids in nutrient solution with no aluminum and 154 µmol/L (4.0 ppm) aluminum and concluded that the genetic control of tolerance was complex. In 1982 the author, utilizing five F_1 crosses involving two lines considered tolerant (SC 175-14 and SC 237-14) and two sensitive lines (TX 415 and 7B113) and the transgressive segregation of the F_2 populations of these crosses, showed that different genes were probably involved in aluminum tolerance. The author suggested that three or more pairs of genes were involved in the control of aluminum tolerance.

Preliminary results of Borgonovi et al. (unpublished data) indicated differences between the hybrids made with the aluminum tolerant line SC 283 and various susceptible female lines (Table 7). The relative seminal root growth of the hybrids made with the female lines Wheatland, CMS XS 168 A, and Redlan was superior to the RSRG of the hybrids made with the female lines TX 623 A and BR 007 A. There is an apparent specific combining

Table 7. **Relative seminal root growth (RSRG) of sorghum lines and their hybrids in nutrient solution grown at 4.8 ppm aluminum, CNPMS/EMBRAPA, Sete Lagoas, Minas Gerais, Brazil.**

Identification	RSRG (%)
SC 283	34.2
TX 623 A	5.8
TX 623 A x SC 283	10.8
BR 007 A	5.1
BR 007 A x SC 283	10.1
Wheatland A	3.3
Wheatland A x SC 283	21.7
Redlan A	5.0
Redlan A x SC 283	17.4
CMS XS 168 A	4.8
CMS XS 168 A x SC 283	24.0

SOURCE: Borgonovi, R. A.; Guimaraes, D. V.; Magnavaca, R.; and Schaffert, R. E. (Unpublished data.)

ability effect for aluminum tolerance, indicating that the inheritance of this trait maybe complex. At CNPMS, we currently have several studies underway involving various sensitive and tolerant lines, their F_3 and F_2 hybrids, and the respective backcrosses, that should help clarify the inheritance patterns for this trait.

In general, it seems reasonable to assume that there are a few major genes with a dominance trend and several minor genes with, at least, some additive effect involved in the genetic control of tolerance to aluminum. The major genes with some dominance can be exploited and transferred to elite germplasm for immediate use. Whereas, it appears that the population improvement approach seems most adequate to exploit all the desirable genes controlling the inheritance to aluminum tolerance in the long run.

Development of aluminum-tolerant elite cultivars

The development of cultivars tolerant to the Cerrado soil complex at CNPMS has been based on methods traditionally employed in sorghum improvement. Basically, the following methodology is being adopted:

Introduction and evaluation of germplasm for tolerance to toxic aluminum

The CNPMS breeding program has been working increasingly with the introduction and evaluation of germplasm because only a small portion of the world collection has been effectively evaluated for Al tolerance. This program collaborates with researchers of the Agronomic Institute of São Paulo, at Campinas, Brazil, in association with projects of the National Sorghum Research Program of EMBRAPA. The CNPMS has been using field-screening techniques at Sete Lagoas, MG, Brazil, complemented with nutrient solution techniques at both Sete Lagoas and Campinas. The best elite breeding lines identified at present are listed in Table 5.

Transfer of genes for aluminum tolerance from exotic lines to elite lines

The transfer of the major genes identified in exotic lines (e.g., SC 283) to the elite breeding lines of the CNPMS program and the development of new cultivars with aluminum tolerance are being conducted utilizing nutrient solution screening in the greenhouse to identify tolerant plants in segregating families. We are utilizing a "fast lane" breeding approach to incorporate the major effect genes into our elite B and R lines and, in a second stage, more attention will be given to the modifying genes.

Population breeding approach

Utilizing the best elite lines and the best exotic aluminum tolerant lines of the breeding program at CNPMS, a random-mating population has been developed using the genetic male sterile gene ms_3. This population, BRP5BR (Table 8), has undergone three cycles of random-mating and is currently planted to select S_0 plants. The following selection procedure will be used in each cycle:

1. Selection of S_O plants in a uniform Cerrado soil (1000 S_O plants).

2. Screening of S_1 progenies in nutrient solution to select about 40-50% of the superior progenies.

Table 8. **Sorghum lines used to synthetize the random-mating population (BRP5BR), for Al tolerance.**

Identification	Origin
IS 12564 C (SC 048)	Sudan
IS 12612 C (SC 12-14)	Ethiopia
IS 12666 C (SC 175-14)	Ethiopia
IS 7173 C (SC 283)	Tanzania
IS 1309 C (SC 322)	Tanzania
IS 1335 C (SC 418)	Tanzania
156-P-5-Serere-1	Uganda
IS 3758 C (SC 326-6)	Ethiopia
TX 2536	USA

SOURCE: Borgonovi, R. A.; Santos, F. G.; and Schaffert, R. E. 1982.

3. Evaluation of approximately 400 S_2 progenies from step 2 in a uniform Cerrado soil with 40-50% aluminum saturation.

4. Recombine the best 20% (seed of remnant S_1 progenies) of the S_2 progenies, approximately 40 families.

This selection procedure should effectively concentrate both the major genes and the minor modifying genes and increase the degree of tolerance to the Cerrado soil complex.

Summary and conclusions

There is, apparently, a large amount of genetic variation in sorghum for tolerance to the Cerrado soil complex. Moreover, the sorghum world collection needs to be systematically evaluated to identify additional sources of aluminum tolerance. The inheritance of this tolerance appears to be complex and needs to be studied in greater detail. Some rapid progress for aluminum tolerance can be made by utilizing sources like SC 283, which probably have major genes.

