Discipline Interactions in the Quest to Adapt Plants to Soil Stresses through Genetic Improvement

Robert E. Schaffert
EMBRAPA/CNPMS
Sete Lagoas, Mg, Brazil

ABSTRACT

Tropical soils are inferior in fertility compared to temperate soils. The "Tropical Belt" of the world contains 58 percent of the world's land area suitable for agriculture production. The adaptation of plants for tropical agriculture is frequently synonymous with adapting plants to soil fertility stress constituents. This phenomenon is by no means limited to the tropics, as the acid soils and subsoils of the Southeast U.S. are examples where plant improvement programs are often associated with adapting plants to soil stress. Modern plant breeding has traditionally produced crop cultivars that are very productive when combined with an intensive input management regime. The merits and difficulties of establishing collaborative, multidisciplinary, interdisciplinary research and crop cultivar development programs to increase nutrient use efficiency and tolerance to toxic elements are reviewed and discussed. The goal for increasing nutrient use efficiency is not to increase the mining potential of soils by plants or develop a temporary fix for soil fertility problems, but rather to transform marginal agriculture land suitable for agriculture production into productive sustainable agriculture land by developing and utilizing cultivars with soil stress tolerance and improved nutrient use efficiency.

INTRODUCTION

I wish to thank the organizing committee for the honor and opportunity to address this distinguished group of scientists and research administrators. The theme of this workshop, "Adapting Plants to Soil Stresses" has been one of the principle thrusts of my professional agenda for the past two and one-half decades. Over the past 22 years I have had the opportunity to work collaboratively in research programs that promote increased sustainable food production in the tropics. In general, I have learned that tropical soils are inferior in fertility, compared to temperate soils. What are classified as good soils in the tropics, in many cases would be classified as only marginal soils in the "breadbasket" of the Midwest of the United States. The "Tropical Belt" of the world contains 58% of the world's land area suitable for agriculture production as well as 73% of the world population (FAO,1991). The adaption of plants for tropical agriculture is frequently synonymous with adapting plants to soil stress. This phenomenon is by no means limited to the tropics. The acid soils and subsoils of the Southeast U.S. are examples where plant improvement programs are often associated with adapting plants to soil stress.

Much of what I have to express today is built on the experience of nearly 17 years of conducting research in the acid savannas of Brazil and over four years as the project manager of the Sorghum and Millet, and Peanut Collaborative Research Support Programs (CRSPs). These CRSPs of the Agency for International Development (A.I.D.) maintain collaborative research projects in the tropics of Africa, Asia, and Latin America.

Initially I would like to emphasize the point that the goal for increasing nutrient use efficiency is not to increase the mining potential of soils by plants or develop a temporary fix for soil fertility problems. Low and marginal fertility of the majority of tropical soils requires Research and Development (R&D) institutions located in these regions to develop crop production systems that utilize crops with enhanced efficiency in the ability to utilize nutrients from the soil or applied fertilizer. The overall goal of this type of research thrust is to increase the area of land suitable for agriculture production as well as reduce the amount of fertilizer required for sustainable crop production. This has implications on food security, nutrient reserves for fertilizer production, environmental degradation caused be fertilizer nutrient erosion, and sustainable crop production.

A BRAZILIAN EXAMPLE

The "Cerrado", an acid savanna eco-region of Brazil considered unsuitable for agriculture crop production as recently as 20 years ago, covers an extension of 205 m ha, of which 175 m ha are in Central Brazil. Approximately 112 m ha of the "Cerrado" are considered adequate for developing sustainable agriculture production in Central Brazil (FAO, 1992). The soils of the "Cerrado" are commonly characterized by low pH, low phosphorus availability, low fertility, and toxic aluminum (Sanchez and Salinas, 1981). Today, 12 million hectares of the Brazilian "Cerrado" are in crop production, producing 25% of the Brazilian rice, maize, and soybean production, 20% of the coffee production, and 15% of the bean production. Another 35 million hectares of improved pastures have been developed in the "Cerrado", carrying 53 million head of cattle and producing 40 % of Brazil's meat production and 12% of its milk production.

