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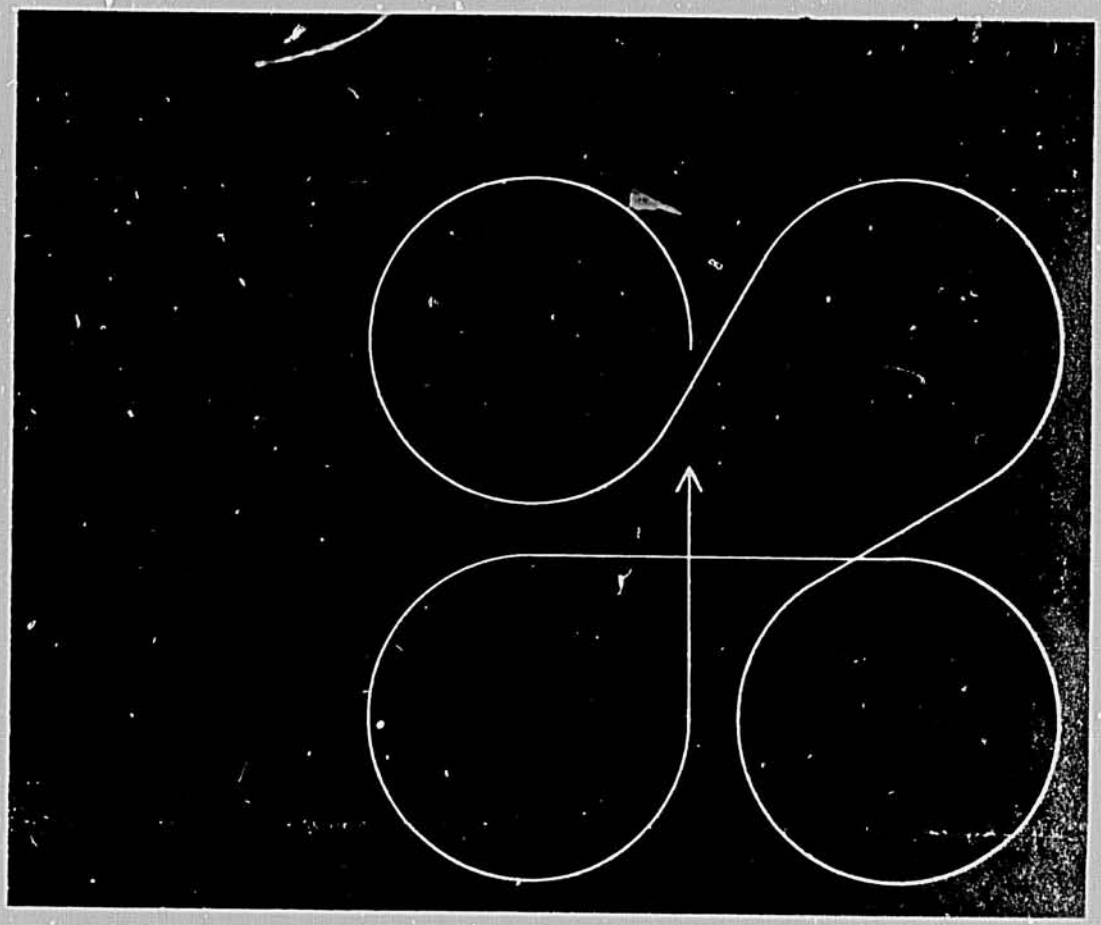

# THE INFLUENCE OF SUBSOIL ACIDITY ON CROP YIELD POTENTIAL

A summary of cooperative projects performed by
Centro de Pesquisa Agropecuaria dos Cerrados, Planaltina, Brazil
University of Puerto Rico, Rio Piedras, Puerto Rico
Soil Research Institute, Kumasi, Ghana
Yurimaguas Experiment Station, Ministerio de Agricultura, Yurimaguas, Peru
North Carolina State University, Raleigh, North Carolina
Cornell University, Ithaca, New York

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**January 1979**

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# The Influence of Subsoil Acidity on Crop Yield Potential*

Edited by David R. Bouldin†

## SUMMARY

Experiments in Brazil and Puerto Rico on highly weathered, acid soils demonstrate that subsoil acidity limits crop yields even when the plow layer is adequately limed. This limitation is probably the result of inhibition of root proliferation in the subsoil; and, consequently, the water stored in the subsoil is unavailable to crops. This subsoil water is essential to crops, because several consecutive days without rain are common during most growing seasons.

Limitations imposed by subsoil acidity can be minimized as follows:

- by selecting for immediate development those areas where subsoil acidity is least severe;
- by selecting locations where rainfall distribution and soil-water storage capacity will minimize dependence of crops on subsoil water;
- by selecting crops that are tolerant of subsoil acidity;
- by selecting cultivars with appropriate length of growing season, which, with proper planting date, will often avoid the periods when moisture stress is most likely to occur;
- by incorporating lime as deeply as economically feasible;
- by waiting until the effect of surface-applied lime has leached into acid subsoils to promote root growth; this has occurred within 2 to 5 years in cropped soils with limited amounts of Al where ordinary superphosphate and nitrogen fertilizer were used.

