PN-ABP-327
82833
7.088

FINAL REPORT

Covering Period: JUNE 15, 1988 - DECEMBER 15, 1992

Submitted to the Office of the Science Advisor
U.S. Agency for International Development

MAPPING CROP AND SOIL NUTRIENT STATUS FOR IMPROVED FERTILIZER RECOMMENDATIONS

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Project Number : 7.088

Grant Number: DPE-5542-G-SS-8034-00

A.I.D. Grant Project Officer: Dr. Tejpal Gill

Project Duration: June 15, 1988 - December 15, 1992

CC: COIR+BOST/D

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EXECUTIVE SUMMARY

Efficient use of fertilizers is of critical importance to sustainable agriculture in most developing countries. Countries like Malawi can ill-afford their current practice of importing and distributing fertilizers on the basis of national blanket recommendations, when, in fact, fertilizer needs differ greatly with different soil conditions. This project aimed at developing, based on soil and plant sampling surveys, a method of assessing which types of fertilizers are needed in which regions of the country. Analysis of nutrient ratios in crop leaves (DRIS indices) was proposed as a key factor in mapping geographic distribution of fertilizer needs. A preliminary survey was carried out in three test areas in 1989. A full survey was carried out in four areas in 1990. On-farm fertilizer trials (N,P,S and micronutrients) were conducted in the same areas in 1990 and 1991 to validate the survey results. The US principal investigator and his Malawian collaborator at the University of Malawi worked closely to plan, administer, and implement all phases of the project. Several Malawian soil scientists in the Ministry of Agriculture were responsible for supervising the laboratory analysis of project samples in the country's principal agricultural research station, but results were unreliable. Material, financial and consultative assistance provided to the MOA lab by the project helped improve analytical accuracy and reliability, but not in time for this project. It eventually became necessary to ship samples to the US for analysis. Results from the surveys and fertilizer trials both showed that phosphorus fertilizer is not needed in areas in which it was sometimes distributed, and that sulfur fertilizer (possibly derived from indigenous sources) should be used far more than was the case prior to the initiation of the project. DRIS indices, especially for young plants, were useful in highlighting elements most limiting for crop growth in each area, although severe drought prevented field validation of DRIS results that indicated widespread boron deficiency. The project generally met its goals of demonstrating that a rapid survey of crop fields can be used to assess regional fertilizer priorities, and that the data from such a survey can also delineate localized variation in fertility status. Larger scale application of the techniques developed is warranted, to improve fertilizer distribution and use efficiency in Malawi.

A. Research Objectives:

The overall aim of this research was to develop techniques for determining and mapping geographical variability in soil and crop nutrient status so as to enable fertilizer recommendations to be modified to fit local and sub-regional needs. The specific objectives were:

1. To determine whether surveys involving analysis of plant and soil samples taken from randomly distributed peasant farmers' fields can be used to detect differences in fertilizer requirements related to the geographic distribution of different soil groups.

2. To evaluate the results of these surveys by means of appropriately distributed on-farm experiments that test the response of corn to those nutrients identified by the surveys as most limiting to crop production.

3. To test the feasibility of producing soil fertility maps identifying the degree of nutrient element limitations to crop production on a regional to sub-regional scale within Malawi.

Description of the Problem

Land availability, and the experience of the past few decades, dictate that most of the increase in crop production needed in the future will be achieved by increasing the productivity of land now under cultivation, rather than by expanding cultivation to new lands. One of the most effective components of most technological packages designed to achieve this increased productivity is the proper application of nutrients to soils that are unable to supply essential nutrients in amounts sufficient for high yielding crops.

Blanket fertilizer recommendations used in most developing countries do not allocate scarce fertilizer resources efficiently, in that they often encourage unneeded nutrient applications in some cases and fail to include nutrients necessary to allow efficient crop response to fertilizer in other cases. By developing new ways of tailoring fertilizer recommendations to local requirements, the project may help farmers to increase their yields and/or reduce their fertilizer costs. The model crop for the project is maize (*Zea mays, L.*), which is the principle staple food and cash crop for much of southern and central Africa. It is also a crop for which a large body of plant nutrition information exists, worldwide. The technology developed by this project, if implemented widely, could have immediate and broad positive impacts in Africa. In principal, the approach developed could also be applied to other crops and other regions of the world where low-input, smallholder agriculture is practiced.

Blanket fertilizer recommendations are still the rule in Malawi and most developing nations in Africa. Alternative approaches to improving the site-specificity of fertilizer

recommendations have focused on soil testing programs for small farmers and/or regional field research plots to predict crop responses to fertilizer applications. These approaches both have such serious defects that little real progress has been made. The approach taken by this project was entirely different in concept, namely surveying geographical variability in crop nutrition status and using the resulting information to modify blanket recommendations so that they better fit local fertility needs.

The components of the new methods developed by this project, while state-of-the-art, are not new to this project; they have resulted from recent developments in plant nutrition and spatial variation research. In the study of spatial variability, the science of geostatistics has been developed to the point of widespread practical application in mining and ecological survey (Bridges and Becker, 1976) and is now beginning to be applied to problems of mapping the variability of soil chemical and physical properties (e.g. Yost, et al., 1982; Oliver and Webster, 1991). The DRIS system of plant nutritional status evaluation is just to be used instead of, or along with, the older "critical range' and 'critical value' approached used by most universities and agriculturalists in the USA and elsewhere. Few applications of the DRIS have been made in developing countries (eg.Escano, et al., 1981).

The combination of these two recent technologies (spatial analysis and DRIS) in this project is an important innovation which generated significant synergisms and has considerable potential for application elsewhere. The use of combined plant and soil data in a survey for mapping fertility is also a major innovation of the project. The results of this project should prove useful in bridging the gap between simple generalized blanket recommendations and individual field soil testing.

The Problem of Soil Variability

One of the basic facts about soil is its tremendous spatial variability. Within the root zone of a single plant, soil properties will vary considerably over distances of a few millimeters. On a larger scale, every farm field has a degree of soil variability within it. Crops often show responses to these variation in soil properties in the uneven growth seen in so many uniformly-treated fields. On a still larger scale, soil properties vary markedly from field to field, from one landscape unit to another, and from region to region.

In a country like Malawi, soil properties such as nutrient supplying power or H ion activity may vary by several orders of magnitude within a 50 km radius. Some of this variability is related to the topographic positions of different soil bodies, the lower members of a catena being much higher in base saturation, shrink-swell potential, and CEC, as compared to the upper catena members in a landscape. However, even when considering only the upper catena members (since in Malawi most crops are grown on these), differences in rainfall, parent material mineralogy, human

influences, slope and vegetation result in a high degree of soil variability. Mwandemere (1980) found, for example, that unfertilized soils varied greatly in their availability of N, P, K, and S among 35 well-drained soils on different parent materials in Malawi. Mwenitete (1979) demonstrated a wide difference among soil from different regions in Malawi, in regard to their rates of P fixation and mineralization.

The problem of soil variability must be dealt with by different approaches at the three scales cited above. Within the root zone of a plant, the plant itself can usually compensate for the variability present by adapting the morphology of its root system to the variable conditions, proliferating in zones with favorable properties and putting down minimal growth in less favorable zones. Plants do not require a uniformly favorable root zone, except, perhaps, for the supply of water. The effectiveness of band or dollop placement of fertilizer proves this point.

Variability from place to place within a field is usually addressed in three ways. First, soil management practices (fertilizer, lime, tillage) are applied as uniformly as possible to avoid creating unnecessary variability. Secondly, where relatively large, homogenous areas exist, management practices can be tailored to specific areas within a field. Recent advances in Geo-positioning Systems and computerized application equipment have made this approach effective (albeit quite expensive) on an increasingly small scale. Third, most often the problem of within-field variability is "solved" in the absence of such equipment, by applying management practices appropriate for the average soil condition in the field, usually as determined by composite sampling.

At the regional and sub-regional scale, where the soil management unit is equal to or larger than a farm field in size, maximization of crop yields and resource use efficiency requires that soil management practices be site-specific. Managing for 'average' soil conditions will be too far from the mark too much of the time. Some means of tailoring soil management practices to localized site conditions must be employed.

It is not enough to study nutrient uptake patterns and responses to fertilizer additions by a crop at a handful of sites in a country as diverse as Malawi and then issue a blanket fertilizer recommendation for the whole country. For example, the Malawi peasant farmer growing hybrid maize is currently given a blanket recommendation to apply 20-20-0 at planting time and a side-dressing of calcium ammonium nitrate or urea to supply a total of 100 kg N and 50 kg P2O5/ha. By its very nature, a blanket recommendation will be wrong most of the time. For some fields it will be too high, resulting in wasted resources or even nutrient imbalances. For other fields it will be too low in one or more nutrients, resulting in sub-optimal yields and profits. For example, the P2O5 in the blanket maize recommendation is unlikely to give an economic response on certain soils in the Lilongwe Plain, but may be essential to good yields on other soils. In some

areas, other nutrients such as sulfur, potassium, zinc or boron may be required, though ignored by the blanket recommendation. Sillanpaa (1982) found a wide range of macro- and micronutrient contents in Malawi soils and corn plants. In some cases geographic trends were suggested even by a crude analysis of spatial variability of soil fertility data.

The more site-specific the fertilizer recommendations, the more likely they are to optimize the cost-effectiveness of the fertilizer used. But the cost of making the recommendations also increases with the decreasing size of the recommendation domain. This project pioneers an intermediate solution to the problem, one in which the costs of tailoring fertilizer recommendations to local conditions do not outweigh the benefits of doing so.

In most developed countries, and on many commercial-scale farms and plantations in less-developed countries, the practice of regular soil-testing has proven to be an invaluable tool in making appropriately site-specific fertilizer recommendations. To be effective, a soil testing program requires laboratory facilities and personnel capable of analyzing a large number of soil samples annually (usually most during limited times of the year) that represent a significant fraction of the nation's farm fields. Also, the interpretation of the test results requires an expensive, on-going program of field calibration experiments at sites representing the major soils of the area served. It is difficult to find a single soil test procedure that will work well for soils of widely differing chemistry and mineralogy such as those found in Malawi (Maida, 1973). The soil samples themselves must be collected in a precise and careful manner, or the results may be worthless, even misleading. Soil testing has been very successful where these conditions are met. To be economically viable, the cost of the program must represent only a very small fraction of the cost of the fertilizers recommended, generally meaning that each sample represents (for agronomic crops) about 10 hectares or more.

Unfortunately, most of these conditions are not met in the peasant agriculture sector of most less-developed countries including Malawi. As a result, the idea of soil testing has been given lip-service but has not found widespread application in the peasant farming sectors of developing countries. In Malawi, for example, it is <u>theoretically</u> possible for a peasant farmer to bring in a soil sample from his field and get a site-specific fertilizer recommendation in return (without even a charge for the service). However, <u>in practice</u>, the soil testing service almost exclusively runs samples from the estate farming sector and research projects. Experience has shown that it is not practical to conduct a soil testing program for a peasant agriculture sector such as the several million, 0.1 - 1.0 hectare fields in Malawi's smallholder areas (Weil, 1985). Plant tissue analysis is subject to most of the same constraints as soil testing, but has the added disadvantage that the results are generally not known in time to correct any diagnosed deficiencies in the crop that was sampled.

Another approach that might be thought to hold promise is that of soil mapping. Malawi soils have been mapped at a reconnaissance scale (Young and Brown, 1962; Brown and Young, 1965) and selected areas in special projects that have been mapped at second and third order scales. However, the mapping units delineated on these maps are essentially taxonomic and bear only limited direct relationship to fertility needs. By themselves, the soil maps have only minor utility in modifying blanket fertilizer recommendations to meet local conditions.

The Fertility Capability Soil Classification of Boul and Sanchez (Sanchez et al, 1982) attempts to bridge the gap between soil classification as used in soil surveys and soil fertility management. This system has been shown to be helpful in identifying major constraints to crop production associated with mapped soil units on detailed soil maps where units are based on detailed analysis of soil profiles. Some extrapolations can also be made from more general soil maps, but only to a limited extent. The system does not address the issue of limiting nutrients and fertilizer rates directly, although it can identify soils with potentially high P absorption or low K reserves.

The value of soil surveys to soil fertility management in Malawi would be much enhanced if areas of particular plant nutrient deficiencies or imbalances could be correlated with mapped soil units. One of the purposes of the current project was, in fact, to test the feasibility of establishing such correlations, and to use these relationships to generate pilot maps of soil fertility status.

The general approach taken by the project to the problem of making fertilizer recommendations more site-specific was to attempt generate soil fertility maps useful at a village level with mapping units as small as 10 - 20 km2. The maps would be based on the results of plant and/or soil analyses of samples from a large number of peasant farmers' fields. The mapping units would identify kind and degree of nutrient limitations present. The standard blanket fertilizer recommendation could then be modified to increase or decrease the recommended levels of N, P and K and/or add other nutrients where specific deficiencies are shown to be prevalent.

The use of DRIS indices to generate the maps were compared to that of using tissue concentrations and soil test indices. Geostatistical and distance weighted regression techniques were used, where appropriate, to estimate the fertility status between sampled points and to produce smoothed maps showing spatial variability of fertility status. Attempts were made to correlate these soil fertility maps with soil survey maps, so as to permit extension of the results to other areas with soil surveys. The validity of this approach was tested by conducting fertilizer experiments in a number of field locations to compare the yields and costs of fertilizers associated with the blanket recommendations and those derived from the soil fertility maps.

Use of DRIS Indices

The Diagnosis and Recommendations Integrated System is a method of interpreting plant tissue analyses so as to rank the importance of the various nutrients in limiting plant yield and to estimate the degree to which each of the limiting nutrients are deficient. This information, in turn, tells us what remedial steps can be taken to enhance the growth of the sampled or subsequent crops. The system was developed and tested first in South Africa (Beaufils, 1973), and has been used to successfully diagnose nutritional problems in many perennial and annual crops, including maize (Sumner, 1981). Although not yet in wide use by farmer-advisory labs, it has attracted much recent research attention.

In contrast to classical plant analysis systems, the DRIS uses a system of nutrient balance indices rather than critical values or ranges for each nutrient. The first step in the system is to measure plant tissue, nutrients and yields from a large number of diverse fields. Using this data, a scatter plot of yield against the tissue concentration of a given nutrient (e.g., dry matter vs. N percentage) will peak at the optimum concentration of that nutrient (Walworth, et.al., 1986). The DRIS norms can be determined either from the intersection of the lines bounding the scatter plot or by taking the mean of the higher-yielding half of the sampled population. Ratios of the various nutrients measured (e.g., N/K, N/P, P/K, etc.) are calculated and also plotted against dry matter yield. The means and standard deviations of the ratios for the high-yielding population are then tabulated as DRIS norms which are used to calculate the DRIS index for a given sample.

A DRIS index is essentially the sum of the deviations of all the ratios involving a particular nutrient from the respective DRIS norms. Thus, a N DRIS index = 0 indicates an optimal balance between N and all the other nutrients considered. A negative DRIS index indicates a relative deficiency; a positive index indicates a relative excess. The more negative the index, the more serious the deficiency. The nutrient most limiting to growth is that with the most negative index.

The DRIS has several advantages over the more commonly used "critical nutrient level" approach to fertility status diagnosis. The "critical level" of a nutrient is usually determined by means of single factor experiments and so the critical level is specific to the conditions of the experiment and may not hold under other conditions (Andrew, 1968). Also, the critical level is very sensitive to the stage of growth or plant age when the sample is taken. This means that the plant sample must be taken at precisely the correct time, thus greatly limiting the flexibility of the system. This characteristic alone would make the critical level system impractical for a survey-type study as proposed here. Another problem with the critical level approach is that the concentration of one nutrient cannot be directly compared to that of another nutrient, so there is no way to rank nutrients in order of the seriousness of their deficiencies.

Soil analysis data, while useful and to be included in the proposed projects, also presents several disadvantages for mapping fertility needs. One is that the relationship between measured indices of nutrient availability and actual plant uptake and growth is usually very tenuous. The growth of a plant and its nutrient uptake rate in the field is dependent on many environmental factors and interactions. The growing plant integrates all these factors and is the best measure of true nutrient availability. In addition, soil samples are more laborious to obtain and analyze than are plant samples.

It has been shown that DRIS indices are not much affected by stage of growth, precise leaf position on the plant, cultivar differences, or even by varying degrees of moisture stress (Islam, 1984; Sumner, 1979). Recently published DRIS norms for maize (Elwali, et al, 1985) should be applicable to the proposed project, in that the norms were developed using nearly 10,000 observations on leaf nutrient content and yield from fields in many countries, including many observations from southern Africa. Thus, although some workers have found a slight improvement in diagnostic accuracy by developing locally calibrated DRIS norms (Escano, et al, 1981), it should be possible to use published norms in the proposed survey study, thus avoiding the necessity of measuring yields in the sampled fields. Del Rosario, et al, (1983), using 144 observations from research plots on soils in three USDA soil taxonomy families, found that some nutrient ratio optima differed among soil families, while others did not, but that their locally-derived DRIS norms did not differ greatly from the published norms.

To our knowledge, the only report in the literature of the use of DRIS indices in a sampling program designed to study geographic distribution of fertility status, is the work by Weil et al (1991) which was a preliminary study for the current project. This use of DRIS data is a principal innovative aspect of our project. The validity of published DRIS norms for certain nutrients may have to be validated for local crops and conditions. It is also important to map soil properties as well as DRIS indices.