The area planted with maize in the "Cerrado" of Brazil has increased from 1.6 million hectares in 1970 to over 3.5 million hectares in 1990 while the average productivity has increased from less than 1.4 t/ha to over 2.4 t/ha. The average maize yield, in several municipalities (counties) located in the "Cerrado", where EMBRAPA-generated technology for acid soils is utilized, is over 4.0 t/ha.

Total grain production (rice, maize, beans. soybeans, and wheat) in the "Cerrado" has increased from 5.6 m T in 1970 to over 20 m T in 1990. During this time period average grain productivity of both maize and soybeans increased from 1.4 and 1.2 t/ha to over 2.4 and 2.0 t/ha respectively. This reflects the results of **interdisciplinary and multidisciplinary** crop improvement programs directly aimed to overcome soil fertility problems by utilizing genetic resources more efficient in nutrient uptake and utilization.

IDENTIFYING THE PROBLEM

The world's arable land resources are finite. For approximately 15 billion hectares of land surface on the planet earth, only 22%, or 3.3 billion hectares are considered agriculturally productive (Buringh, 1989). Eighty-five percent of this productive land is classified as low or medium in productivity. Nutrient stress is one of the leading causes for reduced crop productivity.

The expanding human population or "population monster" in it's search for food and fuel for today's needs puts tomorrow's sustainable agriculture production and natural resources preservation in jeopardy in many areas of the world (Lal, 1991). A logical and effective approach to arrest and invert this type of environmental degradation is to increase the production and productivity on land suitable for agriculture. This includes increasing sustainable agriculture production on productive land as well as transforming marginal lands into sustainable productive lands. A study on soil research priorities by the National Research Council (National Research Council, 1992) prioritized developing and selecting appropriate crops and cultivars for specific soil conditions as one of four major research thrusts needed for future agriculture sustainability.

The underling principal of plant improvement programs is the presence of genetic variability (Hallauer, 1991) for the trait or traits in question and the ability to manipulate this genetic variability for improvement of the characteristics desired. During the past several decades, plant scientists from several disciplines have improved food and feed production systems around the world. Plant breeders, working collaboratively with plant pathologists and entomologists have identified genetic variation for disease and insect resistance and utilized this resistance in developing highly efficient production systems (Khush, 1991; and Ponti and Mollema,1991). Plant breeders working collaboratively with other disciplines have also made improvements in food and feed quality (National Research Council, 1988). Collaborating with agronomists and agriculture engineers, plant breeders have contributed to advances in mechanization, harvesting and utilization improvements (Hauptli et al., 1990). However, if we observe closely, much or nearly all the success of collaborative breeding programs have been associated with aspects of the production system above the soil surface.

Modern plant breeding has produced crop cultivars that are very productive when combined with an intensive input management regime (Hauptli et al., 1990). The Symposium on Plant Breeding in the 1990s (Stalker and Murphy, 1991) had one session on modification of plants to tolerate environmental stresses. However, only one paper was presented in the area of soil fertility stresses. In this paper (Dvorák et al., 1991) emphasized the importance of understanding the genetic and physiological mechanisms by which plants cope with adverse conditions in order to develop efficient strategies for breeding stress tolerant cultivars. He divided stress caused by soil conditions into two categories; deficiencies of nutrient elements, and toxic concentrations of elements or salts. He defined toxic stress as being more important, as deficiencies may often be remedied by the application of appropriate fertilizers. In reality, the scenario is often not this simple; nutrient deficiencies and toxicities are often found together. Acid soils of the tropics are in general characterized by low pH and low levels of available phosphorus, potassium, and micro-nutrients (principally zinc), low cation exchange capacity, as well as toxic aluminum and manganese. Aluminum toxicity in the top soil, due to soil acidity, can be ameliorated with the application of lime, but this practice is not realistic for the subsoil. Likewise, the addition of adequate fertilizer may not be an economical sustainable practice, especially in the tropics. In my judgement, a breeding strategy for more efficient use of macro- and micronutrients is at least as important as a strategy for breeding for toxic elements, if not more so.