An international cooperative research program involving the International Sorghum and Millet Program (INTSORMIL) and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), in addition to the existing program in Brazil—Centro Nacional de Pesquisa de Milho (CNPMS), Instituto Agronómico de Campinas (IAC), and Instituto de Pesquisas

Agronómicas (IPA)—should be developed in order to identify regions of Africa with high Al saturation, sources of germplasm from these regions, and to exchange germplasm for use in national programs.

An interdisciplinary research approach involving plant breeders, plant physiologists, soil specialists, and economists for the development of technology and production systems needs to be undertaken for a rational exploitation of the Cerrado and similar soils. This interdisciplinary "team" needs to develop and/or to improve screening techniques for the complex interactions involved in Cerrado and similiar type soils.

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Finding and Utilizing Exotic Al-Tolerant Sorghum Germplasm

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Introduction

Today's frontiers of agriculture are the marginal, underutilized land areas in the tropics. It has not been possible to apply traditional agricultural practices successfully in these areas because of limiting factors including: lack of access to capital; inadequate transportation and marketing systems; limited irrigation systems; and the high cost and inequitable supply of production inputs for resource-poor farmers. The major production constraints in the tropical savannas of South America are related to low pH soils with inadequate nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and trace elements, toxic levels of soluble aluminum (Al), and various other environmental factors such as insects, diseases, and uneven distribution of rainfall. National research agencies in South America and elsewhere are searching for low-cost production technology that will alleviate their food and feed grain deficits.

The distribution of soils in the tropics occurring generally between 23°N to 23°S latitude is shown in Table 1 (Sánchez and

Table 1. **Distribution of soil orders in the tropics[a].**

Soil order	Americas	Africa	Asia	Total	Land area of tropics (%)
	(millions of hectares)				
Oxisols	502	316	15	833	23
Ultisols	320	135	286	741	20
Inceptisols	204	156	169	529	14
Other	467	536	340	1343	43
Total	1493	1143	810	3446	100

a. Generally includes areas between latitudes 23° N and 23° S.
SOURCE: Sánchez, P. A. and Salinas, J. G. 1981.

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Salinas, 1981). In tropical America there are over one billion hectares of acid, infertile soils. This vast area is dominated by Oxisols and Ultisols in the savanna regions of the Llanos of Colombia and Venezuela, the Cerrados of Brazil, and much of the Amazonian area (Table 2). The constraints of these soils are usually chemical rather than physical (Table 3). Nearly 75% of the unproductive area has Al-saturation levels that are toxic to most grain crop species. Associated with the high levels of Al are the added constraints of very low quantities of exchangeable Ca and high P fixation (Reeve and Summer, 1970).

When chemical constraints to crop production are eliminated by liming and fertilization, these soils can be among the most productive in the world. However, the cost of lime required to reduce soil acidity to allow high-yielding crop production is generally beyond resource-poor farmers. Moreover, liming the soil surface does little to correct the chemical impediments to root penetration found in the subsoil. Consequently, crop yields are reduced by drought stress whenever rainfall or irrigation is inadequate to replenish water in the limed topsoil as the soil moisture level approaches the crop wilting point.

A more feasible alternative to the Al-toxicity problem is to breed and select plants that are more tolerant to acid soil production constraints than those currently available. Research at the international center, Centro Internacional de Agricultura Tropical (CIAT), has demonstrated that several pasture grass species introduced from the acid soil savannas of Africa and Brazil grow well in the Llanos of Colombia with minimum soil amendment (CIAT, 1983). Recently, the Andean Pact countries and Brazil have shown an interest in increasing grain sorghum production in Latin America, mainly for poultry feed (Table 4). It has been suggested that the introduction of sorghum ecotypes from Africa—the center of origin for sorghum where more than 50% of its tropical land mass has acid soils—could provide Al-tolerant germplasm for use in tropical America (Dogget, 1970).

The purpose of this paper is to report a systematic approach for selecting and identifying sorghum cultivars from the world collection that are tolerant to the acid soil environment of tropical America, and to present the U.S. Title XII International Sorghum/Millet Program (INTSORMIL) breeding strategy for tropical acid soils.

Table 2. **Distribution of Oxisols and Ultisols by country in Latin America and the Caribbean Basin.**

Country	Area distribution (millions of hectares)	Percentage of country's total area
South America		
Brazil	572.71	68
Colombia	67.45	57
Peru	56.01	44
Venezuela	51.64	58
Bolivia	39.54	57
Guyana	12.25	62
Suriname	11.43	62
Paraguay	9.55	24
Ecuador	8.61	23
French Guiana	8.61	94
Chile	1.37	2
Argentina	1.28	0[a]
Total	840.45	48
Central America		
Mexico	4.42	2
Panama	3.59	63
Honduras	3.13	29
Nicaragua	2.92	30
Guatemala	0.96	9
Costa Rica	0.70	14
Belize	0.40	18
Total	16.12	6
Caribbean		
Cuba	2.42	21
Haití	0.52	19
Jamaica	0.45	41
Trinidad	0.42	84
Dominican Republic	0.42	9
Puerto Rico	0.16	18
Guadeloupe	0.09	47
Martinique	0.05	43
Total	4.53	21
Grand total	861.10	42

a. Percentage of total area is 0.4.
SOURCE: Cochrane, T. T. 1978.