Use of Spatial Analysis

To analyze and display the spatial variability in the survey data, several approaches are possible. Most simply, each of the regions surveyed will be characterized and compared to one another. Secondly, within a sampled region, the data may be analyzed by distance weighted least squares regression techniques which can produce contour maps interpolating values in between actual measured sites. One limitation of this method is that accuracy may be poor near the edges of a mapped area, and trends may be extrapolated beyond the available data. To minimize the latter problem, maximum and minimum limits can be set to reflect the range of actual data.

The science of geostatistics provides a number of tools which may have advantages in dealing with the data. Geostatistics quantifies the spatial dependence among measurements from different

sample sites. The methods of geostatistics were originally developed to estimate the extent and properties of ore formations in South Africa (Journal and Huijbregts, 1978), but have recently been successfully applied to the analysis of soil variability, both on the scale of a few meters (e.g., Vieira, et al, 1981) and hundreds of km2 (e.g., Trangmar, et al, 1984). Yost, et al, (1982) were able to produce maps of soil variability on the island of Hawaii using 144 sample sites. Their maps correlated well with the distribution of rainfall and other soil-forming factors.

Geostatistics assumes that a value observed at one site is affected by the position of the sample site in relation to other nearby sites. Thus, the closer two sites are together, the more similar their values are likely to be. This relationship is expressed as the semi-variance. A semi-variogram describes the spatial dependence of a variable. In a semi-variogram, the semi-variance of a property is plotted against the distance between samples. Interpretation of a semi-variogram allows one to estimate the size of the zone of influence for the variable, its random or micro-variability, and parameters useful in interpolating between samples points.

There are several geostatistical methods of 'smoothing' spatial data and generating continuously varying two and three dimensional displays. The techniques of splining (Harder and Desmarais, 1972) and kriging (Burgess and Webster, 1980) have been used to interpolate between sampling sites at various scales. Yost, et al, (1982) found kriging to produce more useful large-scale soil maps than did spline interpolation. Kriging makes a robust interpolation between sample points, and as such minimizes the influence of rare, extreme values. However, it is sometimes necessary to delete such extreme values prior to kriging. A third method is distance-weighted least squares regression, in which the "tension" of the regression can be adjusted to avoid undue influence from isolated extreme values (McLain, 1974). The parameter value at each grid location is estimate by regressing against the x and y coordinates and parameter values of all other points, with the influence of each point decreasing logarithmically with its distance from the grid location being estimated.

Most reports in the literature applying geostatistics to soils have been concerned with the spatial variability of basic soil physical and chemical properties (particle size, hydraulic conductivity, CEC, pH, etc.) over distances of only a few meters to a few tens of meters (e.g., Bos, et al, 1984; Vieira, et al, 1981; Campbell, 1978). Studies at this scale will identify spatial dependence over distances of a few meters down to perhaps 0.5 meter; but micro-variability (variation over distances of a few cm or mm) will be hidden in the "nugget" semi-variance. In the same way, when geostatistical analysis is applied to large areas, spatial dependence over several kilometers is identified, but the small-scale dependencies of only a few meters is hidden in the "nugget" semi-variance.

There are studies in the literature that clearly show the

applicability and usefulness of geostatistics over large areas (e.g., McBratney, et.al., 1982; Yost, et al, 1982). In a report by Uehara, et al, (1985), a number of successful studies are documented on a scale very similar to that of our project in Malawi. While our project studied the spatial variability of soil fertility variables, one of the really innovative aspects of our project was the study of the spatial variability of plant (maize crop) nutrient status. We do not know of any published studies that have done the latter, but there is no inherent reason why plant data should not be spatially dependent. Indeed, plants often more accurately reflect soil fertility than do chemical analyses of the soil. The use of DRIS for this purpose has been discussed previously.

Hypotheses to be Tested

1. Surveys of farmers' fields, based on plant and soil analysis, can delineate, at the level of the ADD or sub-units within an ADD, areas that differ with respect to the order and degree of nutrient limitations to crop production.

2. Such maps can be used to modify the national blanket fertilizer recommendation for hybrid maize so as to make more site-specific and more cost-effective use of fertilizer.

3. Geographic analysis of DRIS indices for maize leaf tissue composition will produce maps of significantly more utility than maps based on soil test or tissue nutrient concentrations alone.

Assumptions

1. DRIS norms established in the literature for maize are applicable to the population of maize to be surveyed. Expectation of such applicability reasonable, since these norms are based on thousands of samples, including many from Southern Africa.

2. Management practices on the farm fields sampled fall within specific ranges of cultivar, fertilizer use, planting date and manuring. Information was collected during the survey that would allow confirmation of this assumption, or that would allow proper sample stratification, if needed.

3. In addition to field-to-field and micro-variation reflecting past and present soil management, soil fertility varies in patterns affected by such geographic factors as soil parent material and rainfall. This effect was established in our preliminary work in Zimbabwe. See also Sibanda and Le Mare (1985).

The project involved close collaboration between scientists at the University of Malawi's Bunda College of Agriculture and the University of Maryland at College Park. Scientists and technicians from the Malawi Government Ministry of Agriculture and Natural

Resources were also directly involved. As the project progressed, cooperation was also developed with the Rockefeller Foundation's program involving the Maize Commodity Team, and a World Bank sponsored project in one of the study areas (Lilwonde). Ideas for data analysis and survey approaches were shared with a scientists who surveyed the fertility status of soils in The Gambia, West Africa (see Peters and Schulte, 1992).

Research Materials and Methods

Nutrient Status Surveys

In the initial phase of the project we focused on identifying sampling areas in Malawi and developing the protocols for field sampling, lab analysis of samples, and statistical analysis of the resulting data. Preliminary work had been carried out in Zimbabwe within a 100 km^2 area in the Chiota and Seke communal areas (peasant farming areas of Zimbabwe), where a well-defined distribution of red epidiorite-derived clay loam and light colored granite-derived loamy sand occurs. Because of the marked contrast between the properties of those two soil groups, we were able, in the Zimbabwe work, to easily detect the effect of soil type on maize nutrient status (Weil, et al, 1990). In Malawi, one of the first tasks was identifying geographic areas from which samples could be obtained. We developed the following criteria for these sampling areas: 1. that each area should be 50 to 100 km^2 in size, 2) that the area should have maize cultivated throughout, and 3) that there should exist substantial areas of adjacent contrasting soil types. A preliminary survey was carried out in 1989 using three sample areas, each with a distinctive set of climatic and edaphic conditions. Using maps of major soil groups and maize-growing regions, we initially delineated approximately 60 km^2 in three Agricultural Development Divisions (ADD's): Mzuzu ADD in the Northern Region and Salima and Lilongwe ADD's in the Central Region.

Based on the results of this survey, in 1900 we conducted a full survey of four sample areas. The fourth sampling area was added to the project in 1990 for several reasons, namely that 1) the 1989 surveys revealed less soil heterogeneity within the sample areas than had been presumed to exist, so inter-area differences assumed more importance 2) the addition of relatively fertile

Table I. Selected characteristics of the sampling areas used in the 1989/90 survey in Malawi.

Name	Maize Season	Main Soil Groups	Fields Sampled	Elevation	Rainfall	Sample Area
				m	mm/y	Km^2
Balaka	early Nov-mid Apr	Ustolls, Aquepts, Fluvents	57	600-650	1000-1200	42
Salima	mid Nov- mid Apr	Aquepts, Psamments, Fluvents	57	500-550	800-1000	58
Lilongwe	mid Nov-early Apr	Ustalfs, Ustox	59	1100-1200	1100-1300	68
Mzuzu	early Dec-mid Apr	Ustox, Ustalfs, Ustults	65	1100-1300	1300-1500	68

Ustolls, Aquepts and Fluvents soil suborders would give the project wider applicability, and 3) the inclusion of a sample area from the

Southern Region of Malawi would give the project a more politically balanced appearance. The fourth sample area was located in the Lilwonde ADD and was designated "Balaka", after a nearby town (in order to avoid confusion with the Lilongwe area). The locations of the four sample areas are shown in Figure 1. Some characteristics of the sampling areas are given in Table I.

The following set of criteria were developed for the selection of farmers' fields to include in the survey: 1) the field location should contribute to as even a distribution of sample sites over the sampling area as possible; 2) the principal crop must be maize (but may be intercropped); 3) the maize stage of growth must be within broad limits (For the first sample date the plants could have from 6 to 12 leaves, but no ear or silk; for the second sample date the plants should be between the silking and early milk stages of development); 4) the field must have a relatively uniform area at least 10m x 10m, for sampling. Decisions to include or exclude fields were made on the spot. In each sample area approximately 55 farmer's maize fields were sampled, for a total of some 220 fields.

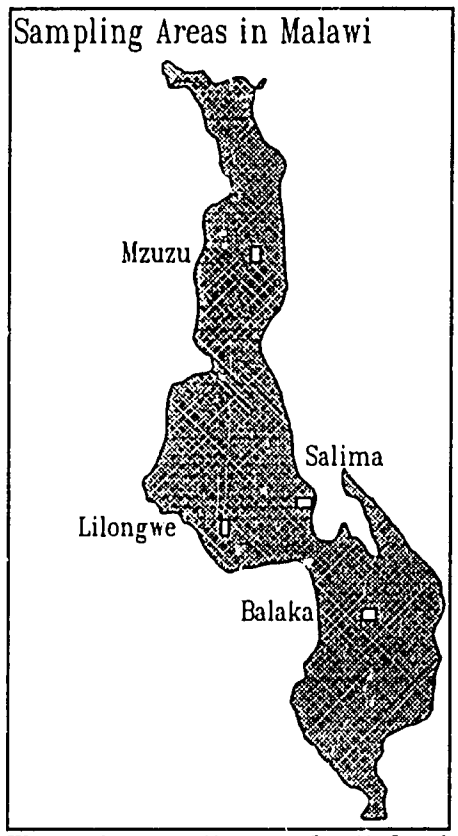

Figure 1. Map of Malawi showing the locations of the four sample areas used in this project.

All sampled fields grew local, open pollinated maize or one of two maize hybrids. All fields were under hand-hoe ridge cultivation. In each field to be sampled, a relatively homogeneous area of 100 m2 was marked for sampling with colored poles 2.5 m long, which could be seen above the mature maize canopy. Each field was plotted on a 1:50,000 scale map and assigned coordinates for spatial analysis. As an examples of the spatial distribution of sample sites, Figures 3 and 4 show the sample sites used for the 1990 survey in the Lilongwe and Balaka sample areas.

From each field, leaves from 15 to 20 maize plants were sampled on two dates: the most recently matured leaf on the early date and the earleaf (leaf blade opposite and below the ear) on the later date. No whole plants, but only leaves, were sampled, because we found that farmers objected to the removal of whole plants; the ensuing negotiations made the survey progress much more slowly. On the early date a composite sample of the upper 15cm of soil was also taken. In approximately 5 fields from each sample area, soil profile samples were obtained by augering up to 1.8m deep. Additional information was recorded from observations and interviews with agricultural extension agents and farmers. A field data form was developed to aid in rapidly and consistently characterizing the sample sites.

Soil samples were air-dried and sieved (< 2mm) for storage until analyzed. Laboratory analyses of soil samples were initially performed at the Ministry of Agriculture Soil lab at Chitedze. Chemical analyses included exchangeable bases, CEC (sum of bases + exchange acidity), EDTA extractable Zn, Cu, Mn, and Fe, Bray (Ammonium fluoride) extractable P, organic matter, and total nitrogen. The percent sand, silt and clay were also determined (hydrometer method). Because of delays and unreliable results, as many soil samples as could be recovered (90%) were shipped to Maryland for analyses. Unfortunately, the lab at Chitedze had used up all the soil (approx. 600 g) in several samples, and misplaced several others. Many of the soil samples lost were from profiles of representative soils, thus our results will be limited primarily to the surface soil. Because of the very limited sample size remaining in most cases (≈ 15g), only the following analyses were performed at Maryland: Total C and N by LECO CHN determinator; available P by $NaHCO_3$ (Olsen) extraction; 'exchangeable' Ca, K, Mg by dilute double acid (Melich I) extraction[1]; pH in water and in 1 MKCl (2.5:1 solution:soil ratio by weight) by glass electrode; effective CEC by sum of cations plus exchangeable H; sulphate S extractable in $CaHPO_4$; and sand, silt and clay by semi-micro hydrometer method.

Leaf samples were washed in distilled water in the field and placed in cloth bags for transport to Bunda College, where they were dried in a forced air oven at 70 °C and ground in a stainless steel mill to < 1 mm. Sub-samples were taken to Chitedze to be analyzed for 1) total Kjeldahl N by acid digestion, 2) total S by turbidimetry after dry-ashing, 3) total P by ascorbic acid colorimetry after dry ashing, and metallic cations (Ca, Mg,K,Fe, Mn, Zn, and Cu) by atomic absorption spectrophotometry after dry ashing. Dry ashing was carried out in a muffle furnace at 450°C. In 1991,some 1200 new plant samples from the 1990/91 on-farm experiments (see below) were collected, dried and ground at Bunda College and submitted to the lab in Chitedze for nutrient analysis. In addition, most of the 1300 plant tissue samples from the 1989/90 surveys and experiments were re-submitted because the results of the first analysis lacked both accuracy and precision.

After long delays and chronically inaccurate analytical results from the lab at Chitedze, samples of both soils and plant tissue from the 1990 survey and the 1991 on-farm experiment plots were shipped to Maryland for preparation and analysis. Total C and N were determined by LECO high temperature combustion CHN Determinator. Total S was determined by turbidimetry after dry ashing. Because of the small sample size remaining, the remaining nutrient elements (including P, B and all the metallic cations) were determined by emission spectrophotometry at the Plant and Soil

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[1] Melich extraction solution consists of a dilute combination of H2SO4 and HCl. Although not in regular use in Malawi, this extractant has been shown to be well correlated with P uptake and response to fertilizer by crops in West Africa (Botiono, et al. 1992). It was therefore used for convenience, as it is the extractant regularly use in Maryland.

Analysis Lab of the University of Georgia, Athens.

DRIS indices were calculated for both young maize plants and for earleaf samples using the norms and computer programs of W.S. Letzsch (1986; M.E. Sumner, personal communication 1988;) and Walworth and Sumner (1987). DRIS norms available for whole above-ground maize plants were used both for whole plants sampled from on-farm experiments as well as for survey samples consisting of only the most recently matured leaf of young maize plants. DRIS norms for earleaf samples were used for the second sampling, which consisted of earleaves taken from plants between silking and early milk stages. DRIS indices were calculated using ratios for all nutrients, including Ca and Mg, since using products instead of ratios for these two nutrients resulted in highly negative Ca indices for nearly all samples, even from calcium-rich soils. Dry Matter ratios (nutrient/ dry matter) were included in all DRIS calculations in order to assist in distinguishing indices that indicate deficiency (indices less than the index for DM). The general expression used to calculate DRIS indices was given by Walworth and Sumner (1987):

$$AI = [+ \underline{f}(A/B) - \underline{f}(C/A) + \underline{f}(A/D) \ldots + \underline{f}(A/N)]/\underline{z} \qquad \text{eq. 1}$$

where, A....N are nutrients (including dry matter), AI is the DRIS index for A, and when $A/B \geq a/b$,

$$\underline{f}(A/B) = (((A/B)/(a/b))-1)*(1000/CV) \qquad \text{eq.2}$$

or, when $A/B < a/b$,

$$\underline{f}(A/B) = (1-((a/b)/(A/B)))*(1000/CV) \qquad \text{eq.3}$$

in which A/B is the observed ratio of two elements in the tissue, a/b is the norm for that ratio in a large population of high-yielding plants, CV is the coefficient of variation associated with the norm, and $\underline{z}$ is the number of functions comprising the nutrient index.

Nutrient availability indices were also calculated for maize at silking-tasseling by the method suggested by Beverly (1987). In this calculation, the observed nutrient concentration is compared to the mean concentration of that nutrient in a world-wide data base of maize nutrient concentrations. Peters and Schulte (1992) found this method useful in their maize nutrient survey of the Gambia. By this method, availability index of nutrient, N is defined by the availability index, Ni....

$$Ni = (N_o - \bar{N}) \;/\; 0.5*(SD_{Malawi} - SD_{world}) \qquad \text{eq.4}$$

where N_o is the observed concentration in the sample, $\bar{N}$ is the mean concentration of that nutrient in the world-wide population, SD_{Malawi} is the standard deviation of the concentrations of that nutrient in the Malawi survey population; and SD_{world} is the standard deviation of the concentration in the world-wide population.

Several approaches were taken to analyzing the spatial variability of the soil and plant data. Semi-variograms were plotted for selected soil and plant nutrient variables, including DRIS indices, using GEO-EAS version 1.2.1 (Englund and Sparks, 1991). Distance-weighted least squares regression estimates of variables at a large number of grid points were calculated and plotted using the SYSTAT/SYGRAPH version 5.03 program (Wilkinson, 1990).

On Farm Fertilizer Trials

The 1989 preliminary survey results suggested that the N, S, P, Mg, Zn, Cu, and Mn were likely to be deficient in one or more of the sample areas. Concurrent with survey sampling in 1990, a series of fertilizer experiments were established on five farmers' fields in each of the four study areas (20 experiments in all). These experiments determined the response of maize yield and nutrient uptake to the application of N, P, S and two of the other four nutrients listed above, in a partial factorial design. The experimental use a randomized complete block design with two replications at each site and the 16 treatments described in Table II.