Analyzing this more closely, two major factors can be identified that contribute to the lack of breeding strategies that deal with developing cultivars for soil fertility stresses. First, it is much simpler to identify and score resistance and susceptibility to a disease like anthracnose or rust than to identify a plant with greater efficiency in phosphorus uptake and utilization or nitrogen utilization. We might indirectly select for certain soil characteristics by selecting for greater yield. Dr. Charles Foy (Foy et al.,

1974) relates the case where the best wheat cultivars developed in Indiana, such as Monon, performed poorly when evaluated in Ohio, however the wheats developed in Ohio, such as Seneca, performed well in both Indiana and Ohio. Carefully evaluating these data, Foy and co-workers identified differences in innate response to soil acidity as the cause of differential yield responses. The soils in Ohio are more acid and have higher aluminum saturation. Consequently, the wheat cultivars bred and selected in Ohio were more tolerant to this soil condition, whereas those selected in Indiana were susceptible to the higher levels of aluminum saturation in the Ohio soils and consequently performed poorly when tested in Ohio. The development and refinement of screening and selection methodologies for improving nutrient use efficiencies is of utmost importance. Interdisciplinary collaboration, including biotechnology, is essential in developing these new development tools.

Secondly, the basic philosophy of R&D of the U.S. research and extension system over several decades, from the 1940's to the mid 1980's and even continuing at some institutions until today, is based on the capacity of soil scientists to develop technologies for nutrient management (King, 1990) and to correct soil deficiencies (Kellogg, 1975) while the plant breeder conducts his crop breeding program using all the latest technologies developed by the soil scientists. In this system, the presence of any genetic variability for improved efficiency in soil nutrient utilization will be completely unrecognized. In fact, we may actually be selecting for reduced efficiency in utilizing soil nutrients in these high input scenarios.

The great success of the U.S. research and extension system in developing technologies for increasing productivity with the use of fertilizers and promoting increased fertilizer use to enhance production has resulted in increased crop productivity over the past decades. This highly successful program has also lead to the promotion of outstanding soil scientists to head agronomy and plant and soil science departments throughout the land grant university system of the U.S. I believe it is safe to say that the research philosophy in many land grant universities today promotes plant breeding systems where segregating germplasm is evaluated under "ideal" or "optimum" soil fertility. I do not intend to discuss the merits or shortcomings of this research philosophy, however, I believe it is obvious that it will not lead to the identification and selection of germplasm with improved efficiency in plant nutrient utilization.

I do not want to leave the impression that the lack of collaborative interdisciplinary research activity to develop cultivars more efficient in nutrient use and more tolerant to toxic elements is caused by the lack of collaboration by the soil scientists. During the past five years in my quest to foster this type of collaborative research, I have encountered as much resistance from the plant breeders as from the soil scientists. An exception to this resistance has been the interdisciplinary breeding and soil fertility management projects involving maize and sorghum development for the "Cerrado" at the National Maize and Sorghum Research Center of Brazil (CNPMS/EMBRAPA).

The merits of a collaborative, multidisciplinary, interdisciplinary research program to increase nitrogen, potassium, and phosphorous efficiency in U.S. agriculture are obvious when the total consumption of N, P, and K is considered. U.S. agriculture consumed over 20 million tons of plant nutrients in 1992 (USDA/ERS, 1993). During 1992, U.S. maize production alone consumed 4.9 million tons of nitrogen, 1.9 million tons of phosphate, and 2.3 million tons of potash, nearly half the plant nutrients consumed in all agriculture activity. An increase in the efficiency of only five or ten percent represents an enormous savings. A ten percent increase in the efficiency of the plant nutrient use in maize would represent a savings of over 900,000 tons. At an average value of $150 per ton this would represent an annual savings of $136 million to maize producers. This becomes even more important when economic and ecological sustainability, and reserves of known world nutrient stocks are concerned. Considering the large quantity of nitrogen consumed in the U.S. for maize production, a gain in utilization efficiency has strong ecological implications.

GENETIC VARIABILITY FOR EFFICIENCY OF SOIL NUTRIENT UTILIZATION

Plant breeding is the science and art of effective management of genetic variability to attain desired breeding goals (Hallauer, 1991). The presence of genetic variation for efficiency in nitrogen, phosphorus, and potassium uptake and utilization in crop species is intuitively obvious. The more complex the biochemical process, the more enzymes involved in controlling

Table 1. Total U.S. consumption of plant nutrients (1,000 nutrient tons) and plant nutrient use by maize and soybeans in 1992.

