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Management of Soil Acidity

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Summary

Generalizations about food crop response to liming of acid soils in the tropics are illustrated. Current methods of extrapolating and interpolating experimental results to other soils and crops are examined, and none are found to be universally useful. Future network actions should include the following:

a. *Interested countries should be encouraged and supported to collect and summarize their in-country data on management of soil acidity, including current research and an appraisal of research needs. There should be an effort devoted to collecting and summarizing these reviews.*
b. *There is need for 5 to 10 long-term lime experiments with careful attention to measuring critical soil and crop parameters so that results of all experiments can be compared and used for purposes of extrapolation and interpolation.*
c. *There is a need for two basic research projects: one to describe in detail the reactions and chemistry in the root-soil interface, and another to describe the long-term changes in chemical properties throughout the soil profile following liming. These two projects are essential to using our experimental data for all economic, soil, crop, and climatic conditions.*

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Introduction

Soil acidity is only one of many factors that must be managed in order to increase food production on acid tropical soils; however, unless acid soils are managed correctly, sustained production of food crops will not be feasible. This paper (1) reviews selected aspects of present knowledge about food-crop response to lime on acid soils and (2) proposes a comprehensive research program for soil acidity. Similar reviews have been published by Pearson (1975), Lathwell (1979), van Raij et al. (1983), and Adams (1984).

Generally, the focus is on well-drained acid soils, and the emphasis is on food crops. We concentrate on experiments in which nutrients (other than lime) were at levels appropriate for high production, and we do not discuss interactions with other nutrients to any great extent.

One aspect of the utilization of acid soils not discussed here includes situations in which land area relative to population is large and high yields of food crops per unit area are not critical. In some of these situations, pasture production with acid-tolerant species and small additions of Ca are sufficient to increase and sustain beef production. Food crops can be produced in rotations when the nutrients are carefully conserved during crop growth and when a deep-rooted crop is grown periodically to recover any nutrients that have been leached below the rooting zone of the food crops. Periodic additions of nutrients, including Ca, are usually necessary to sustain production, but these additions of Ca are not always referred to as liming in the usual sense of the word.

We do not use the term "lime requirement" except when it refers to the relationship between amount of lime added and degree of amelioration of soil acidity. In general, others use "lime requirement" to describe the recommendations made to farmers; this use implies an economic judgment has been made, which means that as one travels around the world the amount of lime recommended in any given situation changes with differing economic situations. Because this review is aimed at an international audience, we restrict our discussion to the biological input-output relationships (e.g., yields vs. lime inputs) so we can avoid the ambiguities associated with "low input" vs. "high input," "developed" vs. "developing," "poor" vs. "rich," "large" vs. "small," etc. Because the role of agronomists is to provide the biological input-output relationships necessary to any rational economic and social analysis, we must be sure to provide the output possibilities for the whole range of inputs—from none to those required for maximinum biological yields. If we do this, then our data can be used in all economic and social strata, including "large" and "small," "rich" and "poor" farmers.

Example of a Well-Planned Lime Experiment

In 1972 a lime experiment was initiated at CPAC (Planaltina, Brazil) on a virgin soil recently cleared from native *Cerrado*. In the Brazilian soil classification system it is called *Latossolo vermelho escuro* (CPAC 1976), and according to the U.S.

Soil Taxonomy it is classed as a Typic Haplustox, fine, kaolinitic, isohyperthermic (Salinas 1978). Some characteristics are listed in Table 1.

The treatments included 0, 1, 2, 4, and 8 t ha^{-1} of lime, and each was mixed to depths of 15 and 30 cm. Phosphorus, N, K, S, and micronutrients were added in amounts judged sufficient to eliminate these nutrients as important factors limiting yield. Yields of crops were measured each year for 10 years, and soil samples were taken at intervals of time for laboratory analyses (CPAC 1976, 1979, 1981, 1982). Figure 1 illustrates the accumulated yields of the first three crops of maize (two wet-season crops and one irrigated dry-season crop) for the different lime levels and the two depths of incorporation. Additions of more than 4 t of lime per ha gave only small increases in yield when lime was incorporated to the 30-cm depth; yields decreased slightly where more than 4 t of lime was incorporated to the 15-cm depth.