*This study was supported in part by the United States Agency for International Development (AID) under research contracts with Cornell University, csd 2490, ta-c-1104, and ta-c-1441 and with North Carolina State University, csd 2806 and ta-c-1236.

†Professor, Department of Agronomy, New York State College of Agriculture and Life Sciences, Cornell University, Ithaca, N.Y.

**Table 1.** Chemical properties of highly weathered soils in Brazil, Puerto Rico, Ghana, and Colombia

| *Soil designation and location* | *Depth of sample* | *Sand* | *Silt* | *Clay* | *C* | *N* | *Exchangeable cations* | | | | *pH* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | *Ca + Mg* | *K* | *Al* | *Σ* | *$H_2O$* | *KCl* |
| | *cm* | *percent* | | | | | *me/100 g* | | | | | |
| Latossolo Vermelho* | 0 – 10 | 36 | 19 | 45 | 1.8 | 0.21 | 0.4 | 0.10 | 1.9 | 2.4 | 4.9 | 4.2 |
| Escuro; Planaltina, | 10 – 35 | 33 | 19 | 48 | 1.2 | 0.08 | 0.2 | 0.05 | 2.0 | 2.2 | 4.8 | 4.3 |
| D. F., Brazil | 35 – 70 | 35 | 18 | 47 | 0.9 | 0.05 | 0.2 | 0.03 | 1.6 | 1.8 | 4.9 | 4.2 |
| | 70 – 150 | 35 | 18 | 47 | 0.7 | 0.05 | 0.2 | 0.01 | 1.5 | 1.7 | 5.0 | 4.4 |
| Latossolo Vermelho* | 0 – 12 | 28 | 27 | 45 | 1.9 | 0.13 | 0.2 | 0.08 | 1.8 | 2.1 | 5.1 | 4.2 |
| Amarelo; Planaltina, | 12 – 30 | 26 | 30 | 44 | 1.4 | 0.09 | 0.2 | 0.05 | 1.4 | 1.6 | 5.0 | 4.4 |
| D. F. Brazil | 30 – 50 | 25 | 27 | 48 | 1.0 | 0.07 | 0.2 | 0.03 | 0.6 | 0.8 | 5.2 | 4.4 |
| | 50 – 85 | 24 | 28 | 48 | 0.8 | 0.08 | 0.2 | 0.02 | 0 | 0.2 | 4.9 | 4.9 |
| Catalina clay,† | 0 – 15 | 6 | 18 | 76 | 3.8 | 0.32 | 6.8 | 0.3 | 0.3 | 7.4 | 5.1 | 4.3 |
| Torrecillas, Puerto | 15 – 35 | 5 | 13 | 82 | 1.2 | 0.14 | 1.9 | 0.1 | 0.7 | 2.7 | 4.8 | 4.2 |
| Rico (S59PR-10-7) | 35 – 55 | 1 | 14 | 82 | 0.9 | 0.11 | 1.6 | 0.1 | 0.7 | 2.4 | 4.9 | 4.2 |
| | 55 – 80 | 5 | 20 | 76 | 0.6 | 0.08 | 1.0 | – | 1.3 | 2.3 | 5.0 | 4.0 |
| Humatas clay,† | 0 – 10 | 6 | 29 | 65 | 4.9 | 0.43 | 3.9 | 0.4 | 4.0 | 8.3 | 4.6 | 3.9 |
| Oeste SCD, Puerto | 10 – 22 | 2 | 28 | 69 | 2.0 | 0.21 | 3.5 | 0.1 | 5.4 | 9.0 | 4.7 | 3.7 |
| Rico (S61PR-8-1) | 22 – 38 | 3 | 34 | 63 | 1.2 | 0.12 | 3.7 | 0.1 | 4.5 | 8.3 | 4.9 | 3.8 |
| | 38 – 62 | 6 | 46 | 48 | 0.6 | 0.07 | 1.6 | 0.1 | 7.0 | 8.7 | 5.0 | 3.8 |
| | 62 – 80 | 11 | 50 | 39 | 0.4 | 0.05 | 1.0 | 0.2 | 9.1 | 10.3 | 4.9 | 3.8 |
| Carimagua, Colombia‡ | 0 – 8 | – | – | – | 3.1 | – | 0.5 | 0.1 | 3.4 | 4.0 | 4.8 | 3.6 |
| | 8 – 22 | – | – | – | 1.7 | – | 0.3 | 0.1 | 3.2 | 3.6 | 4.7 | 3.6 |
| | 22 – 46 | – | – | – | 1.1 | – | 0.3 | 0.1 | 1.9 | 2.3 | 4.4 | 3.8 |
| | 46 – 132 | – | – | – | 0.6 | – | 0.2 | 0.1 | 0.6 | 0.9 | 4.9 | 4.1 |
| Kumasi series,§ | 0 – 7 | 60 | 13 | 27 | 4.6 | .29 | 5.8 | 0.2 | | | 4.1 | |
| Kwadaso Central | 7 – 11 | 76 | 9 | 15 | 1.1 | .07 | 1.1 | 0.1 | | | 4.6 | |
| Station, Ghana | 11 – 18 | 64 | 11 | 25 | 0.5 | .05 | .7 | 0.04 | | | 4.5 | |
| | 23 – 46 | 43 | 12 | 45 | 0.6 | .06 | .7 | 0.05 | | | 4.7 | |
| | 87 – 114 | 36 | 18 | 44 | 0.4 | .02 | .8 | 0.01 | | | 5.1 | |

Sources: *Equipe de Pedologia e Fertilidade do Solo, 1966.
†Soil Conservation Service, 1967.
‡Guerrero-Muñoz, 1971.
§Soil Research Institute, unpublished data.