	Maize	Soybeans	Other	Total
Nitrogen	4,886	97	6,417	11,400
Phosphate	1,854	319	2,037	4,210
Potash	2,256	583	2,206	5,045
Total	8,996	999	10,660	20,655

Source: USDA/ERS Statistical Bulletin #842.

the system, and the greater the probability for genetic variation; or to put it another way, the greater the genetic variation.

I remember some 25 years ago, when I was a graduate student at Purdue University, I became involved in selecting sorghum lines for greater protein content. In 1970, I planted 270 lines selected for high protein content and 30 lines selected for low protein content in a newly acquired area of the Agronomy Farm. Side-dressing of nitrogen was delayed due to frequent rains. The block of 30 low protein lines had symptoms of nitrogen deficiency, whereas the block of 270 high protein lines did not portray any symptoms of nitrogen deficiency. This does not necessarily establish a correlation between protein content and nitrogen use efficiency, but does exemplify the availability of genetic variance for nitrogen use efficiency.

My first experience with genetic variability for tolerance to low soil pH and toxic aluminum was in 1973. I had recently arrived in Brazil and had planted several sorghum evaluation trials. One trial of U.S. commercial hybrids planted on the state experiment station near Sete Lagoas, Minas Gerais began showing variability for moisture stress. After several days of mid-season moisture stress, some hybrids were near the permanent wilting point. Coincidently, Dr. Charles Foy, a plant physiologist of the USDA at Beltsville, Maryland was visiting Brazil and presented a seminar on his experiences with plant tolerance to toxic levels of exchangeable aluminum in the soil. This seminar alerted my colleagues and me to the possibility of a chemical barrier in the soil impeding root development into the subsoil. After the seminar, Dr. Foy accompanied us to the field where it was established that the top 20 centimeters of the soil had been corrected for soil acidity with a previous application of lime. The sorghum hybrids suffering from moisture stress had roots concentrated in the top 20 cm layer of the soil, whereas the root system of the hybrids showing no stress, had developed well below the top 20 cm layer. Later analysis of the soil confirmed a difference of pH and aluminum saturation between the top 20 cm soil layer and the 20 to 40 cm soil layer. As it turned out, this was a narrow window of opportunity; all the hybrids were susceptible to aluminum toxicity at slightly higher levels of aluminum saturation.

These observations lead to the development to an interdisciplinary research project to develop screening methodologies, to screen sorghum germplasm for tolerance to aluminum toxicity, and develop improved cultivars with tolerance to aluminum toxicity. More recent research results indicate that some Ugandan sorghum lines (CMSXS 189, 3DX57/1/1/9/D; CMSXS 208, 5DX61/6/2; and CMSXS 209, IS2744) selected and developed for tolerance to aluminum toxicity were also more efficient in the use of phosphorus and potassium (Pitta and Santos,1992). Selecting under field conditions has also given us an array of changes in nutrient use efficiency. I believe our program has in fact been selecting genotypes tolerant or more efficient to the "Cerrado soil fertility complex", than to just tolerance to aluminum toxicity.

This interdisciplinary project resulted in the development of an array of screening tools involving controlled nutrient solutions, greenhouse pots and flats, and field screening. The development and perfection of these methodologies involve close monitoring and evaluation by the multidisciplinary research team. The germplasm (Tables 2 and 3) identified as tolerant to the "Cerrado Complex" (Borgonovi et al., 1984 and 1986) in the early stages of this interdisciplinary program still remain competitive in 1990. However, new sources of aluminum tolerance has been identified in the last four years with more production potential and apparent superior tolerance to aluminum toxicity (Santos and Pitta, 1992). High yielding aluminum tolerant sorghum hybrids (Table 4) developed at CNPMS/EMBRAPA using susceptible female lines and newly developed restorer lines are being evaluated in the "Cerrado" of Central Brazil (Santos et al., 1992) with excellent results.

Table 2. Sorghum lines tolerant to aluminum toxicity under field and greenhouse conditions at CNPMS/EMBRAPA, Sete Lagoas, MG. Brazil.