The superior yields at the 30-cm depth of incorporation were shown in associated research to be the result of more favorable root growth in the soil below the plow layer (Gonzalez et al. 1979). Because the soil acidity is so intense, the roots of aluminum-sensitive plants do not penetrate the subsoil layers and do not use water and nutrients below the depth of incorporation of lime in the initial year or two of cropping. As a consequence, yields are improved by deeper incorporation of lime since the crops have more water and nutrients available for use during prolonged periods without rain (Bouldin 1979; Gonzalez et al. 1979).

This experiment was continued in succeeding years using different crops. In the later crops, differences in yields between the depths of incorporation of lime gradually disappeared. Field observations and chemical studies of soil confirmed that

Table 1. Selected properties of the fine, kaolinitic, isohyperthermic Typic Haplustox at the experimental site for lime experiments at CPAC, Planaltina, Brazil, after the virgin soil was cleared from *Cerrado*. (From Salinas 1978.)

Soil property	Depth of sampling (cm)		
	0-20	20-40	40-60[4]
Clay (%)	45	51	—
Silt (%)	20	17	—
Sand (%)	35	32	—
pH (1:1 soil:H_2O)	4.7	4.6	4.5
Exch. Ca + Mg (cmol kg^{-1})[1]	0.15	0.15	0.15
Exch. Al (cmol kg^{-1})[1]	1.04	0.90	0.92
Effective CEC (cmol kg^{-1})[2]	1.25	1.10	1.09
Aluminum saturation (%)[3]	83	82	84
Available P (Mehlich I method) (kg mg^{-1})	1.9	1.0	Trace

1. Extracted with 1*N* KCl, 1:10 soil-solution rates.
2. Σ Ca + Mg + K + Al.
3. (Al/Σ Ca + Mg + K + Al) × 100.
4. Dashes indicate data not determined.

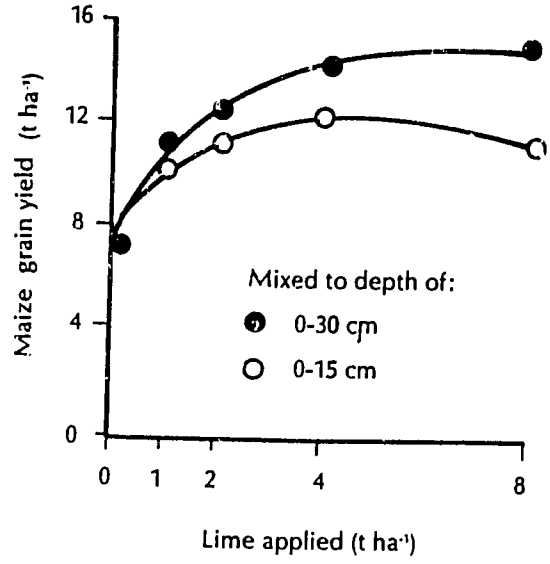

Fig. 1. Accumulated maize grain yields from the first three crops after lime application to an Oxisol from the *Cerrado* of Brazil in 1972. (After CPAC 1976.)

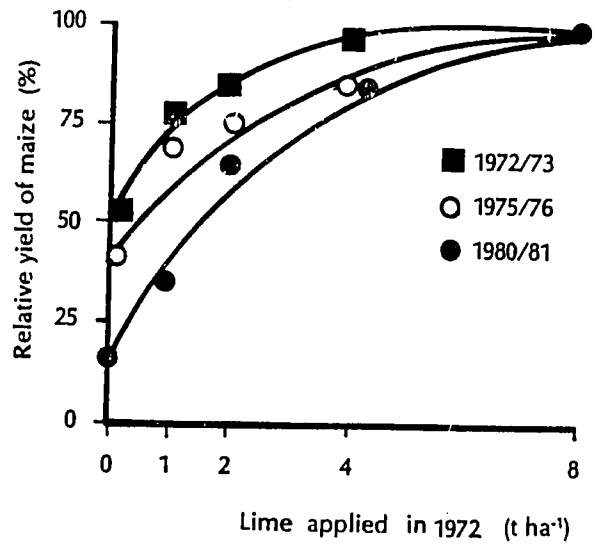

Fig. 2. Residual effects of lime applied in 1972 on maize on the same soil as Fig. 1. Each point is the average of the 0-15 and 0-30 depth of mixing. Lines are for reference purposes. (After CPAC 1976, 1979, 1982.)

as cropping continued the beneficial effects of liming gradually moved into the soil below the depth of incorporation: root penetration and water use extended to over 1 m in depth several years after liming. In addition, gypsum, as a component of ordinary superphosphate, speeded the process of improving deep root growth (Ritchey et al. 1980). In a similar study in Africa carried out by IITA, there was no evidence that the leaching process neutralized extractable Al in the soil below the depth of lime incorporation after 3 years under 2500 mm of rain annually (Friesen et al. 1982). On the other hand, others have reported changes in subsoil properties several years after liming the cultivated layer (Chaves et al. 1984, Quaggio et al. 1982). The explanation for the differences among locations is not evident.