Table II. Fertilizer treatments used in 20 on-farm trials in 1990 to validate the 1989 and 1990 survey results.

Treat ment No.	N	S	P	M1	M2
	kg / ha				
1	80	20	0	0	0
2	80	20	20	0	0
3	80	20	0	+	0
4	80	20	0	0	+
5	80	0	0	0	0
6	80	0	20	0	0
7	80	0	0	+	0
8	80	0	0	0	+
9	0	20	0	0	0
10	0	20	20	0	0
11	0	20	0	+	0
12	0	20	0	0	+
13	0	0	0	0	0
14	0	0	20	0	0
15	0	0	0	+	0
16	0	0	0	0	+

+ indicates application of M1 or M2 which were either Mn (10 kg/ha as MnO), Cu(6 kg/ha as CuO), Zn (8 kg/ha as ZnO) or Mg (20 kg/ha as MgO), depending on the nutrient limitations suggested by DRIS analysis of the 1989 survey.

The 16 treatments were factorial combinations of nitrogen (N, 80 kg/ha), sulfur (S, 20 kg/ha), and either phosphorus (P, 20 kg/ha), M1 or M2. Treatments designated as M1 and M2 varied from site to site, but were either Mn, Cu, Zn, or Mg, depending on what the previous survey suggested were the two most limiting of these four nutrient elements. The experiments were laid out in November, 1989, and the treatments applied in December 1989-January 1990. Plot lay-out, fertilizer application, soil and plant sampling, and harvest were carried out by the principal investigators. All other aspects of crop management, including sowing and weeding, were the responsibility of the farmer cooperator. Harvest of the experiments and measurements of grain yields were completed by the end of June, 1990. Of the 20 experiments established, 5.5 were lost prior to grain harvest due to natural factors (termites,

drought) or to management errors (done with the best of intentions) on the part of the farmer cooperators. Most of the lost experiments were located in the Salima area.

Because approximately 30% of the 1990 on-farm experiments were lost, it was decided to conduct a new set of on-farm experiments in 1991. Since in 1990 sulfur responses were widespread and the only micronutrient responses found were for Zn in the Mzuzu area, the treatment structure shown in Table III was used for the 1991 experiments. These consisted of a set of randomized complete block experiments with three replications on each of 20 farms, a total of 690 plots. This structure achieved three goals in an efficient design. Eight treatments (1-4 and 8-11) comprised a N*P*S factorial arrangement for investigating responses to these three major elements and their interactions. Five treatments (4-7 and 11) were used to construct a sulfur response curve. Finally, for the Mzuzu area, four treatments (3,4,12 and 13) were used to test for responses to Zn and Zn*P interactions.

The 1991 experiments were planned in July 1990, and arrangements made with cooperating farmers in September-October. Planting was done by the farmers in December 1990 and fertilizers were applied by the project collaborators after stand establishment was assured in January, 1991. Dry weights and tissue samples were obtained for whole maize plants at stem elongation about one month after fertilizer application and at harvest maturity. Leaf samples were also taken at tasseling for nutrient analysis. DRIS indices and sufficiency indices were calculated as described above for the survey samples. Total uptake of various nutrients was calculated for the maize in v8 to v12 stage as the product of tissue concentration and above ground dry matter. Of the 20 experiments, vegetative stage dry matter and whole plant samples were collected from all 20 experiments, but two experiments were lost before grain harvest, due to factors beyond our control. This was success rate was much better than that achieved for the 1990 experiments.

Table III. Treatments used in 20 on-farm fertilizer experiments in 1991. Treatments 12 and 13 were used only in the Mzuzu area.

Trt.	Nutrient Applied			
No.	N	P	S	Zn
	------- Kg/ha --------			
1	0	0	0	0
2	0	50	0	0
3	80	0	0	0
4	80	50	0	0
5	80	50	5	0
6	80	50	10	0
7	80	50	15	0
8	0	0	20	0
9	80	0	20	0
10	0	50	20	0
11	80	50	20	0
12	80	0	20	10
13	80	50	20	10

Additional field experiments were laid out in 1992 in order to test indigenous sources of S, and to assess boron and copper responses, but all sites suffered crop failure, in one of the driest seasons on record.

RESEARCH RESULTS

Nature of the Surveyed Farm Fields.

Although we had originally planned to stratify our survey sample into unfertilized, inorganically fertilized, and manured fields, this plan was found to be unnecessary as only a very small proportion of the fields had received any fertility amendment at all. Of the 57 fields sampled in the Balaka area, not one had been fertilized during the past five years. Figure 2 shows that in the other three sample areas, only 1.5 to 10% of the fields had received fertilizer in 1990. A few fields had received both a basal and a side dressing. Diammonium phosphate was the most common basal dressing and urea was the most often used for sidedressing. One field in Mzuzu and one in Lilongwe had received a 23-21-0-4(S) compound fertilizer, a material which was just becoming available in Malawi. Only one field (in Mzuzu) had received animal manure. That field was adjacent to a cattle coral.

Since all four areas were in Agriculture Development Divisions with active extension and fertilizer credit programs, the low incidence of fertilizer use is somewhat surprising. The incidence we observed in our sampled fields was certainly far below official statistics and some field reports. Gladwin (1989) studied 40 farmers living throughout the Salima, Kasungu and Lilongwe districts. Of these, 28 used some fertilizer and 15 used animal manure on at least some of their fields. However, this higher use of amendments may reflect the fact that farmers in Gladwin's sample were more experienced and had holdings (mean of 3.02 ha) about twice the size as the average for Malawi smallholders (1.5 ha). It may also be that she sampled farmers near to towns and main roads, while we made every effort to include the more representative, but less accessible farms. Our efforts to drive down the smallest four-wheel drive tracks and visit some fields on foot is reflected in the distribution of fields sampled in the Lilongwe area (shown in Figure 3). Still, some parts of the sample area were under-represented because non-fordable streams, steep mountains or other obstacles prevented our access. Such problems of access can be noted in the map of sample sites in the Balaka area (Figure 4), in which an impassable river prevented us from sampling in the upper right-hand quadrant.

Logistical considerations also prevented us from sampling all fields at exactly the same stage of maize maturity. This was an anticipated problem, and would be the case in any such survey, since planting dates vary quite widely among individual farmers in a given area. Most fields were sampled when the maize had six to nine leaves and had not yet initiated stem elongation (Figure 2). The maize at first sampling was significantly more mature in Lilongwe and Salima than in the other two areas. At the time of the

second sampling, up to 28 per cent of the maize crops were in early milk (grain forming) stage, with those in Mzuzu being the least advanced. This variability in growth stage was an important reason for including DRIS analysis in the project. The nutrient ratios used in the DRIS tend to change less with growth stage than do the nutrient concentrations themselves.

The height of the maize plants also varied greatly from field to field; but in all areas most plants were between 30 and 60 tall at first sampling. By the second sampling in all four areas, maize in most fields had grown 140 to 180 cm taller. Final maize height generally exceeded 200 cm, except in the Mzuzu area (Figure 5).

An important factor in determining maize growth and nutrient uptake is the weediness of a field. Weeds can compete with a crop for nutrients. Weeds may also be stimulated by the application of fertilizer. Timely weed control is often a mark of a good crop manager, especially when all weeding is done by hand tool (hoe) cultivation (Weil, 1982). Singa (1990) has suggested that an adult African can properly manage less than one ha with hand tools. We scored the degree of weed infestation in each field, finding some fields completely weed-free (score=0) and others nearly overrun with weeds (score=4). Farmers in Balaka practiced significantly better weed control than those in the other three areas.

Table IV. Mean values for selected properties of soils sampled from the four study areas in 1990.

Soil Property	--------Sampling Area--------			
	Balaka	Lilongwe	Mzuzu	Salima
sand, g/kg	750	666	754	711
silt, g/kg	106	106	78	152
clay, g/kg	143	226	167	136
pH in water	6.11	5.59	6.20	6.09
pH in KCl	5.65	5.05	5.33	5.70
pH_{H2O}- pH_{KCl}	.46	0.84	0.86	0.39
Exch. Ca, cmol(+)/kg	5.26	2.94	1.74	6.91
Exch. Mg, cmol(+)/kg	1.72	0.745	0.621	1.689
Exch. K, cmol(+)/kg	0.542	0.384	0.387	0.703
ECEC, cmol(+)/kg	7.52	4.07	2.75	9.30
Extrac. P, mg/kg	60.1	13.0	11.1	102.5
Carbon, g/kg	7.9	12.2	5.96	14.8
Nitrogen, g/kg	0.29	0.59	0.37	0.46
C/N	40.4	26.7	23.6	44.3

Soil properties in the four sample areas.

With regard to most of the soil properties measured, the four sample areas could be placed into two broad groups of soils (Table IV). Balaka and Salima areas can be characterized as Lake shore soils, which are mostly Inceptisols formed from

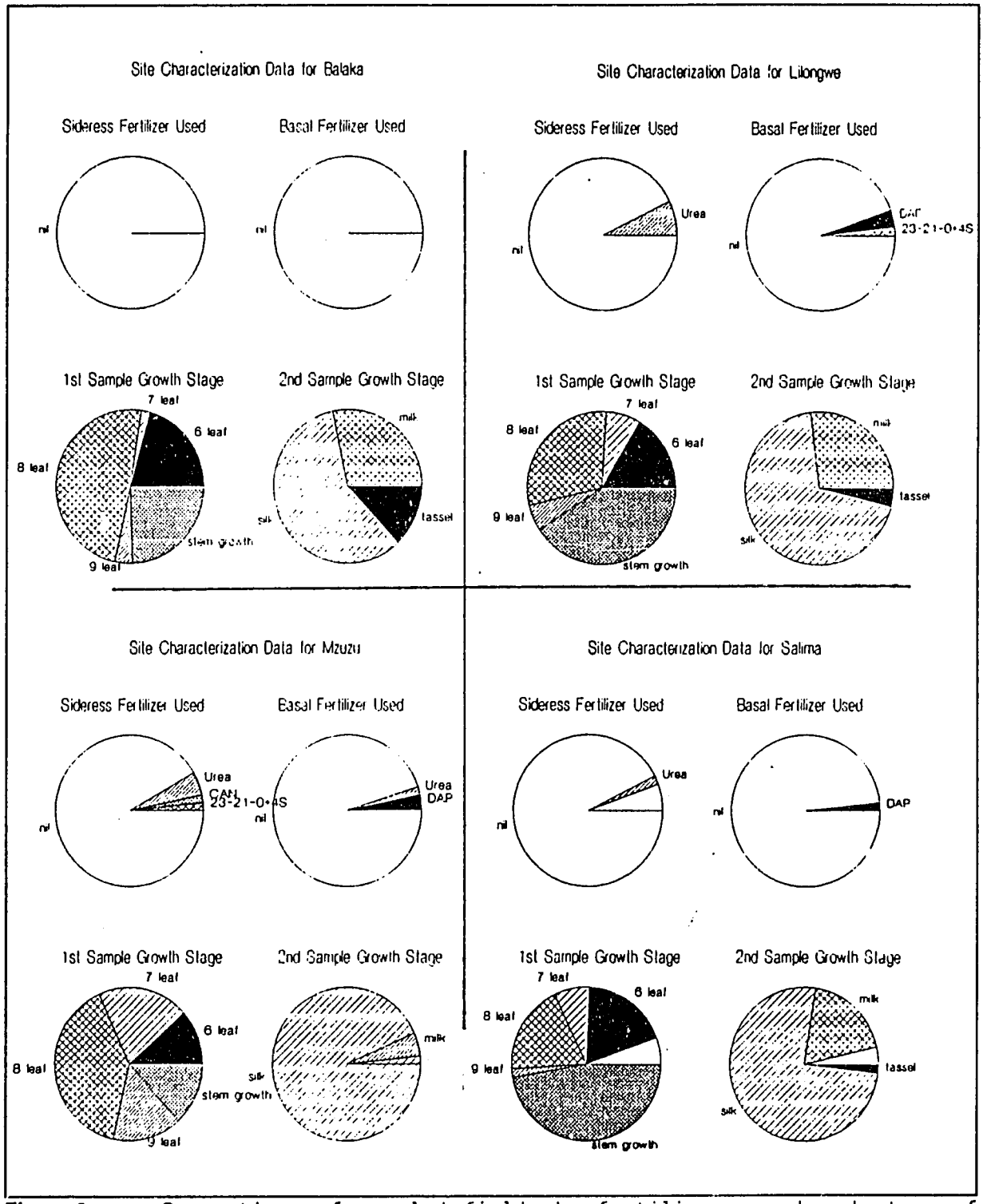

Figure 2. Proportions of sampled fields by fertilizers used and stage of maize growth during sampling for four areas surveyed in 1990.

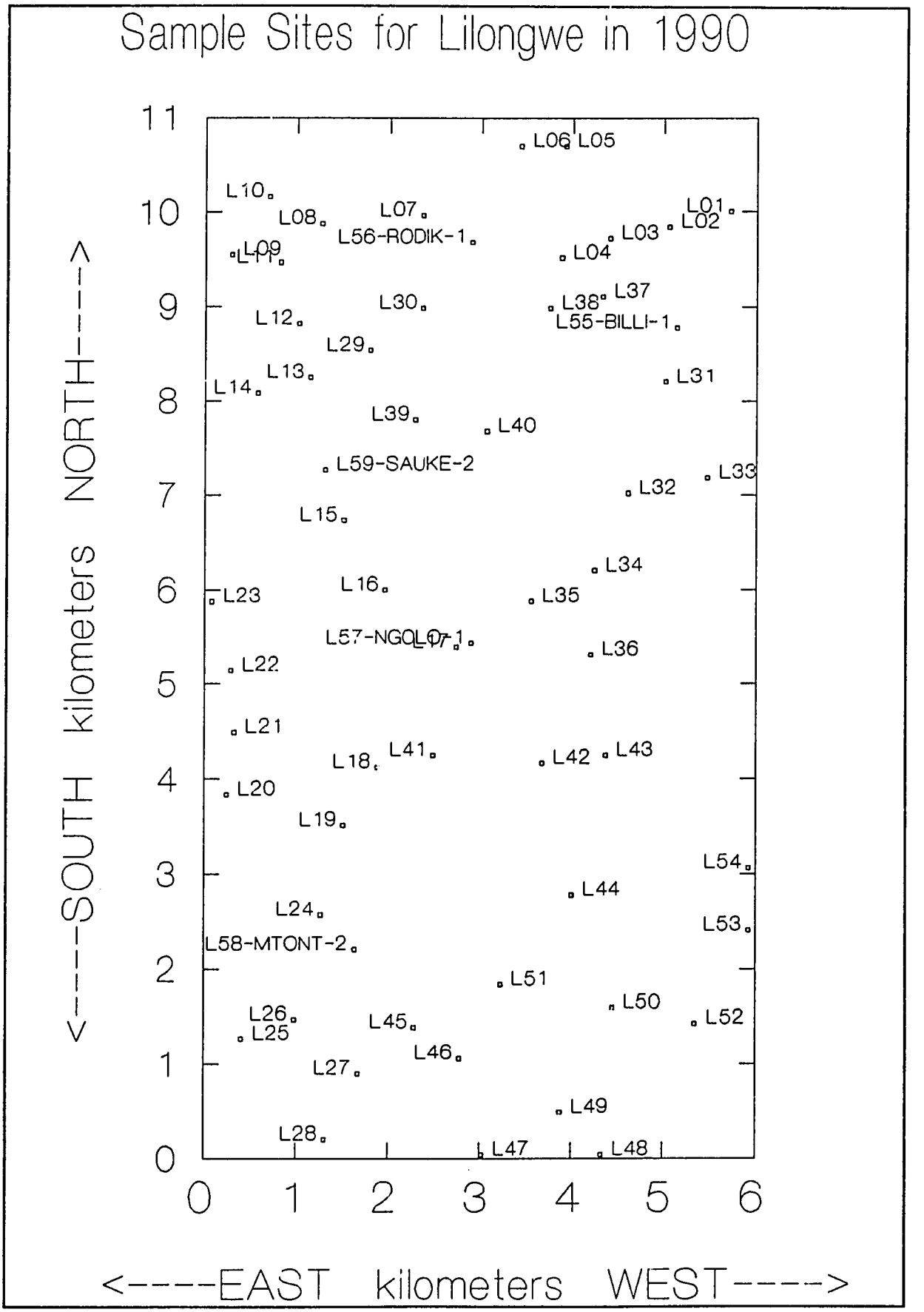

Figure 3. Spatial distribution of fields sampled in the 1990 survey of the Lilongwe area. Sites identified by name were used for on-farm fertilizer experiments.

