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AN INTENSIVE EDAPHOLOGICAL CHARACTERIZATION OF THE SOILS OF MALAMBITO EXPERIMENTAL STATION AND ITS IMPLICATIONS IN FUTURE AGRICULTURAL RESEARCH

by

William L. Rubink

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Soil Science and Biometeorology

Approved:

[redacted]

UTAH STATE UNIVERSITY
Logan, Utah

1973

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William L. Rubink

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

Figure Page

ABSTRACT

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by

William L. Rubink, Master of Science

Utah State University, 1973

Major Professor: David W. James
Department: Soil Science and Biometeorology

Malambito Experiment Station, in the Atlántico III project area, Department of Atlántico, Colombia, had almost no quantitative edaphological data on which to base agricultural research. Unexplainably low general yields as well as problem areas of deficient plant growth only confounded the results of field plot experiments. Intensive soil sampling and subsequent measurements of pH, EC_e of the saturation extract, and the four major cations disproved the previous suggestions that the crop growth problems were related to saline, sodic, or degraded sodic soil conditions. The Ca/Mg + K + Na ratio, although significant when correlated with plant height, was sufficient explanation for only a small portion of the Malambito problem. The heavy soil texture (50 percent clay) was also shown to be of minor importance in the overall problem. Although no definitive answer was given to explain the variations in plant growth, a basis for further research was provided, including estimates of soluble plus exchangeable cations and their field variability, pH, organic carbon, EC_e and CEC. Future studies in the areas of micronutrient deficiencies and toxicities and possible resistant crops were advocated.

Recent research based on the results of this thesis has now implicated heavy metal toxicity as a probable cause for the growth deficiencies and low yields at Malambito.

(81 pages)

INTRODUCTION

In 1969 a cooperative on-farm water management research and demonstration project involving Utah State University (USU), the United States Agency for International Development (USAID), the Colombian Agricultural Institute (el Instituto Colombiano Agropecuario, ICA), and the Colombian Institute for Agrarian Reform (el Instituto Colombiano de la Reforma Agraria, INCORA) was initiated in the Atlántico III Irrigation Project, Colombia. The primary objectives of this project were the evaluation of optimum soil moisture-fertility relationships for maximum plant growth, and the long range increased efficiency of land and water resources in the production of food and fiber for the country.

Since the establishment in 1963 of Malambito Experiment Station, one of the two agricultural experiment stations at which USU was involved, the little understood soils were recognized as the greatest obstacle to further agronomic research. Although quantitative observations were not yet available, data of a qualitative nature had begun to indicate the perplexing variations present in plant growth. Overall yields were generally low (only about one-half those obtained in other regions of Colombia), and many experimental plots and neighboring fields were spotted by large areas of deficient crop growth. Affected plants were observed to occupy as much as 30 percent of the cultivated fields. Although these problems were later described quantitatively by field trials, results were only confounded by the puzzling areas of poor plant growth, and the objectives of the research were not achieved.

Corn, sorghum, and sesame grown in the affected areas were usually chlorotic in younger tissues shortly after emergence, and the apical leaves of younger plants were deformed and tended to stick together, indicative of magnesium or calcium deficiencies. Later stages of growth were marred by severe stunting, necrotic patches on the perimeter of the older leaves, and general interveinal chlorosis (Figures 1 and 2). Although a foliar application of manganese sulfate gave a definite response in sesame (based on visual symptoms), a reduction in yield was still noted in the final analysis. Corn grown in these areas reached only a fraction of the ordinary height and produced very few ears. This suggested boron deficiency although in preliminary trials the plants showed no response to this element. Other hypotheses concerning fundamental chemical and physical properties, as well as availability of zinc, copper and other microelements, and possible biological factors remained unexamined. On similar heavy clay soils throughout the region, it has been the general consensus among farmers that nothing except grasses would grow well (growth disorders are still present, but to a lesser degree).

In the past, researchers had attributed the problems described above to saline, sodic, or degraded sodic conditions in these soils, or to a low total nutrient status (caused by excessive leaching). However, the few chemical analyses performed were not well correlated with field observations. Thus, crop production data were confounded by soil and crop heterogeneity. A sound basis for agronomic research at Malambito was practically nonexistent.

Figure 1. An example of the extreme variations in plant growth occurring under natural conditions.

Figure 2. Appearance of typically stunted corn plant. (Water stress is also apparent.)

Objective of research

The objective of this thesis, therefore, is to provide a basis for future agricultural research by:

1. Providing a physical and chemical characterization of the soils of Malambito
2. Providing data by which future research may be guided, concerning the observed deficiencies in plant growth.

Historical perspective

The experimental station under study, Malambito, comprises 100 hectares of land on the Magdalena River flood plain in the Atlántico III project area, between the towns of Suán and Calamar, Department of Atlantico, Colombia (Figure 3). Until recently the entire project area was covered by a multitude of swamps and was subjected to frequent flooding. In 1951 thoughts turned to the possibility of transforming the swampland enclosed by the two existing waterways[1] into a region of promising agricultural potential, as well as eliminating the poor living conditions created by the yearly inundations. A plan was proposed by which approximately 15,200 hectares of land on the western bank of the Magdalena might be irrigated (19).

In 1955 the Colombian government built a dike from Pto. Giraldo on the Magdalena to the bifurcation of the Canal del Dique, and along the Canal to Villa Rosa (Figure 3). The dike served as a road and was thus the first modern means of communication among major population centers

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[1] On the west the Magdalena River, and on the southwest the Canal del Dique, a canal built by the Spanish to afford safe transport of goods from the country's interior to the fortified port of Cartagena, thus avoiding pirates on the high seas.

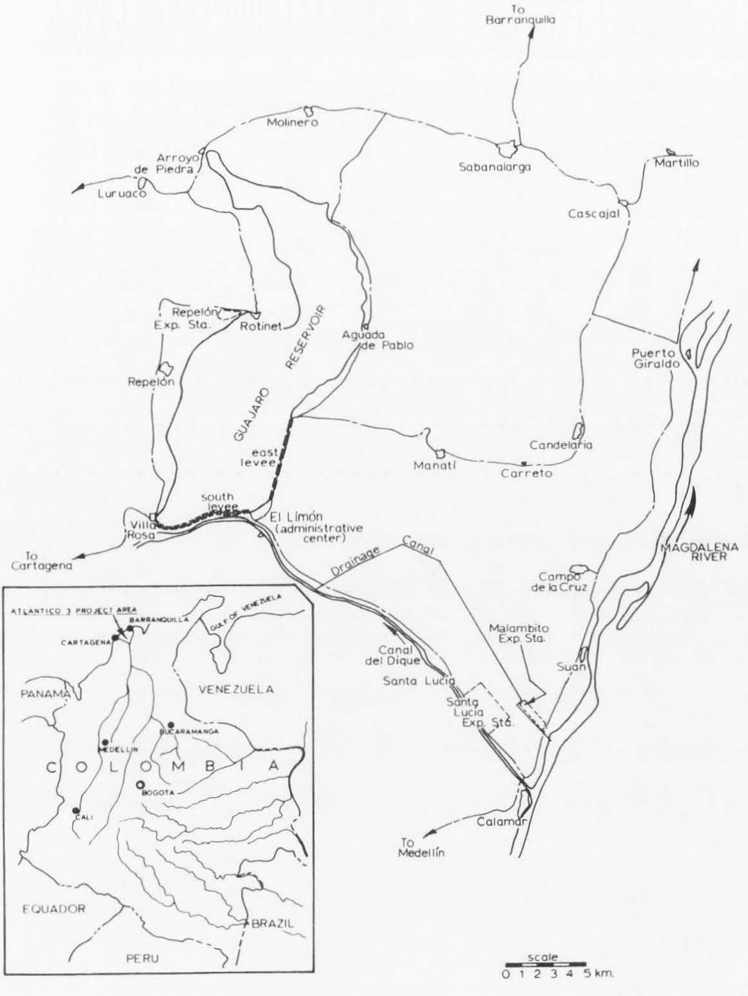

Figure 3. Map of Atlántico III project area with inset showing location in Colombia.

of the region. Slowly the waters in the swamp began to recede, and hitherto unsuspected social problems were created as 45,000 hectares of newly dried, unclaimed lands became the center of dispute for encroaching old-time landowners, immigrant farmers, and thousands of deprived fishermen. The entire situation worsened when the fishermen, upon seeing their only livelihood evaporating, forcefully opened the levee retaining the waters of the Guájaro Reservoir; the lands encompassed by the dike (already 60 percent dry) were reinundated and 5,000 now established farmers were forced to abandon their lands. In 1963, the Colombian Institute for Agrarian Reform (el Instituto Colombiano de la Reforma Agraria, INCORA) was assigned the responsibility of finding an integral solution to the problem. INCORA compiled all existing data, and in December of 1963 the Atlántico III Project Irrigation District was created. Concrete water control structures replaced the earthen dike at Villa Rosa and provided controlled water flow to the Guájaro Reservoir. Drainage canals were designated for the complete elimination of inundated lands in the 4,000 hectares of the Southern Sector, and irrigation canals, pump stations, and sprinkler irrigation equipment were specified for later agronomic research. Nationally coordinated and supervised colonization efforts under the auspices of the agrarian reform prevented a recurrence of many of the problems of the spontaneous 1950 colonization. Three experimental farms were established according to the criteria of principal soil types as described in a 1965 soil survey. Malambito, the second largest of the three, was created with the objective of demonstrating the capabilities of the heavy clay soils which, according to the soil survey, occupy nearly 45 percent of the total project area (19).

REVIEW OF LITERATURE

The importance of knowing the physical-chemical variability of a soil within a given area of field plot research may, in some cases, be greater than that of having an estimate of the mean fertility status (21,34). This is especially true on non-virgin lands (17,24,26) and in certain other cases (3,21), such as the one under study, where highly variable crop growth indicates a distinct horizontal heterogeneity of soil fertility. This review of literature, then will be devoted to the three stages of soil investigation (soil sampling, soil analysis, and interpretation of the results) which are necessary in order to achieve a knowledge of the mesoscale variations in such an area.

Soil sampling

The earliest attempts in describing soil hererogeneity as a continuum of edaphic characteristics were based on the inefficient, however effective, crop uniformity trial (25), where measures of crop yield at various points within the field gave a general indication of soil fertility at those points and, when depicted graphically, provided a contour map whose contours represented lines of isofertility (37). Advances in soil science have now displaced the need for such time consuming, general tasks, and chemical and physical laboratory determinations have enabled the researcher to study the subject of soil-plant relationships in more detail.

In their analyses and interpretations of data most researchers attempted to assess only the mean fertility of the field (8,9) and its range of variation. This was needed for a reasonable estimate of the number of samples necessary or economically feasible in a particular situation for specific chemical or physical characteristics (13,14,34,37). Soils were assumed to vary little over small areas, at least in terms of measurable chemical characteristics, but this was not always the case (8,13,21,34,42,43).

Sampling techniques for achieving an accurate description of the horizontal variation in both chemical and physical properties have not been studied extensively, but general indications of reasonable procedures have been outlined by several authors (8,21,34,42,43). It has been suggested that these methods be placed in four general classes: composite, simple random, stratified, or systematic (3). In cases where only the mean fertility status is the quantity desired, and depending on the complexity and knowledge of the soil at hand, one might most practically choose any of the first three of the foregoing methods. However, where information concerning average fertility as well as its variability and distribution within the field are desired, systematic sampling is superior (8,10,21,34,42,43). This is especially true when little is known of the heterogeneity of the soil beforehand, and when the objectives of the sampling include modern fertility evaluations for use in field plot trials.

Both vertical and horizontal variations in soil properties are important in the characterization of a given soil. Cline (9) indicated that both horizontal and vertical sampling subdivisions are restricted mainly by the soil complexity, the size of the area fulfilling the given purpose, and certain economic considerations. A very large area might well be broken up into smaller, more uniform areas, even though these areas, too, might be highly variable in terms of one or a number of quantities in question. He suggested that in field experiments the minimum unit practicable would be "an experiment, a plot, or a block," while for the needs of a farmer it may be a much larger unit, perhaps as great an area as is devoted to a single crop. Generally, however, the sampling intensity will probably be a compromise between the numbers necessary for accuracy and economy.

Rigney and Reed (34) removed duplicate composite samples from each half of each of twenty eight-acre fields, each section half being composed of two randomly spaced sets of twenty systematically chosen borings. They showed the effects of varying the number of subsamples or field samples on the variance of the mean. In a later paper (37) the same authors sampled two fields of uniform and non-uniform soil types on a 36' by 45' (11 m by 13.7 m) grid. Statistical comparisons were made of analyses of duplicate subsamples of each composite point sample in an attempt to discern horizontal field variations in the constituents measured, variations due to analytical procedure. Results indicated that in the case of nonuniform areas, it is the field variation which is the limiting factor; laboratory precision in these areas is far greater than is actually needed (14,37). In 1956 Rigney (36) again reflected upon the need for well designed sampling methods as well as the need for more work on statistical methods for evaluation and comparison of data.

Jacob and Klute (20) gave the components of variance for plots, samples and sample determinations as a guideline for future work. They optimized combinations of plots, samples, and determinations for a single measured characteristic.

Leo (26) similarly demonstrated a highly variable optimum sample size for chemical determinations of different soil constituents, but did not include a limiting economic factor in the optimization.

Hammond et al. (13) demonstrated that two and three stage sampling (subsampling) was economically more efficient than the random method on uniform strata.

Welch and Fitts (44) compared the use of 6 different sampling tools at three depths on soil analysis data, and Hulburt and Menzel (17) evaluated the soil mixing characteristics of several tillage implements, work which may prove important in interpretation of intensive soil investigations on fertilized lands.