These studies by CPAC show that the ability of the crop to extract subsoil water increases with time after liming because the rooting depth is extended, and thereby the impact of prolonged periods without rain on crop yields is reduced. This is extremely important because it means that the yield potential of the soil increases with time after liming. The data from CPAC also demonstrate that deep incorporation of lime increases crop yields during the first few years of cropping; thus, the economic feasibility of deep incorporation (compared with incorporation only by normal cultural practices) will depend on local economic conditions. Furthermore, the beneficial effects of deeper incorporation of lime can be obtained, providing one is willing to wait a few years. To date, no one seems to have developed a good means to predict rates of amelioration of subsoil acidity as influenced by soil properties and climate.

Relative yields of maize as the experiment progressed are shown in Figure 2. Two points are illustrated: (1) the residual effect of lime is considerable and (2) without lime, yields decrease from even their low initial level, presumably as a consequence of further acidification of the profile (CPAC 1982).

For this latter reason, care should be used in proposing that selection of crops tolerant to acidity is a universally viable alternative to liming or additions of Ca. As shown in Table 1, the total Ca and Mg in the top meter of soil is only a few hundred kg, and this small amount can be quickly depleted by crop removal and accelerated leaching likely to accompany food-crop production. Selection of crops tolerant to acidity is useful when the cultivated layer is limed, but the subsurface layers remain acid when there are more ample supplies of Ca and Mg than in soils similar to those described in Table 1. As an additional precaution, perhaps some attention should be given to the possibility that the Ca and Mg content of crops tolerant to acidity may not supply sufficient Ca and Mg for the human/animal diet.

The experiments described provide input-output data for several crop cycles, data on residual effects over several years, and information on amelioration of acidity throughout the soil profile. Several other experiments furnish the same kind of information (Friesen et al. 1982, Chaves et al. 1984, Quaggio et al. 1982). With these data economists can carry out a detailed study of the benefits of different rates of liming, crop sequences, and residual effects, and they can project the economic benefits of different liming programs under different crop prices and dif-

ferent interest and inflation rates. With these calculations, the data can be extrapolated to any economic situation. This is the kind of input-output data agronomists should supply to farmers, extension workers, economists, bankers, public planners, and so on so they can make informed decisions about lime as an inp .

Extrapolation and Interpolation

For all practical purposes, the experiments we have described are history at one location for a fixed set of weather conditions and management variables. How can we extrapolate the results to other soils, to other crops, to other varieties of the same crop, to other climates, to other management regimes, to a multitude of economic and social regimes, etc.? How can we compare the data with those from other experiments?

To accomplish these more ambitious objectives, we must know more about many soil, crop, and climatic factors. The factors that appear to be most important to these objectives are the following: Al toxicity, Ca deficiency, crop response to each of these factors, interactions of crop variety/species with Al and Ca, the buffering capacity of the soil with respect to liming, the rate of amelioration of acidity throughout the profile, soil physical conditions, and the intensity and duration of the residual effects. In the following sections we review the current knowledge about some of these factors.

Soil Chemical Measurements

Soil pH. Soil pH is the easiest parameter to measure. All one needs is pH-sensitive indicators or relatively inexpensive electronic equipment.

A vast amount of research has shown that Al toxicity (Foy 1984) and Ca deficiency (Clark 1984) are two major factors determining crop response to soil acidity. Both are related in indirect ways to pH (Thomas and Hargrove 1984). Thus, the simplicity of pH measurement has proved to be useful, although it is a fairly imprecise guide to crop behavior. Pearson (1975) concluded that pH does not appear to be as useful a guide in the tropics as in the temperate regions. Some of the following are more often used with acid soils in tropical settings.

Neutral salt extractions. Commonly, cations extracted with a neutral salt (such as *N* KCl) are useful to estimate the toxic effects of Al, Ca deficiency, lime requirement, and the effective cation-exchange capacity.