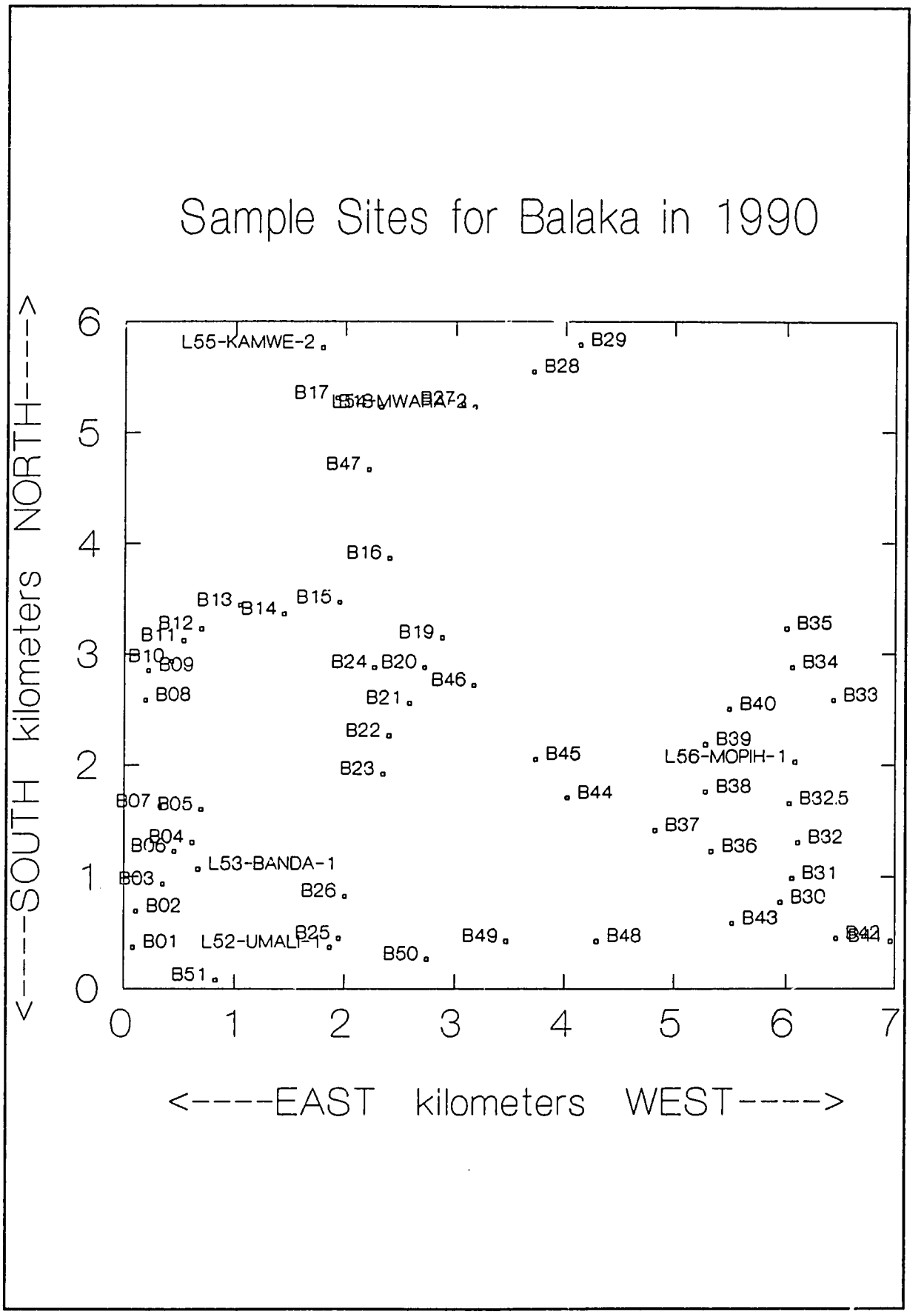

Figure 4. Spatial distribution of sites sampled in 1990 in the Balaka area. Sites identified by name were used for on-farm fertilizer trials.

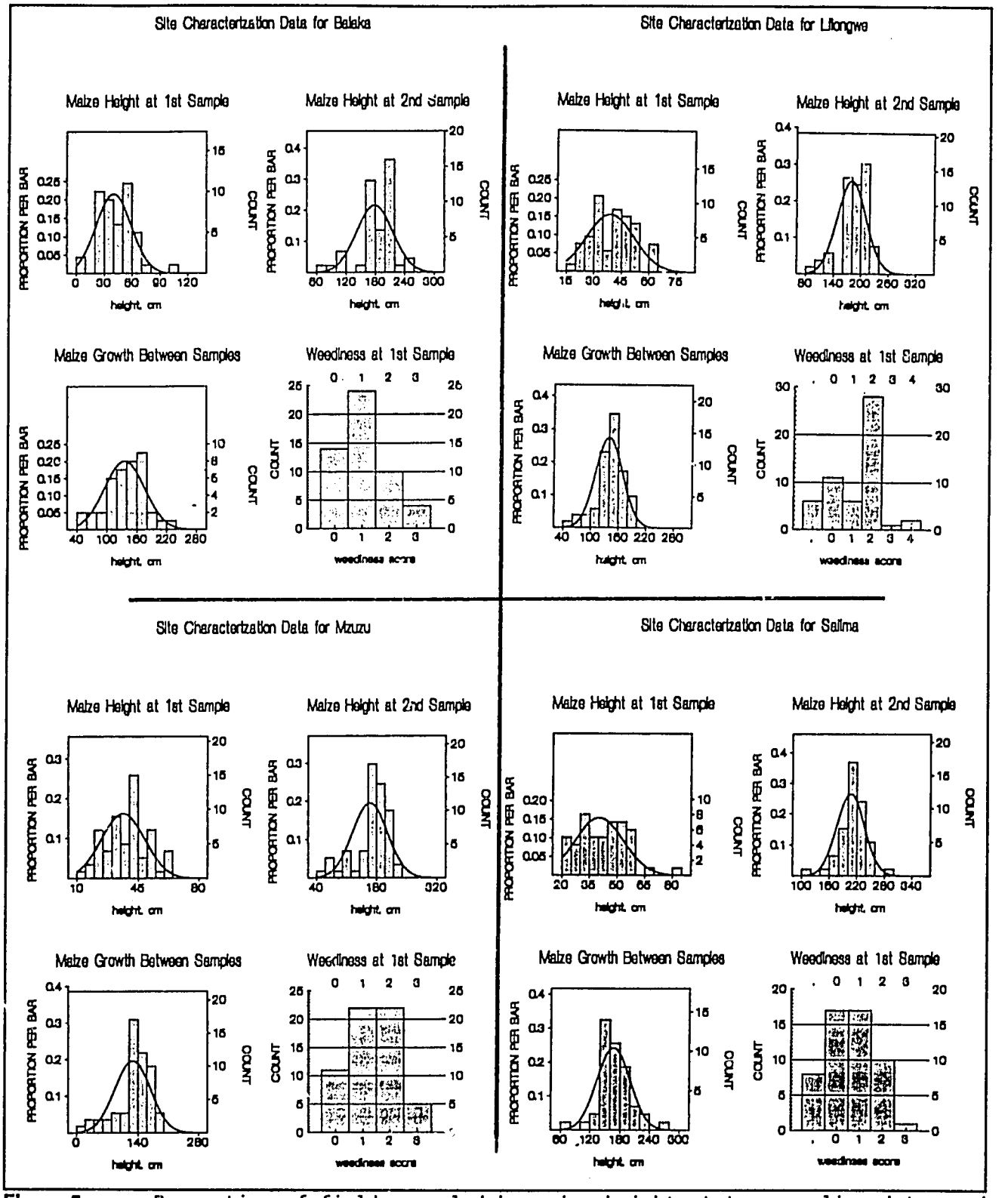

Figure 5. Proportion of fields sampled by maize height at two sampling dates and weediness score for four areas surveyed in 1990.

mostly Inceptisols formed from lacustrine sediments. Many of these soils are imperfectly drained with high water tables during the rainy season. They tend to be lower in clay, but higher in carbon than soils from the other areas. One striking chemical feature of these soils is the relatively high effective CEC (two to three times as great on the average than in the other areas). Also notable are the very high extractable P contents, more than five times as great in the Lake shore soils than in the other areas. Values of extractable P greater than 55 are considered to be very high and indicative of fields in which a positive yield response to added P is extremely unlikely.

In contrast, the Lilongwe and Mzuzu areas are dominated by well to excessively drained, highly weathered residual soils, which are rich in iron oxides. These are most likely kandic subgroups of Ustalfs and Ustoxs, known in the Malawi classification system as Ferruginous and Ferralitic soils. The soils in all four sample areas were found to be moderately acidic with pH values near 6.0. However, the Δ pH values (difference between pH_{water} and pH_{KCl}) for the Lilongwe and Mzuzu soils were nearly twice as great as those for the Lake shore soils, indicating differences in mineralogy and possibly in zero point of charge (ZPC). The Δ pH values and other parameters for the Lilongwe area were very similar to those reported for the soils of the nearby Bunda College Farm (Lupwayi, 1990) Extractable P in these weathered soils was generally in the low to medium range, suggesting that responses to added P would be quite likely.

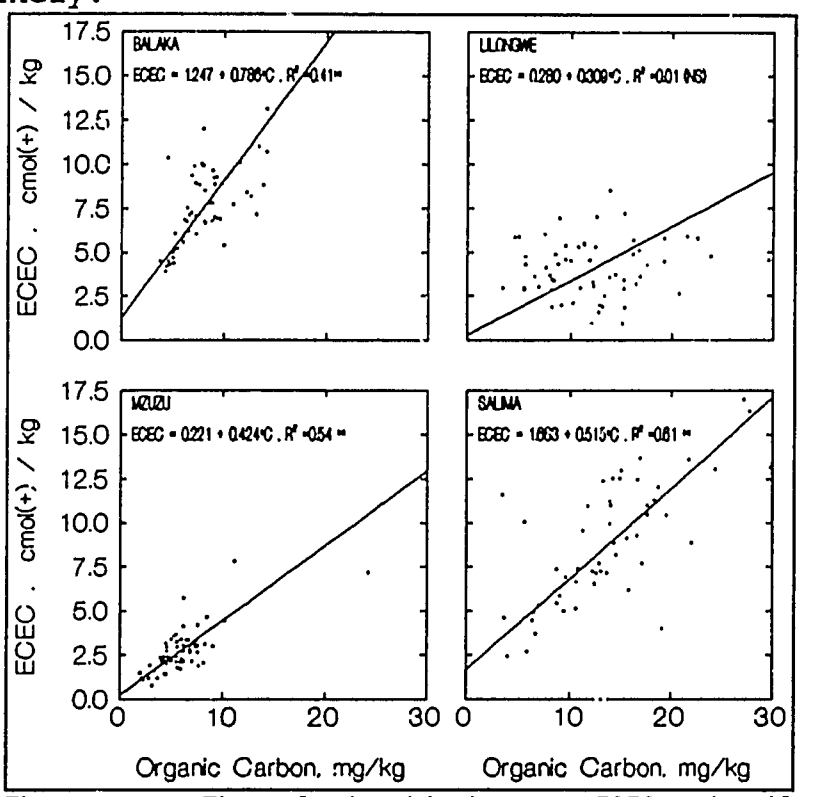

Figure 6. The relationship between ECEC and soil organic C in the soils of the four sample areas.

Total soil nitrogen was quite low (<0.6 g/kg) in all four areas, resulting in unusually high mean ratios of C/N. Since the results by LECO high temperature oxidation analysis (which would include carbonate and charcoal carbon) were very similar to the results by Walkley-Black oxidation (which would include only organic carbon), it is unlikely that either charcoal or carbonate account for the high C/N ratios. Also, no free carbonates or charcoal were observed in the samples. The reason for the low total N values is not known, but the maize responses to N fertilizer, discussed in a later section of this report, suggest that the soils

were indeed low in N. Also, Lupwayi (1990) reported low values (0.08 to 0.1 % N) in similar soils at Bunda.

As can be seen in Figure 6, there was a close relationship between organic carbon and ECEC in all of the areas except Lilongwe. The relationship between ECEC and clay content, however, was generally not significant, indicating that most of the soil ECEC originated with the humus fractions rather than with the clay. This finding is not surprising for soils with low-activity clays and clay contents (Figure 7) mostly within the range of 10 to 30 per cent. According to the slopes of the linear regression lines, the increase in soil ECEC with every mg/kg increase in C was approximately 0.8 in Balaka, 0.5 in Salima, and 0.4 in Mzuzu. Assuming soil organic matter to be 58 per cent C, the regression suggested that the organic matter contributed approximately 70 to 140 cmol(+)/kg. For the soils of the Lilongwe area, step-wise multiple regression showed that the ECEC was unrelated to clay, sand, silt, or carbon contents of the soils, or to soil acidity and ΔpH. The ECEC was closely related to exchangeable Ca, as would be expected, since Ca was the dominant exchangeable cation in nearly every soil analyzed.

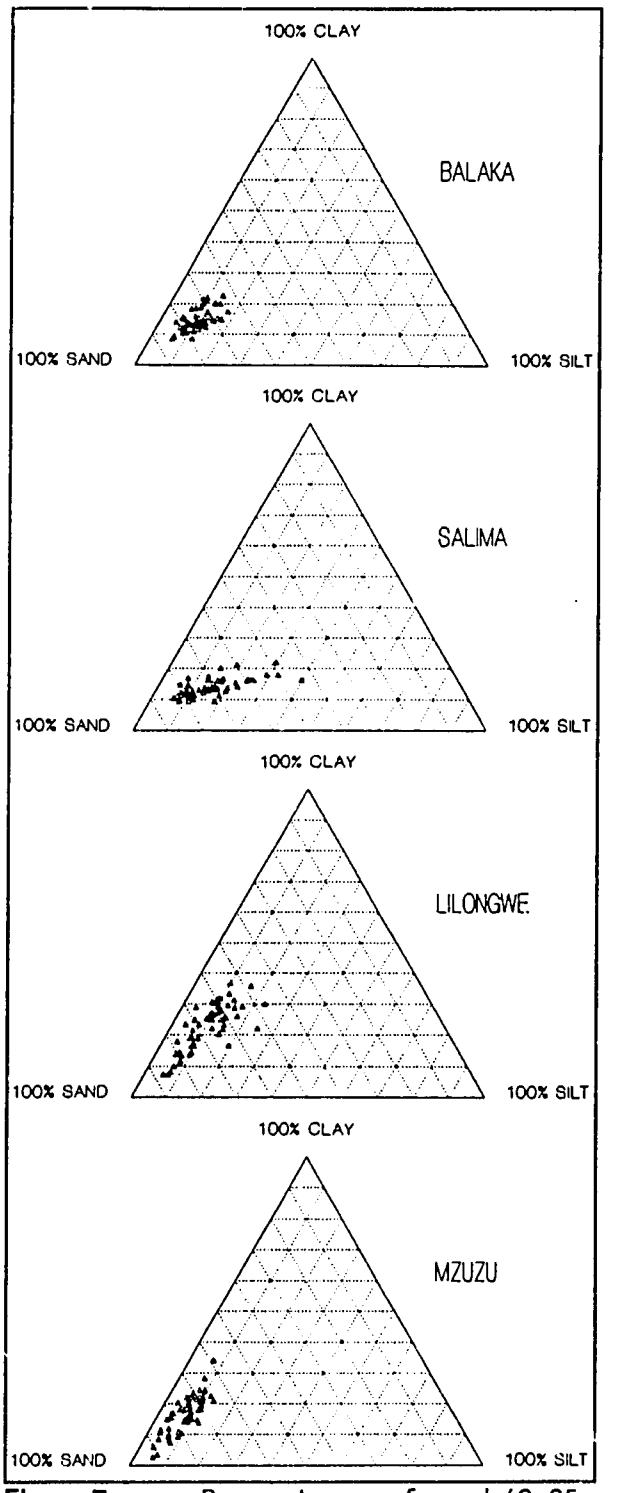

Figure 7. Percentages of sand (0.05-2.0 mm), silt and clay (<0.002 mm) in the mineral fraction of surface soils in the four sampling areas.

Although Table IV shows that there were major differences in soil properties among the four sample areas, the variability within each sample area was not so great. Nor were soil differences within a sample area as clearly geographically delineated as would be ideal, for the purposes of testing the ability of our survey data to detect local spatial variability. None of the sample areas in the present project had the kind of clear boundary between highly contrasting soil parent materials, as was found in the Zimbabwe area studied by Weil, et al. (1990) where similar survey

methods were used. However, the fact that we were able to detect pronounced differences among sample areas could contribute to a sound basis for differentiating fertilizer rates and types used in different regions of Malawi. The inter-region site specificity gained by this exercise could result in considerably greater economy of fertilizer use.

Figures 8a and 8b illustrate the type of spatial variations in soil properties that were observed <u>within</u> a sample area. These maps of the Lilongwe area show the occurrence of finer textured, lower organic matter soils in the Southern third of the sample area. The transition between sandy clay loams and sandy loams (200 g clay/kg) coincides closely with the boundary shown on the national soils map (Dept. of Surveys, 1983) as dividing Weathered Ferralitic soils (mostly coarse-textured, highly leached Oxisols) from Ferruginous soils (finer textured, redder, less leached Alfisols). Nutrient availability, however, did not tend to be spatially distributed in patterns closely related to those of texture and organic C content. For example, dilute acid extractable phosphorus did not decrease in the southern portion of the Lilongwe sampling area (Figure 8c), as did clay and organic C content.

As is typical of most soils on the African continent, the surface horizons of the soils analyzed for this project had relatively low contents of silt sized particles. With the parent rock for most of these soils being granite, gneiss, and syenite, it is not surprising that the sand contents are quite high. Figure 7 shows the particle size distribution for the soils from the four sampling areas. Most soils fell into either the sandy loam or sandy clay loam textural classes. The lacustrine soils of the Salima area had the widest range of silt contents, but were still mainly sandy loams and loams. On the other hand, in the granitic soils of the Mzuzu area the silt contents ranged only from 3 to 13 percent.