We can see from the above experiments that the most usual forms of sampling include some form of composite from a fairly large area, intended to supply only the mean fertility, and perhaps its variance, in a given area. Such sample composites supply little knowledge concerning the meso-variations commonly occurring in the field (21,25), let alone the micro variations.

A few of the basic formulas and statistics useful in soil sampling and interpretation are as follows:

$$S^2 = \frac{\sum_{i=1}^{n} (Xi - \overline{X})^2}{n - 1} = \frac{n \cdot \Sigma X_i^2 - (\Sigma Xi)^2/n}{n - 1}$$

S^2 = sample variance

Xi = value of the ith observation

n = number of observations

$$V(\overline{Y}) = S^2/n$$

$V(\overline{Y})$ = variance of the sample mean

$$r = \frac{n \cdot \sum_{i=1}^{n} XiYi - (\sum_{i=1}^{n} Xi)(\sum_{i=1}^{n} Yi)}{\sqrt{n \cdot \sum_{i=1}^{n} X_i^2 - \sum_{i=1}^{n} (Xi)^2}\ \sqrt{n \cdot \sum_{i=1}^{n} Y_i^2 - (\sum_{i=1}^{n} Yi)^2}}$$

r = correlation coefficient

Xi,Yi are the values of the ith (paired) observations

Soil testing and interpretation

Chemical soil tests should be designed to provide a reasonable estimate of available plant nutrients in the various forms in the soil (40). In many cases correlation of quantitative data with plant growth or yield can provide a more direct means of evaluating the general fertility status, or diagnosing a particular problem, such as locally chlorotic plants, subsoil exposures, low soil pH, and saline or sodic areas (19,40). The main problem is the development of an appropriate chemical means for estimating plant available nutrients (15,19,40).

Probably the most commonly employed method for determination of many soil chemical properties, due mainly to its simplicity, rapidity, and value in soil fertility predictions, is the use of an extracting solution (40). Through this method we may achieve estimates of exchangeable cations as well as elements available in other forms. The most common of the extracting solutions presently in use is neutral, normal, ammonium acetate, which, although it tends to give values exceeding the cation exchange capacity (15,40), is sufficiently accurate to make it a useful tool in the assessment of the fertility status of the soil. Where the soil is high in soluble salts, analysis should be made of the soil solution to provide an accurate measure of exchangeable cations, but for well leached soils, the soluble salt content is a relatively insignificant quantity (15,40,41). The usual extraction process includes a leaching column, or extraction by centrifugation (3,15,19). The centrifugation method obviates the problems encountered in leaching soils of low permeability (19).

Of the four principal cations usually encountered in the soil, calcium is usually predominant, occurring in several forms: carbonate, phosphate, silicate, fluoride, sulfate, and adsorbed (exchangeable). It can be fixed by phosphates in neutral soils and is usually deficient in acid media. Insufficiency of Ca may permit the accumulation of toxic concentrations of other ions (15). Actually, the proportion of calcium present in relation to other cationic species seems to be more significant than the absolute amount available (2); calcium has been noted to reduce toxicity of high boron irrigation waters (11), increase potassium fixation (46), and decrease both manganese and phosphorous availability (27). Black (2) emphasized the importance of the antagonisms among calcium, potassium, magnesium and sodium in plant uptake.

Magnesium and potassium, too, are essential in plant nutrition. Their interaction has been observed in the competition of potassium for exchangeable sites on the roots, preventing the proper functioning of magnesium, and the way in which it decreases the rate of magnesium displacement (16). Magnesium uptake is strongly influenced by hydrogen, ammonium and calcium ions as well (45). Here, too, it has been recorded that potassium-magnesium ratios are much more meaningful than the individual measurements of either element (28). Other problems related to potassium measurements and their interpretations will be covered subsequently in the discussion of the effects of air drying.

Sodium, the least abundant (in most cases) of the four principle metallic cations, is edaphologically relevant in only a handful of situations: sodic, saline-sodic, and degraded sodic soils. Abundance of sodium may be responsible for a plethora of problems, physical as well as chemical. Sodium causes dramatic changes in soil physical properties (which usually persist in degraded sodic soils). Deflocculation, caused by a high exchangeable sodium percentage, as well as other factors reduces permeability considerably (2). Other chemical changes with high sodium include a toxicity of sodium ions and accompanying high pH (4). Except in the case of a few plant species, such as Chenopodium, sodium is generally toxic at moderately low concentrations (that is, exchangeable sodium percentages on the order of 10-20 percent or greater (35)). However, it has been shown that small additions of sodium to potassium deficient soils improve yield (23,29), possibly due to stimulated phosphorous uptake (23) or sodium-potassium interactions (4).

Another characteristic essential to the description of the fertility of a soil is the cation exchange capacity (CEC). Until recently a relatively precise method of determination of this quantity had been plagued by two problems inherent in the basic analytical procedure:

1. Hydrolysis of the index cation during the washing step (31,32).
2. Fixation of the index cation (22).

These difficulties were resolved (31,32,40) by an elimination of the washing step (thus eliminating a possible error due to hydrolysis), use of ammonium as the index cation, and subsequent determination of adsorbed ammonium by microkjeldahl distillation (31,32,40). Keeney and Bremner

(22) showed fixation of the index cation to be of little importance in their procedure, thus reasonable estimates of CEC should be possible.

There is one other major point of discussion concerning the testing phase of soil characterization: the profound effects of method of soil preparation on measurable chemico-physical constitutents (1,8,9,15,19, 40,44). The preparatory stage which contributes most to this error in measurement of available plant nutrients is probably air drying (15). Chemical effects may include release or fixation of potassium (1), an increase in acid soluble phosphorous (as high as 100 percent in high temperatures) (15), and increase in sulfate release, changes in pH, and increases in exchangeable manganese (15).

Other possible errors inherent in testing are due to improper mixing, or contamination of samples, but careful preparation (with the final objectives in mind, and proper subsampling reduce these errors considerably (8,9,15).

MATERIALS AND METHODS

Soil sampling and preparation

Presampling efforts included the layout of a square grid system with stations spaced at twenty-meter intervals over an initial area of approximately eight hectares of Malambito Experimental Station (Figure 4). These efforts also included the construction of a detailed topographic map (Figure 5).

Soils were sampled at each grid point by taking four borings (9 cm diameter by 30 cm deep) with a soil auger at random within a two-meter radius circle, mixing them together thoroughly, and removing a subsample consisting of approximately 1/2 to 3/4 the total volume composited. The first samples were taken along grid diagonals in the preliminary sampling area (traverses A-D, Figure 4) in order to assess the general salinity and pH status of the entire section and provide guidelines (spacing, area of intensive sampling, vertical variations present) for the second stage of sampling. The final study plot, selected for intensive sampling on the same grid system, measured 120 by 200 meters (Figures 4,5). At approximately 10 percent of the grid points of the preliminary sampling area, and at seven of the grid points of the intensive sampling area, chosen at random, a composite was not made and each of the four subsamples was collected separately. In preparation for analysis all samples were air-dried until they reached a moisture content of less than 10 percent, passed through a 4 mm screen, and stored in plastic bags for analysis of pH and EC of the saturation extract within two weeks of removal from the field.

Figure 4. Location of soils study area at Malambito Station.

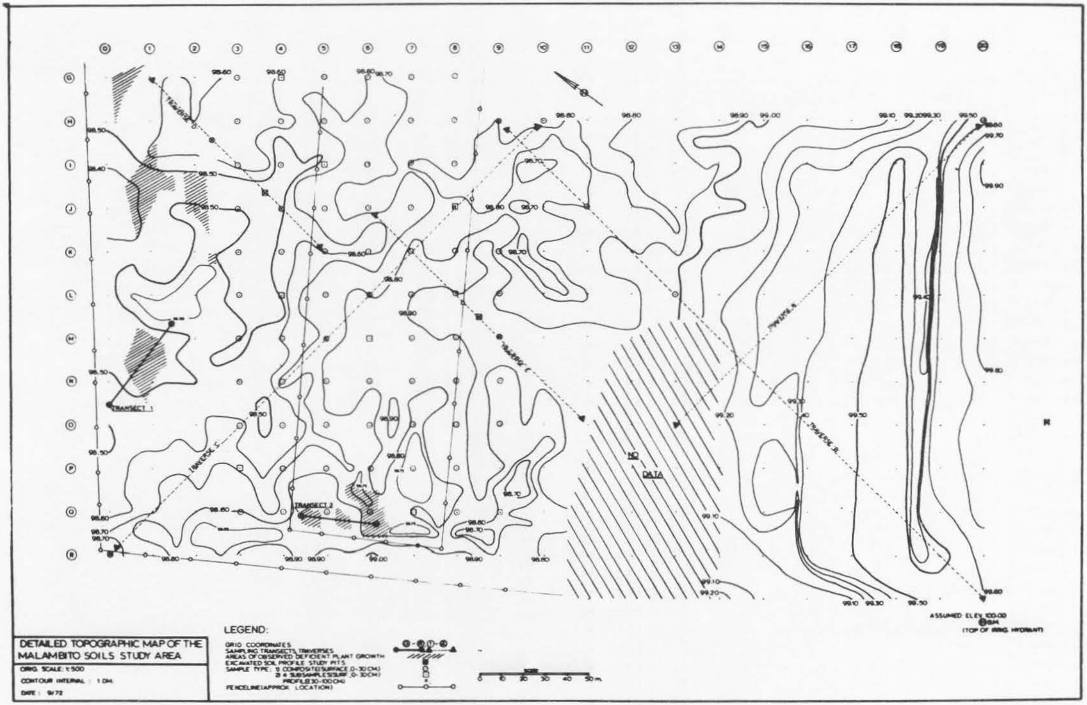

Figure 5. Detailed topographic map of the Malambito soils study area.

Since a large amount of variability is present in the preparation of saturation extracts, especially on very coarse or very fine textured soils (6), the usefulness of EC_e for estimating relative concentrations of harmful salts is diminished. In the present study attempts were made on a field wide basis to estimate the horizontal variations in salt distributions. This was found to be possible only after all EC_e values were corrected to a mean saturation percent (60 percent in this case), thus eliminating most of the error associated with preparation of the saturated soil paste. The actual values were adjusted to a 60 percent equivalent by the following relation:

$$EC_e = [EC]_{M_{meas}} \times (\text{percent } M_{meas}/\text{percent } M_{std}) \qquad [1]$$

where EC_e is the electrical conductivity at the common moisture value,

$[EC]_{M_{meas}}$ is the electrical conductivity at the measured moisture value,

Percent M_{meas} is the measured percent moisture at which the extraction is made,

Percent M_{std} is a percent moisture assumed to be common for all samples (= 60 percent, the average saturation percentage, in this case).

Fifty-four samples were taken on two transects which covered areas of reported (transect 1), and known (transect 2) deficiencies (see Figure 5). The first twenty-four were removed using a hydraulic soil sampler at two meter intervals from two and three depths with a single 3.5 cm diameter core. The second set of samples comprised transect 2, lying in an experimental plot of corn which demonstrated extreme variation in growth (Figure 1); thirty samples of the surface twenty centimeters of soil were obtained using a 9 cm diameter soil auger. Samples were taken on the ridges at 0.9 meter intervals and corn plant height was recorded as the average height of the plants on either side of the sample. Preparation for analysis was performed in the manner previously described.

After analyses of pH and ECe in Colombia were complete, two surface and two subsurface composites were made from the areas of deficient and normal plant growth in transect 1 and packaged in cloth bags. Each of the thirty samples of transect 2, as well as twenty-three profile samples and 100 samples of the surface 30 cm of the intensive study plot, were packaged in the same manner. All the samples were steam sterilized upon entry to the U.S.A. by the USDA Plant and Health Inspection Service in Miami, Florida, and shipped to Utah State University in Logan for more complete analyses.

Soil chemical and physical analysis

Moisture content of the samples was estimated by drying duplicate subsamples at 105° for 24 hours. This enabled computations of the number of grams of moist soil and number of milliliters of water necessary for the soil suspensions, and also facilitated more precise estimations of saturation capacity and hence, salt content of the soil.

Measurement of pH was by three methods: a) in 1:1 soil:water, b) in 1:2, soil: 0.01 M $CaCl_2$, c) in the saturation extract. A Corning glass electrode and pH meter were used. After a constant value registered on the pH meter (usually 4-5 minutes following insertion of the electrode), pH was recorded.

The saturation extract was prepared with 100 g subsamples as described by Bower and Wilcox in Methods of Soil Analysis (3); analyses were performed on 15 to 30 ml volumes of extract. Electrical conductivity of the extract was measured with a conductivity meter to precision of ± .01 millimhos. The number of milliliters of water added to make the paste was also recorded to enable the indirect computation of the saturation percentage. Results for the surface soils are reported as electrical conductivity (EC) of the saturation extract adjusted to 60 percent moisture capacity, the average saturation percentage of the surface soils. Subsurface EC's are reported without adjustment.

Oxidizable organic carbon (OC) was estimated by the microprocedure of Chesnin (7). Excess chromic acid was employed to oxidize the carbon present; the excess chromate ion was then reduced by excess ferrous ion, which was subsequently titrated with standardized potassium permanganate solution. Equal additions of reagents to each sample made it necessary to standardize only the permanganate solution. Results are expressed in percent readily oxidizable organic carbon (to convert to percent organic matter, multiply by 1.72).

Exchangeable plus soluble cations were determined optically using a Perkin-Elmer Atomic Absorption Spectrophotometer after triple extraction of 5.0 grams of soil with neutral, normal, ammonium acetate, utilizing the centrifugation procedure outlined by Jackson (19). Results are reported in terms of milliequivalents per 100 grams of oven dry soil.