Extractable Al. Commonly, two parameters are based on 1*N* KCl-extractable Al: the percentage of Al saturation and the lime requirement. Percentage of Al saturation is usually defined as the ratio of extractable Al to the sum of extractable cations, expressed as percent. The utility of this parameter is illustrated by a number of experiments (e.g., Kamprath 1984); an example is shown in Figure 3 using the CPAC data referred to above. Figure 3 illustrates that this parameter is often better correlated with crop response than is pH.

6

Kamprath (1984) cited several experiments where the percentage of extractable Al was correlated with yield. However, when the relationship between percentage of extractable Al and relative yield is compared from several experiments, the relationship differs among locations, as illustrated with maize grown in Brazil, Africa, and Puerto Rico (Fig. 4). Presently we can only speculate about why the different relationships were found at the different locations. Possibilities include differences in Al tolerance of the varieties, differences in laboratory techniques, differences in soil properties, and differences in absolute yields. Clearly, yield of maize is not a single-valued function of the percentage of Al saturation.

Extractable Al has also been found to be a useful guide to lime requirement (the amount of lime that must be added to achieve a given yield potential). However, the soil contains constituents other than Al that react with lime and, as a consequence, the reaction of 1 equivalent of lime does not reduce the extractable Al by 1 equivalent. In general, between 1.5 and 3.3 equivalents of lime must be added to reduce *N* KCl-extractable Al 1 equivalent (Kamprath 1984). The size of the factor increases as the organic-matter content increases (Kamprath 1984). It has been reported that other salts extract an amount of acidity so that the lime requirement is approximately equal to the amount of Al extracted (Oates and Kamprath 1983a, 1983b).

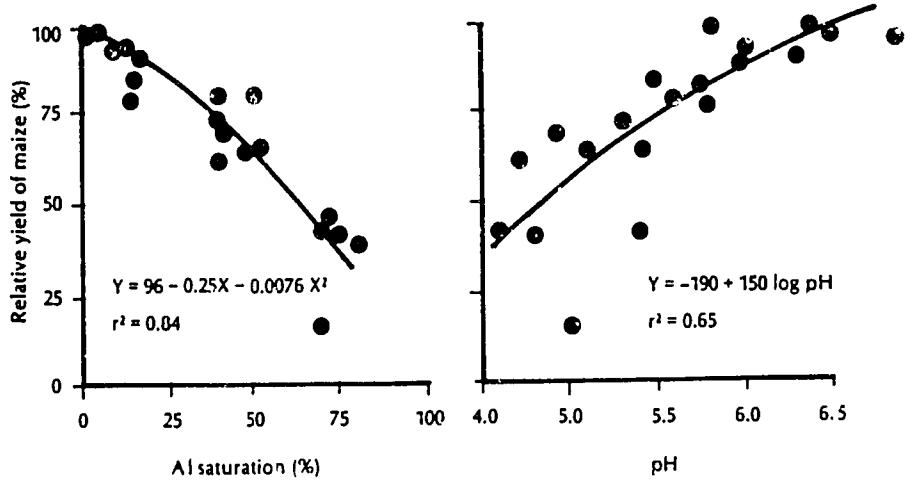

Fig. 3. Effect of aluminum saturation and pH on relative yields of maize for 1972/73, 1973/74, 1975/76, and 1976/77. The percentage of aluminum saturation and the pH of soil samples were taken the year the crop was grown.

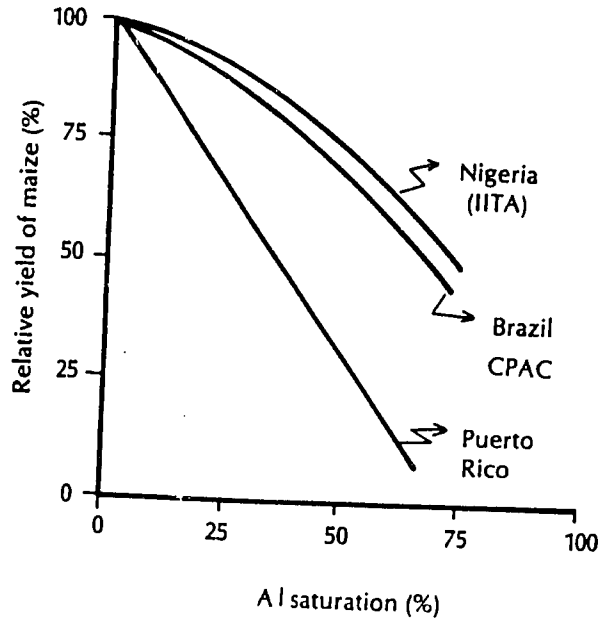

Fig. 4. Regressions of relative yield of maize on percentage of aluminum saturation from three experiments on different tropical soils. (After Friesen et al. 1982, Pearson 1975, CPAC 1976, 1979, 1981.)