Because of the loss of most soil profile sample in the Chitedze lab, little analytical information was obtained for subsoil horizons.

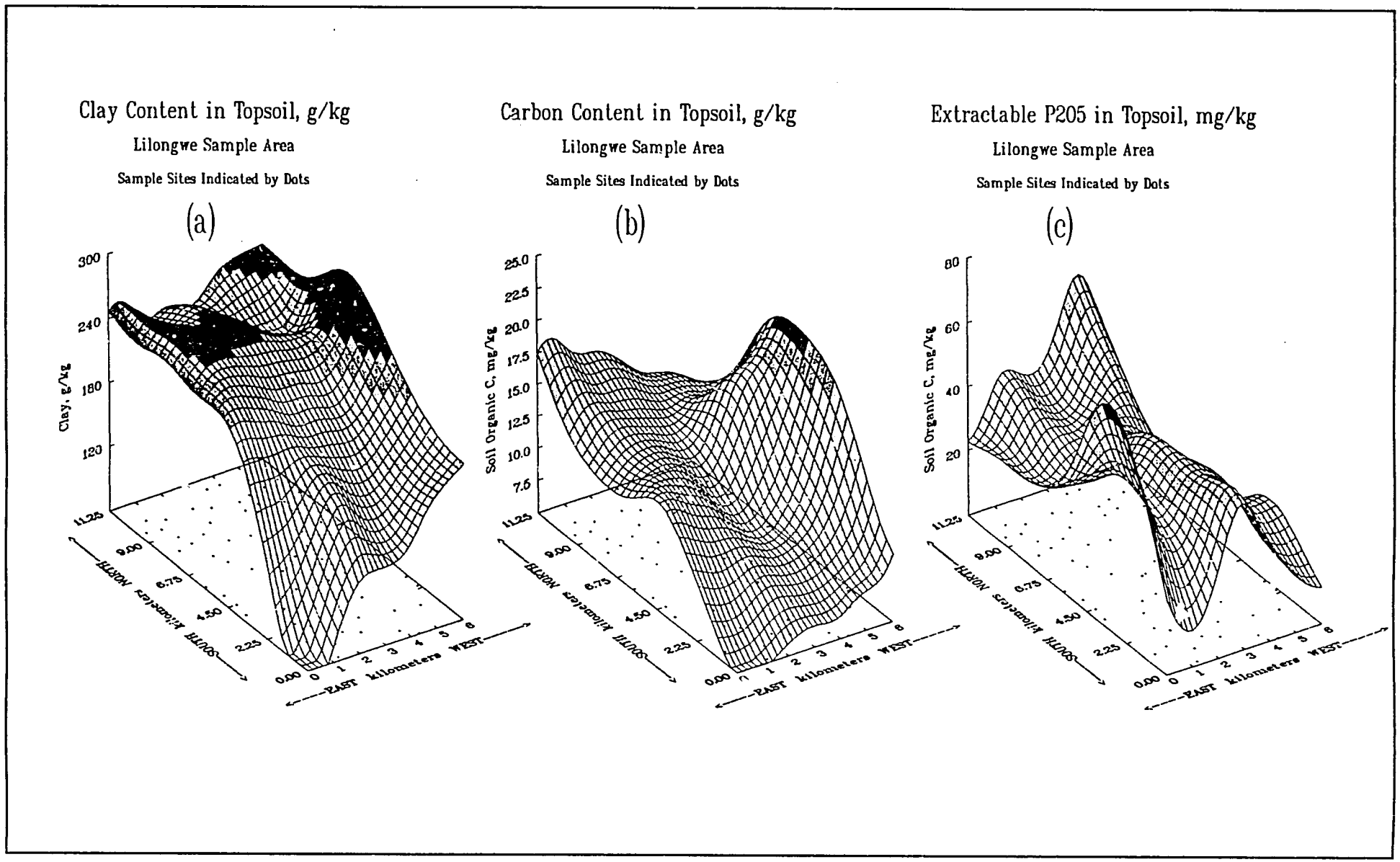

Figure 8. Spatial distribution (DWLS regression) of clay content (a), organic C (b), and dilute acid extractable P_2O_5 in the surface horizon of Lilongwe area soils surveyed in 1990.

Maize Tissue Parameters in Smallholder Survey

Young Maize Plants.

Figure 9 summarizes the results of analyses for macronutrients in tissue from young maize plants samples taken from 232 farm fields in 1990. In this figure and several others in this report the "box and hinge" diagrams depict the distribution of the data in each of the four sampling areas. The central "box" in each graph includes 50 per cent of the values observed. Note that the boxes are notched at the median and return to full width at the upper and lower 95 per cent confidence intervals. Therefore, if the notches do not overlap in two boxes in a given graph, we can be 95 per cent confident that the two medians are different (Velleman and Hoaglin, 1981). Outlying observations are shown as asterisks and very far outlying data as circles.

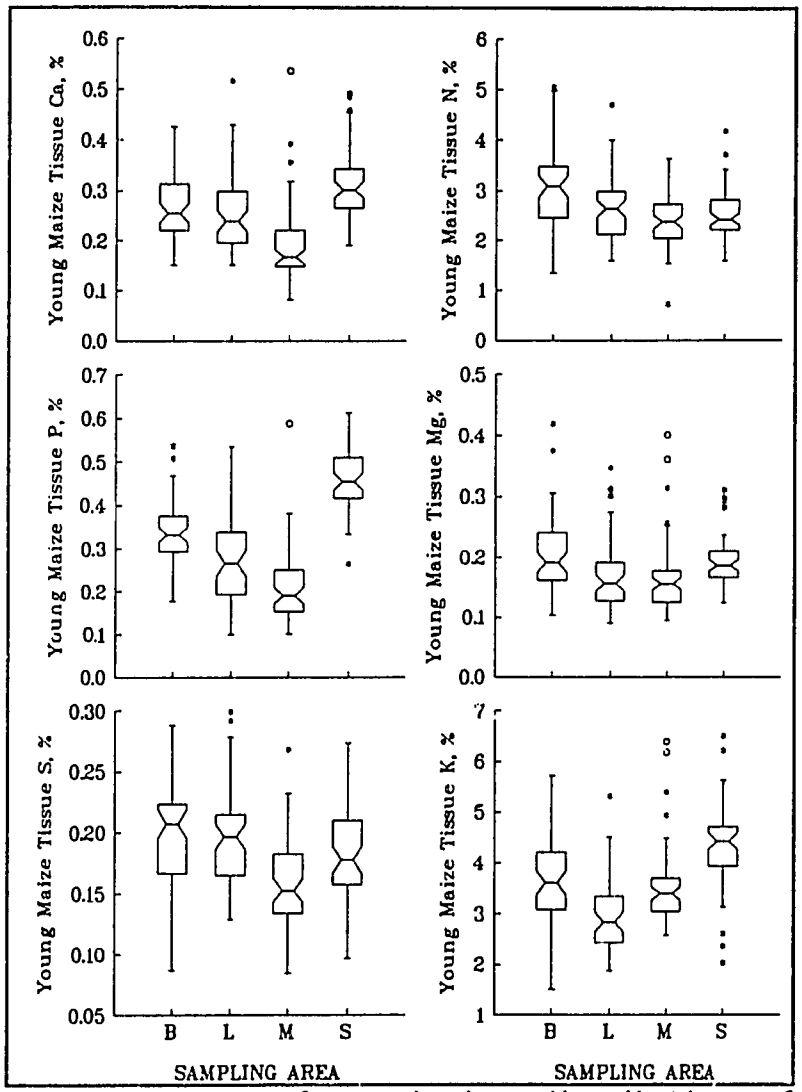

Figure 9. Box plots showing distribution of macronutrient concentrations in young maize plants from Balaka (B), Lilongwe (L), Mzuzu (M), and Salima (S) areas in Malawi.

With regard to the concentrations of macronutrient cations in the young maize tissue, the results in Figure 9 indicate that there were significant differences among the sampling areas. For K and Mg, plants from Mzuzu and Lilongwe were significantly lower than those from Balaka and Salima. This difference correlates with the higher exchangeable K and Mg found in the Lake shore soils (see Table IV). However, for Ca, the plants from Mzuzu were significantly lower than those from the other three areas, and the plants from Salima were significantly higher. In general, then, the young maize growing on the Lake shore soils had higher concentrations of basic cations than those growing on the more weathered residual soils of Mzuzu and Lilongwe. If 2.0

per cent K is taken as the critical concentration for young maize (Reuter and Robinson, 1986 was used as a source of published nutrient sufficiency values), then only in Lilongwe did a significant proportion of the fields fall in the deficient range. In fact, only in Lilongwe did we observe foliar symptoms of K deficiency, and there only in two out of 59 fields. If adequate levels of Ca and Mg in young maize leaves are taken as 0.25 and 0.15 per cent, respectively, then most of the fields in the Mzuzu area were marginal to deficient in Ca; about half the fields in both the Lilongwe and Mzuzu areas were marginal in Mg. About 30 per cent of the fields in Balaka were marginal in Ca, but few if any of those in Salima were low in any of the basic cations.

With regard the median P concentration in young maize tissue, each of the four areas was significantly different from all the others. As with the extractable soil P, Salima was by far the highest in maize P concentration, and Mzuzu was the lowest. If the critical P level at this stage is taken to be 0.22 per cent, then a few of the Lilongwe fields and most of the Mzuzu fields were marginal to deficient in P. We observed mild to severe foliar symptoms of P deficiency in about 10 per cent of the fields of young maize in the Mzuzu area.

The nitrogen status of young maize in Balaka was significantly higher than that in the other areas. However, about 50 per cent of the Balaka fields and nearly all of the fields in the other areas had young maize plants with N levels below the range (3.0-5.0 per cent) reported to be adequate for maximum yields. No foliar symptoms of N deficiency were observed in the Balaka fields; but 25 to 30 per cent of the fields in the other areas showed mild to severe N deficiency. It was clear from the above evidence, and from the experimental results discussed later, that N was a major limiting factor for maize growth in most fields sampled.

Young maize plants sampled from Mzuzu area fields had significantly less S in them than those from the other four areas. The lower boundary of the range of S concentrations adequate for high yields in young maize, has been reported to be either 0.16 or 0.20 per cent. If the lower of these values is used, then only Mzuzu had many fields apparently inadequate in S fertility. However, if the higher of these values is applicable, then Salima and Lilongwe also had a majority of fields marginal in S, and Balaka had a significant number of low-S fields, as well. We observed foliar symptoms of mild to moderate S deficiency in 65 per cent of the fields in the Balaka area. In the Lilongwe, Mzuzu and Salima areas we observed symptoms of mild to severe S deficiency in 86 per cent, 91 per cent, and 87 per cent of the fields. Maize growth responses (discussed in a later section) were also observed in most of the on-farm trials in these three areas.

The relationships among the young maize tissue concentrations of the six macronutrients are shown in Figure 10. Note that all

the macronutrients show a normal distribution of values, with the possible exception of Mg which has values skewed slightly toward the low end of the range. In fact for all six of these nutrients, the median (shown in Figure 9) was nearly identical to the mean. No negative relationships were found, although levels of K are often reported to be negatively related to levels of Mg and Ca. A close linear correlation between N and S was observed. The ratio of N to S is considered to be a more reliable indicator of the S status of maize than is the S concentration by itself. This ratio averaged somewhat lower in Lilongwe and Salima (13.6 ± 1.47 sd and 14.1 ± 3.25 sd) than in Balaka and Mzuzu (15.3 ± 2.2 sd and 15.6 ± 2.9 sd). Values reported to be critical or marginal for this ratio in 1.5 to 2 month old maize are 10.2 and 16. This measure, then, indicates very few or very common S limitations, depending on which critical value is applicable. Obviously, conclusive interpretations of tissue analyses cannot be made based on critical tissue concentrations from the literature

Box plots of the micronutrient concentrations in young maize tissue from the four sampling areas are shown in Figure 11. As with the macronutrients, there were significant differences among the four area medians for each of the elements. Aluminum, a phytotoxic metal, not a nutrient, was distinctly higher in the maize growing in the two areas of weathered residual soils (L and M). Although no symptoms of Al toxicity were observed in any fields, a few of the fields in Mzuzu and Lilongwe had over 400 mg/kg of Al, a concentration that has been reported to be indicative of potential toxicity. Aluminum may be toxic to maize without elevated concentrations being present in the leaf tissue, and leaf content is not a reliable guide to toxic Al conditions. Aluminum toxicity is closely related to soil pH, usually becoming a serious problem when pH_{water} is less than 5.0. The lowest pH_{water} values measured in Mzuzu and Lilongwe areas were 5.18 and 5.04. Iron was also higher in Lilongwe than in the other areas, but in all cases the Fe concentrations were well above that considered marginal (ie. >50 mg Fe/kg) for young maize.

For most fields in all areas except Salima, Zn concentrations were between 20 and 30 mg/kg, below adequate levels according to some reports, but above the 14 to 18 mg/kg level reported to be indicative of deficiency. Three fields near Salima, and one field in each of the other areas were observed to exhibit symptoms of Zn deficiency, which are easily recognized in young maize plants. Manganese, like Zn, was found in many fields to be either near or below the lower limit of the adequate range, depending on which published value is applicable, 50 or 20 mg Mn /kg. No symptoms of Mn deficiency were seen during the survey. None of the values of Mn measured were high enough to suggest toxicity, although Mn toxicity is known to occur at higher soil pH levels than does Al toxicity.

Two micronutrients, namely B and Cu, did consistently appear at levels indicative of mild to severe deficiency. Both of these

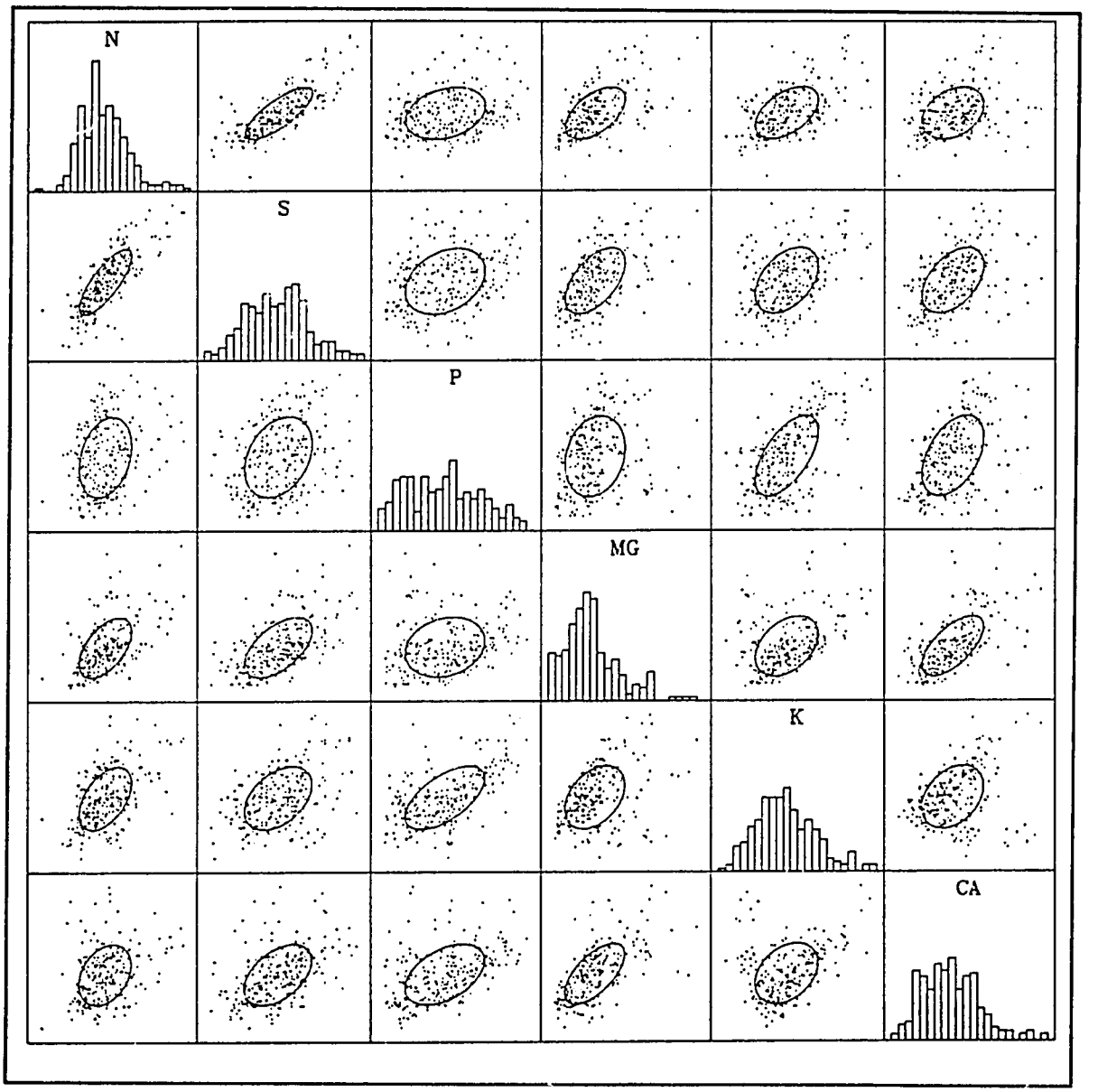

Figure 10. Relationships among six macronutrients in young maize plants, sampled in 1990 from four areas in Malawi. Histograms show relative distribution of values. Ellipses enclose the 50% probability area.

micronutrients were especially low in maize from the Mzuzu area. For young maize, adequate B concentrations have been reported to be 7 to 25 or 4 to 25 mg B/kg. Using either range, nearly all the samples analyzed in this survey were below adequate levels. Many plants had extremely low B concentrations of < 2 mg/kg. Most samples from Mzuzu had 1 mg/kg. No B deficiency symptoms were noted in the field, although such symptoms usually are expressed on the cob, and thus would not have been detected during the survey, since, in most cases, we visited the fields prior to cob formation. As will be discussed later, others researchers (Kumwenda and Scott-Wendt, personal communications, 1993) have recently found responses

to B in several field sites in Malawi.