Table 3. **Typical characteristics of two orders of tropical soils*.**

Soil order	Depth (cm)	Clay (%)	Organic matter (%)	P (ppm)	pH	Exchangeable cations Al	Ca	Mg	K	Effective CEC	Al saturation (%)
						(meq/100g)					
Ultisol	0-20	71	7.1	1.8	4.1	2.7	.65	.49	.36	4.21	64
	20-35	77	4.0	1.1	4.0	2.7	.31	.04	.13	3.25	83
	35-62	84	1.9	0.9	4.3	3.2	.24	.02	.09	3.65	88
	62-91	88	0.7	0.9	4.4	1.1	.15	.02	.06	1.43	77
	91-105	89	1.5	1.2	4.4	2.0	.22	.01	.04	2.34	85
Oxisol	0-12	38	4.0	1.0	4.5	3.8	.20	.20	.10	4.40	86
	12-32	41	2.0	1.0	4.6	2.8	.10	.10	.10	3.10	89
	32-58	43	1.7	Trace	4.8	2.1	.10	.10	.10	2.30	91
	58-88	45	0.9	Trace	5.2	0.7	.10	.10	.10	0.90	78
	88-148	45	0.6	Trace	5.1	0.6	.10	.10	.10	0.80	75

* Ultisol characteristics from CIAT-Quilichao substation; Oxisol characteristics from a well-drained savanna, CIAT/ICA-Carimagua substation. Method of extraction and/or determination was P - Bray II, pH-1:1 soil:water, exchangeable cations - neutral salt from 100 g of soil, effective CEC - sum of exchangeable cations, and Al saturation-exchangeable Al divided by effective CEC times 100. Data from CIAT.

Table 4. **Changes in selected commodities in JUNAC[a] countries and Brazil for periods 1974-76 and 1980-82.**

Commodity	Percentage of growth per annum		
	Area planted or number of animals	Yield	Production
Wheat	-2.1	-0.3	-2.4
Corn	1.1	2.4	3.7
Paddy rice	2.0	0.9	6.0
Sorghum	13.0	-1.9	9.6
Cattle	0.9	—	1.6
Pigs	4.0	—	4.5
Chickens	7.4	—	19.1

a. JUNAC (Junta del Acuerdo de Cartagena); also known as the Andean Pact. Countries in JUNAC are Bolivia, Colombia, Ecuador, Peru, and Venezuela.

SOURCE: FAO (Food and Agriculture Organization of the United Nations). 1983.

Evaluation for Al tolerance

A review of the literature of the different methods used to screen plants for tolerance to Al toxicity is beyond the scope of this paper. A few examples will be provided, however, to help explain the rationale for the system recommended here for sorghum.

Early successful evaluations of the tolerance of sorghum to toxic effects of Al were conducted in field tests on acid soils of the Cerrados in Brazil (Schaffert et al., 1975; Pitta et al., 1976). The Brazilian National Program, Empresa Brasileira de Pesquisa Agropecuaria (EMBRAPA) staff has screened sorghum germplasm sent to them from Uganda by Dogget, as well as converted lines from the Texas A&M University/United States Department of Agriculture (USDA) conversion program. Less than 1% of the sorghum world collection has been screened for Al tolerance in Latin America due to the lack of availability.

Prior to coming to Colombia, the author and some of his students at Mississippi State University used a modification (increase of Al and decrease of P concentrations) of a nutrient culture technique to screen sorghum seedlings for tolerance to Al (Bastos and Gourley, 1982) developed by Clark and his students at the University of Nebraska (Furlani and Clark, 1981). The correlation coefficient obtained when a range of Al-tolerant genotypes were being field validated in Colombia was positive. However, less than one-half of the variability was accounted for by the association of relative primary root growth using the nutrient culture technique and Al-tolerance rating under field conditions (Gourley, unpublished data). Researchers in Brazil have reported similar findings of a coefficient of determination of 51% or less (dos Santos et al., 1980).

Using sorghum pure lines selected from nutrient culture screening trials and their F_1 hybrids, Bastos (1981) found that a significant portion of the variance for Al tolerance was under genetic control according to the results from a study of two diallels. Both general combining ability (GCA) and specific combining ability (SCA) contributed significantly ($P \leq .01$) to the genetic variance of both diallels. Further, the variance for GCA accounted for most of the genetic variance and GCA effects of the parents were consistent with their ranking for Al tolerance. However, continuing the study of some of the diallel tolerant-by-tolerant and tolerant-by-susceptible crosses in segregating generations, Bastos (1982) found no genetic gain in selecting the upper 10% of 700 seedlings from each of five F_2 populations and their F_3 offspring using the nutrient culture method of evaluation.

A greenhouse screening technique was developed at CIAT using a virgin Oxisol soil from the Colombian Llanos with different levels of Al saturation (Gourley, 1983). Three levels of Al saturation (82%, 60%, and 45%) were obtained using different levels of lime. Four sorghum plants were grown per pot in these soils for a 3-week period. The intermediate level of 60% Al saturation produced the best separation of genotypes. Dry matter yield of roots, tops, and total plant, as well as visual ratings did not, however, correlate well enough with the top dry weights of field-grown plants at anthesis to continue using this technique in a breeding program.

Because of a lack of confidence in the so-called "quick tests" for Al tolerance, a field screening technique was developed. The procedure was designed to measure Al tolerance and, insofar as possible, not the effect of P or the Al-P interaction. The objective was to establish an Al-toxicity level high enough to kill sensitive genotypes but not too high to prevent tolerant genotypes from producing a reasonable yield of grain. An Al-saturation level of 60% to 70% was selected to accomplish the research goal.

This high level of Al saturation was selected for several reasons. In the initial screening of 3000 entries from the world collection, only the most tolerant genotypes were desired for further evaluation or breeding purposes. Severe Al-toxicity stress was applied in order to reduce the number of genotypes quickly by eliminating lines with low to moderate levels of Al tolerance and "escapes." To have economical potential, genotypes with the highest level of Al tolerance would allow resource-poor farmers to apply a minimum quantity of lime for commercial production. Since only the topsoil is usually modified with soil amendments, the roots of genotypes with the highest level of Al tolerance would not be completely inhibited from penetrating the higher level of Al saturation encountered in the subsoil. Field observations show that the 60%-70% level of Al saturation will accomplish these goals.