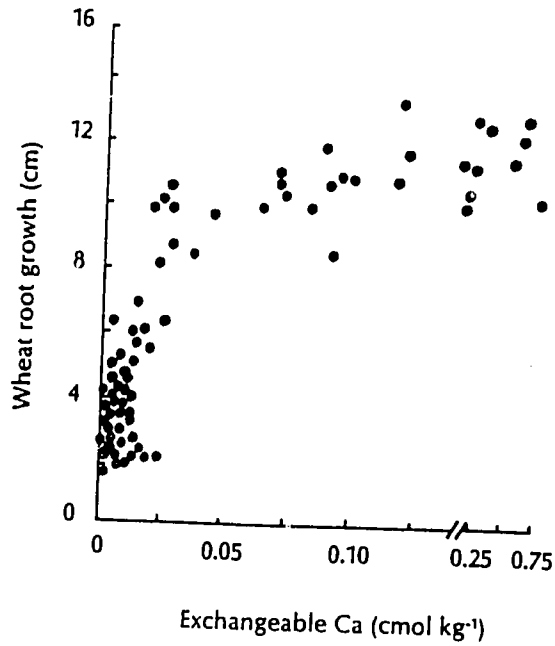

Fig. 5. Relationship between growth of roots of wheat in 4 days in greenhouse tests and exchangeable calcium in the soil. (From Ritchey et al. 1983.)

Exchangeable Ca. Generally Ca is not translocated within plants toward growing root tips of annual crops. As a consequence, the Ca required for root growth must be obtained from the soil immediately adjacent to the root. As might be expected, Ca is so low in some soils that root growth is limited by Ca deficiency in localized regions of the soil even though the plant is well supplied with Ca taken up in other portions of the soil (Ritchey et al. 1982). An example of such a situation is illustrated in Figure 5. Note that the parameter correlated with root growth was exchangeable Ca and not Ca as a percentage of exchangeable cations.

Soil solution composition. Recently considerable work has been done on the relationship of the various species of Al present in solutions and in soil solutions to plant response. For a long time soil chemists have recognized that polymeric forms of Al as well as several monomeric species exist in solution (e.g., White et al. 1976). Two recent studies (described in the next paragraph) illustrate the importance of the different Al species to plants.

The response of coffee to different lime levels in greenhouse culture was studied, and the correlations between relative root growth and various soil acidity parameters were determined (Table 2). The best correlation was between Al activity in the saturation extract and relative root growth in six soils, each with several levels of added lime. Later nutrient culture studies with soybean demonstrated that the activity of monomeric forms of Al in solution were best correlated with relative root growth (Fig. 6). These results make clear what soil chemists have been telling agronomists for years: the solution chemistry of Al is exceedingly complex. Now we must study the relationships between this complex chemistry and crop response.

Interactions. The preceding studies on the effects of Al species in solution on plant response raise some important questions on how to interpret observed interactions between Ca, Mg, Al, S, and P. Some of the interactions are probably

Table 2. Correlation between relative root growth of coffee and soil chemical parameters in a greenhouse experiment with six soils, each limed to several levels of exchangeable Al. (From Paven et al. 1982.)

Soil acidity parameters (variables)	Regression equation	Correlation coefficient
Relative root growth (%) vs.:		
Exchangeable Al	$Y = 95.6\ e^{-0.18x}$	−0.73
Percentage of Al saturation	$Y = 97.8\ e^{-0.01x}$	−0.81
Concentration of Al in soil solution	$Y = 99.0\ e^{-0.08(10^6)x}$	−0.82
Concentration of Al^{+3}	$Y = 98.3\ e^{-0.12(10^6)x}$	−0.92
Activity of Al	$Y = 97.1 e^{-0.2(10^5)x}$	−0.97