For Cu, if 7 to 20 mg Cu/kg is considered the adequate range, then nearly all fields had inadequate levels in the young maize. However, if 5 to 20 mg Cu / kg is considered adequate, then only Mzuzu had a large proportion of less than adequate Cu levels in the young maize. Copper deficiency symptoms occur very rarely in maize, and we observed none during the survey.

Figure 12 shows that the distributions of Fe, Mn, and B were not normal, but skewed with a long "tail" consisting of a few relatively high values. Maize tissue concentrations of Al and Fe were very closely related (upper right and lower left corners of Figure 12), one increasing with the other. Manganese also increased with Al, but not with Fe. A weak positive relationship was seen between Cu and Zn.

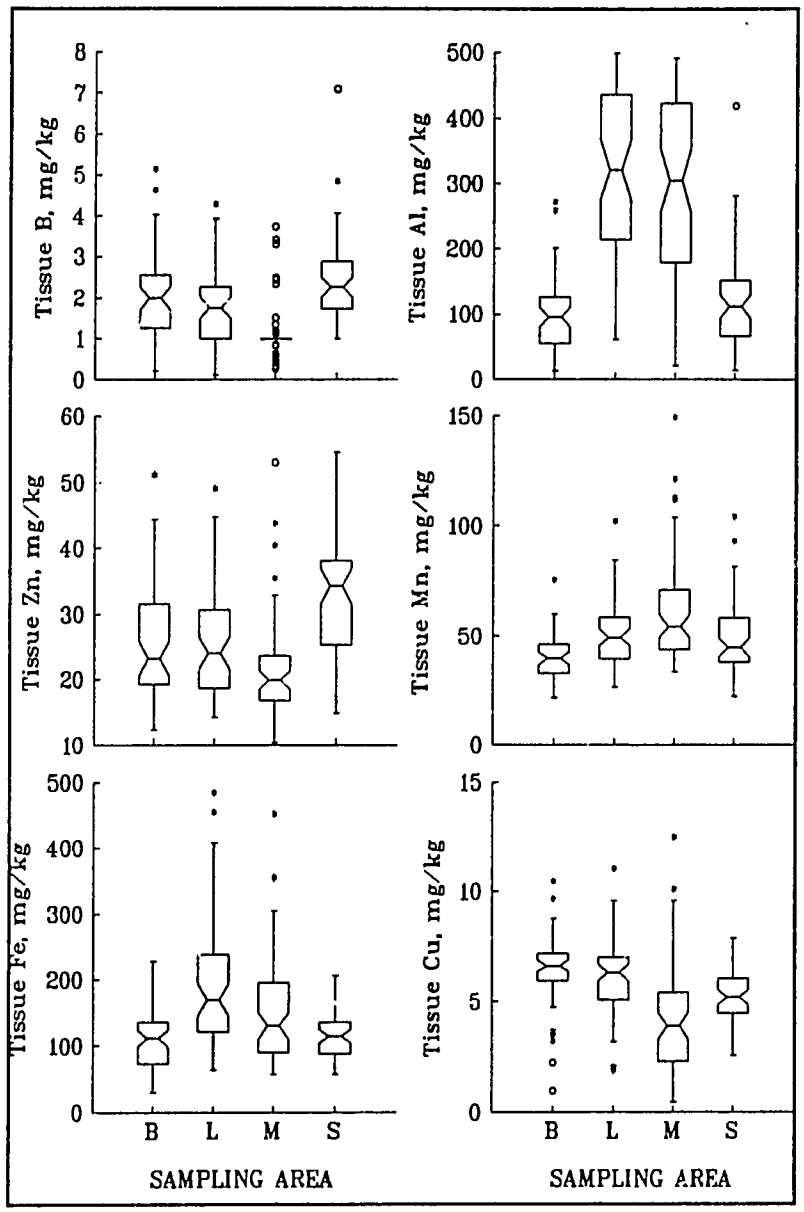

Figure 11. Box plots showing distribution of trace element concentrations in young maize plants from Balaka (B), Lilongwe (L), Mzuzu (M), and Salima (S) areas in Malawi.

In some respects, young plants in the V8 to V12 stages may be better for micronutrient deficiency diagnosis than more mature plants inspected after tasselling. Many micronutrient deficiency symptoms are more readily observed in young plants. Also, limitations of such macronutrients as N, P or S on maize growth are more likely to be fully expressed as the plant uses up the readily available reserves of these nutrients in its late growth stages. These macronutrient deficiencies, if present, tend to mask any micronutrient deficiency symptoms that may have been visible earlier. On the other hand, benchmarks for critical tissue

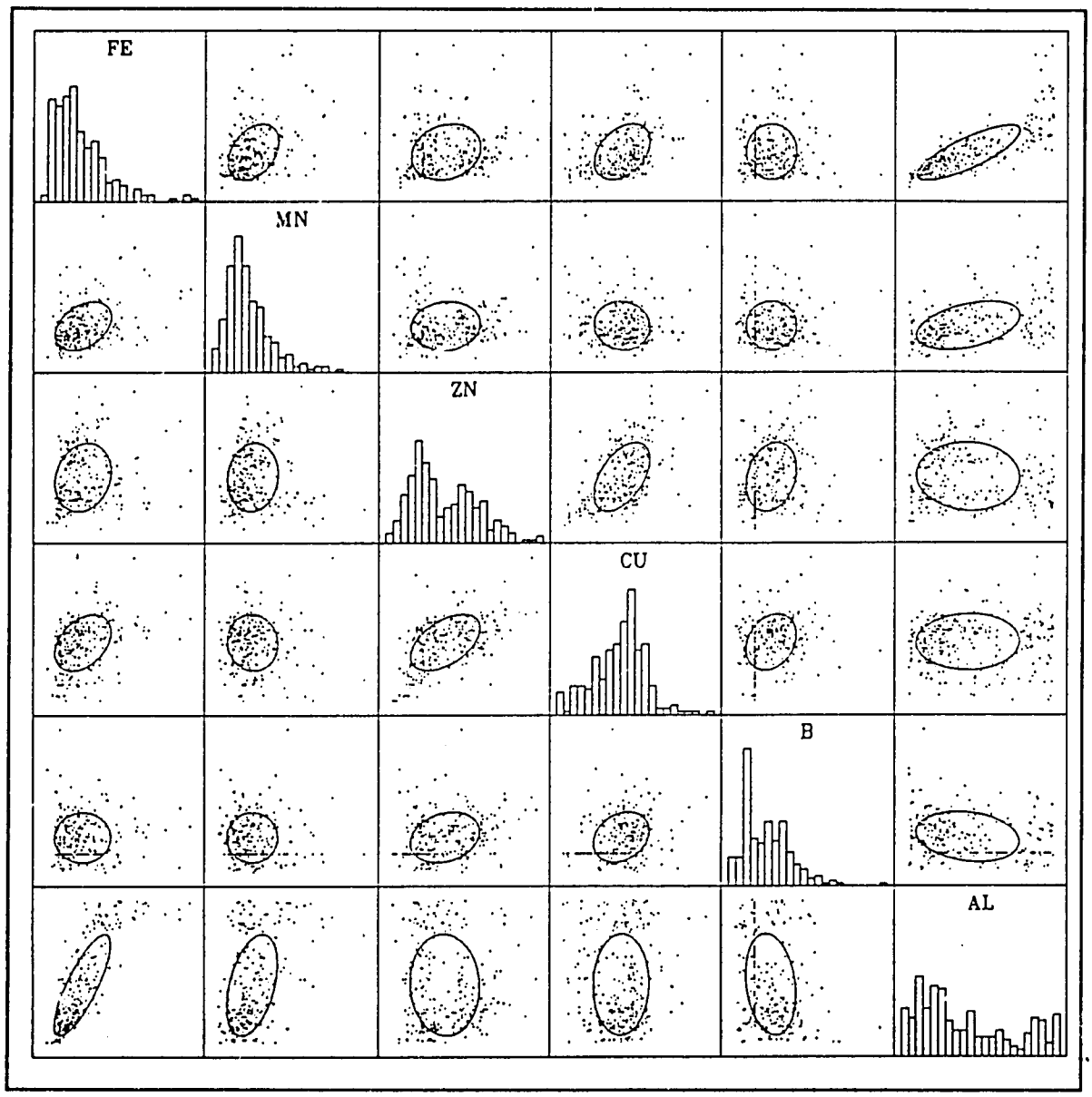

Figure 12. Relationships among six trace elements in young maize plants, sampled in 1990 from four areas in Malawi. Histograms show relative distribution of values. Ellipses enclose the 50% probability area.

concentrations are considered to be less relaiable for young maize plants, as compared to plants at tasseling. A great deal of information is available in the literature on the critical values and sufficiency ranges for nutrient concentrations in maize tissue at tasseling, especially for earleaf tissue (from the leaf opposite and below the ear). These data will be discussed next.

Maize Near Tasseling Stage

Figure 13 uses box plots to show the distributions of macronutrient concentrations in earleaf tissue from the second

sampling (at the tasseling to early milk stages) of maize in the four sampling areas. The dashed lines indicate published lower limits of the adequate range. Concentrations falling between these lines are probably marginally adequate. The narrow point of the notch on these box graphs represents the median value. The mean values of earleaf macronutrient concentrations for each sampling area are given in table V. As is expected for more mature plants (Walworth and Sumner, 1987), the tissue concentrations of most nutrients were lower at the second sampling than the first. This reduction was especially pronounced for N and K, and least evident, if at all, for Ca and Mg.

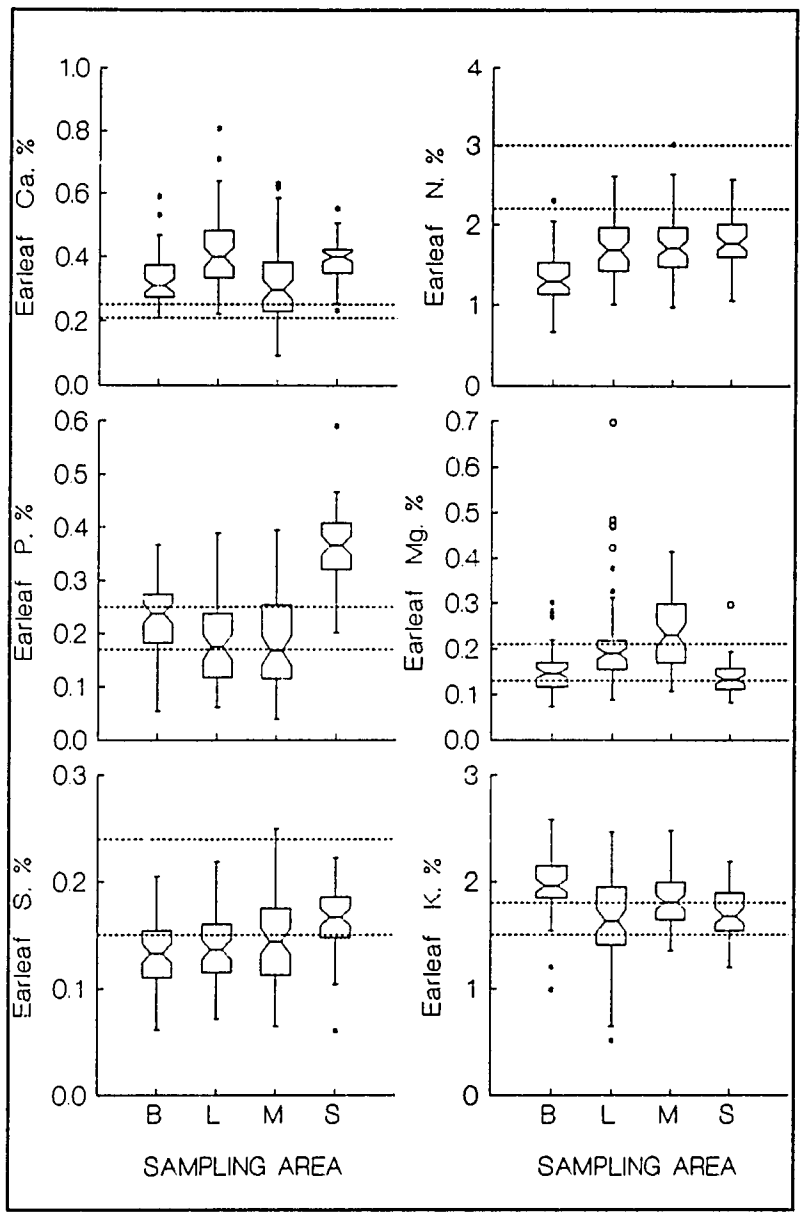

Figure 13. Distribution of maize earleaf macronutrient concentrations from Balaka (B), Lilongwe (L), Mzuzu (M), and Salima (S) areas in Malawi. Dashed lines indicate published lower limits of adequate range.

It can also be seen, by comparing Figures 9 and 13, that for certain nutrients, the relative status in the four areas remained quite similar at the tasseling stage to that observed at the vegetative stage. For example, P concentrations in maize grown in Salima were well above the marginal range and much higher than for those grown in the other three areas. Lilongwe, however, was no longer higher in maize P status than Mzuzu, both of these areas being characterized by maize in or below the marginal range of P concentrations at tasseling. On the other hand, for certain nutrients, the ranking of the four areas had reversed between the two sampling dates. Maize from Salima, for example, was highest in K and well above the marginal range at the first sampling, but only third highest and well within the marginal range at he second sampling. Maize from all four areas was below the

lower limits of the adequate range for N at the second sampling, but Balaka, which had earleaf N concentrations significantly above those of the other areas at the first sampling, had concentrations significantly below the others at the second sampling. Nutrients for which more than 50 per cent of the fields had earleaf concentrations below the lower published boundaries for adequacy included N for all four areas, P for Mzuzu, and S for Balaka, Lilongwe, and Mzuzu (see Figure 13).

Table V. Mean earleaf tissue concentration of macronutrients from four sampling areas in Malawi.

Area	N	S	P	K	Ca	Mg
Balaka	1.33	0.134	0.226	1.98	0.330	0.151
Salima	1.78	0.166	0.365	1.70	0.385	0.138
Lilongwe	1.70	0.137	0.187	1.63	0.421	0.213
Mzuzu	1.73	0.146	0.187	1.84	0.311	0.235

Of the trace elements analyzed in the earleaf tissue (see Figure 14), the metals were generally in greater concentration in the two areas of weathered residual soils (Mzuzu and Lilongwe), than in the two lacustrine areas (Balaka and Salima). The distinction between these areas with regard to earleaf trace metal concentrations may be related to the slightly higher pH range found in the lacustrine soils. Those nutrients for which the earleaf concentrations fell below the lower published boundary for the adequate range included B for all areas except Lilongwe, Zn for Balaka, and Cu for all areas except Mzuzu. For both Cu and Zn, Mzuzu had the lowest median tissue concentration at the first sampling date, but the highest at the second sampling date. We do not know the reasons for this reversal of ranking. We speculate that subsoil horizons, reached by the more mature root systems, may have been relatively rich in Cu and Zn. Mean values for micronutrient concentrations in each area are given in Table VI.

Table VI. Mean concentrations of micronutrients in maize earleaves from four sampling areas in Malawi.

Area	Fe	Mn	Zn	Cu	B
Balaka	28.4	32.3	8.4	0.79	2.0
Salima	45.9	42.0	13.1	0.78	1.6
Lilongwe	80.6	70.8	13.1	3.31	2.7
Mzuzu	112.0	86.9	16.6	3.30	1.6

Maize DRIS Indices for the Smallholder Survey

The Diagnostic and Recommendation Integrated System (DRIS) pioneered by Beaufils (1973) in South Africa and further developed by Sumner's group in Georgia, provides a means of evaluating plant tissue analysis data that considers the balance among nutrient elements and not simply the concentration of any one element. As such, the DRIS provides an alternative to the critical value or critical range as a means of determining whether a tissue analysis indicates a deficiency in a given nutrient and whether the plant can be expected to respond to an additional of that nutrient. Theoretically, the DRIS has several advantages over the critical value approach. The evaluation is less sensitive to variations in

the exact stage of growth and plant parts sampled; and several nutrients may be ranked with respect to their relative degree of deficiency. These factors make the DRIS especially attractive for evaluating plant nutrient status in a farm field survey such as undertaken by this project. On the negative side, the DRIS calculations require very accurate data on many nutrient elements, in order to evaluate the status of any one element.