Cation exchange capacity was determined by the micromethod suggested by Keeney and Bremner (22): saturation with ammonium ion, leaching with 1 M and analyzing the total sample for both ammonium and nitrate, the difference of which represents adsorbed ammonium. Results are expressed in meq per 100 gms of oven dry soil.

Particle size distribution curves were prepared by hydrometer analysis after Boyoucos (5). Forty grams of air dry soil were soaked in 50 ml of

10 percent sodium hexametaphosphate solution in order to disperse the soil. Both soil and solution were then mixed in a mechanical mixer, transferred to a one-liter soil suspension cylinder, and diluted to volume. Cylinders were shaken and measurements of specific gravity taken at approximately .5, .75, 1, 3, 10, 90, and 540 minute intervals. With the exception of the first three intervals, each measurement was recorded after complete resuspension by shaking. Results are reported as percent sand, percent silt and percent clay, and in the form of particle size distribution curves.

The data were analyzed statistically in four general aspects:

1. Correlation coefficients were computed to test the effects of soil variables on plant height
2. The point variance, an estimate of the variability of a measured quantity at a given grid point due both to sampling and laboratory analysis, was estimated by the Analysis of Variance (33,38)
3. Significant horizontal field gradients were tested for by comparison of grid row, column and diagonal mean squares (34); homogeneity of variances was first established by Bartlett's test (33,38)
4. The means, standard deviations, and standard errors of the mean were computed for the intensive sampling area, thus supplying estimates of statistical parameters useful in future studies.

RESULTS

Qualitative and quantitative observations made at Malambito

The topography in the area of study is relatively level with a net northwesterly slope of two to three percent containing minor undulations. Scattered depressions are 20 to 40 cm lower than the surrounding area (see Figure 5). However, even small changes in elevation were found to be of interest. Comparison of the field elevation of various areas with deficient plant growth suggested that a correlation existed between the scattered depressions of the field and areas of plant growth disorders (Figure 5). Further observations of the actual study plot substantiated this hypothesis. It should be noted, however, that in a few cases plants in certain other areas, not occupying topographically lower portions of the field, were also deficient in growth.

Typical vegetative cover (revegetation after initial clearing and disking) consisted principally of weeds such as Malva, Ipomea (and other trailing vines), Chenopodium, and some grasses (Figure 6). These bore few recognizable relationships to either the physical features of the soil or topography and did not show any easily recognizable growth disorders. Ipomea, other trailing Convulvaceae, and some Gramineae, nevertheless, seemed to be most prevalent in the lower parts of the landscape, while Malva and Chenopodium inhabited the higher, seldom flooded portions. A large flat area in the center of the intensive study plot seemed to be the only exception (refer to Figure 5); although relatively high in elevation, the abundant vegetational cover was trailing vines of Ipomea and grasses.

Figure 6. Typical revegation of intensive study plot (after initial clearing and plowing).

Field estimation of texture indicated three interesting points:

1. In the topographically lower portions of the landscapes, the surface soil was predominantly clayey, while higher points were more variable.
2. The soil profile usually consisted of less clay with depth, grading to a fine sand about one meter depth in most of the area studied (in some of the lower areas at the northeast end of the intensive study plot the high clay content persisted to a greater depth, but still graded to a lighter material in the lower profile).
3. Although surface variations in the intensive study area were miniscule, subsurface textures were highly variable; sand, silt,

and clay lenses, and wide textural variations were common. Since the soil is of fairly recent alluvial origin, no differentiable layers other than depositional strata, and a surface soil darkened slightly by organic matter, were apparent.

The three principal vertical divisions recognized, then, were the following visible variations in texture and color (Figure 7):

1. 0-40 cm, dark clay to silty clay, massive and hard when dry, little structure, plastic and very sticky when wet, abundant roots, gradual transition to next stratum.
2. 40-80, a lighter colored silty clay, hard when dry, structureless, mottled (with what appear to be iron and manganese oxides), some roots, boundary uneven with underlying stratum.
3. 80+ cm, a silty loam grading to a sandy loam, structureless, non-plastic, few fine roots.

Figure 7. Typical soil profile.

The water table at Malambito varies from between one and two meters of the surface from the wet to the dry seasons, respectively.

Soil pH was lowest as measured in 0.01 molar $CaCl_2$, ranging from 5.5 to 6.5 in the surface 30 cm and increasing gradually to a range of 6.0 to 6.8 at lower depths (∿ 1 meter). Each of the two other methods registered values slightly higher, but a pH of 7.9 was not exceeded by any of the three at any depth. In Table 1 are listed the means of soil pH at four depths by three methods for approximately thirty samples of the preliminary study plot (the "fourth depth" refers to the upper portion of the sandy layer lying beneath the final stratum mentioned in the above paragraph).

Table 1. Variations in pH by depth and method of measurement

	1:1, soil:H_2O	1:2, soil: .01^M $CaCl_2$	sat. extract
0- 30 cm	** 6.40	6.05 **	6.63 *
40- 80	6.67 *	6.24	6.77
80-100	6.85	6.30	6.76
100-110	6.93	6.33	6.83

**Difference significant at 99 percent level.
*Difference significant at 95 percent level.

Transect 1 (see Figure 5), taken to evaluate any readily apparent differences in pH between areas of normal and deficient plant growth, indicated little consistent change in pH with either sample position or elevation, as well as a high variability in measurements (Figure 8).

Horizontal concentrations of salts, represented by EC_e, varied rather continuously in the surface soils, and increased with depth. Point

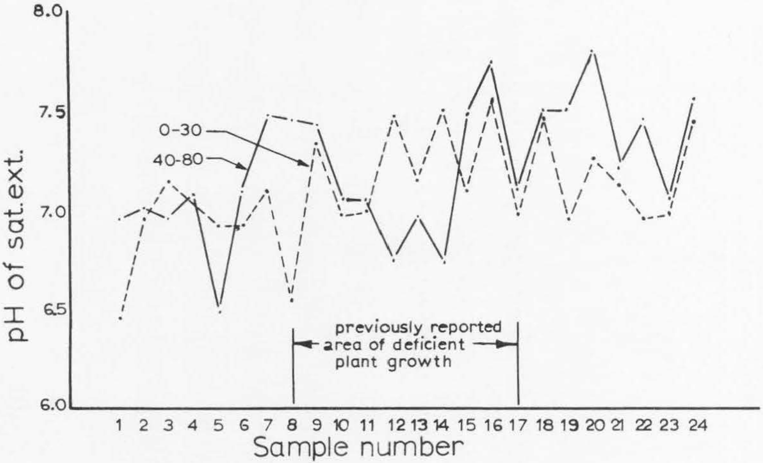

Figure 8. Variability in pH at two depths for samples from transect 1.

variance, although high, still indicated a significant difference between points (Table 2). Figure 9 demonstrates the horizontal variation in salt concentration, and Figures 10, 11, and 12 delineate the vertical changes as well along the various transects or traverses. Although several points did have surface soil salt concentrations which would be prejudicial to plant growth, these samples without exception have been removed from the areas of exposed subsoil. Nearly the entire southeast fourth (grid lines 15-20) of the preliminary sampling area had been leveled recently; Figure 11 indicates the salt concentrations present in that section. In Table 3 the increase in salt concentration (EC_e) with depth, and the higher concentrations in samples from lower depths, also attest the non-saline nature of the surface soil. Topographically related salt distributions are not apparent.

Qualitative tests for the presence of gypsum in the soil extracts also proved negative.

Quantitative results obtained at Utah State University

Measurements of pH made at Utah State University gave similar "drifting" readings as those made at Malambito, but even so, more consistency was noted. Measurements differed slightly from those made in Colombia, but final analysis showed that this difference ($\sim$ 0.1 pH) was insignificant. No topographical relationship was found (Figure 13; Table 4, col. 2). Horizontal variability in pH throughout the field was significant. Significant differences were registered in comparisons of the lower (southwest) vs. upper (northwest) ends, the mean pH's and 95 percent confidence limits being 5.92 ± 0.07 and 6.09 ± 0.09, respectively. Figure 14 depicts the horizontal variability of pH in the intensive study plot.

Table 2. Components of variance for sampling and analysis

	Source	D.F.	M.S.	E.M.S.
pH by three methods:				
In 1:1 soil to	(Points*	4	0.7186	$\sigma_d^2 + 2.82\sigma_s^2 + 8.73\sigma_p^2$
water	(Points*	4	0.2219	same as above
suspension	(Points*	4	0.0076	same as above
in saturation	(Subs**	15	0.4985	$\sigma_d^2 + 2.33\sigma_s^2$
extract	(Subs**	15	0.1487	same as above
	(Subs**	15	0.0040	same as above
in 1:2	(Dets***	24	0.3348	σ_d^2
soil: 0.01 M	(Dets***	24	0.1067	same as above
$CaCl_2$ suspension	(Dets***	24	0.0025	same as above
EC of sat. ext.	Points	5	0.6577	$\sigma_d^2 + 2.15\sigma_s^2 + 8.77\sigma_7^2$
	Subs	17	0.0921	$\sigma_d^2 + 2.18\sigma_s^2$
	Dets	27	0.0345	σ_d^2
Analysis of variance				
Calcium	Points	6	47.9945	$\sigma_d^2 + 2\sigma_s^2 + 8\sigma_p^2$
	Subs	21	22.2720	$\sigma_d^2 + 2\sigma_s^2$
	Dets	28	11.6500	σ_d^2
Magnesium				
	Points	6	1.0998	$\sigma_d^2 + 2\sigma_s^2 + 8\sigma_p^2$
	Subs	21	0.1888	$\sigma_d^2 + 2\sigma_s^2$
	Dets	28	0.0232	σ_d^2
Sodium				
	Points	6	0.0264	$\sigma_d^2 + 2\sigma_s^2 + 8\sigma_p^2$
	Subs	21	0.0081	$\sigma_d^2 + 2\sigma_s^2$
	Dets	28	0.0017	σ_d^2

Table 2. Continued

	Source	D.F.	M.S.	E.M.S.
Potassium				
	Points	6	0.0140	$\sigma_d^2 + 1.81\sigma_s^2 + 6.55\sigma_p^2$
	Subs	20	0.0041	$\sigma_d^2 + 1.66\sigma_s^2$
	Dets	19	0.0003	σ_d^2
Mg/K				
	Points	6	0.9639	$\sigma_d^2 + 1.81\sigma_s^2 + 6.55\sigma_p^2$
	Subs	20	1.2744	$\sigma_d^2 + 1.66\sigma_s^2$
	Dets	19	0.0937	σ_d^2
Ca/Mg + K + Na				
	Points	6	0.6254	$\sigma_d^2 + 1.81\sigma_s^2 + 6.55\sigma_p^2$
	Subs	20	0.1915	$\sigma_d^2 + 1.66\sigma_s^2$
	Dets	19	0.1891	σ_d^2

*refers to variation between grid points.

**refers to variation between cores.

***refers to variation between determinations on the same laboratory sample.

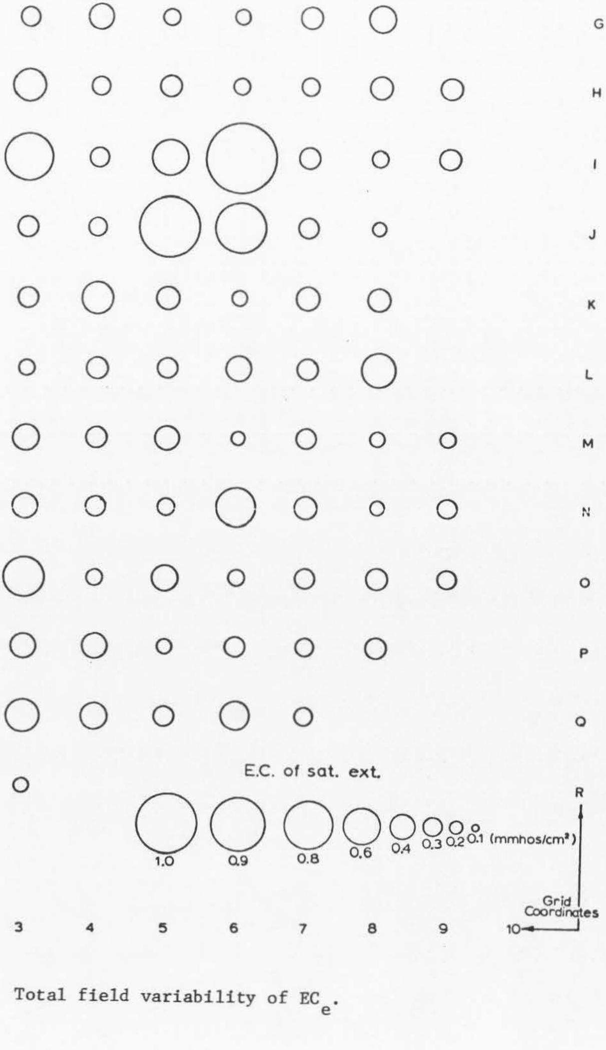

Figure 9. Total field variability of EC_e.