## INTRODUCTION

The objective of this paper is to describe some of the soil-water – crop problems that were encountered by researchers in Puerto Rico on Oxisols and Ultisols and in Brazil on Oxisols and to suggest some important management practices and consequences for highly weathered soils in other areas of the tropics.

In the tropics, several hundred million hectares of soils have the following characteristics: they are well drained, highly weathered, and reasonably level; they have savannah-type vegetation; and during 5 to 7 months of the year, precipitation is sufficient for crop production. These soils are not extensively used for growing crops primarily because fertility is low and acidity high, especially in the subsoil. Furthermore, the levels of available nutrients are not only depleted, but the soils contain no primary minerals and, hence, no appreciable reserves of calcium (Ca), magnesium (Mg), and potassium (K) to be released by weathering. Even if a crop were found that would yield reasonably well on the nutrients native to these soils, removal of a few crops would deplete the Ca, Mg, and K.

Sustained production of high yields of food-grain crops such as maize, beans, rice, and sorghum on these soils of the humid and subhumid tropics requires addition of lime or fertilizers, or both, to supply most of the nutrient elements required by crops. However, these soil amendments may not eliminate all soil problems; in many cases, soil-water – crop relationships will have an important influence on crop yields. Adams et al. (1967) studied the effect of variation in subsoil pH on cotton yields when the plow layer was adjusted to approximately pH 6.0. Results showed reduced cotton yields when subsoil pH was below about 5. They also found that cotton roots did not proliferate into the acid subsoils (below pH 5) and did not fully use the water in the subsoil unless the pH was above 5, even during a 17-day period without rain. These experiments demonstrated that subsoil acidity restricted cotton root growth in the subsoil, even if the plow layer was adequately limed, and that use of subsoil water was restricted when subsoil pH was below 5. Presumably, yields were reduced during years of uneven rainfall distribution when the water storage capacity of the limed layer was insufficient to supply transpiration needs of the plants.

The Ultisols and Oxisols at the experimental sites in Brazil and Puerto Rico were largely depleted of exchangeable basic cations and were very acid to a depth of several meters (table 1). In early experiments, the plow layer (15 cm) was adequately limed and fertilized to supply the necessary mineral nutrients. These experiments were conducted during the rainy season, and the crops were not irrigated. Initial crop response indicated that subsoil acidity limited the capacity of the soil to supply water to acid-intolerant crops. Crops wilted after a relatively few days without rain, and rooting depth was restricted, even though no physical barriers were evident. Consequently, subsequent experiments focused on distribution of precipitation during the rainy season, the water-holding capacity of the

soil, and the effects of acidity on rooting of crops.

Included in the experiments were studies of the water relationships in Oxisols and Ultisols in Puerto Rico and Brazil, the probability distribution of consecutive rainless days in Brazil and the effects of depth of liming on crop yields in Brazil and Puerto Rico.

## SOIL WATER RELATIONSHIPS

The details of the following procedures and results on soil water relationships have been published elsewhere (Wolf, 1975; Wolf and Drosdoff, 1976a, 1976b). Briefly, the procedure involved installing tensiometers in the field, flooding the area around them, and covering it with plastic to prevent water loss by evaporation. Periodically, soil samples were taken for gravimetric water determinations, and tensiometer readings were made. After several days, pits were dug, and undisturbed samples were taken for bulk density measurements and for use in pressure-plate studies in the laboratory. Soil water contents up to ¼ bar tension were measured on undisturbed cores. Soil water contents between ¼ and 15 bars were measured on disturbed samples.

Drainage rate and soil moisture tension in an Oxisol from Brazil are illustrated in figure 1. Soil moisture tension increased to 100 cm water (1/10 bar) after two days, while percolation rate diminished to less than 4