Table 5 contains a list of the soil test results of a virgin Ultisol in permanent pasture (Quilichao, Colombia) before and after amendments were incorporated. Broadcast applications of 500 kg dolomitic lime, 1000 kg 10-30-10 mixed fertilizer, 5 kg zinc (Zn), and 1 kg boron (B) per hectare were incorporated into the upper 20 cm of soil. Aluminum saturation was reduced from 80% to 63% but the pH remained unchanged. The quantities of amendments required to achieve similar conditions in other soils will depend upon many factors so it is recommended that the breeder work closely with a soil scientist familiar with the chemical characteristics of the soil in question.

Table 5. **Topsoil characteristics of a virgin Ultisol before and after amendment with 500 kg/ha dolomitic lime and 1000 kg/ha of 10-30-10 mixed fertilizer (and small amounts of Zn and B) at Quilichao, Colombia.**

Soil characteristics	Before amendment	After amendment
pH (H_2O)	4.5	4.4
P (ppm)	2.3	17.9
Ca (meq/100 g)	0.68	1.24
Mg (meq/100 g)	0.18	0.52
Al (meq/100 g)	3.9	3.4
Effective CEC (meq/100 g)	4.91	5.40
Al saturation (%)	80.4	63.0

The following simple visual rating scale was used to evaluate the exotic sorghum genotypes:

1) Good plant color, well-filled panicles, few stress or Al-toxicity symptoms.

2) Some yellowing of leaves, reduced panicle size, some stress and Al-toxicity symptoms.

3) Stunted plants, yellowing and dead leaves, small panicles with little grain, many stress symptoms.

4) Severely stunted or dead plants 2 to 3 weeks after emergence.

Field observations

Field evaluations are less controlled by the researcher than those conducted in the laboratory. Therefore, the cause-and-effect relationships of the final observation or result must, in many instances, be obtained by deduction or await further elaboration. Such appears to be the case in field evaluations of sorghums to the "tropical acid-soil complex." Several of these factors are discussed in the following paragraphs.

Aluminum. Tolerance to Al is, of course, the foremost factor in the screening procedure. Without an adequately high level of Al in the test media, a susceptible genotype with no practical degree of Al tolerance could be selected and the measure of any other genetic or agronomic factors would be negated. The degree of Al saturation in the upper 20 cm of the topsoil can be altered to the desired level with a relatively high degree of accuracy. This level is quite stable for a period of a few years. Experience has shown that most sorghum genotypes appear to tolerate Al-saturation levels of about 20% with little yield reduction. Of the genotypes evaluated to date, few will tolerate 80% Al saturation, and these produce very little grain.

Phosphorus. Although not intended as a variable in this screening procedure, the association of P availability and Al saturation must be considered. Some genotypes screened showed the typical purple-leaf symptom of P deficiency up to four weeks after planting even though the high rate of 300 kg/ha of P_2O_5 had been applied when the test plot was prepared. Mineral soils readily fix added phosphates; thus added soluble phosphates are only partially recovered by plants under optimum conditions. The high hydrous oxide content of many tropical soils can result in enormous phosphate-fixing capacities. Mycorrhizae can also aid plants in P utilization. Sorghum is used to maintain strains of mycorrhizae in greenhouse studies, and the association of mycorrhizae and P uptake is being elucidated. Genetic variability for root mass and mycorrhizal association could possibly account for apparent differences in P uptake observed in the field.

Calcium and magnesium. Calcium and magnesium carbonates in liming materials will reduce the level of Al saturation when applied to tropical acid soils. In these leached, low-base status soils, Ca and Mg in fertilizer quantities are also important in plant nutrition. Calcium is essential to root elongation as it is not translocated to the root tip. The quantity of Ca in some tropical subsoils is insufficient for root growth. Ritchey et al. (1980) have shown that the Ca ions of some compounds such as $CaSO_4$, $CaCl_2$, and $CaNO_4$ will move downward in the soil profile (up to 100 cm in a year) in association with the anion. This is not the case with $CaCO_3$. The critical Ca concentration for sorghum root growth in these soils is not known. Without a sufficient degree of Al tolerance, however, the question is academic.

Root mass. The relative rate of root and shoot growth of a particular sorghum genotype will affect its visual Al-tolerance field rating. Some genotypes produce rapid top growth in the juvenile stage of development while others appear stunted and stressed. Many of those lines producing good early top growth die before or during the grain-filling period while the slow-growing lines seem to recover and produce grain yields nearly equal to their genetic potential on a soil with a lower Al-saturation level. This phenomenon appears to be due to a priority in the partitioning of photosynthate throughout the stages of growth of the different genotypes. Those genotypes tolerant to high levels of Al apparently partition a greater portion of their photosynthetic resources to developing roots. The results of this difference will influence the visual Al-tolerance rating at different stages of plant growth. Since grain production is the ultimate goal under the prescribed conditions, visual field rating for Al tolerance is of little value before the genotype reaches physiological maturity.

Drought. Drought can be a production constraint on acid soils in the tropical savannas even during favorable rainfall periods. Despite a clay content of 40% to 70%, Oxisols and Ultisols in the tropics respond more like a sandy loam in the temperate zone with regard to water infiltration. The aggregate structure of these soils allows field operations within hours after a rain. Water-holding capacity in the upper soil profile is therefore reduced. During short periods without rain, *veranicos*, plants with only sufficient Al tolerance to root normally in the topsoil frequently fail because of drought. Therefore, it is important to have a sufficiently high Al-saturation level in the topsoil for adequate Al-tolerance screening and to use irrigation only to "rescue" or prevent the loss of the screening trial. When plants are in full foliage, wilting during short periods of drought provides an additional measure of the degree of Al tolerance. Those genotypes not wilting under full radiation are undoubtedly obtaining sufficient water from the subsoil. Genotypes that wilt under these conditions do not have the Al tolerance necessary for the roots to penetrate the higher Al-saturation level of the subsoil. Root mass and other drought-tolerance related factors will also influence observations on Al tolerance.