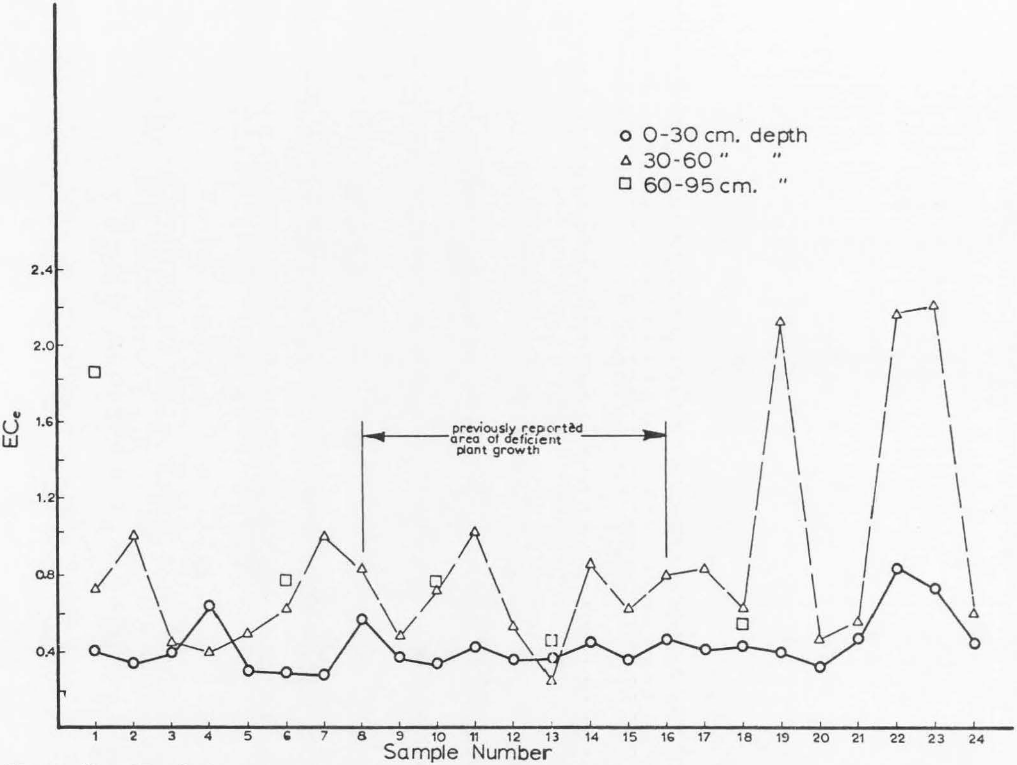

Figure 10. EC of the sat. ext. vs sample position in transect 1.

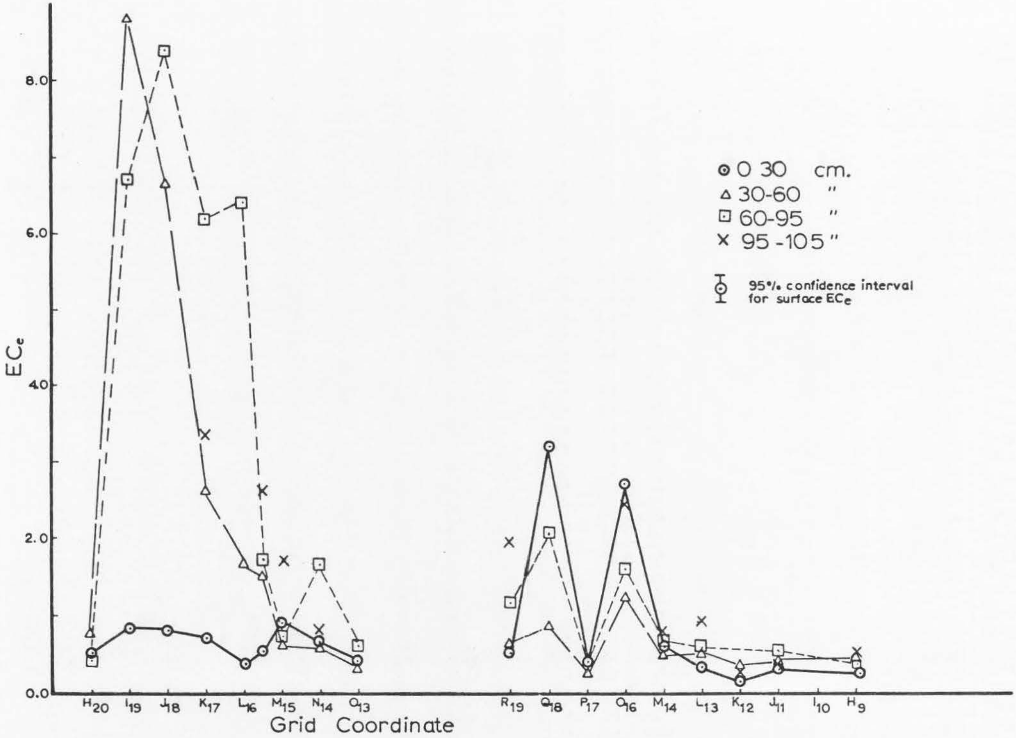

Figure 11. EC of the saturation extract at four depths vs sample positions in traverses A and B.

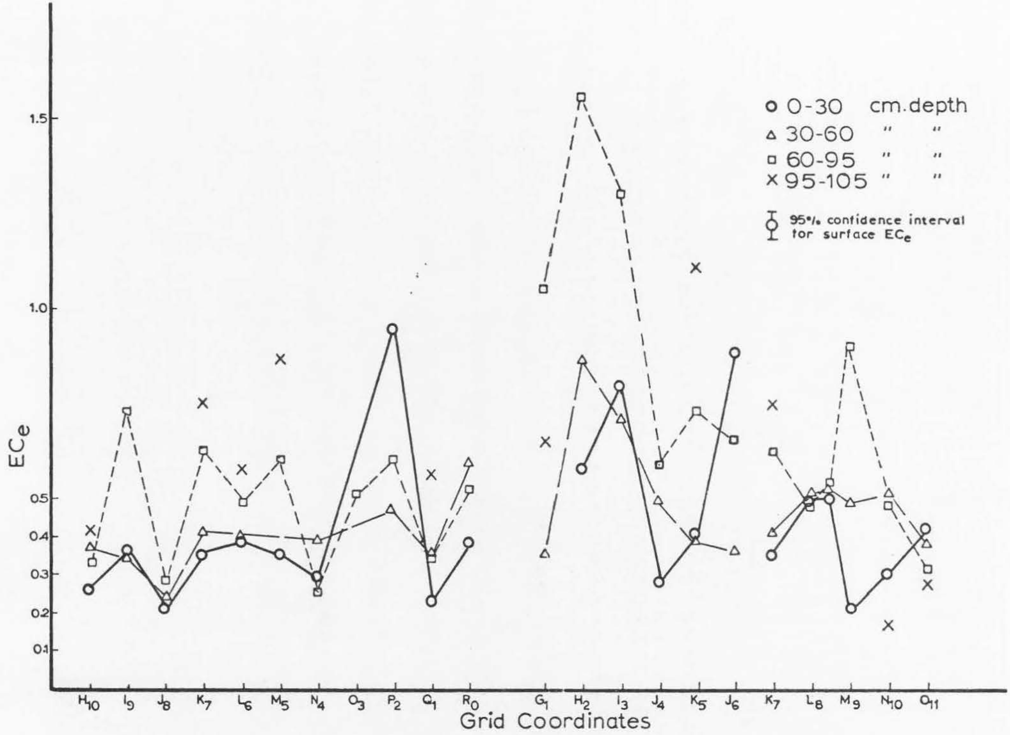

Figure 12. EC of the saturation extract at four depths vs sample position in traverses C, D and E.

Table 3. Soil profile analysis

Field Coord	Sampling depth (cm)	pH	EC$_e$ (mmhos/cm)	Saturation %	O.C.* (%)	CEC (meq/100 gms)	Available cations (sol. & ex.) (meq. per 100 gms.)				Mg/K ratio	Ca/Mg+Na + K ratio	SA %	SI %	CL %	Relative elevation of sampling point (meters)
							Ca	Mg	K	Na						
H-9 comp***	0- 30	6.05	0.36	64	1.32	24.1	22.2	7.8	.94	.36	8.3	2.7	6	40	54	0.91
H-9 C-2***	50- 80	6.54	0.32	61	0.24	19.4	16.3	7.5	.42	.76	17.9	2.1	13	39	48	---
H-9 C-3***	80-100	6.51	0.42	62	0.24	19.0	17.3	8.1	.40	.88	20.3	2.0	9	41	50	---
M-9 comp	0- 30	6.19	0.21	55	1.36	20.6	19.1	7.0	.74	.32	9.5	2.6	16	36	48	0.91
M-9 C-1	30- 55	6.22	0.52	57	0.70	20.2	19.1	8.2	.63	.84	13.0	2.2	15	35	50	—
M-9 C-2	55-100	6.96	1.00	38	0.21	17.1	15.7	7.8	.40	1.00	19.5	1.9	22	39	39	—
O-10 comp	0- 30	6.21	0.30	54	0.70	20.2	15.4	6.4	.60	.22	10.7	2.4	21	34	45	0.83
O-10 C-2	45- 80	6.60	0.38	30	0.45	---	13.2	6.0	.33	.35	18.2	2.2	41	27	32	—
O-10 C-3	80-100	6.85	0.44	28	0.13	12.1	13.7	5.1	.25	.45	20.4	2.6	56	24	20	—
L-6 comp	0- 30	6.16	0.38	60	0.95	22.0	16.5	7.2	.70	.32	10.3	2.2	13	37	50	0.80
L-6 C-1	30- 40	6.72	0.42	45	0.49	19.1	21.9	7.5	.45	.59	16.7	2.8	24	30	46	—
L-6 C-2	40- 60	7.06	0.48	42	0.25	20.2	17.1	4.8	.32	.65	15.0	3.3	27	34	39	—
L-6 C-3	60-100	7.67	0.58	62	0.14	17.9	21.3	5.3	.25	.83	21.2	3.7	7	49	44	—
M-5 comp	0- 30	6.14	0.35	55	0.82	23.0	18.6	7.6	.64	.39	11.9	2.4	11	38	51	0.73
M-5 C-2	40- 70	6.87	0.40	51	0.19	15.6	16.0	5.8	.39	.78	14.9	2.5	19	42	39	—
M-5 C-3	70-100	6.86	1.31	28	0.16	9.6	12.5	3.7	.22	.62	16.8	3.0	66	18	16	—
J-8 comp	0- 30	5.88	0.20	58	0.85	---	22.2	8.0	.46	.85	17.4	2.6	11	39	50	0.71
J-8 C-2	70- 85	6.48	0.30	49	0.24	17.2	15.4	8.8	.44	.70	20.0	1.7	20	31	49	—
J-8 C-3	85-100	6.71	0.26	33	0.30	13.2	11.2	6.1	.28	.57	21.8	1.8	52	19	29	—
R-0 comp	0- 30	6.18	0.32	71	1.00	24.6	20.6	8.2	.71	.49	11.5	2.4	9	37	54	0.63
R-0 C-1	30- 50	6.77	0.32	63	1.00	23.6	20.6	9.1	.44	.90	20.7	2.2	11	29	60	--
R-0 C-2	50-100	6.72	0.56	52	0.17	16.5	17.8	7.2	.27	.63	26.7	2.4	7	53	40	—
R-0 C-3	100-110	6.99	0.59	40	0.23	---	15.0	5.7	.29	.40	19.7	2.6	36	41	23	—
H-2 comp	0- 30	6.51	0.47	74	1.21	26.5	28.6	8.4	.55	.43	15.3	3.4	9	38	53	0.60
H-2 C-1	30- 45	6.71	1.22	60	0.31	23.4	20.6	8.9	.30	.90	29.7	2.3	5	39	56	—
H-2 C-2	45- 75	6.90	1.66	44	0.27	18.6	20.2	8.1	.33	1.12	24.5	2.3	4	48	48	—
H-2 C-3	75-100	7.07	2.85	45	0.19	15.1	23.0	6.9	.24	.98	28.8	3.1	16	53	31	—
**IT 3,4,5, surf	0- 50	6.48	0.43	70	0.90	22.9	30.0	8.1	.57	.50	14.2	3.6	9	38	53	0.55
IT C-1	50- 85	6.90	0.45	62	0.14	16.7	16.5	6.6	.27	.80	24.2	2.4	20	40	40	—
J-4 comp	0- 30	6.28	0.28	60	1.11	24.1	17.4	8.1	1.00	.42	8.1	2.0	6	39	55	0.49
J-4 C-1	30- 55	6.54	0.49	68	0.39	23.4	21.2	10.0	.61	1.07	16.4	2.0	0	35	65	—
J-4 C-2	55-110	7.05	0.62	57	0.22	18.6	15.1	8.7	.46	1.03	18.9	1.6	21	34	45	—
**IT 17,18, 19, surf	0- 40	6.38	—	65	0.80	23.8	19.0	8.4	.59	.58	14.2	2.2	6	38	56	0.46
IT C-1	40- 80	6.61	—	55	0.17	18.8	19.1	8.2	.35	1.13	23.4	2.2	16	41	43	—

*O.C. refers to oxidizable carbon, "Organic matter" is approximately 1.72 times O.C.

**IT 3,4,5, and IT 17,18,19, refer to the composites of transect 1.

***comp designates a surface composite; C-1, C-2, and C-3 designate succeeding distinguishable layers.

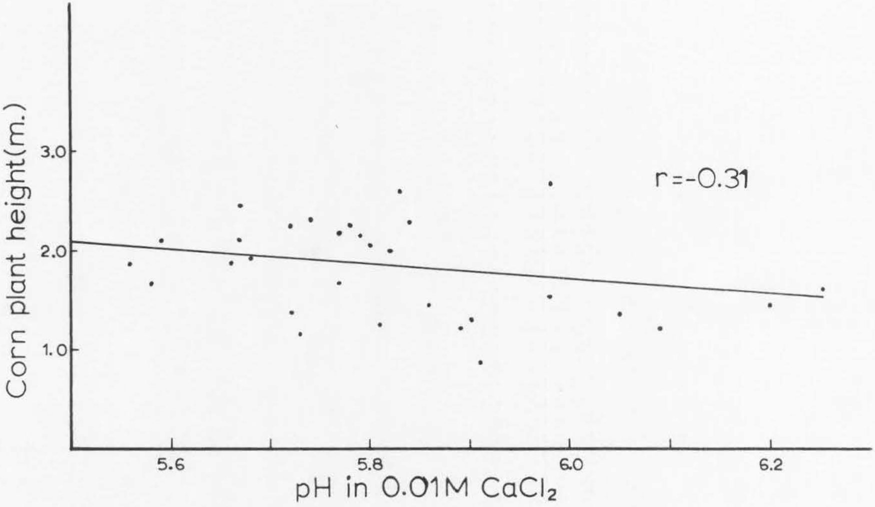

Figure 13. Corn plant height vs pH for samples from transect 2.