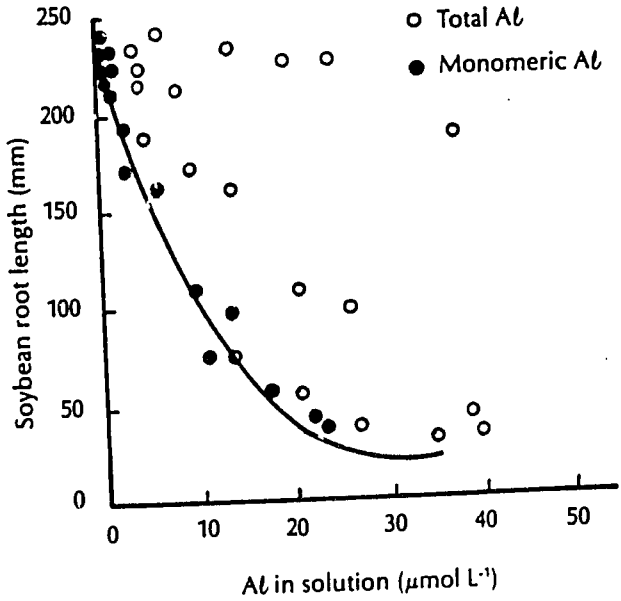

Fig. 6. Relationship between soybean root growth in nutrient solution and total aluminum in solution or monomeric aluminum in solution. Points are experimental observations; line is regression of root length on monomeric aluminum in solution. (After Blamey et al. 1983.)

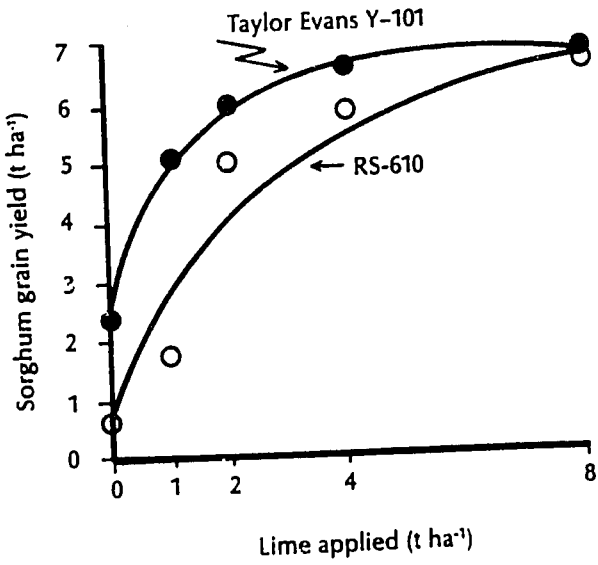

Fig. 7. Response of two grain sorghum varieties to lime application. Points are experimental observations; lines are regression equations fitted to the data. (From Salinas 1978.)

the result of solution chemistry and not interactions with the physiology of the plant. However, in soils where Ca levels are low, there may well be important plant physiological interactions.

Summary of soil chemical studies.

a. Each of the above parameters has been demonstrated to be useful under specific conditions.
b. We will probably not obtain a single-valued function between relative yield and any one soil chemical parameter if the range of soils, crop varieties, and climates is wide enough.
c. As we increase the number of parameters measured, we will probably increase the confidence in our predictions. The degree of refinement that we should seek depends to some extent on what is an acceptable level of uncertainty.

Methods of Evaluating Variety/Crop Tolerance of Soil Acidity

The ultimate test of crop tolerance is field trials. Illustrated in Figure 7 is a classic example of one field experimental trial (Salinas 1978). There can be little doubt of the differences between the two varieties.

There are a large number of studies in the literature reporting results of nutrient solution and soil cultures in the greenhouse that illustrate differential tolerance of cultivars to Al toxicity and/or Ca deficiency. In some cases these greenhouse studies have been shown to be correlated with yields in field experiments and, hence, they are useful tools for the plant breeder and can be used to give relative rankings to different varieties. It is not clear to us whether these procedures are precise enough to be useful for interpolating among lime experiments nor whether they are precise enough for purposes of predicting input-output relationships.

Along with agronomists, most plant breeders have not availed themselves of the knowledge of Al chemistry. Consequently, the results of many of the nutrient-culture studies cannot be compared with each other in any clear fashion.

Amelioration of Subsurface Acidity and Duration and Pattern of Residual Effects

The amelioration of subsurface acidity and the duration and pattern of residual effects are related in that they both depend upon leaching phenomena. Leaching rates are influenced by supplies of soluble anions (such as nitrate, chloride, and sulfate) plus the amount of water moving through the soil. Soil chemical factors are also important. Studies in the literature document the changes in contents of extractable Ca, Al, and other ions with depth after different periods of time following treatment of the superficial layers with lime (e.g., Ritchey et al. 1980, Friesen et al. 1982, Quaggio et al. 1982, Chaves et al. 1984). We could not find

an example where these data had been interpreted for use in predicting leaching phenomena under a range of conditions; we do not yet have a model useful for these purposes.