Interactions. The total sum of these factors and their interactions will affect the visual rating for Al tolerance. From a practical standpoint, the plant breeder at this stage of investigation is observing what a farmer always sees—the end result. Consistently high ratings for Al tolerance under the conditions prescribed in the screening process will denote the upper extent of the range of genetic variability for the overall "Al tolerance complex."

Under the 63% Al-saturation conditions of the screening trial, a fairly large number of genotypes exhibited a moderate-to-high degree of tolerance to Al toxicity. Most of these genotypes, however, are agronomically unacceptable as grain sorghum varieties in their present form. Table 6 shows the ratings of the first 775 world collection genotypes evaluated, by country of origin. Acid soils areas in Kenya and Uganda had a higher percentage of entries in categories 1 and 2 than those evaluated from the other countries listed. The rating procedure was designed to eliminate the poorer 50% to 75% of the genotypes in categories 3 and 4. It appears that an Al-saturation level of between 60% to 70% is sufficient stress for this purpose. Additional world collection entries are being screened currently. Final conclusions concerning the best source countries in Africa will not be made until all 3000 of the genotypes originally selected have been tested.

Table 6. Al-tolerance ratings[a] of 775 world collection lines by country of origin.

Country of origin	Total lines	Al-tolerance rating 1	2	3	4
		Percentage of lines			
Burkina Faso	82	4	36	32	28
Ethiopia	158	13	21	37	29
Kenya	16	15	37	30	18
Nigeria	161	6	25	38	31
Tanzania	14	14	36	29	21
Uganda	104	14	48	22	16
Zaire	16	12	37	31	19
Miscellaneous	224	10	23	35	32
Total	775	11	31	32	26

a. 1 = Al tolerant; 4 = Al susceptible.

A few of the more agronomically desirable Al-tolerant genotypes are now being evaluated for yield. Preliminary results of yield trials a lime-rate study at Quilichao, Colombia, are given in Table 7. After further testing, the release of some of these genotypes for direct commercial use may be recommended. At the very least, parental material for breeding programs has been identified.

Breeding strategy

Delegates to "The 1983 Plant Breeding Research Forum" outlined five steps required to utilize exotic germplasm (Conservation and utilization..., 1984). They were: collection, maintenance, evaluation, enhancement, and distribution. The breeding strategy used in this project parallels those of the forum. The steps in the INTSORMIL acid soils research program are: select genotypes from the sorghum world collection; increase the seed in the tropics; evaluate for Al tolerance under field conditions; incorporate Al tolerance into elite lines and hybrids; and distribute superior germplasm to national programs and commercial seed companies.

Table 7. **Results of 1984 grain yield trials of sorghum grown in field plots with 0.5, 1.5, and 4.0 t/ha lime ($CaCO_3$) at Quilichao, Colombia.**

Cultivar	Lime (t/ha) 0.5 Visual rating[a]	0.5 Height (m)	0.5 Yield (t/ha)	1.5 Height (m)	1.5 Yield (t/ha)	4.0 Height (m)	4.0 Yield (t/ha)
IS 2765	1.3	1.4	4.0	1.5	4.6	1.7	7.1
IS 7132	1.0	1.4	4.3	1.3	4.9	1.5	6.9
IS 7151	1.7	1.6	4.8	1.7	5.7	1.8	5.2
IS 8577	1.3	1.4	5.0	1.5	6.2	1.7	5.7
IS 8612	2.0	1.4	3.2	1.4	3.3	1.6	5.6
IS 8860	2.0	1.9	3.1	2.0	3.6	2.3	5.4
IS 8933	1.0	1.4	4.1	1.6	4.9	1.7	6.7
79 SEPON 8	2.7	1.2	2.3	1.5	3.2	1.6	6.3
79 SEPON 11	3.0	1.2	2.0	1.4	3.2	1.5	3.6
79 SEPON 54	2.0	1.0	3.8	1.2	3.7	1.3	5.0
M-91057-117	2.0	1.1	4.6	1.3	4.4	1.4	4.9
M-90378	3.0	1.0	2.9	1.3	3.1	1.2	3.2
(F3B55XF3B441)-1	2.0	.9	2.5	1.0	2.8	1.0	3.9
(F3B554XF3B441)-2	2.3	1.1	2.8	1.2	3.4	1.2	3.9
(GPR168XCS-170-6-17)-1-1	2.0	1.3	4.4	1.4	4.7	1.4	5.1
(IS12573CXSC108-3)7-3-5-1-1-1	1.7	1.2	4.4	1.2	4.5	1.2	5.5
3DX57/1/1/910	1.3	1.3	4.5	1.4	4.6	1.4	5.1
IS 7173C	1.0	1.3	3.6	1.3	4.3	1.3	4.8
TX 415	4.0	.6	.5	.6	1.2	.7	2.2
Mean	2.0	1.2	3.5	1.4	4.0	1.4	5.1

a 1 = Al tolerant, 4 = Al susceptible. Visual ratings for cultivars in 1.5 and 4.0 t/ha trials were all 1.0. Aluminum saturation levels for the 0.5, 1.5, and 4.0 t/ha lime rates were 63%, 45%, and 32%, respectively.

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has a worldwide mandate for sorghum improvement research, which includes germplasm collection and conservation. The world collection of some 22,000 sorghum lines is maintained by ICRISAT at Hyderabad, India. More than 15,000 of these lines are in long-term storage at the U.S. National Seed Storage Laboratory at Fort Collins, Colorado. An additional 9000 lines are maintained in the U.S. by the USDA and other research agencies (Acheampong et al., 1984).