Table 4. Correlation analyses for transect 2

	CORN I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
	Plant				Soluble plus exchangeable									
	height	pH	O.C.*	CEC	Ca	Mg	K	Na	SAR	Ca/ Mg&K&Na	Mg/K	Clay	Silt	Sand
	(meters)		%	milliequivalents/100 gms. O.D. soil								%	%	%
30	0.87	5.91	1.46	22.2	18.9	7.6	.77	.29	0.08	2.18	14.6	52	38	10
5	1.17	5.73	1.06	19.9	19.4	8.0	.50	.30	0.08	2.20	16.0	46	37	17
6	1.22	6.09	1.01	21.2	19.0	8.1	.46	.32	0.09	2.14	17.6	46	38	16
3	1.23	5.89	0.86	20.3	20.8	8.3	.46	.33	0.09	1.84	18.0	46	36	18
2	1.27	5.81	0.86	21.2	17.5	8.7	.49	.36	0.10	1.83	17.8	48	35	17
29	1.30	5.90	1.63	23.8	19.6	7.7	.84	.24	0.06	2.23	9.2	52	39	9
17	1.36	6.05	1.26	23.7	18.4	7.6	.57	.31	0.09	2.17	13.3	50	40	10
7	1.38	5.72	1.01	19.9	18.5	7.6	.51	.31	0.09	2.20	14.9	46	35	19
1	1.45	5.86	0.88	20.3	20.5	8.3	.57	.39	0.10	2.21	14.6	47	35	18
4	1.46	6.20	0.63	19.4	20.8	8.5	.46	.44	0.11	2.21	18.5	50	40	10
9	1.54	5.98	1.39	21.1	19.0	6.8	.52	.26	0.07	2.51	13.1	46	35	19
10	1.66	5.58	1.26	22.1	16.8	7.4	.51	.28	0.08	2.05	14.5	44	38	18
16	1.68	5.77	1.23	22.2	19.1	8.5	.61	.32	0.09	2.03	13.9	52	39	9
28	1.70	6.34	1.50	23.3	20.2	7.5	.75	.32	0.09	2.36	10.0	52	36	12
11	1.86	5.56	1.44	21.9	17.9	7.1	.54	.32	0.09	2.25	13.1	46	38	16
8	1.89	5.66	1.19	20.2	18.8	7.5	.47	.30	0.08	2.27	16.0	44	40	16
27	1.93	5.68	1.74	24.2	21.6	7.6	.73	.32	0.08	2.50	10.4	48	40	12
26	2.00	5.82	1.25	22.4	18.9	7.4	.73	.31	0.09	2.24	10.1	49	38	13
18	2.05	5.80	1.10	23.8	20.1	8.1	.57	.34	0.09	2.23	14.2	51	40	9
15	2.10	5.67	1.20	23.2	18.7	8.0	.60	.31	0.08	2.10	13.3	49	37	14
12	2.10	5.59	1.36	21.6	19.7	7.3	.52	.31	0.08	2.42	14.0	48	38	14
19	2.15	5.79	1.50	22.6	20.1	7.5	.63	.31	0.08	2.38	11.9	52	38	10
24	2.18	5.77	1.48	22.7	19.2	7.3	.68	.26	0.07	2.33	10.7	50	36	14
25	2.25	5.78	1.49	22.0	19.5	7.2	.67	.31	0.08	2.38	10.7	50	38	12
20	2.25	5.72	1.54	23.3	18.3	7.5	.63	.28	0.08	2.18	11.9	50	39	11
21	2.30	5.84	1.44	23.9	19.5	8.1	.68	.32	0.09	2.14	11.9	50	38	12
22	2.30	5.74	1.42	23.6	20.9	7.5	.64	.29	0.08	2.48	11.7	50	40	10
13	2.45	5.67	1.23	20.5	22.3	7.9	.55	.35	0.09	2.53	14.4	48	38	14
23	2.60	5.83	1.49	22.0	26.2	7.7	.71	.27	0.07	3.02	10.8	49	39	12
14	2.66	5.98	1.34	22.5	22.2	7.9	.56	.29	0.07	2.54	14.1	49	40	11
Corn plant height correlation coefficient r														
	---	-0.310	0.443	0.372	0.549	-0.261	0.214	-0.176	0.299	0.614	-0.348	0.191	0.380	0.343
Percent organic carbon correlation coefficient r														
	0.443	-0.201	---	0.723	0.253	-0.671	0.740	-0.708	0.740	0.509	-0.875	0.379	0.204	-0.403

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*Organic carbon; organic matter = 1.72 X (O.C.)

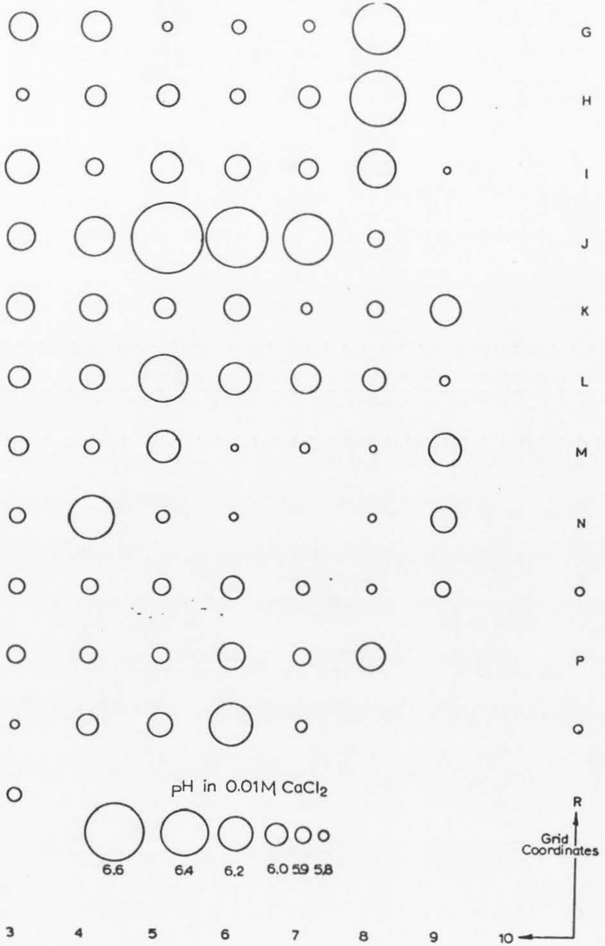

Figure 14. Total field variability of pH.

Measurements of the Cation Exchange Capacity of a selected number of samples indicated a range of from 17 to 25 meq/100 gms soil, usually decreasing with depth to a minimum of 9.6 meq/100 gms. No correlation with plant height was apparent (Table 4, col. 4), and although a correlation with O.C. yielded a significant result, it probably has little bearing on the crux of the problem at Malambito. The mean CEC as well as its overall variability in the study plot are expressed in Table 5.

Soluble plus exchangeable calcium, measured in all the samples, ranged from 14.8 to 30.0 meq/100 gms soil in the surface soils, constituting nearly two-thirds of the exchangeable plus soluble cations measured, but fell as low as 11.2 meq/100 gms in the sandier, subsurface soil. Calcium presented one of the highest correlation coefficients when compared to plant height (Table 4, col. 5,10) and also one of the largest variances within the two meter sampling radius (Table 2). Differences between grid points for calcium alone were not deemed important due to large measurement as well as sampling variances (Table 2), although a significant field gradient was present (Figure 15). However, differences were significant for the Ca vs Mg + K + Na ratio (Table 4, Figure 16). Figure 17 delineates the total horizontal variability of the latter quantity, and Table 5 supplies its study plot statistics.

Magnesium and potassium were second and third in abundance of the total cations measured, ranging from 6.3 to 8.7, and 0.6 to 1.3 meq/100 gms, respectively, in the surface soils. In the subsurface, values of nearly 1/2 and 1/3 those amounts were recorded (Table 3). These cations registered two of the lowest point variances (Table 2), and showed some horizontal variability in the study plot (Figures 18 and 19). Interestingly the Mg/K ratio correlated very well ($r = 0.875$) with OC although correlation with plant height was weaker (Table 4, col. 11). The analysis of

Table 5. Field statistics for intensive sampling area

					Soluble plus exchangeable cations								
	pH	EC mmhos/cm	O.C. %	CEC	Ca	Mg	K	Na	Ca/ Mg+K+Na	Mg/K	Clay %	Silt %	Sand %
				milliequivalents per 100 gms soil									
$\bar{y}$	6.03	0.37	0.96	22.2	19.9	7.6	0.79	0.37	2.3	9.8	50.0	37.7	12.3
S.D.y	0.27	0.16	0.21	2.0	3.4	0.5	0.15	0.16	0.3	1.6	4.0	1.9	5.2
V($\bar{y}$)	0.03	0.02	0.03	0.3	0.4	0.1	0.02	0.02	---	0.04	0.7	0.3	0.9
Range	5.64-6.81	0.21-1.04	0.66-1.56	17.4-26.5	14.8-30.0	6.3-8.7	0.55-1.33	0.24-0.64	1.77-3.10	5.9-14.7	43.0-56.0	34.0-41.0	6.0-25.0

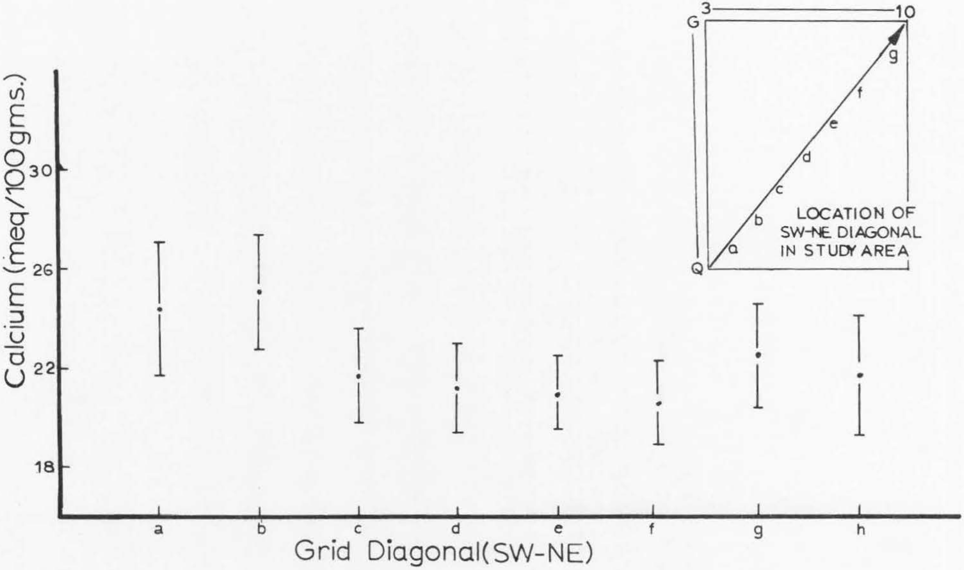

Figure 15. Field gradient of soluble plus exchangeable calcium in the study area. The vertical lines represent 95 percent confidence intervals.

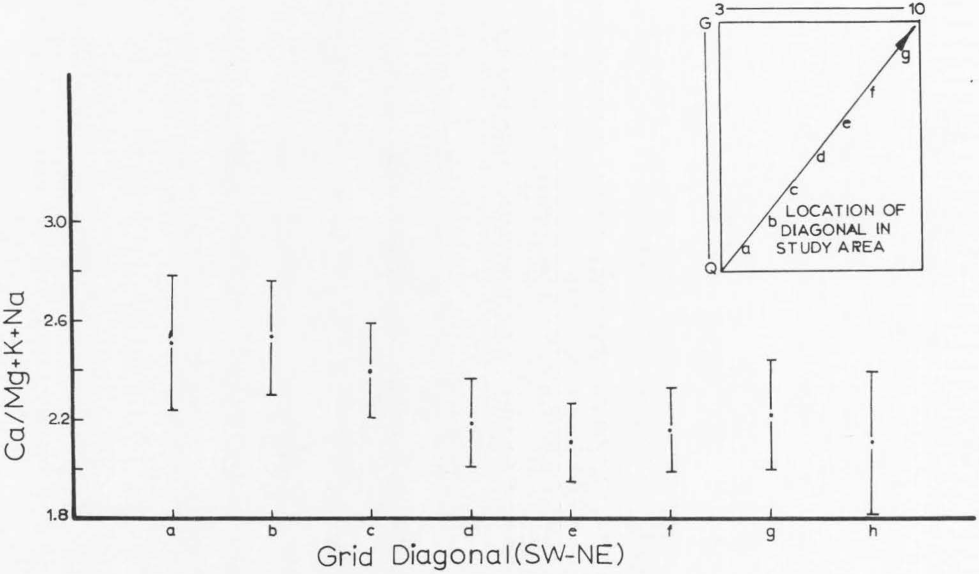

Figure 16. Field gradient of the Ca/Mg K ratio in the study area.