Summary of the State of the Art of Interpolating among Lime Experiments

Both Al toxicity and Ca deficiency reduce root growth and thereby reduce crop yields because of water deficits and nutrient deficiencies; a major consequence of liming is to provide more favorable levels of both these factors. Tolerance to these factors varies greatly among crops and varieties.

In many regions of the tropics, irregular distribution of rainfall, low available water-holding capacity, and excessive subsoil acidity require more than amelioration of the acidity in the cultivated layer; subsoil acidity must also be ameliorated so that crops can use subsoil water.

In both temperate and tropical regions there is a reasonable body of experimental field data that serves as a basis for recommendations in the locality where the experiments were run and for current local economic conditions. However, many experiments do not include a wide enough range of treatments nor enough chemical measurements to serve as a basis for evaluating a wide range of management options with respect to liming. They cannot be extrapolated through time and space to different economic, soil, crop, and climatic conditions.

Most of the soil and crop relationships are based on statistical correlations, and few have any status as cause-and-effect relationships. For example, the percentage of Al saturation referred to earlier is not likely to be the real variable, but, because it is related in an indirect way to both Al toxicity and Ca deficiency, it is correlated with crop response under a restricted set of conditions. As the range of conditions is widened, the degree of correlation weakens.

Future Research Needs

In our judgment, we should strive to improve our ability to explain the differences among experiments. We have pointed out several important discrepancies that need attention, and surely there are others. Until we can explain the differences among experiments, we cannot be very confident about any extrapolations we make. Many of the most used relationships are based on statistical correlations and not true cause-and-effect relationships. We should strive to establish the true cause-and-effect relationships, however, because extrapolations are not likely to be reliable until we do so. We also need complete response curves and residual effects so that the results can be extrapolated to all economic situations.

Following are our recommendations for future research.

12

Synthesis of What We Know and Do Not Know

Individual countries should be encouraged and supported to do a comprehensive in-country review of past, present, and needed research on the management of soil acidity.

A working group of 10 to 15 soil and crop scientists should be established to examine the available experimental data and:

1. Identify conclusions consistent among experiments that apply to all present data;
2. Identify conclusions that vary among experiments;
3. Based on the above analysis, develop hypotheses for future study;
4. Develop the hypotheses into requests for donor support and requests for proposals from scientists and institutions.

The working group should be encouraged to develop hypotheses of a size suitable for a thesis project or a 1- to 3-year study leave. The study leaves could be used to facilitate exchange among complexes of research groups, soils, crops, and climates and perhaps could be on an exchange basis (e.g., scientists from stations A and B exchange places for 1 to 3 years).

Our recommendation for the composition of the group is as follows:

- A chairman who can devote perhaps a total of 4 months to the project over the next 12 to 18 months.
- The following who can devote 1 to 3 months to the project over the next 12 to 18 months:
  - Four agronomists/soil chemists: one who has access to the data at CPAC and Brazil in general; one who has access to the data at IITA and Africa in general; one who has access to the data at Puerto Rico, CIAT, and South and Central America (except Brazil); and one who has access to the data in Asia and southeastern Asia.
  - One crop physiologist who has experience with physiological aspects of crop response to soil acidity.
  - One soil chemist who has experience with acid soils.
  - One soil physicist who has experience with leaching of soil constituents.
  - One soil taxonomist who is familiar with soil classification in the tropics.
  - One economist who is familiar with interpretation of agronomic input-output data.
  - One soil chemist/soil fertility person familiar with modeling the root-interfacial zone.
  - One editor-manager who will be able to spend 6 months working on the necessary editorial-management aspects.