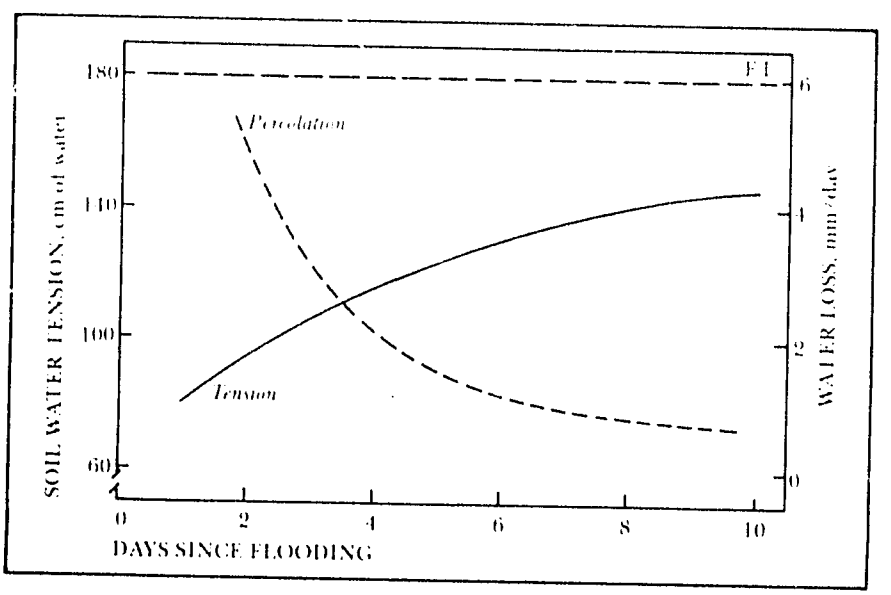


**Figure 1.** Soil moisture tension at 30-cm depth and percolation rate at 60-cm depth plotted against days after flooding for Latossolo Vermelho Escuro, Planaltina, Brazil (Wolf, 1975; Bandy, 1976).

mm/day. Bandy (1976) reported evapotranspiration rates of 6 mm/day during the rainy season in Brazil, a value 50 percent greater than the percolation rate at 1/10 bar. Percolation rate decreased at higher tensions and became insignificant in relation to evapotranspiration. Consequently, water loss at tensions greater than 1/10 bar in a cropped soil would be primarily due to evapotranspiration.

Definitions of field capacity are somewhat arbitrary. A common procedure for estimating available water is to define field capacity as ⅓ bar and to define the water content between ⅓ and 15 bars as "available". Maclean and Yager (1972) defined field capacity as the water content following 48 hours of drainage. While working in Zambia, they found that, in most soils, tensions between 1/10 and 1/20 bar resulted after 48 hours of drainage, and estimates calculated in the common procedure underestimated by 35 percent available water measured directly in the field. Figure 2 illustrates data on cumulative water removal from 30 cm of soil with increasing tension for Oxisols from Brazil and Puerto Rico and an Ultisol from Puerto Rico. It indicates that in some soils an appreciable amount of water may be held in tension ranges less than ⅓ bar. Consequently, we found that the usual calculation procedures underestimate available water and that some alternative such as that of Maclean and Yager is needed. Clearly, the measurement of field capacity is best made in the field, and the ⅓-bar value measured in the laboratory is likely to be misleading.

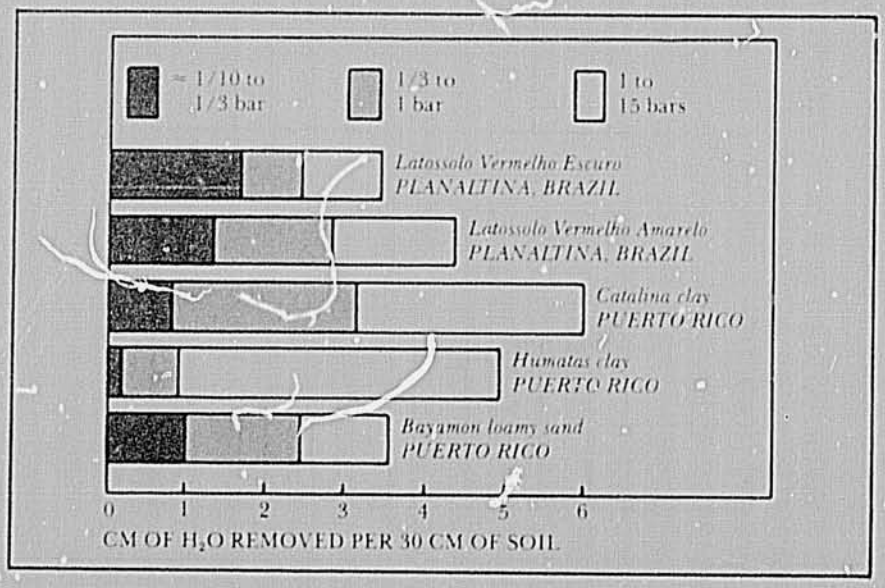


**Figure 2.** Water removal from soils in Brazil and Puerto Rico versus increasing soil moisture tensions (Wolf, 1975; Wolf and Drosdoff, 1976b).

## RAINFALL DISTRIBUTION

Short-term droughts commonly occur during the rainy season and cause decreased crop yields. Weather records were examined to determine rainfall distribution (fig. 3) and to identify the frequency and duration of rainless periods (table 2). On the basis of averages over 42 years, several consecutive days without rain are likely each year, and hence plants must rely on water stored in the soil. Soil depths (initially at field capacity) required to supply evapotranspiration at 6 mm/day were calculated (from fig. 2) for two soils and are presented in table 2. These soil depths (table 2) indicate liming depths required to avoid water deficits in crops sensitive to soil acidity.