The first step in utilizing this exotic germplasm was nonrandom selection of those lines that have a higher probability of being Al tolerant and that were obtainable in the Western Hemisphere in order to avoid quarantine delays. In 1982, the author, in cooperation with John Axtell, agronomist at Purdue University, developed a plan to select about 3000 lines from the portion of the world collection maintained at Purdue. Using soil classification maps of Africa to trace the location where a particular line was originally collected, lines were systematically selected from the acid soil areas. One would reasonably expect to find the greatest genetic diversity for Al tolerance in these tropical areas.

Seed of the first 1000 lines was planted at CIAT, Cali, Colombia during the winter of 1982-83. Since these lines were maintained in medium-term storage, they were planted in soils of optimum pH and fertility. It is necessary to increase the seed of these exotic lines in the tropics because about 60% of the world collection is photoperiod sensitive. Where plants were obtained, the seed from 10 self-pollinated heads of each line was harvested.

Evaluation for Al tolerance under field conditions was conducted as previously described in this paper. Additional advantages of field-screening trials over laboratory methods are the agronomic notes that can be collected. Plant height, number of days to anthesis, panicle shape, seed color, and foliar diseases are examples.

Based on observations in Colombia and discussions with EMBRAPA scientists, it appears that the inheritance of tolerance to the "tropical acid-soil complex" depends upon the parents used in the different studies and the degree of Al-toxicity stress. Some general conclusions can be drawn. Hybrids are generally more tolerant than either of their parental lines. Some lines (e.g., IS 7173C) appear to possess one or two major dominant genes for tolerance while others with more moderate levels of tolerance produce an epistatic response in hybrids. This would seem to indicate that several genes are interacting, but each gene contributes less than a major response in both hybrid and parent. When either TX 2536 or NB 9040 is used as a pollinator on Wheatland, all three lines being susceptible to all but low levels of Al toxicity, the hybrids are reasonably tolerant. When other factors in addition to Al tolerance are considered for the genotype grown in the field, it is not surprising that major, minor, modifier, and interacting genes should be encountered.

Additional inheritance studies are underway to determine whether Al-tolerant sources differ and if so, to see if they can be combined to produce lines with higher degrees of Al tolerance. Based on the differing quantities of Al in the leaves of tolerant lines, it seems probable that different mechanisms of tolerance are possible.

Several different approaches for incorporating the best sources of Al tolerance into elite sorghum lines are being employed in the Colombian INTSORMIL breeding program. Selected exotic genotypes with good Al tolerance are first crossed to a standard U.S. male sterile or A-line, and the seed set of the hybrid panicle (covered with a pollinating bag) is observed. No seed set indicates the exotic is a maintainer or B-line; full seed set, a restorer or R-line. Genes for other traits can be determined by observing the hybrid for height and maturity interactions, seed color, panicle characteristics, combining ability for yield, etc. If the hybrid is planted in the screening plot, the presence of major dominant genes for Al tolerance can be determined by the high degree of tolerance to Al toxicity.

Once the restorer/nonrestorer status is determined for the exotic, hybrids are made using elite lines with the same restorer response, restorer by restorer and nonrestorer by nonrestorer. A general improvement program is followed using the pedigree breeding method.

Of the nearly 100 evaluated B-lines released from the U.S. and ICRISAT programs, only a few indicate a slight tolerance to Al toxicity under field conditions. On the other hand, several exotic B-lines from the Texas A&M University/USDA sorghum conversion program produce a range of tolerance, IS 7173C being the best. Backcrossing into sterile cytoplasm is currently being carried out with IS 1309C, IS 3625C, IS 7173C, IS 12539C, and IS

12685C to produce Al-tolerant tester A-lines. Most of these lines are unsuitable as parents for commercial hybrids; therefore, lines IS 7173C, and IS 12685C have been crossed to elite U.S. B-lines in a standard pedigree breeding approach.

Two random-mating populations with ms_1 genetic male sterility from the author's Mississippi breeding program were used as disease-resistant base populations for the development of Al-tolerant B-line and R-line pools. As promising new Al-tolerant exotics are found, they are crossed into the appropriate pool. By replanting these populations on soil with 60-70% Al saturation twice each year, genes for Al tolerance will be concentrated in the surviving plants. This population improvement approach is ideal for Al tolerance because the susceptible plants die before they contribute their genes to the population.

This screening and breeding effort is without value unless the Al-tolerant germplasm is distributed freely to national sorghum improvement programs and on to commercial seed companies and the farmer. Each year, the best agronomically desirable Al-tolerant genotypes are made available for regional yield trials. Other exotic genotypes, improved lines, and segregating populations are sent to breeders upon request.

Summary

A systematic screening procedure is being employed to evaluate a significant portion of the sorghum world collection for tolerance to the Al-toxic low base status soils in the tropics. Through cooperation and collaboration with international agricultural research centers, national programs, universities, and commercial companies, INTSORMIL has helped make available a large infusion of Al-tolerant exotic sorghum germplasm to scientists conducting research on the tropical acid soil frontiers in developing countries.

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WORK GROUPS

Group 1 (Scientists) Report on Working Session

Researchers

Group 1 met on 30 May 1984 and discussed the provided agenda. The meeting was chaired by Dr. Vartan Guiragossian and notes were recorded by Dr. Oscar de Cordoba. Conclusions and recommendations are listed below.

Improvements and selection of sorghum for aluminum toxic soils: goals and strategies

The sorghum investigators would like to recognize the preliminary work initiated by the International Sorghum and Millet Program (INTSORMIL) and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in seeking new germplasm which can be grown on South American tropical soils that have high acidity and Al toxicity problems.