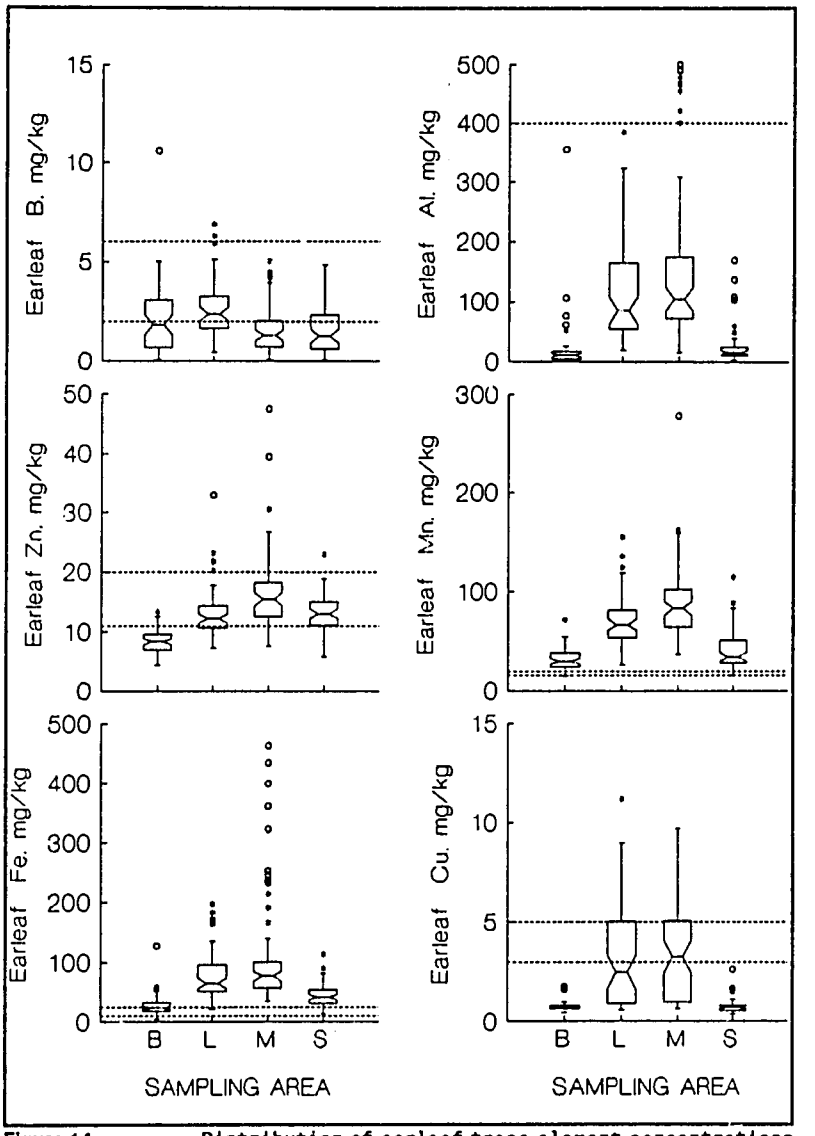

Figure 14. Distribution of earleaf trace element concentrations from Balaka (B), Lilongwe (L), Mzuzu (M), and Salima (S) areas in Malawi. Dashed lines are published lower limits of adequate range (toxic range for Al).

The mean values of DRIS indices (based on earleaf tissue analysis) for ten elements are given in Table VII. The more negative the index, the more severely deficient is that nutrient. Conversely, positive indices indicate a relative surplus of a nutrient. It is obvious that the most negative indices found were those for Cu and B. This was true for all four areas, although the B indices were less extreme in Lilongwe. The indices for nitrogen were negative, on the average, in all areas except Salima. Only Lilongwe had negative index means for P and S. The mean index for iron was quite negative in the two lacustrine soil areas. No iron deficiency symptoms were observed in the field, however. As discussed below, the occurrence of extremely large negative indices for B and Cu tended to mask the expression of negative indices for other nutrients, which were found at low, but not extreme, concentrations in the sampled maize tissue. For the purposes of focusing on certain elements which appeared to be deficient on the basis of foliar symptoms and yield responses, DRIS indices were re-calculated without inclusion of B and Cu. The results of these calculations are discussed in a later section, but it should be noted here that the re-calculated N, P

and S indices were more frequently negative. The relative ranking of the four sampling areas, and of fields within these areas, remained largely unchanged by the re-calculation.

The DRIS index calculations are quite sensitive to extremely low values for tissue concentrations occurring in the denominator of the summed ratios. Therefore, the presence of very low levels of one or two nutrients may so alter the indices of all the other nutrients, that useful interpretations are difficult. In the 1990 survey of smallholder maize fields, in each area except Mzuzu, several samples of maize earleaf tissue contained < 1 mg/kg of B or Cu. The extremely low levels of these nutrients resulted in DRIS indices < -250. Since all the DRIS indices for a plant sum to zero, the remaining elements tended to have positive indices. Thus, in some cases, where foliar deficiency symptoms were observed in the field for elements such as S or Zn, the DRIS indices for these elements turned out to be positive. Figure 15 illustrates both the usual linear relationship between the DRIS index and tissue concentration of an element (Zn and S are usd as examples), and the unusual artifact logarithmic relationship that occurred for Cu and B in the 1990 survey samples. The triangle symbols in Figure 15 represent those samples with extremely negative DRIS indices for B or Cu. It can be seen that those samples were responsible for the logarithmic relationship expressed for Cu and B. The samples which were extremely low in Cu and B also accounted for the major deviations from the usual linear relationship between tissue concentration and DRIS index for Zn, S, and other (not shown) elements. It can be seen that, even for the low B-Cu group of samples, this relationship was still linear, if more steeply slope. We conclude that even where extreme tissue concentrations of certain nutrients caused the DRIS indices of other nutrients to increase to positive values, the indices still indicate the relative deficiencies or growth limitations. If B and Cu were omitted from the data set, then the indices of most other nutrients are decreased (data not shown). In particular, negative indices for N, P, and S occured much more frequently. Rather than

Table VII. Mean values for maize earleaf DRIS indices of five macro- and five micro-nutrients in four sampling areas in Malawi.

Element	Sampling Areas in Malawi			
	Balaka	Lilongwe	Mzuzu	Salima
	----------DRIS Index----------			
N	-3	-8	-4	11
S	20	-3	6	28
P	42	-2	1	82
K	56	9	24	32
Ca	24	13	5	27
Mg	27	16	37	18
Fe	-52	-3	15	-3
Mn	24	27	60	27
Zn	-10	-8	5	-8
Cu	-125	-56	-50	-56
B	-91	-24	-151	-24

arbitrarily omit certain elements in the analysis, we will proceed to interpret the relative values of the indices as representing the relative degree of limitation to growth, elements with lower index value being more limiting, even if the values are positive.

We do not believe that the extremely low values for Cu and B were the result of inaccurate analysis, because repeated analyses were very close, control samples included in each batch had accurate (much higher) levels of both of these elements, and the low values occurred in two runs of the emission spectrograph, several months apart. However, as already mentioned, plant symptoms of B and Cu deficiency were not seen in the field. Maize grown in on-farm experimental plots receiving adequate amounts of N, P, and S yielded well and produced well-formed, well-filled ears. The great majority of the maize sampled in our survey consisted of local, open-pollinated farm-selected land races. Even the few commercially bred culitvars were the products of selection on local soils, generally fertilized with only N and P. It is therefore not unlikely that the maize in our survey was adapted to the low levels of B and Cu found in many Malawi soils. The norms on which the calculated DRIS indices were calculated may not have reflected such an adaption by Malawi land races of maize. Therefore, we suggest that the extremely low indices for B and Cu may have been artifacts of inappropriate norms, rather than incorrect analyses or actual extreme deficiencies. The development of localized DRIS norms would require many more crop yield measurements, and was beyond the scope of this project. We did not test for growth response to added B in the field experiments because our preliminary survey in 1989 did not show low levels of B. The B analyses of samples from the 1989 survey, done by wet chemistry at the Chitedze soils lab, gave results (data not shown) about an order of magnitude higher (10 to 40 mg/kg) than the results reported here. It is possible that the higher B reported by

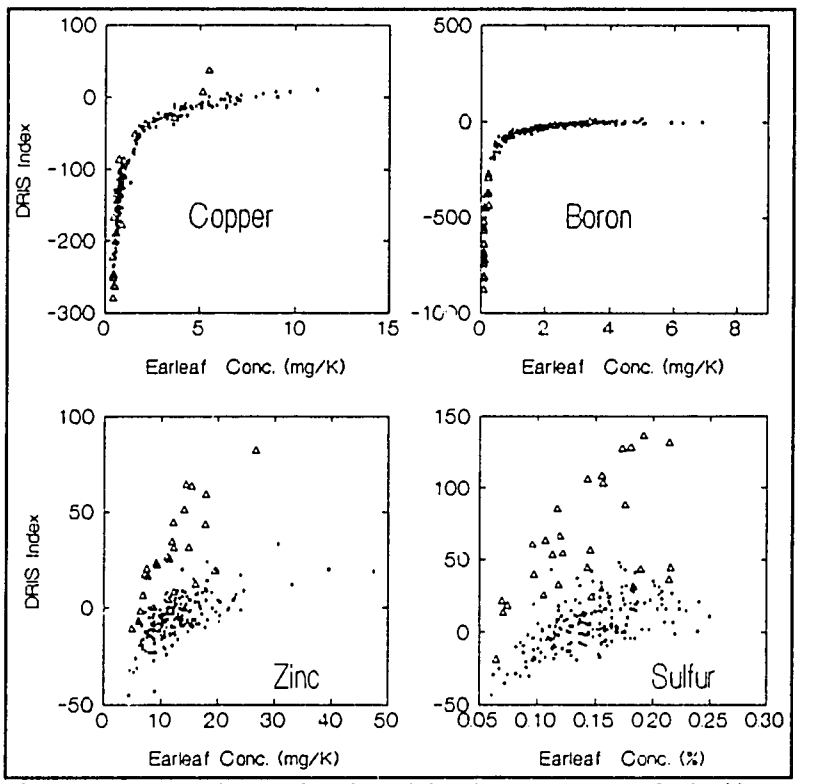

Figure 15. The relationship between DRIS indices and earleaf concentrations of four elements in the 1990 survey of smallholder maize fields. Triangles represent samples with DRIS indices < -250 for either B or Cu.

the Chitedze lab could have been an artifact resulting from the use of borosilicate (Pyrex) glassware, or water distilled in such glass.

At any rate, the widespread occurrence of such extremely low tissue concentrations of Cu and B in the 1990 survey material, and their generally marginal concentrations in nearly all of the maize sampled in 1990, suggests that further investigation of these two nutrients in Malawi agriculture is warranted. This conclusion is also supported by the observation of maize growth responses to added B in a number of experiments currently being conducted by the Maize Commodity Team of the Malawi Ministry of Agriculture (Kumwenda and Scott-Wendt, personal communication, 1993).

Perhaps a clearer picture of the suite of nutrient limitations for each of the four sampling areas can be seen in Figures 16 and 17, which are box plots showing the median and spread of DRIS index values for each area. These figures illustrate how the DRIS can be used to compare sufficiency or deficiency among all nutrients on a common scale, something which cannot be done with the tissue concentration data itself. As was can also be seen in table VII, the most striking feature of the data for all four areas is the extreme negative B indices for both young maize plants (Figure 16), and plants in the reproductive stage (Figure 17). This anomaly aside, the follow trends are evident for the young growth stage of maize: N, P, Ca and Zn had relatively low indices in the highly weathered soil areas (Mzuzu and Lilongwe); in Salima, N and S indices were nearly all substantially negative; in Balaka, Ca and Zn indices were the most negative.

The suite of DRIS indices for maize at tasseling, shown in Figure 17, was quite distinctive for each area. In Balaka, only N, Fe and Zn indices (in addition to those for Cu and B, discussed above) were frequently negative. For Salima, none except Fe (plus Cu and B) were frequently negative. For Mzuzu and Lilongwe, N was more frequently negative than in the lacustrine areas, but S, P, and Ca were also frequently quite negative.

In a final approach to examine the maize tissue analysis data, we calculated availability indices for each nutrient according to the formula suggested by Beverly (1987). This availability index compares the sample earleaf concentration of a nutrient to that of a world-wide population of maize. Unlike the DRIS, this system considers each nutrient independently. An index of -1 indicates that the sample is 1.0 standard deviation below the world mean for the nutrient in question . Indices between +1 and -1 are considered to be in the sufficiency range for the nutrient in question. A sample with an index of -1 to -2 is considered to be low; an index < -2 suggests outright deficiency.

The data in table VIII show that in all four areas, the mean earleaf concentrations of all nutrients were below the world mean.

Also, while individual samples had "deficient" indices, only N would be considered below the sufficiency range, on the average. The next lowest indices were for S and Cu. The occurrence of a few very low Cu and B concentrations did not appear to skew the results with this index, in the manner seen with the DRIS method.

Table VIII. Mean availability indices (by the method of Beverly, 1987) of five macro- and five micro- nutrients for four sampling areas in Malawi.

Element	Sampling Areas in Malawi			
	Balaka	Lilongwe	Mzuzu	Salima
	--------Availability Index---------			
N	-1.23	-0.99	-0.98	-0.94
S	-0.70	-0.68	-0.63	-0.53
P	-0.25	-0.35	-0.35	-0.08
K	-0.24	-0.43	-0.32	-0.39
Ca	-0.33	-0.18	-0.36	-0.24
Mg	-0.21	-0.06	-0.01	-0.24
Fe	-0.56	-0.03	-0.15	-0.47
Mn	-0.27	-0.01	-0.12	-0.20
Zn	-0.40	-0.29	-0.21	-0.29
Cu	-0.74	-0.58	-0.58	-0.74
B	-0.46	-0.42	-0.49	-0.49

With either the DRIS or the availability indices, it is relatively easy to determine at a glance which nutrients the indices suggest are limiting, and which appear to be in sufficient or surplus supply. The data which have been just discussed clearly demonstrate that regional differences in fertility status of crops and soils can be defined by sampling maize leaves from farmers' fields. For certain nutrients, the differences between sampling areas was sufficiently great to imply a need for changes in fertilizer distribution policy. For example, there can be little question that Mzuzu and Lilongwe should be much higher priority areas for P fertilizer distribution than either Salima or Balaka. Copper suppliments would appear to be most needed in the Lakeshore areas. Relationships between tissue and soil parametrs will be discussed next, after which variability <u>within</u> each sampling area will be addressed. Confirmation of the tissue diagnosis with field experiments will be discussed in the final part of the results section.

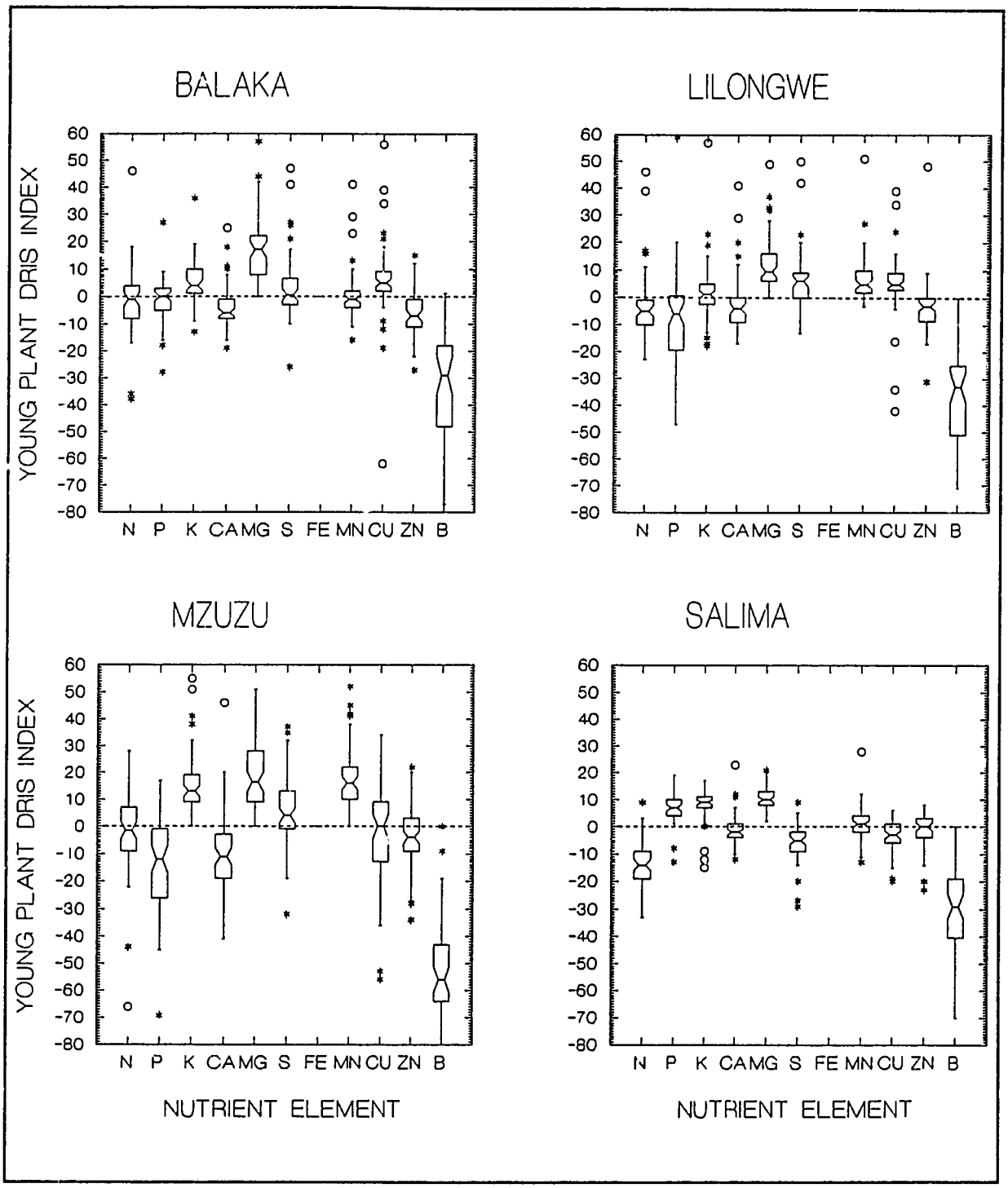

Figure 16. Box plots depicting medians and distribution of DRIS indices for young maize plants in four areas in Malawi. Young plant DRIS norms for Fe are not available.