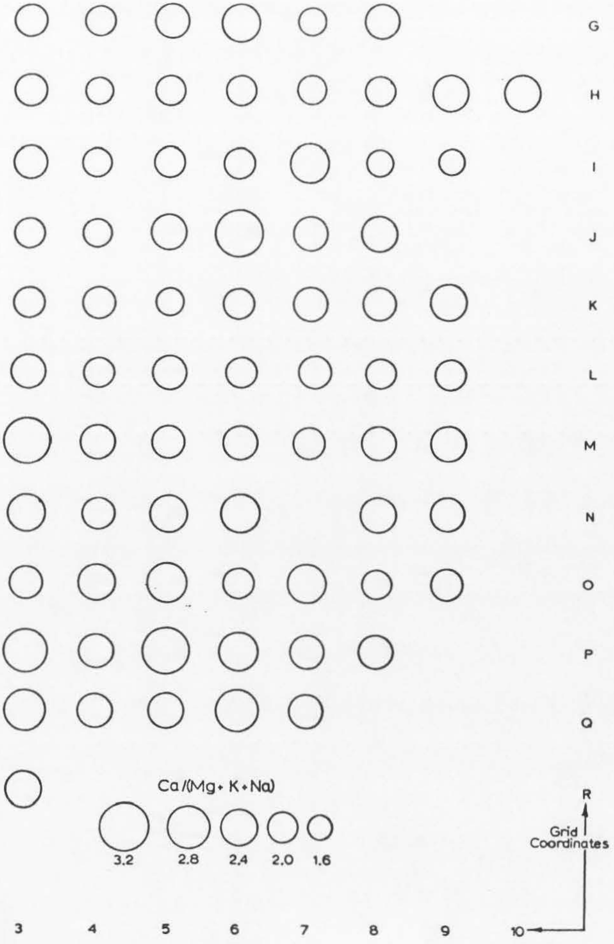

Figure 17. Total field variability of the Ca/Mg+K+Na ratio.

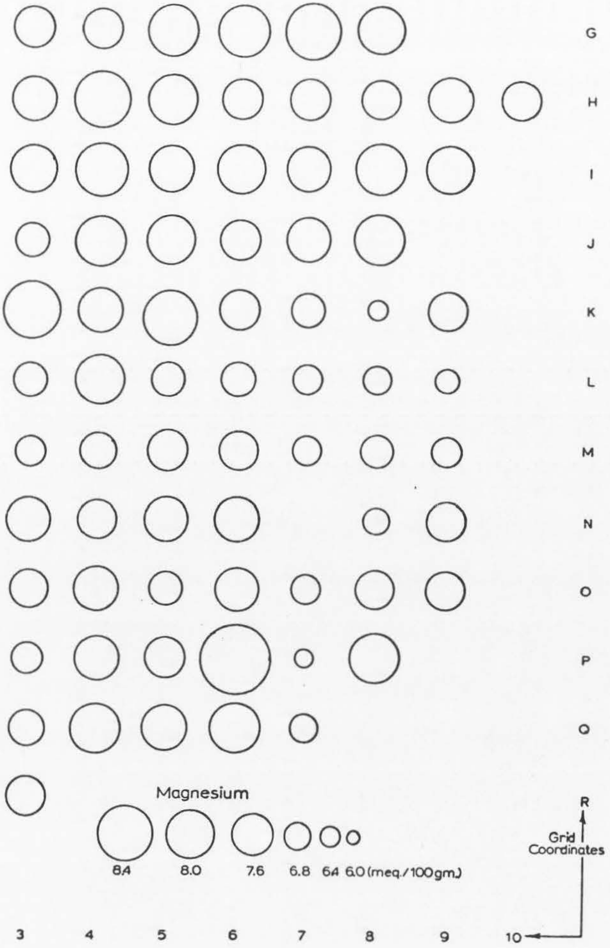

Figure 18. Total field variability of magnesium.

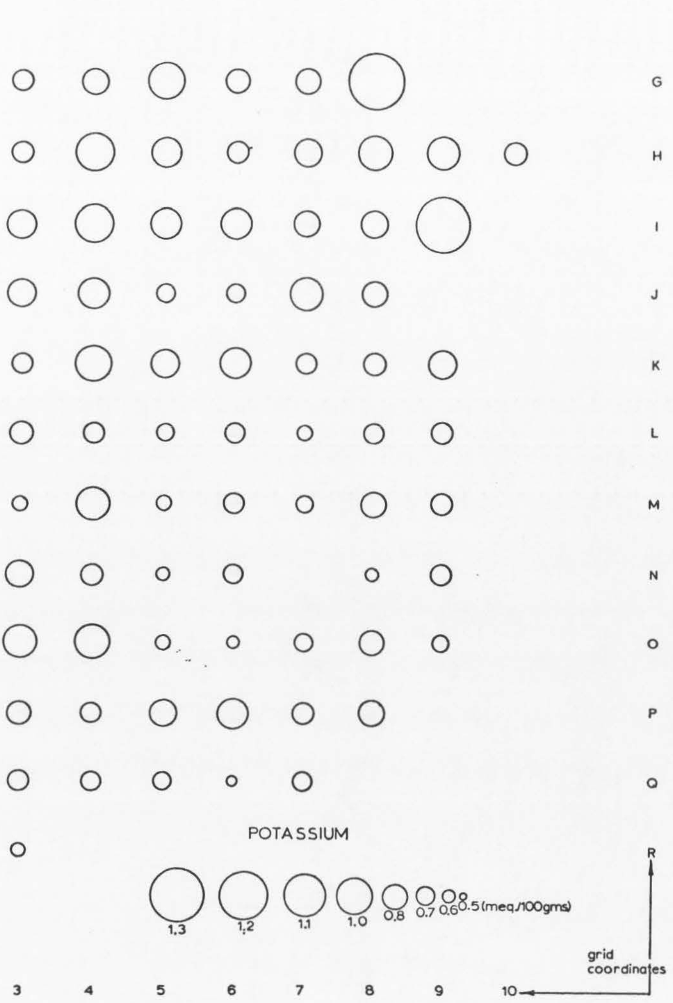

Figure 19. Total field variability of potassium.

variance for the Mg/K ratio (Table 2) indicates a large point variation, and its horizontal distribution, as determined for the intensive study plot, is random. Both magnesium and potassium also showed individual correlations of a significant magnitude when compared with organic carbon, but correlation with plant height was lower (Table 4, col. 6,7). Field statistics for Mg, K, and the Mg/K ratio are found in Table 5.

Sodium, the least abundant of the measured cations, presented a picture nearly opposite to that of potassium both in the profile and in relation to plant growth. Measurements of sodium in the profile ranged from 0.24 to 0.64 meq/100 gms in the surface soils (Table 5) to 0.4 to 1.1 meq/100 gms in the subsoils (Table 3). An insignificant correlation was found with plant height; however, as with magnesium and potassium the correlation coefficient unexplainably was significant only when sodium or the sodium absorption ratio were compared to OC (Table 3, col. 8,9). The point variance of sodium was the highest of the four cations, and significant gradients do not exist in the intensive study plot.

Organic carbon, the fifth and final chemical property for which a selected number of samples were analyzed, was highly variable, ranging from 0.66 to 1.56 percent in the surface soils (Table 5) to less than 0.2 percent in the sandy subsurface (Table 2). Comparison with plant height revealed a small positive correlation coefficient ($r = 0.44$) of possible significance. Other field statistics for this quantity may be found in Table 5.

Particle size distribution curves (Figures 20-25) prepared for both general soil characterization and correlation purposes, demonstrated the narrow but in some ways significant range of variations in surface

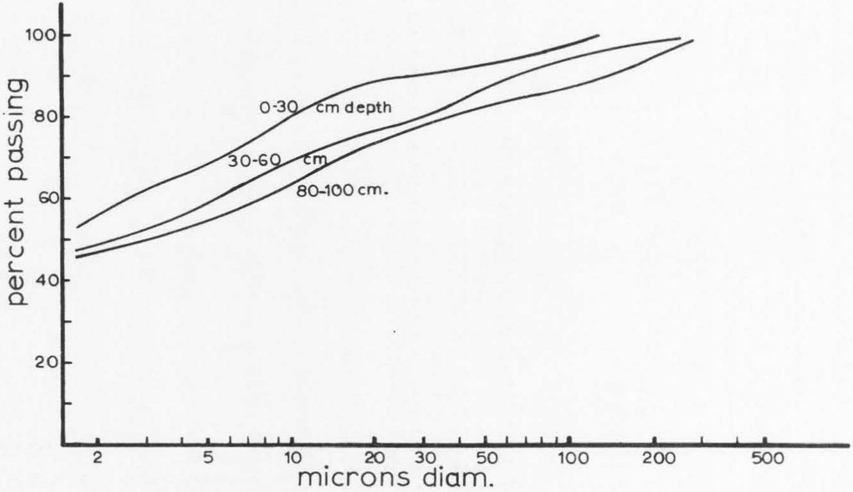

Figure 20. Typical particle size distribution curves for samples from grid coordinate H-9 (see Table 2).

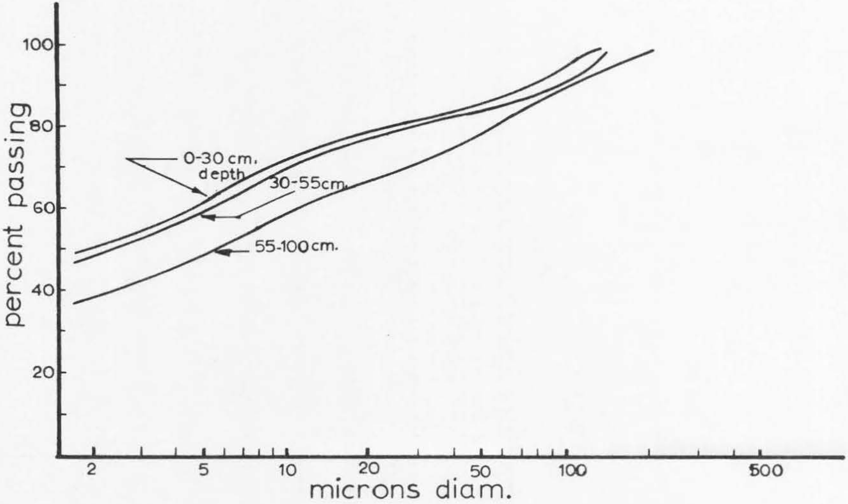

Figure 21. Typical particle size distribution curves for samples from grid coordinate M-9 (see Table 2).

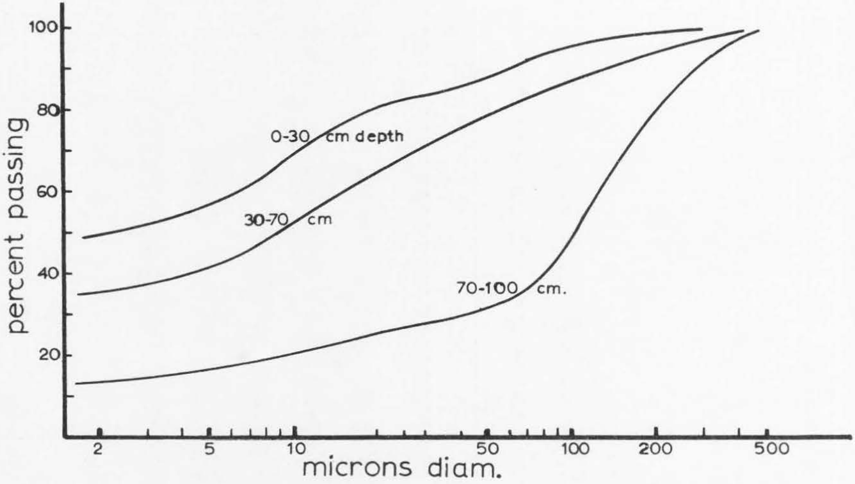

Figure 22. Typical particle size distribution curves for samples from grid coordinate M-5 (see Table 2).

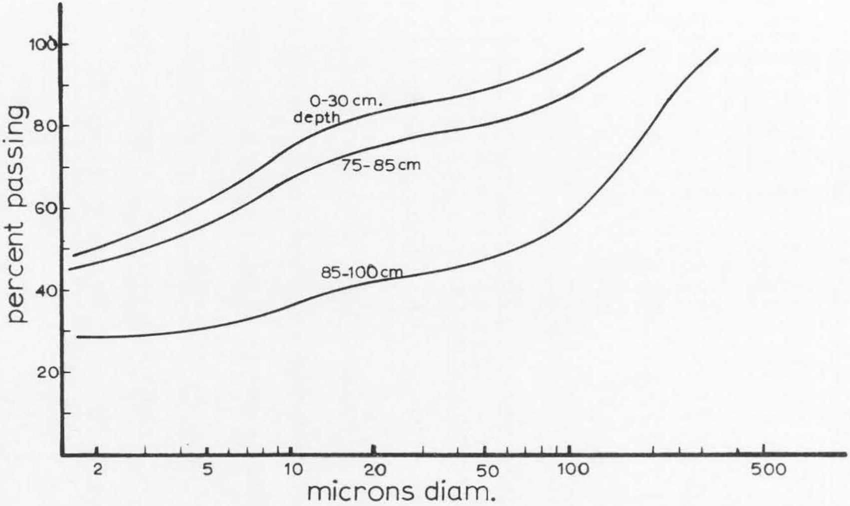

Figure 23. Typical particle size distribution curves for samples from grid coordinate J-8 (see Table 2).