Pedigree	Origin	Type of screening[1]
9-DX-9/11	Uganda	C/Sn/S
5-DX-61/6/2	Uganda	C/Sn/S
IS-7173-C (SC283)	Tanzania	C/Sn/S
156-P-5-Serere-1	Uganda	C/Sn/S
IS-3625-C (SC549)	Nigeria	Sn
IS-12666-C (SC175-14)	Ethiopia	C/Sn/S
IS7254-C (SC566-14)	Nigeria	C/Sn
V-20-1-1-1	Uganda	C/Sn
CMS-XS-604	Brazil	C/Sn
IS-12564-C (SC048)	Sudan	C/Sn/S
IS-1335-C (SC418)	Tanzania	C/Sn/S
3-DX-57/1/1/910	Uganda	C/Sn/S
IS-2744	—	C/Sn
IS-7542-C (SC408)	Nigeria	C/Sn/S
IS-1309-C (SC322)	Tanzania	C/Sn/S
IS-12612-C (SC112-14)	Ethiopia	C
IS-8337-C	Paquistão	C
IS-7419-C	Nigeria	C
MN-1204	—	Sn

[1] C = Field screening
Sn = Nutrient solution screening
S = Greenhouse screening with soil

Source: (Borgonovi et al., 1986).

Table 3. 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[1]	Relative seminal root growth (%)
IS 7254C(SC566-14)	Nigeria	Caudatum	B	39.5
5DX 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 12612C (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

[1] 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 et al., 1984).

Table 4. Response of experimental sorghum hybrids tolerant to aluminum toxicity (45% aluminum saturation) at CNPMS/EMBRAPA, Sete Lagoas, MG, Brazil (1991/1992).

Pedigree	Days to flower	Height (cm)	Grain production (t/ha)	Harvest index
TX 1391AX (SC283 x SC326-6)30-1-1	78	147	4.65	0.55
IS0187A X (SC283 x SC326-6)30-1-2	76	175	4.65	0.49
TX 1399AX (SC283 x SC326-6)30-1-2	82	150	4.52	0.55
IS 0187A x (SC283 x SC326-6) 29-2-1	76	163	4.37	0.49
3DX57/1/1/9D (tolerant line)	96	177	3.6	0.27

Source: (Santos, 1992)

New generation experimental sorghum hybrids developed with aluminum tolerant female and restorer lines are in the initial evaluation stage at CNPMS/EMBRAPA. The goal of this interdisciplinary project is to have these new generation hybrids commercially available in the next one or two years.

INTERDISCIPLINARY RESEARCH APPROACH

I am not sure if Agronomy 101 or Plant Breeding 201 or 520 orients today's agronomy students much differently, compared to 20 years ago, with respect to the presence of this type of genetic variability. However, I feel quite comfortable in predicting that the training of today's plant breeders with respect to soil fertility and plant nutrition and today's soil scientists with respect to genetic variation is not much different today than it was 25 years ago. Assuming that today's agronomy graduates are aware of these differences, it is quite arrogant to think that the plant breeder alone, can effectively develop plant cultivars more efficient in nutrient uptake and utilization without the collaboration of soil scientists, plant physiologists and other disciplines. "Oh, but that's obvious" you say. Then why is it so difficult to get plant breeders and soil fertility experts together in the same research program?

I have had some feedback on this question and some proper thoughts that I would like to discuss with you today. The first prerequisite for collaborative research, is **funding** for collaborative research. This essentially involves "interdisciplinary collaboration" between research administrators who determine where the research dollars are allocated and the research theme team. Research administrators allocate resources to research projects only after they are convinced that a problem exists, are convinced that R&D can efficiently resolve the problem, and are convinced that a reasonable probability exists to resolve the problem and have positive economic and social impact. I agree, it is not intuitively obvious that the maize and soybean producers of the midwest U.S. can and will benefit from cultivars and technology developed for tolerance to toxic aluminum in acid soils and subsoils. A paper to be presented later at this workshop by Drs. Magnavaca and Bahia Filho (Magnavaca, R. and A.F.C. Bahia Filho, 1993) will show the positive correlation between aluminum tolerance and phosphorus utilization efficiency in maize. With this information it is much easier to convince the research administrator from the midwest about the potential returns from such a research program. The array of benefits in developing cultivars more efficient in nitrogen utilization are more obvious, but the probability of success is perceived as even less than more efficient phosphorus utilization.