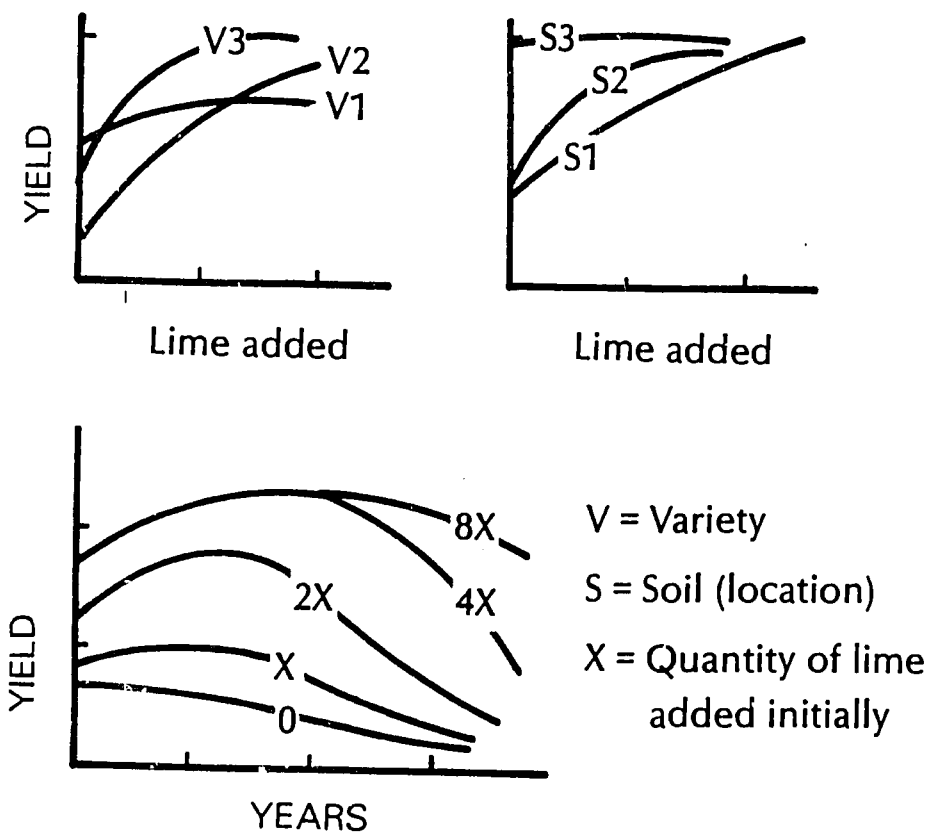

Fig. 8. Influence of liming on crop yields, by variety, location, and quantity of lime added initially.

Future Field Experiments

Either the group described above or a similar group should design 5 to 10 comprehensive, long-term experiments for carefully selected soil-climate complexes. Essential features of the design are the following:

1. Provision of careful studies of soil chemical and physical properties at each site during the duration of the experiment through a depth of 1 to 2 m. Addition of fertilizers at appropriate levels to insure high yields. Characterization of lime and other amendments with respect to chemical and physical properties, and storage of samples for possible future studies;
2. Provision of detailed climatic records for the experimental period and analysis of the historical records (one criterion for each site should include availability of historical data);
3. Careful selection of crops and varieties to insure that genetic variability and stability are such that (a) adequate supplies of seed are available for the experiment, (b) current and subsequent physiological studies can be carried out, and (c) comparisons among crops and varieties at the different sites are facilitated.
4. Provision of seasonal measurements of crop development, nutritional status, and water stress.
5. Paying careful attention to the design and conduct of the experiments to provide comprehensive evaluation of the hypotheses developed by the group described in the preceding section.
6. Inclusion of lime added by variety, soil, and year in the output of the above at each experimental site (Fig. 8).

Project Proposals

One or both of the preceding groups should design project proposals to establish the following two special projects, which in many respects should serve to summarize and integrate the foregoing recommendations.

1. A comprehensive model describing the root-soil interfacial zone including mass-flow and diffusion as transport agents and the impact of differential anion-cation uptake by roots as factors modifying the chemistry of the root-soil complex.
2. A comprehensive model describing changes in the chemistry throughout 1 to 2 m of soil following incorporation of lime into the cultivated layer. The result would be a valuable tool for predicting changes in rooting depth and residual effects of lime.

If the correct measurements of soil/crop/climate variables are made at a new and different site, we should be able to interpolate the results of the experiments to that

15

site. Thus we could describe lime response for any soil, climate, crop, or economic condition.

As agronomists we will have provided the information needed to evaluate liming under any socioeconomic condition and, hence, the data may be extapolated through time and space. Although the program outlined is ambitious and expensive, this is the sort of project IBSRAM should sponsor. If we do no more than review and analyze the synthesis of what we do and do not know, as described above, we will have accomplished a worthy objective.

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16

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