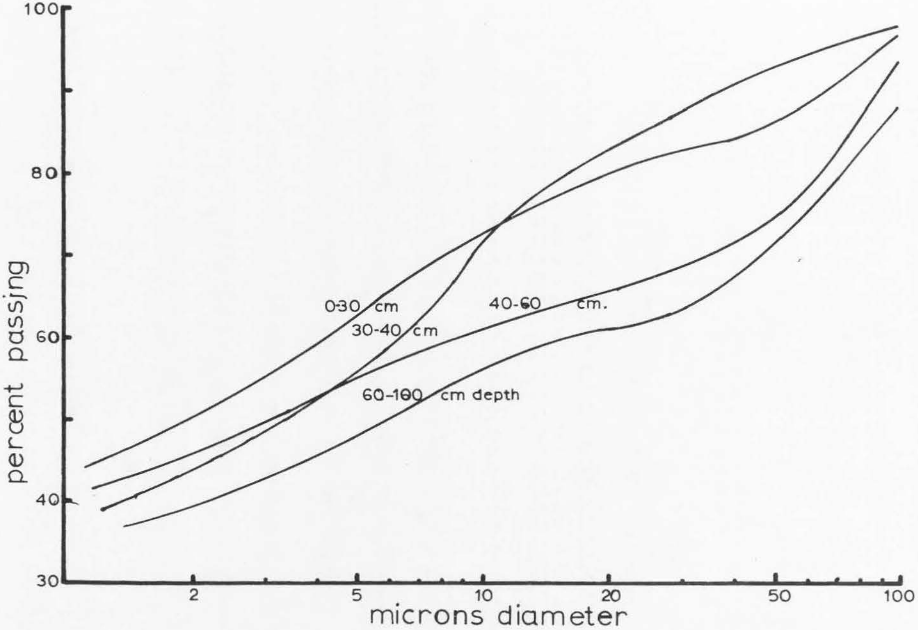

Figure 24. Typical particle size distribution curves for samples from grid coordinate L-6 (see Table 2).

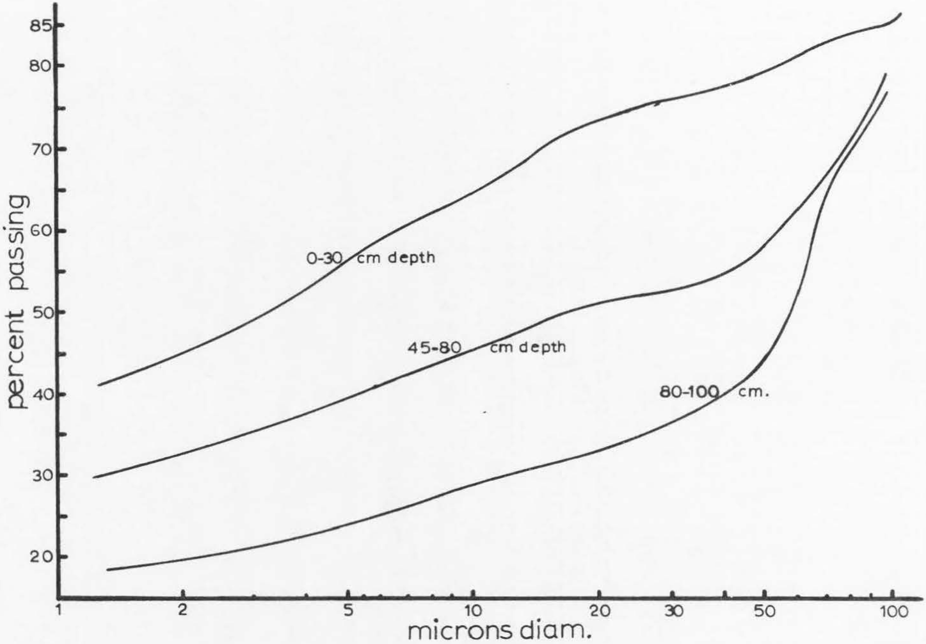

Figure 25. Typical particle size distribution curves for samples from grid coordinates 0-10 (see Table 2).

texture. Clay contents were between 43 and 56 percent (6–25 percent sand) in the surface 30 cm, and between 15 percent and 45 percent clay in the subsurface (∿ 1 m depth). Here, too, standard correlation analysis revealed only a weak relationship between particle size and plant height (Table 4, col. 13-14) which was also the opposite of the effect anticipated; a high sand content seemed to be correlated with the growth deficient areas.

DISCUSSION

Since relatively neutral pH values and low salt contents were measured, the previous notions of saline, sodic, or solodized soils, engendered by extrapolation from neighboring areas with many common soil characteristics, must be discarded. The horizontal variability of pH showed consistent trends in the study plot (Figure 9). In each case the differences between relative diameters of the circles on the map are proportional to the differences in measured pH. This mapping demonstrates the fact that nowhere is soil pH excessively low. Graphical representations of pH versus sample position (Figure 8) and corn height (Figure 13) further demonstrate the small part pH plays under naturally existing conditions in the Malambito soils. No significant correlation of pH with plant growth was evident.

Vertical variations in pH were more substantial (Tables 1,3). Significant differences in measurements occurred between methods and between the surface layer and any one of the other sampling depths. It is important to mention that the method using 0.01 M calcium chloride registered the highest relative efficiency of the methods. The drifting pH readings noted probably were an effect of incomplete suspension (dispersion) of the soil, due to its high clay content.

The horizontal variability in soluble salts (represented by the electrical conductivity of the saturation extract) may also be mapped, although with less precision than the mapping of pH, since point variance is higher (Table 2). Observing Figure 9, one sees that nowhere would surface salt concentrations reflect hazards to plant growth (35).

Figure 10 represents a second aspect of the samples whose pH is represented in Figure 8. It serves to demonstrate that although the horizontal surface variation in EC is rather consistent, subsurface variations are erratic and do not always reflect conditions present in the surface soil. Figures 11 and 12 show the horizontal and vertical variations in salinity on a larger scale; sampling points represent coordinates of the general grid system (∿ 28 meter spacing between composite samples). In the first of the two graphs is seen the low EC of the surface soil, as well as its somewhat consistent variation. The large point variability, represented by the vertical line covering the 95 percent confidence interval, tends to reduce the precision of this observation. The relative increase in soluble salt content with depth is also apparent. Figure 11 demonstrates some of the changes in conductivity of the surface soils induced by land leveling. Areas of subsoil with relatively high soluble salt content were exposed in many parts of the field. This effect was further evidenced by the high conductivity (3-4 mmhos) of several samples taken in the same area at a position of obvious plant growth irregularities. The above observations should serve as a precaution to future land leveling operations, especially in the sandier soils near the Magdalena River. Apparently, the sandier soils closer to the river, and the subsoils of parts of the experimental station contain quantities of salts which could be harmful to plants.

The low soluble salt content and high clay content of the Malambito surface soils have further implications in that the larger part of the "available" cations are present in an exchangeable form. This is precisely the case, especially in the surface soils. The approximate amount of water soluble salts which would be present (35) given the maximum measured conductivity (1 mmho/cm) of the surface soil may be calculated using the empirical relation:

$$\begin{aligned} S &= (M_{meas}/1000)(10 \cdot EC_e) \\ &= (M_{meas})(EC_e) \div 100 \end{aligned} \qquad [2]$$

where: S = meq/100 gms soil of soluble salts,

$10 \cdot EC_e$ = approximate soluble salt concentration (in meq/liter) given the EC_e (in mmhos/cm) of the solution,

M_{meas} = extraction moisture percentage (equivalent to ml of H_2O present in 100 gms soil).

The maximum number of milliequivalents of water soluble salts is then estimated to be 0.6 per 100 gms of soil, an insignificant amount when compared to the 19 to 26 meq/100 gms range of the CEC.

A peculiarity might seem to exist upon comparison of the two possible estimates of exchangeable plus soluble cations (i.e., that made by summation of the measured CEC and estimated soluble salts, and that measured by summing the four major cations found in the ammonium acetate extract). This may be directly attributed to the experimental procedure used; the acetate ion seems to solubilize some compounds which are usually water insoluble (12). This difference is indicative of the variable estimates of a common soil property determined by two different methods.

One of the earlier hypotheses given to explain the extreme differences in plant growth and overall poor yields was an existing cation imbalance. Analysis of the four major cations (calcium, magnesium, potassium, and sodium) did indicate wide variations within the study plot. There were some small, but significant, correlations with observed plant growth, but these were not sufficiently large to explain the problem at hand. Plotting the average cation status along the rows, columns or diagonals of the study plot served to demonstrate the horizontal variability of magnesium, potassium, and the Ca/Mg+Na+K ratio through the length of the study plot (Figures 13,14,26,27). Calcium, sodium and the Mg/K ratio varied randomly in the study plot. The total field variation of potassium, magnesium, and the Ca/Mg+K+Na ratio was depicted in Figures 17, 18 and 19. If, in fact, the measured (exchangeable plus soluble) cation status is of major importance, then stratification of areas of distinct fertility status would be possible.

Correlations of the cations with plant height were for the most part successful, indicating that the true nature of the deficient plant growth at Malambito was still unknown. Figures 28-30 depict the best correlations obtained in comparisons of the various soil variables with plant height. However, only about 38 percent of the difference in plant growth is explained by an increased Ca/Mg+K+Na ratio, and only 30 percent is explained by calcium alone. Although additions of these cations might raise the ratio to an optimum level, it is doubtful that production would be improved significantly. As may be seen from the various other correlations of magnesium, potassium, and sodium with plant height (Table 3), none was significant in itself.

Figure 31 represents a slightly different view from the above, and suggests another remote possibility for examination of nutrient status of the soils. Upon correlating several chemical and physical variables with the percent OC measured in the soil, significant correlation coefficients were obtained. Now, if one assumes that the nutrient status of the soil is such that historically growth has been naturally inhibited in specific

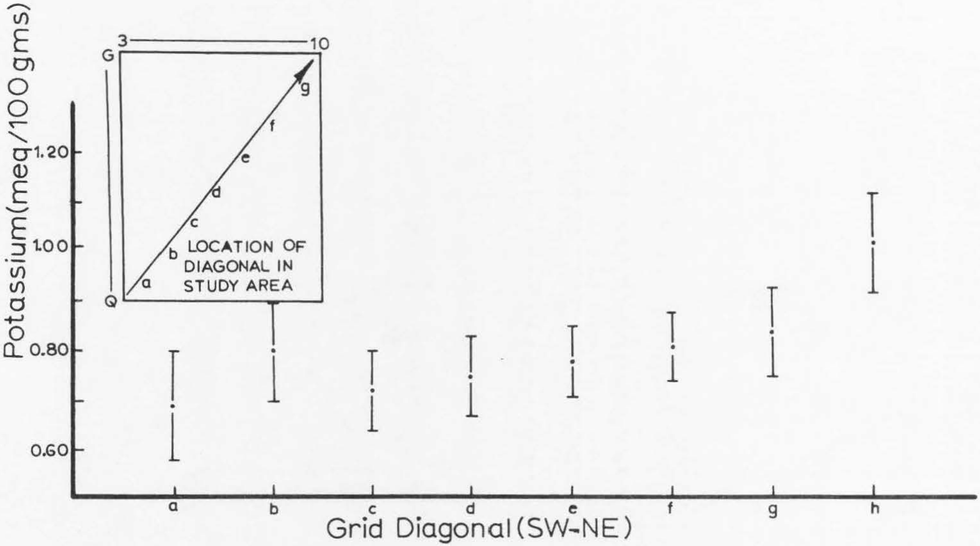

Figure 26. Field gradient of soluble plus exchangeable potassium in the study area. The vertical lines represent 95 percent confidence intervals.

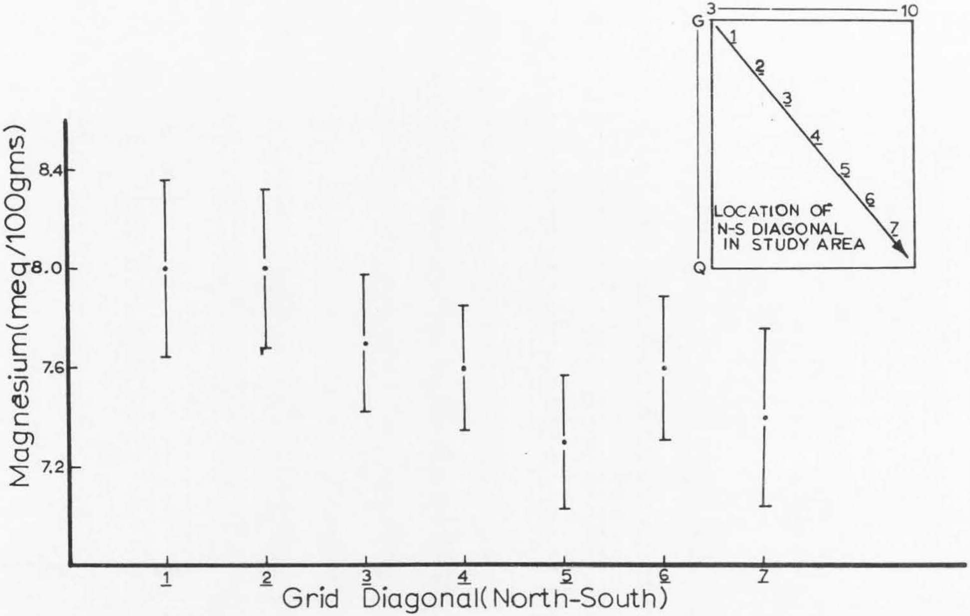

Figure 27. Field gradient of soluble plus exchangeable magnesium in the study area.