I would like to relate another incident regarding collaboration between soil scientists and plant breeders. At the "Second International Symposium on Plant-Soil Interactions at Low pH" held at Beckley, West Virginia in June of 1990, a comment was made in the plenary session that it was hoped that the international symposium would foster a marriage between plant breeders and soil scientists for collaborative R&D, similar to the partnerships between plant breeders and plant pathologists or plant breeders and entomologists formed over the past decades. A prominent international soil scientist responded; "Be careful with this proposed marriage. I was involved in establishing the criteria that resulted in the selection of the miracle rice, IR-8, but who got the credit? The plant breeders seized the credit, with not a mention of the soil scientist who established the selection criteria for high yielding rice. Beware!!!" Now that's a extremely strong statement, but with a very important message. I later had the opportunity to discuss this episode with Dr. John Axtell. He remarked that plant breeders frequently get so evolved and caught up in their work that they neglect to give due credit and recognition to their collaborators. I hope this case is the exception and not the rule; none-the-less, it emphasizes the importance of remembering all collaborators when releasing new germplasm and cultivars, even those involved at the very beginning of the process.

WORKSHOP AGENDA

The spirit of this workshop is to review and document the nature of the problem in adapting or developing plants tolerant to soil stresses, review and discuss solutions to problems, as well as to document impact from ongoing R&D in this area from selected sites around the world. Each session of this workshop will exemplify the complexity of the "Adaption of Plants to Soil Stress". I am not familiar with all the success stories to be related in Session VII, but the ones that I am familiar with, involve both interdisciplinary and multidisciplinary collaboration from research planning and project preparation through the execution and evaluation phases. In my opinion discipline interactions are not a question of choice when addressing this complex theme of adapting plants to soil stresses, but one of necessity.

CONCLUSIONS

In conclusion, I would like to briefly summarize the principal points and recommendations.

Soil fertility stresses or soil nutrient stresses, both deficiencies and toxicities, are phenomenons that reduce crop yields and limit sustainable agriculture production in the tropics as well as in many temperate regions.

Genetic variability for nutrient stress exists and is available in genetic resource banks for use in genetic improvement programs.

Sustainable production systems with improved nutrient use efficiency are achievable and beneficial in temperate soils as well as tropical soils.

The development of crop cultivars more efficient in nutrient utilization and tolerant to nutrient element toxicities is essential for sustained crop productivity increases throughout this decade and the next century.

Collaborative research programs with mutual objectives, involving institutions and scientists from both temperate and tropical geographical regions are desirable and recommended for developing cultivars with improved tolerance to soil stresses.

Interdisciplinary research collaboration is essential for developing cultivars and production technology for tolerance to soil toxicities and improved nutrient use efficiency.

Interdisciplinary collaboration and communication between research administrators and the interdisciplinary research team is essential for allocating adequate research resources to this important problem.

Agricultural land suitable for production, but considered marginal due to soil fertility stress, both toxicities and low fertility, can be transformed into productive sustainable agriculture land by developing and utilizing cultivars with soil stress tolerance and improved nutrient use efficiency.

REFERENCES

Borgonovi, R.A., R.E. Schaffert and G.V.E. Pitta. 1987. Breeding aluminum-tolerant sorghums. In L.M. Gourley, and J.G. Salinas (eds.) Sorghum for Acid Soils, CIAT, Cali, Colombia.

Borgonovi, R.A., R.E. Schaffert, H.L. Santos and G.V.E. Pitta. 1986. Introdução e avaliação de germoplasma de sorgo para tolerância a toxicidade de alumínio. In "Relatório Técnico Anual do Centro Nacional de Pesquisa de Milho e Sorgo - Período 1981-1984". CNPMS/EMBRAPA, 35701-970 Sete Lagoas, MG, Brazil.

Buringh, P. 1989. Availability of agriculture lands for crop and livestock production. In D. Pimental and C.W. Hall (eds.) "Food and Natural Resources", Academic Press, San Diego, CA, USA. Pp 70-85.

Dvorák, J., E. Epstein, A. Galvez, P. Gulick and J.A. Omielan. 1991. Genetic basis of plant tolerance of soil toxicity. In H.T. Stalker and J.P. Murphy (eds.) "Plant Breeding in the 1990s - Proceedings of the Symposium on Plant Breeding in the 1990s". C.A.B. International, Wallingford, Oxon, OX10 8DE, UK.