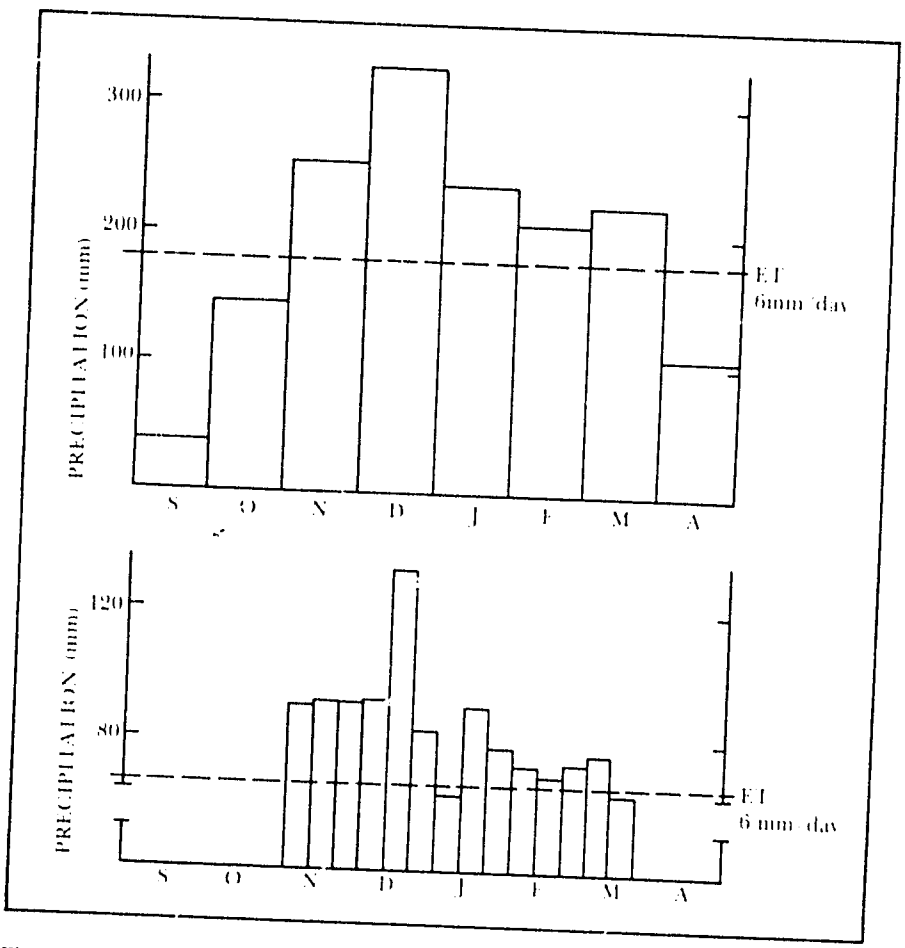


**Figure 3.** Histograms of monthly averages of total rainfall over 42 years (top) and as 10-day average totals (bottom) for Brasília (CPAC, 1976).

**Table 2.** Depth of soil (initially at field capacity) required to furnish 6 mm of ET for selected periods of consecutive days without rain

| *Consecutive days without rain* | *Frequency at Brasilia* | *Depth of soil, initially at field capacity, reduced to wilting point* | |
|---|---|---|---|
| | | *Latossolo Vermelho Escuro (Brazil)* | *Catalina clay (Puerto Rico)* |
| | | *cm* | |
| 8 | 3/year | 40 | 26 |
| 10 | 2/year | 50 | 33 |
| 13 | 1/year | 65 | 43 |
| 18 | 2 years in 7 | 90 | 60 |
| 22 | 1 year in 7 | 110 | 78 |

## YIELDS OF CROPS AS INFLUENCED BY DEPTH OF LIMING

Concurrently with the studies described in the preceding sections, crop yield responses to depth of liming were being measured in Brasilia and Puerto Rico. The results of four cropping seasons on the Latossolo Vermelho Escuro (LVE) at Brasilia are summarized in figure 4 (CPAC, 1976).

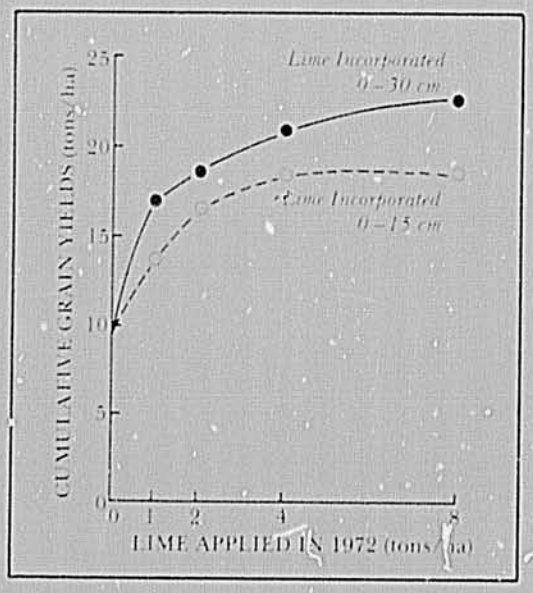


**Figure 4.** Cumulative grain yields of 4 consecutive crops (3 corn + 1 sorghum) on the LVE soil at Planaltina, Brazil, plotted against amounts of lime applied before first crop was planted in 1972. Lime was incorporated either 0–15 cm or 0–30 cm deep (CPAC, 1976).

These results illustrate that during the first three cropping seasons, incorporation of lime to 30 cm resulted in higher yields than incorporation of lime to 15 cm. Presumably, this effect was a consequence of deeper rooting, which allowed access to more available water (Gonzalez, 1976). Bandy (1975) studied the influence of liming depth on water use in this soil and showed higher water stress in plants growing on soil limed to 15 cm than in those growing on soil limed to 30 cm (fig. 5). Two varieties of maize grown on plots of Humatas clay (Ultisol) in Puerto Rico were limed to varying depths (Perez-Escolar et al., 1978). The results (table 3) were similar to those with the LVE in Brazil. Yields increased as the depth of liming was increased; presumably, the roots were better able to use the subsoil water.