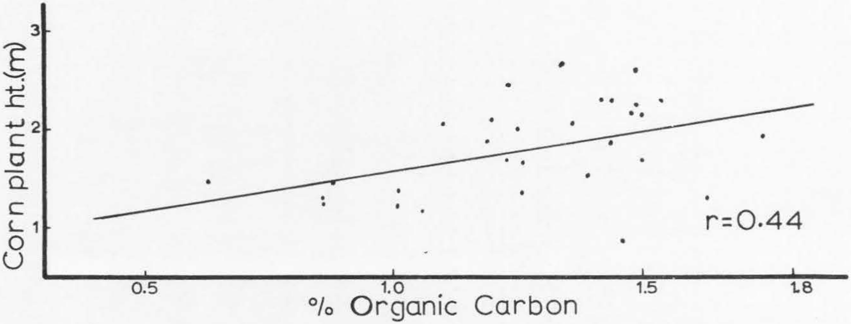

Figure 28. Corn plant height versus percent organic carbon for samples from transect 2.

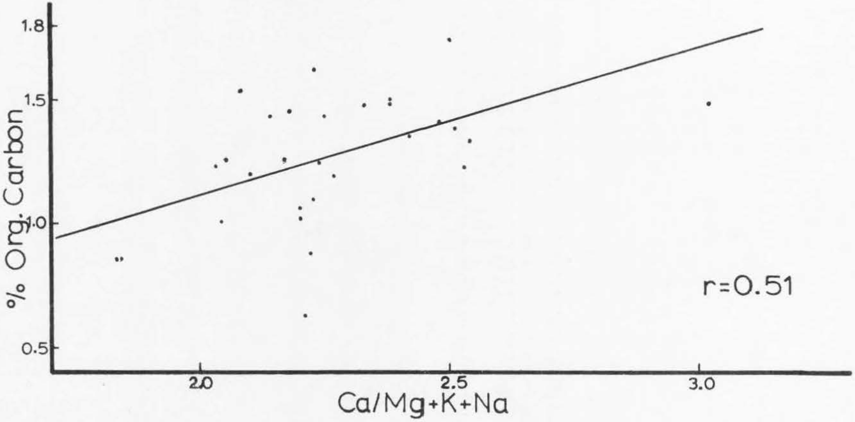

Figure 29. Percent organic carbon versus the Ca/Mg+K+Na ratio for samples from transect 2.

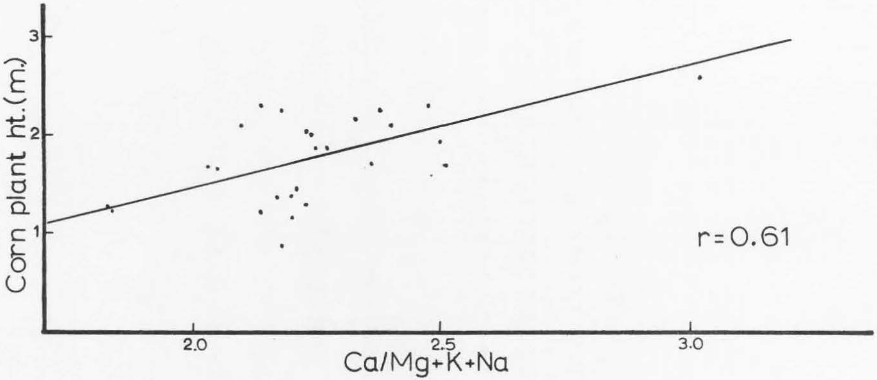

Figure 30. Corn plant height vs the Ca/Mg+K+Na ratio for samples from transect 2.

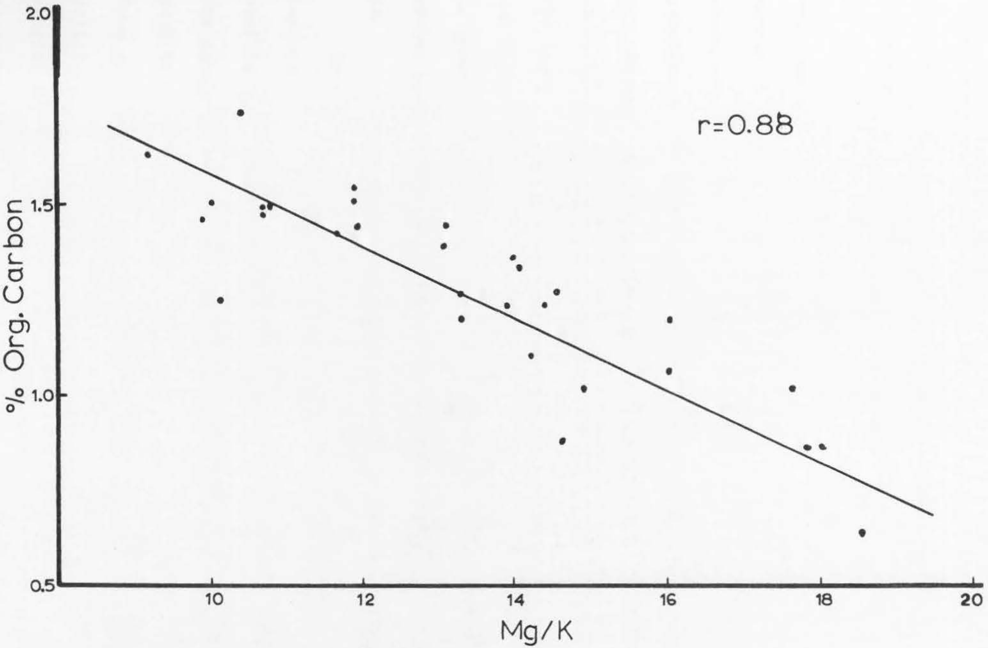

Figure 31. Organic carbon versus the Mg/K ratio for samples from transect 2.

areas, then perhaps the organic matter level, too, would be low. In this manner the importance of each of the cations increases substantially (Table 4). It might be noted that OC does have a small positive correlation with plant height (Table 4), but only 20 percent of the variation in OC corresponds to the variations in plant height. If the previously mentioned assumption had any validity, the magnesium-potassium balance would be of significance. Since soil mixing and translocation of organic matter probably occur naturally to some extent, the veritability of the above assumption should be questioned. Future investigations should provide information to explain these organic matter-cation correlations.

Another major hypothesis forwarded to explain the Malambito problem involved the physical properties of the soils. Field observations indicated the lower parts of the landscape were predominantly heavy textured, it was hypothesized that the heavy texture might have some detrimental effect on growth. The case turned out to be nearly the opposite; plant growth either had no relation to clay content or increased proportionately with it.

In Figure 32 plant heights are plotted on a section of the standard textural triangle in order to ascertain any textural correlations not visible in simple correlation analyses. The lowest plant heights lie in the sandier section of the triangle. This nearly dismisses the Malambito problem as entirely physical. Actually, the poor growth may result from association with the coarser fractions, in which growth seems most deficient. The general topographic-textural relationship, however, remains as described in the field; the variations in texture and phytological relationships depicted in Figure 32 occur within one of the natural depressions. Figure 33 demonstrates the overall textural-

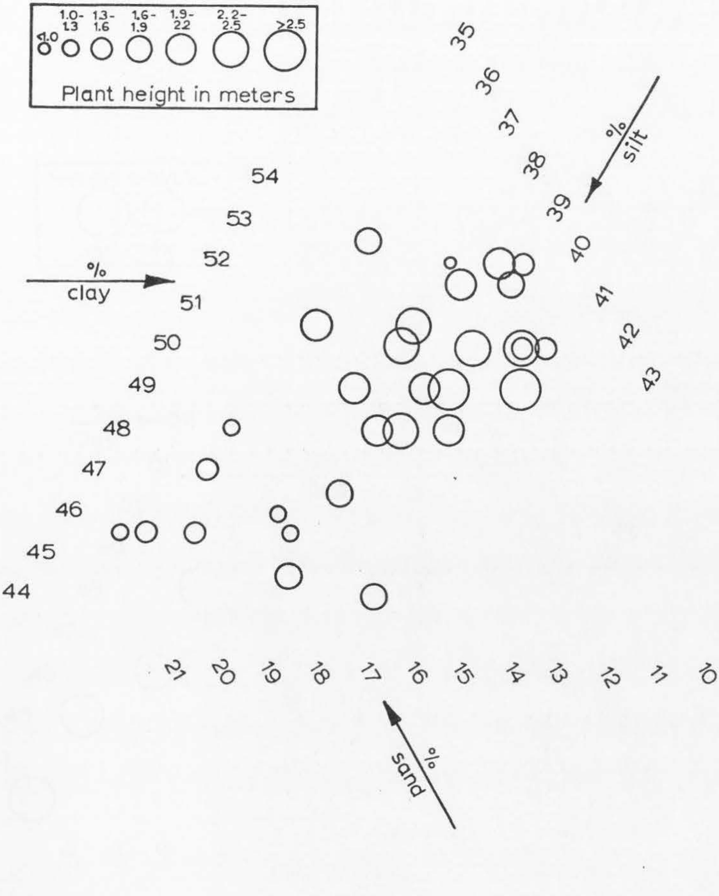

Figure 32. Plant height versus soil texture for samples from transect 2.

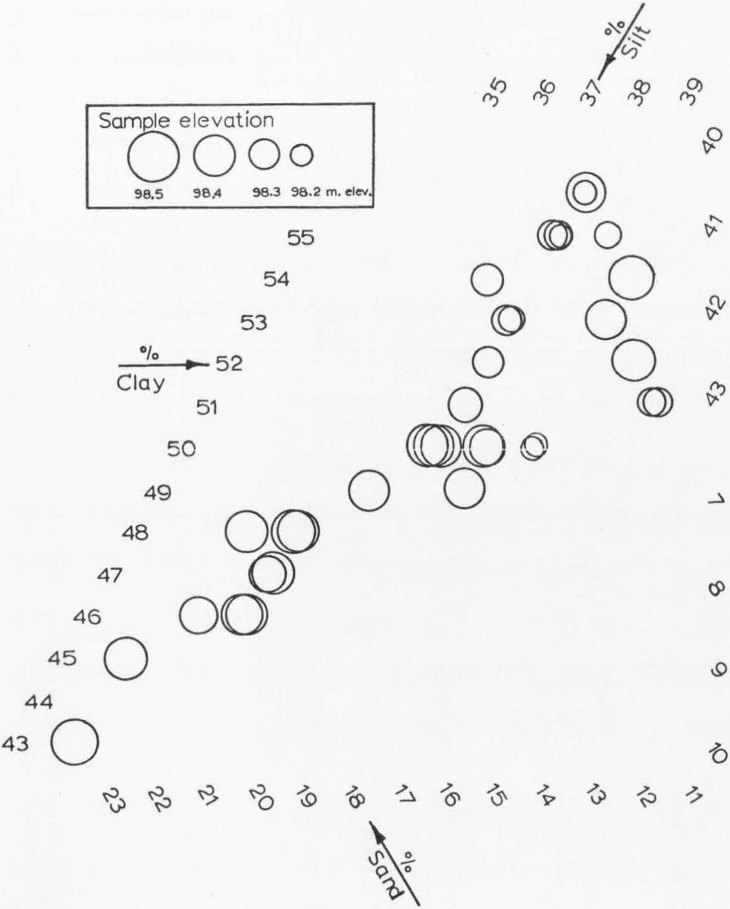

Figure 33. Topography versus soil texture in samples from the intensive study area.

topographical relationships of the study plot. In this case the diameter of the circle (again on a portion of the textural triangle) is proportional to the elevation of the sample. We see that the topographically lower points (smaller circles) are always more heavily textured, while the higher points may vary widely. This characteristic may be indicative of the erosive and depositional forces at work on these soils, perhaps eroding slightly numerous areas, thus exposing an infertile subsoil.

It may be stated that micronutrient investigations done while this thesis was in preparation suggest that heavy metal toxicity is a possible problem in the Malambito soils. This implies the existence of a totally different situation than was previously anticipated.

CONCLUSIONS

Although this research did not provide a definitive answer to the visually most apparent problem at Malambito, a number of possibilities have been eliminated. At the same time the information presented here forms a solid basis on which future agronomic investigations can be conducted.

The previous hypotheses of saline, sodic, or degraded sodic soils have been discarded. The suggested role of a possible cation imbalance is shown to be of minor importance; variations in the quantities of the four principal cations express themselves as only a small portion of the Malambito soils problem. Textural variations, although important, seem to have a result opposite to that expected; the deficiencies in plant growth are probably more closely related to the sand, rather than the clay fraction. The effects of pH are negligible, or opposite to those expected; growth seems to be slightly enhanced by small decreases in pH. Soluble salt concentrations indicate no danger to agriculture; however, future land leveling operations should be planned carefully to avoid subsoil exposures. The intensive measurements of soluble salt contents performed here also provide a basis for the long term evaluation of possible increasing salinity levels.

In future experimentation it should be noted that most of the soil properties examined with the exception of magnesium, potassium, and soil reaction are highly variable on a microscale; the latter three vary more continuously and their variations may be examined on a field wide, or mesoscale basis. Stratification for sampling or other purposes of areas of certain chemical properties is shown to be possible.

The heavy clay nature of the soil implies the need for proper irrigation control; the permanent wilting point for these soils lies at a high moisture content (ca. 20 to 25 percent, as estimated from texture, see Taylor (39)).

Research should now be concentrated in the realm of possible micronutrient deficiencies and toxicities, taking into account the developmental history of the Malambito soils, and utilizing all available information, e.g. aerial photographs and data obtained before the major agricultural engineering projects had begun (i.e., water quality analysis and previous soils investigations). Those crops (corn, sorghum, sesame, etc.) which have been demonstrated to be most susceptible to the problem should be eliminated from field crop experimentation except for edaphological studies. Proximate research should be devoted to those crops which show resistance to the adverse soil conditions.

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