FAO. 1991. The Production Yearbook. FAO, Rome, Italy.

FAO. 1992. (To be completed)
Foy, C.D., H.N. Lafever, J.W. Schwartz and A.I. Fleming. 1974. Aluminum tolerance of wheat cultivars related to region of origin. Agron. J. 66:751-758.
Hallauer, A.R. 1991. Use of genetic variation for breeding populations in cross-pollinated species. In H.T. Stalker and J.P. Murphy (eds.) "Plant Breeding in the 1990s - Proceedings of the Symposium on Plant Breeding in the 1990s". C.A.B. International, Wallingford, Oxon, OX10 8DE, UK.
Hauptli, H., D. Katz, B.R. Thomas and R.M. Goodman. 1990. In C.A. Edwards, R. Lal, P. Madden, R.H. Miller and G. House (eds.), Sustainable Agriculture Systems. Soil and Water Conservation Society, Ankeny, IA 50021, USA.
Kellogg, C.E. 1975. Agriculture Development: Soil, Food, People, Work. American Society of America, Inc., Madison, WI, USA.
King, L.D. 1990. Soil Nutrient Management in the United States. In C.A. Edwards, R. Lal, P. Madden, R.H. Miller and G. House (eds.), Sustainable Agriculture Systems. Soil and Water Conservation Society, Ankeny, IA 50021, USA.
Khush, G.S. 1991. Selecting rice for simply inherited resistances. In H.T. Stalker and J.P. Murphy (eds.) "Plant Breeding in the 1990s - Proceedings of the Symposium on Plant Breeding in the 1990s". C.A.B. International, Wallingford, Oxon, OX10 8DE, UK.
Lal, R. 1991. Strategies for sustainable management of soil and water resources to enhance per capita productivity in the tropics. Scientific Liaison Officers to International Agriculture Research Centers. A.I.D., Washington, D.C. 20523
Magnavaca, R. and A.F.C. Bahia Filho. 1993. In Press, Proceedings of this workshop.
National Research Council. 1988. *Quality Protein Maize*. National Academy Press, Washington, D.C. USA.
National Research Council. 1992. (Information to be completed)
Pitta, G.V.E. and F.G. dos Santos. 1992. O potássio na nutrição e na tolerância ao aluminio em sorgo. In "Relatório Técnico Anual do Centro Nacional de Pesquisa de Milho e Sorgo - Período 1988-1991". CNPMS/EMBRAPA, 35701-970 Sete Lagoas, MG, Brazil.
Ponti, O.M.B. de and C. Mollema. 1991. Emerging breeding strategies for insect resistance. In H.T. Stalker and J.P. Murphy (eds.) "Plant Breeding in the 1990s - Proceedings of the Symposium on Plant Breeding in the 1990s". C.A.B. International, Wallingford, Oxon, OX10 8DE, UK.
Sanchez, P.A. and J.G. Salinas. 1981. Low input technology for managing oxisoils in Tropical America. Adv. in Agronomy, 34:279-406.
Santos, F.G., G.V.E. Pitta and R.E. Schaffert. 1992. Obtenção e avaliação de híbridos para toleráncia à toxicidade de aluminio. In "Relatório Técnico Anual do Centro Nacional de Pesquisa de Milho e Sorgo - Período 1988-1991". CNPMS/EMBRAPA, 35701-970 Sete Lagoas, MG, Brazil.
Santos, F.G. and G.V.E. Pitta. 1992. Introdução e avaliação de germoplasma de sorgo para tolerância à toxicidade de alumínio. In "Relatório Técnico Anual do Centro Nacional de Pesquisa de Milho e Sorgo - Período 1988-1991". CNPMS/EMBRAPA, 35701-970 Sete Lagoas, MG, Brazil.
Stalker, H.T. and J.P. Murphy (eds.). 1991. Plant Breeding in the 1990s - Proceedings of the Symposium on Plant Breeding in the 1990s. C.A.B. International, Wallingford, Oxon, OX10 8DE, UK.
USDA/ERS, 1993. Statistical Bulletin #842: Fertilizer Use and Price Statistics, 1960-92. Washington, D.C., USA.