The limiting effects of shallow liming were not persistent in the experiments in Brazil, as illustrated in figure 6, where yields of grain crops 5 and 6 are shown. The differences caused by depth of liming have largely disappeared. The soil data (fig. 7) illustrate that percentage of aluminum saturation of the 15–30-cm layer decreased with time when the lime was initially mixed only in the 0–15-cm layer (CPAC, 1976). Thus, the initial differences in aluminum content between the 0–15-cm and 15–30-cm layers have largely disappeared, and, presumably, the barrier to use of subsoil water has also been reduced.

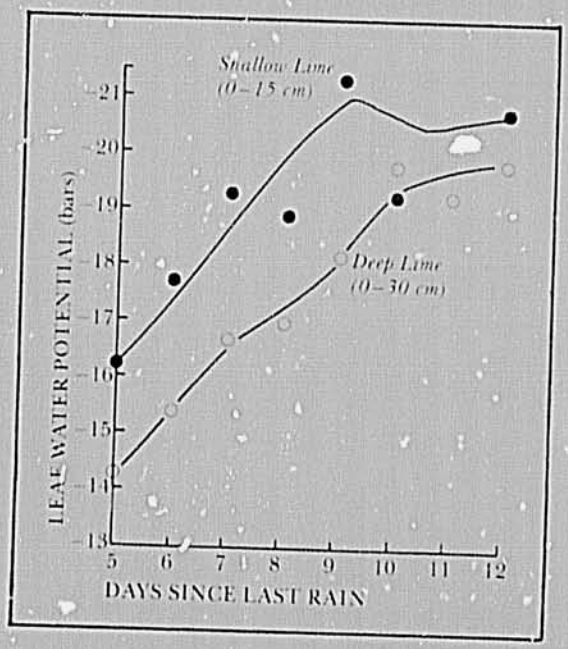


**Figure 5.** Effect of depth of liming on the leaf water potential for corn (third leaf from top) taken during a period without rain (Feb. 27 – Mar. 17, 1975) on LVE soil at Planaltina, Brazil, 1974 – 1975 rainy season (Bandy, 1976).

**Table 3.** Yields of maize on Humatas clay limed to various depths*

| *Depth of liming* | *Yield of grain* |
|---|---|
| *cm* | *t/ha* |
| 0 | 5.0 |
| 20 | 6.4 |
| 40 | 6.8 |
| 60 | 7.4 |

Source. Perez-Escolar et al., 1978.
*All plots disturbed to 60 cm.

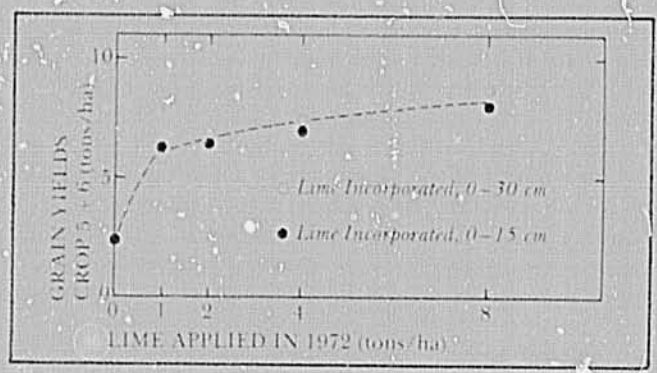


**Figure 6.** Grain yields of crops 5 and 6 (maize) on LVE soil at Planaltina, Brazil, plotted against amount of lime applied before first crop was planted in 1972. Lime was incorporated either 0 – 15 cm or 0 – 30 cm deep (CPAC, 1976).

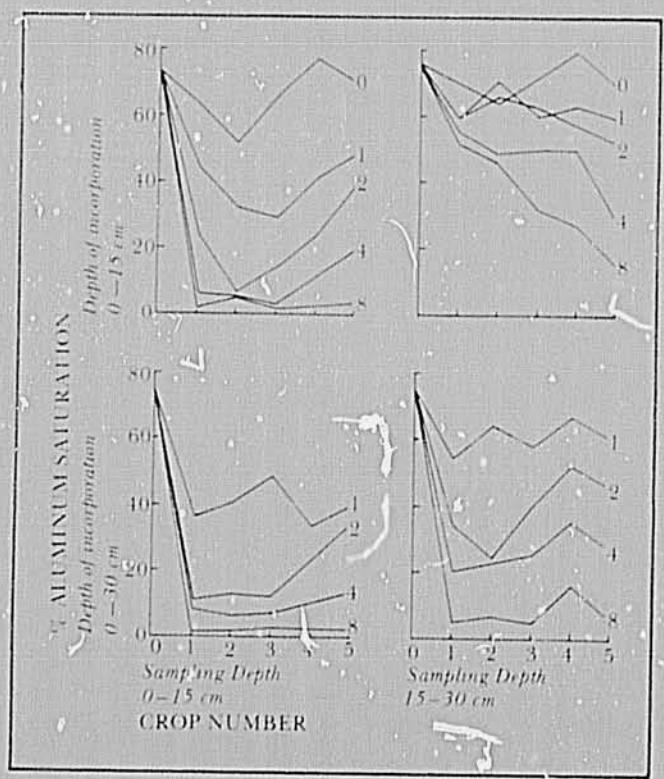


**Figure 7.** Percentage of aluminum saturation of soil samples taken at 2 depths following each of 5 crops on the LVE soil at Planaltina, Brazil. Lime was applied before the first crop was planted and incorporated either 0 – 15 cm or 0 – 30 cm deep. Numbers to the right of lines are tons of lime applied in 1972 (CPAC, 1976).