Coordination in planning and execution of the various areas of investigation among the national programs and the international organizations such as INTSORMIL, ICRISAT, and the Centro Internacional de Agricultura Tropical (CIAT), is an efficient way to resolve and find solutions to pertinent problems, to find adapted genotypes to the acid and high Al soils, and to develop the necessary technology to identify and improve these genotypes.

Apart from the countries involved, the international organizations should also assume responsibility for finding a solution to the problem.

Agroclimatology

The agroclimatology information for the South American areas with acid and high Al soils should be gathered. Dr. Lynn Gourley was given the responsibility to collect the agroclimatologic and edaphic data for the zones with acid and high Al soils in collaboration with representatives of the countries attending this workshop and with Dr. J. Nicholaides who should be an advisor for the collection and interpretation of the data. Dr. N. Seetharama is to send Dr. Gourley all of the information available at ICRISAT relative to agroclimatic data and the methodologies used. The Instituto Interamericano de Cooperación para la Agricultura (IICA) should serve as the center for sending agroclimatic information to the various zones.

Germplasm

For better efficiency in seeking appropriate germplasm for zones with acid and high Al soils, germplasm movement should be through the INTSORMIL research station at CIAT, Colombia, and ICRISAT in Mexico. To do this, interested countries should send 20- to 40- g samples of the seed of each genotype to ICRISAT present legislation and requirements of each country for the import and export of experimental seed samples. Private companies interested in obtaining sorghum germplasm of INTSORMIL and ICRISAT should follow the established regulations of each country. They should inform INTSORMIL and ICRISAT of results they obtain.

The national programs and INTSORMIL, who have some germplasm with tolerance to the acid and high Al soils, should send 20 to 40 g samples of the seed of each genotype to ICRISAT (Mexico) for immediate increase so these materials can be made available to other interested countries.

Since Brazil has conducted some advanced investigations on sorghum tolerance to acid soils, scientists there should receive from ICRISAT the Tanzania, Thailand, INTSORMIL, and CIAT collections for testing. Dr. Gourley of INTSORMIL should evaluate all materials that are collected in the laboratory and/or in the field.

Since the world collection is large and difficult for a single institution to evaluate, INTSORMIL and ICRISAT should ask the country national programs and private companies to help evaluate some of these materials under INTSORMIL and ICRISAT supervision.

The information obtained by the national programs and other institutions on germplasm evaluation should be channeled through INTSORMIL and ICRISAT representatives for distribution to the investigators in each country.

Physiology

Physiological mechanisms for tolerance or susceptibility to high Al levels in acid soils are fundamental not only for a knowledge of the problem, but also for the development of more appropriate methodologies so that tests in the laboratory can be validated within the field. Thus, genotypes with greater agronomic production potential can be selected.

It was recommended that Dr. Dale Ritchey, in collaboration with Drs. P. Furlani and G. Pitta, be responsible for conducting much of the physiological research. INTSORMIL and ICRISAT scientists should study the more basic mechanisms on how the physiological mechanisms for resistance to Al toxicity operate and collaborate with the country scientists. If possible, graduate students should be assigned to collaborate in the investigations oriented to understanding resistance mechanisms.

Dr. R. Clark was designated to collect and distribute methodological information (possibly as a newsletter) suggested or available to the investigators in each of the interested countries. Standardization of methodology, analysis, and numerical expression should be incorporated. A proposed Al toxic soil definition for field evaluation of sorghum lines from the world collection or breeding material was presented by Drs. John Nicholaides Jr., Stanley Buol, and K. Dale Ritchey.

1. Surface soil amended to a maximum depth of 50 cm.
2. Method of analysis and degree of Al saturation according to that method.

a. 1 *N* KCl method

$$\frac{\text{meq (Al)}}{\text{meq (Ca + Mg + K + Al)}} \times 100 = 60\%$$

Unless soil has a very low effective cation exchange capacity (ECEC) the meq Al per 100 cm^3 soil should be at least 1.5.

b. NH_4OH method at pH 7

$$\frac{\text{meq (Al + H)}}{\text{meq (Ca + Mg + K + Al + H)}} \times 100 = 67\%$$

c. $BaCl_2$ TEA method at pH 8.2

$$\frac{\text{meq (Al + H)}}{\text{meq (Ca + Mg + K + Al + H)}} \times 100 = 76\%$$

3. The following elements should be at the level indicated or higher according to the method used.

P	15 ppm	via	Bray II
	12 ppm	via	Olsen or Olsen modification
	18 ppm	via	North Carolina (double acid)
Ca	0.50 meq/100 cm^3 soil		via 1 *N* KCL
Mg	0.25 meq/100 cm^3 soil		via 1 *N* KCL
K	0.20 meq/100 cm^3 soil		via Olsen or Olsen modification.

4. Other elements must not be limiting.

Improvement

Each investigator should use appropriate methods for plant improvement compatible with the availability of economic resources and technology.

The inheritance mechanisms for plant tolerance to high Al in soils is important for understanding the problem. It was suggested that Brazil and INTSORMIL, who have already initiated genetic studies, continue these studies. INTSORMIL should involve graduate students from interested countries to collaborate in genetic studies as part of their thesis work. INTSORMIL and ICRISAT should involve the national programs or other institutions in studying genetic mechanisms for tolerance or susceptibility to acid and high Al soils.

Each country should perform tests in their own countries during 1984 and send the data to Mr. Renato Borgonovi in Brazil who will collect, analyze, and distribute then. From these results, uniform tests can be designed in different problem locations in each country for 1985 and thereafter (Table 1).