In other experiments in Brazil, Ritchey et al. (1978) found that after 3 to 5 years of cropping, subsoil acidity had been reduced under a wide range of treatments. Although the optimum conditions have yet to be determined, additions of fertilizer nitrogen, potassium chloride, and ordinary superphosphate (which contains large amounts of $CaSO_4$) enhance the downward movement of the ameliorating effects of lime. Gonzalez (1976) reports a case in Brazil where lime was applied to plots of *Stylosanthes*, but no appreciable influence of lime was found much beyond the depth of application, presumably because no amendments were made which furnished anions necessary for leaching of the ameliorating effects of lime.

Another aspect of subsoil acidity is illustrated in figure 8, from an experiment in Puerto Rico on a Catalina clay with properties similar to those shown in table 1 (Wahab et al., 1976). During the growing season, maize (variety Pioneer X-306) in unirrigated plots reduced soil water to the wilting point to a depth of 120 cm. This illustrates that roots can use water in fairly acid subsoils and that rather small changes in subsoil chemistry may suffice to appreciably increase a plant's ability to use water. Unfortunately, because we do not yet understand the functional relationships between root growth and soil chemical characteristics, we cannot define with precision where root growth will be adequate.

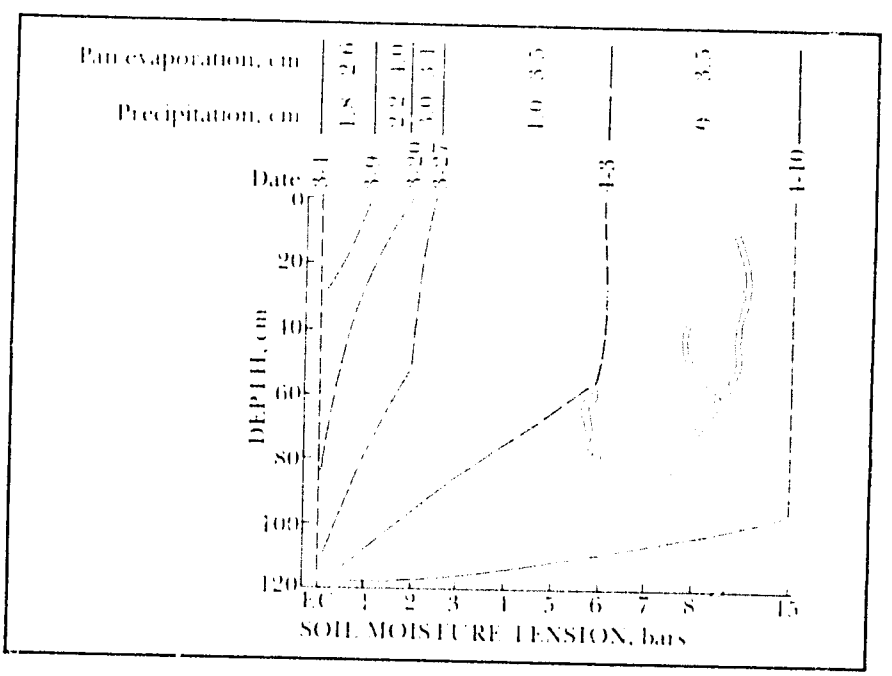


**Figure 8.** Soil moisture tension plotted against depth of Catalina clay at different times during corn growth. Numbers at top of graph are cumulative amounts of precipitation and pan evaporation between samplings (Wahab et al., 1976).

## IMPLICATIONS

The data indicate that subsoil acidity can indeed impose limitations on yield. Yield limitations primarily resulted from water deficits which arose from insufficient storage in the limed layer and from roots that were inadequately proliferated to fully use water stored in the subsoil once the limed layer was depleted of water. Consequently, the plants suffered from water deficits. Deep liming (to 30 cm) ameliorated to some extent the effect of long periods without rain. Leaching of the ameliorating effects of lime was sufficiently rapid that after 3 to 5 years at Planaltina, little difference was apparent between lime applications initially mixed to 15 cm or 30 cm.

The Oxisols and Ultisols studied in Puerto Rico and Brazil are representative of the highly weathered soils of the wet – dry tropics that cover an area of several hundred million hectares. As now used, this area produces a very small amount of human food. Intensifying food production in much of the area will require rather radical changes in land use. Some cases will demand substantial investments, not only in soil amendments but also in infrastructure. Large numbers of people will immigrate, and cropping systems will have to be developed without the benefit of long-term farming in a given area. In a short time, agronomists must assess the virtually infinite set of potential food production systems and, on the basis of current knowledge, select relatively few for further research and development.

We have demonstrated that subsoil acidity imposes limits on yields and, hence, return on investments. However, subsoil acidity need not seriously restrict development of the area so long as the nature of the limitations is understood. Probably, the major restrictions are increased development costs and delayed returns on the initial investment. Additional research may reduce these effects.

The small sample of soils presented here can hardly be typical of all the soils and climates in the vast areas where undeveloped and underused Oxisols and Ultisols occur, but the results have important implications about the kinds of data that would be useful in investigating the potential for development of other Oxisols and Ultisols. First, some measure of average rainfall and its temporal and spacial distribution is needed. Clearly, the effects of subsoil acidity will be less serious where rainfall is more uniformly distributed. The probability of there being several consecutive days without rain varies seasonally. For example, during the rainy season in Brazil, a long period without rain is most likely to occur from mid-December to mid-February. With this information, planting dates and maturity dates of crops can be selected so that a period of crop growth very sensitive to drought is not likely to coincide with periods without rain. Second, the water storage capacity of the plow layer may vary and, as the water storage capacity increases, the need for using subsoil water decreases. Third, the acidity of the subsoil may vary, and hence the rate of root growth and the fraction of subsoil water that plants

can use will undoubtedly vary among different soils.

The results in figures 6 and 7 show that the ameliorating effects of lime are leached downward rather rapidly, especially at high rates of application. Our temperate-region experience suggests that amelioration of subsoil acidity by leaching is a fairly slow process. However, the following points regarding subsoil water are of major importance: subsoil chemistry needs to be changed only to the extent necessary to get root growth; the amount of calcium required for root growth is low; exchangeable Al is the major acidic constituent that must be neutralized; only part of the total exchangeable Al needs to be neutralized in order to obtain good root penetration; the soil studied in Brazil contains a relatively small amount of exchangeable Al and, hence, neutralizing only a small amount of this Al and/or adding a small amount of Ca will insure reasonable root proliferation in the subsoil. Thus, the requirements for ameliorating the adverse effects of subsoil acidity on soils similar to the LVE at Planaltina are to apply generous amounts of lime to the plow layer and to accept reduced yields for a few years until the subsoil acidity has been ameliorated by leaching.

Because the quantity of neutralizing agent and Ca leached from the limed plow layer to the subsoil is independent of the concentration of Al in the subsoil, the ameliorating effect of leaching will be most rapid in those soils with a small amount of exchangeable Al. Table 1 shows that a rather long time would be required to neutralize the subsoil acidity in the Humatas because of the much larger amount of Al present in the subsurface horizons.

An additional remedy is to select crops tolerant of subsoil acidity. Of course, using crops that tolerate soil acidity cannot, in the long run, obviate the need for amendments, because the reserves of calcium, magnesium, and potassium and probably phosphorus are so meager that removing a few crops will entirely deplete the available forms of these nutrients in most Oxisols. However, to the extent that they are available, crops tolerant of subsoil acidity can presumably tap the subsoil water while efficiently using amendments added to the plow layer. Active research into crop varieties that tolerate acidity may develop suitable varieties of many crops in the near future.

Entirely satisfactory procedures for assessing the ability of plants to use subsoil water are not available. The parameters most important to growth of plant roots are not clearly defined, but they include pH, exchangeable Al content, KCl-extractable Al as a percentage of the sum of KCl-extractable cations, soil solution and/or exchangeable Ca, and percentage base saturation (Ca + Mg + K expressed as percentage of base exchange capacity measured by neutral normal ammonium acetate). Usually, any one of these parameters will be correlated with rates of root growth as a given soil is limed; however, the relationship usually varies among soils and, hence, no single parameter seems entirely satisfactory. Roots are able to use subsoil water to the extent that they are able to penetrate and proliferate in the subsoil; however, fairly small differences in acidity

parameters may considerably change the ability of roots to use subsoil water. For these reasons, the usual procedures designed to estimate lime requirements or the need to apply lime are not necessarily appropriate.

In further considering subsoil acidity, not only must we learn how to estimate root growth parameters from soil analyses, but we must also calibrate these parameters against varieties and species. Some varieties or species might use subsoil water at a specific location, whereas others would not. The current limited state of knowledge suggests that plants respond in many different ways to soil acidity, and we are far from a complete understanding or universal solution.

Another alternative is to use supplementary irrigation during dry periods. Installing facilities for irrigation is not necessarily unreasonable, at least in some areas. For example, in the area near Planaltina, Brazil, enough stream water is available during the dry season to irrigate 2 to 4 percent of the land area. Relatively simple delivery systems are the solution in many cases. Irrigation could be used for intensive crop production on a year-round basis and also when natural rainfall is inadequate during the rainy season.

Whereas this paper has emphasized use of subsoil water, use of subsoil nutrients must also be considered. The concentrations of nutrients in subsoils vary among soils and frequently are not inconsequential. Additionally, leaching of nutrients such as potassium and nitrate from the plowed layer is likely to be appreciable. Conservation dictates that nutrients should be used whenever they are available and that root proliferation in the subsoil should be adequate to allow for use of these nutrients.

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## SUPPLEMENTAL PUBLICATIONS

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