Table 1. **Sites of interest to national programs for uniform testing.**

Country	Site
Colombia	La Libertad, Llanos Carimagua, Llanos
Venezuela	El Sombrero, Central Plains El Tigre, Eastern Plains
Peru	Yurimaguas, Amazonia Puerto Maldonado, Amazonia
Brazil	Instituto Agronomico de Campinas (IAC), Mocoa, São Paulo Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), Sete Lagoas, Minas Gerias EMBRAPA/AGROCERES, Capinopolis, Minas Gerais

Agronomic and economic aspects

Both of these aspects are very important and should be considered once basic information has been delivered.

Training and service information

The professionals of interested countries can request the following types of training from INTSORMIL and ICRISAT:

1. ICRISAT offers two courses of training: First, a one week course in Mexico every year about different aspects of management, biological production, and cultivation of sorghum; and second, a five- to six-month training at the principal site in India or Mexico.

2. INTSORMIL offers opportunities for conducting basic research for the M.S. or Ph.D. degrees in the USA on problems associated with the production of sorghum related to South American tropic soils high in Al. Sometimes research is conducted in the home country. Short-term training periods with specific scientists or laboratories should be considered and are often available.

Recommendations with regard to service information are:

1. Persons seeking information on various aspects of sorghum should contact the Sorghum and Millets Information Centre (SMIC) at ICRISAT.

2. It is important that existing information related to Al tolerance in each country be sent to Dr. Lynn Gourley who will collect the information and dispense it to interested persons.

The next investigators meeting should take place in 1987 in one of the countries of the region. However, the national coordinators should meet at least annually to inform each other of recent activities in their countries and to plan actions for the future.

Other recommendations

1. The official representative from each country should request INTSORMIL and ICRISAT authorities to extend their activities to South America on the acid soil problems.
2. The group of tropical American sorghum investigators working on acid and high Al soil problems should be given a name, for example, ISAT (Sorghum Investigators of Tropical America).
3. The group should seriously consider preparing a regional proposal to be presented to international financial organizations so that continued investigations can be assured in case INTSORMIL and ICRISAT terminate their involvement.

The sorghum workers of tropical America acknowledge INTSORMIL, ICRISAT, and CIAT for organizing, financing, and providing excellent facilities for this meeting.

Group 2 (Administrators) Report on Working Session

Administrators

Group 2 met on 30 May 1984 and discussed the provided agenda. It was agreed at the outset that scientific priorities would be set by the scientists and the administrators would focus on organization and structural issues. The meeting was chaired by Dr. Fernando Arboleda and notes were recorded by Dr. R. R. Foil. Conclusions and recommendations are listed below.

Agroclimatology-environment

The International Sorghum and Millet Program (INTSORMIL) with the help from the Tropical Soils Program of North Carolina State University (TROPSOILS) should seek input from the National Programs and the Instituto Interamericano de Cooperación para la Agricultura (IICA) in the development of standardized criteria for test sites in the tropics and protocols for uniform cooperative tests. Potential sites in the tropics are listed in Table 1.

Table 1. **Potential sites in the tropics for the development of standardized criteria and protocols for uniform cooperative tests.**

Country	Site
Colombia	La Libertad, Llanos Carimagua, Llanos
Venezuela	El Sombrero, Central Plains El Tigre, Eastern Plains
Peru	San Ramón, Amazonia Puerto Maldonado, Amazonia
Brazil	Instituto Agronómico de Campinas (IAC), Mocoa, São Paulo Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), Sete Lagoas, Minas Gerais EMBRAPA, Triângulo Mineiro, Minas Gerais

Germplasm

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) should lead in designing and coordinating a mechanism for collection, movement, and cataloging of South American germplasm and networking of breeding programs. This should include the establishment of a working collection at the Centro Internacional de Agricultura Tropical (CIAT) and the Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) to be coordinated by Dr. V. Guiragossian.

Physiology, breeding, agroeconomics, and farming systems

The national programs present agreed to organize and to coordinate activities. Data from uniform trials would be exchanged and reported in a standard format. The secretariat for communication and coordination would rotate beginning with Brazil in 1984-85. INTSORMIL and other international research agencies should participate and follow up with needed detailed and fundamental research.

Training

ICRISAT welcomes trainees from South America to its training programs in sorghum (English language capability required). INTSORMIL should continue and increase the degree training component of its program. Joint or separate ICRISAT/INTSORMIL workshops at CIAT/CIMMYT and other South American locations are needed. The group agreed to explore possibilities for cooperative inservice training activities through personnel exchanges.

A "Sorghum in South America" symposium every three years would be appropriate.

Dissemination of information

ICRISAT will work through the organization of national programs to ensure that South American researchers and INTSORMIL will be on mailing lists.

Other recommendations

Collaboration of IICA in organization and planning for the regional program is highly desirable.

Participation

The following delegates were present:

Dr. Fernando Arboleda, national coordinator and session chairman, Instituto Colombiano Agropecuario (ICA), Colombia.

Dr. Héctor Mena, national coordinator, Fondo Nacional de Investigaciones Agropecuarias (FONAIAP), Venezuela.

Dr. Antonio Pinchinat, project leader and plant breeder, IICA, Lima, Perú.

Dr. Luis Narro León, national program leader, Instituto Nacional de Investigaciones y Promoción Agraria (INIPA), Cajamarca, Perú.

Dr. Cándido Bastos, director of industrial plants, Instituto Agronómico de Campinas (IAC), Brazil.

Dr. Renato Borgonovi, coordinator, National Sorghum Research Program, EMBRAPA/ Centro Nacional de Pesquisa de Milho e Sorgo (CNPMS), Sete Lagoas, Brazil.

Oscar Jurado, Programa de Investigación de Proacol.

Hugo Montealegre, Programa de Sorgo Colsemillas.

Rodney Foil, member of the Joint Committee on Agricultural Research and Development (JCARD) of the Board for International Food and Agricultural Development (BIFAD) and director of the Mississippi Agricultural and Forestry Experiment Station, Mississippi, USA.

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