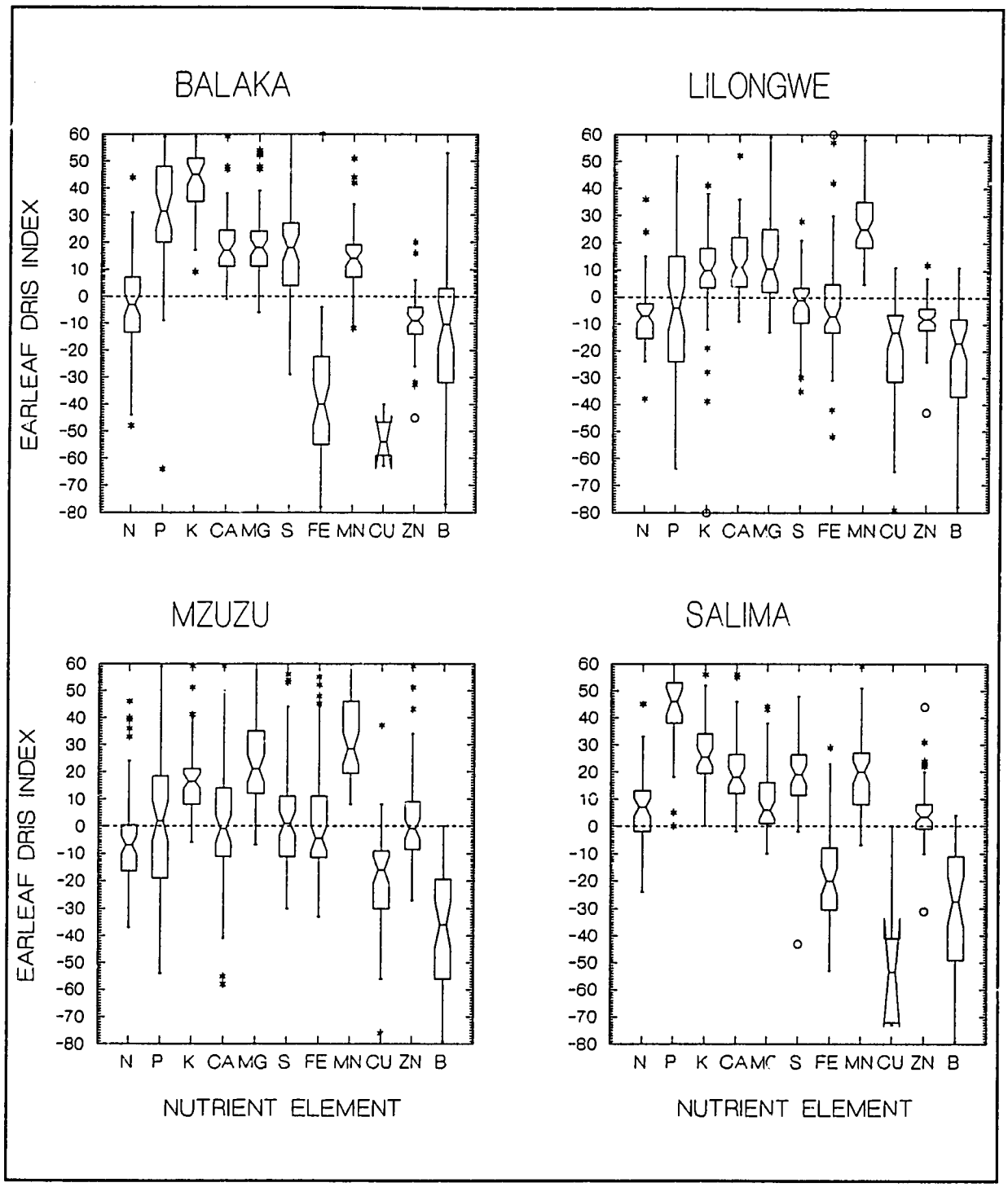

Figure 17 Box plots depicting median and distribution for the DRIS indices calculated from nutrient concentrations in maize earleaf tissue near tasseling. For clarity and scale, extreme data points are not shown.

Relationships between soil and plant parameters.

Our data set of soil parameters is less complete than we had planned it to be, mainly because, after handling at the Chitedze lab, insufficient soil remained in most samples for a complete suite of analyses. A significant gap in the soil data is the lack of soil micronutrient data for the 1990 survey. In 1989, soil samples were collected from approximately 100 maize fields. Of these, 51 from the Lilongwe area were analyzed for micronutrients metals extractable with DTPA. When these values were compared with the concentrations of these nutrients in earleaf tissue from these same maize fields, no significant relationships were found between the soil and plant variables. While the relationship between extractable micronutrients and tissue concentrations is often weak, we suspect that poor analytical quality was a factor. For the 1989 data, there was not even a relationship between soil pH and extractable Fe, Zn or Cu, despite the fact that the solubility of these nutrients is known to increase markedly with a decrease of pH from 6 to 4.5, the range encountered in 1989 in the Lilongwe area.

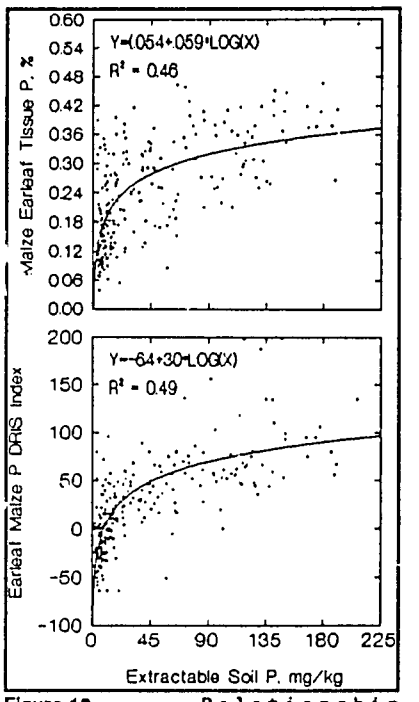

Figure 18. Relationship between extractable soil P and earleaf P concentration or P DRIS index for 238 samples from four areas in Malawi.

In the 1990 survey data, there were significant relationships between soil variables and maize tissue nutrient concentrations. Soil pH tended to be inversely related to the DRIS index for Cu, or the log of the Cu concentration in tissue, as would be expected. Generally, the relationship between soil variables and maize nutrient status was stronger for DRIS indices than for tissue concentrations. Figure 18 shows these relationships for phosphorus. Though the R^2 value was a modest 0.49, the logarithmic relationship between extractable soil P and earleaf DRIS P index was the strongest of all the soil-plant relationships in the 1990 data set. Solving for a DRIS index of 0, the critical concentration of double acid extractable soil P would be approximately 9 mg/kg. The value for this soil test used by the University of Maryland Soil Test Lab to indicate a "low" P soil is 10 mg/kg.

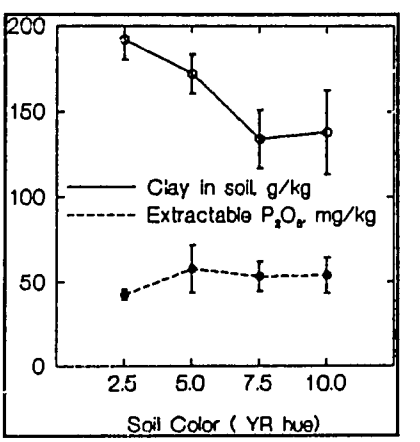

Figure 19. Relationship between clay content, soil color, and extractable P_2O_5 equivalent of Mzuzu area surface soils.

The published soil map of Northern Malawi (Malawi Government, 1983) shows a band

of ferralitic soils running from northwest to southeast through the center of the Mzuzu sampling area, the remaining soils in the area being mapped as ferruginous. On the ground, the ferralitic soils were found not in a solid band, but were observed to be intermingled with the redder ferruginous soils.

During the surveys in 1989 and 1990 we identified distinct areas of light colored sandy soils that contrasted with the surrounding redder, slightly finer textured soils. When the soil at each site was classified by hue from the reddest (2.5 YR) to the least red (10 YR), a fairly strong relationship could be seen between the colors and clay content of the surface soils (Figure 19).

Such red soil hues are generally caused by high contents of iron oxides appearing in the clay fraction or as coatings on sand grains. Iron oxides are a major factor contributing to the capacity of soils to strongly sorb phosphorous, greatly reducing the availability of this nutrient to crops. We therefore expected that soil hue might give some indication of the P fertility status of the soils in the Mzuzu area. Yet, little or no relationship was found between soil hue and soil test extractable P in these soils (Figure 19).

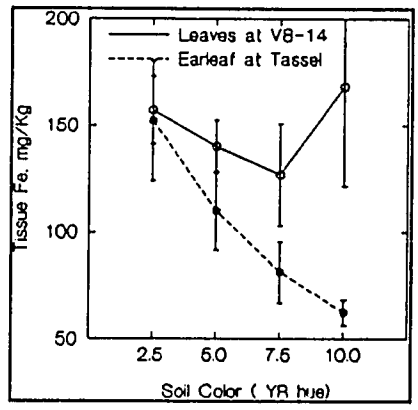

Figure 20. Relationship between Fe concentration in maize tissue at two stages and soil color (redness) in the Mzuzu area.

There were some interesting relationships between soil hue and nutrient contents of earleaf maize tissue, however. The Fe content of the earleaf tissue increased markedly as the soil hue became redder (Figure 20), indicating that some of the Fe must have been labile enough to be taken up by plant roots, possibly after reacting with rhizosphere reductants or chelating agents. The relationship between soil redness and maize tissue Fe content was much more pronounced for maize at tasseling than for young seedling maize, largely because the young plant data was far more variable. Although the leaves were rinsed in distilled water when collected, some of this variability may have resulted from surface contamination of the young plants with soil splashed during rains. It is certainly more likely for young plant leaves 30 cm above the soil surface to become contaminated with soil, than for earleaves approximately 150 cm high to become so contaminated. At

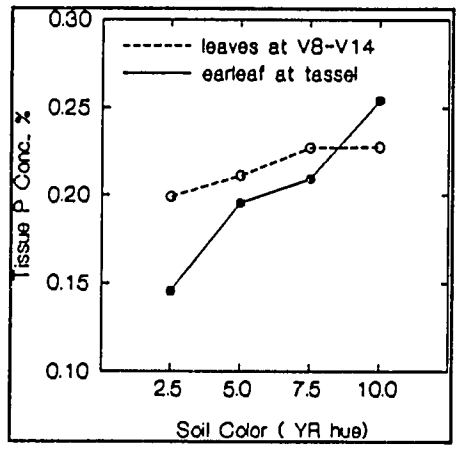

Figure 21. Relationshipbetween tissue P concentration in maize at two stages and soil color (redness) in the Mzuzu area.

the same time, the P content of the maize tissue was markedly lower on the redder soils (Figure 21). Again, the relationship was strongest for the more mature maize.

These results confirmed the hypothesis that iron oxides in these soils reduced the availability of P. Perhaps more importantly, these results showed that soil test extractions, which may detect gross differences in P availability, may be inadequate to predict the differential P supplying power of different soil groups in a landscape. Geostatistical analyses revealed only weak spatial dependencies for any of these variables, possibly because of the extensive inter-fingering of the red and light colored soils at scales smaller than the mean inter-sample distance.

Spatial Variations Within Sampling Areas

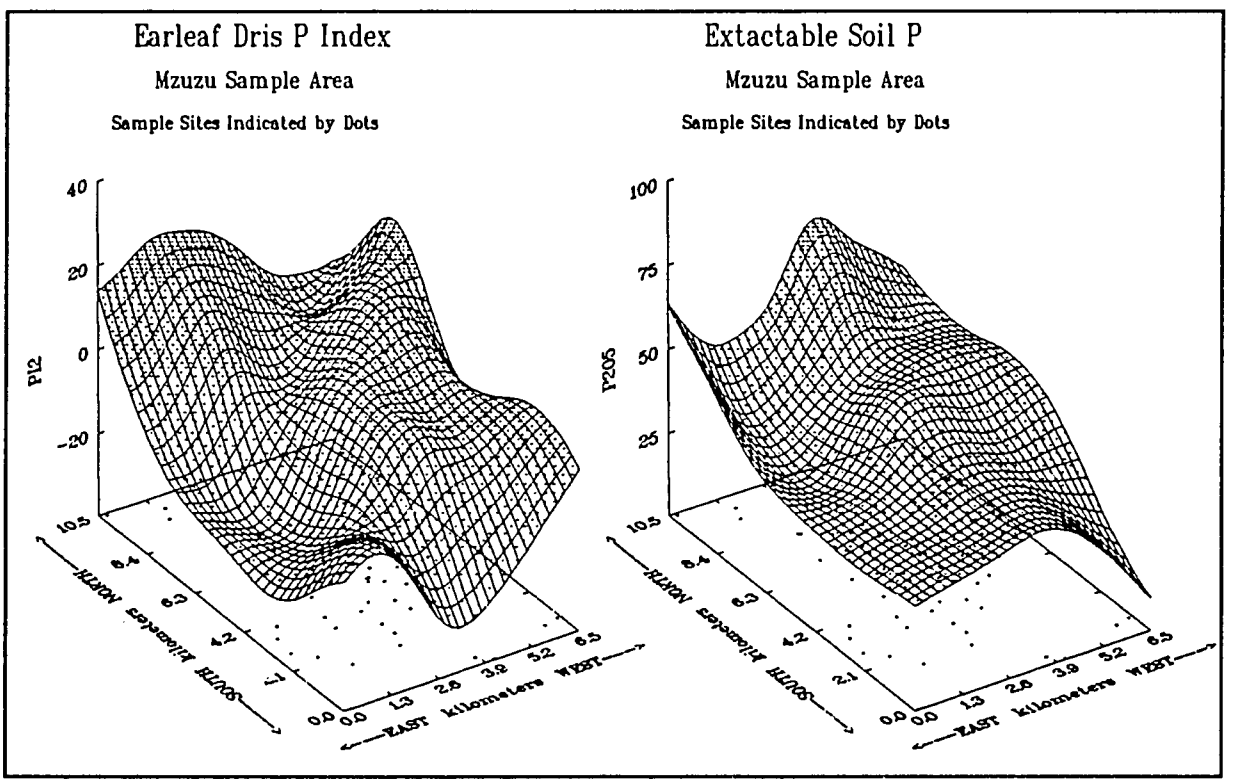

Figure 22. Spatial distribution of maize earleaf DRIS P indices (left) and soil P (right) in 1990 Mzuzu area survey.

Figure 22 illustrates the spatial variation, within a sampling area, of a plant variable (DRIS P index) and a soil variable (extractable soil P). The map of DRIS index distribution for earleaf P (Figure 22, left) shows a declining P status as one moves south and west in the Mzuzu sampling area. This also is roughly the direction of increasing clay content measured in the Ap horizon (data not shown). Extractable P was also lower in the southwest quadrant of the Mzuzu area (Figure 22, right), but the spatial trends of plant and soil P status were only loosely

similar. The areas of low DRIS indices correspond quite closely to the locations in which foliar P deficiency symptoms were observed. The "escarpment" in DRIS index values also corresponds quite closely to the general boundary between the zones of redder and lighter brown soils discussed above. Thus a contour map of DRIS indices constructed by a distance weighted least squares regression algorithm appears to be of some value in delineating the zones of lowest P status.

There are several commonly accepted methods of smoothing spatial data so as to highlight trends and estimate values for locations between actual sample points. The results of two such methods are compared in Figure 23. Both maps in Figure 23 show the distribution of estimated DRIS P Index values in the Mzuzu sampling area. The left hand map was produced using the SYSTAT/SYGRAPH computer package's distance-weighted least squares (DWLS) algorithm. The right-hand map was produced with the same data using a kriging algorithm in the GEOEAS computer package. Both show very similar trends, mainly the lower P status in the south-west quadrant. Care must be taken to avoid over-interpreting either map. The DWLS map suggests more information about localized DRIS index values than is probably justified by the relatively sparse data. The kriged map shows much more boundary detail than can be justified by the relatively few points actually sampled. We believe that the three-dimensional presentations used in this report provide a good overview of the spatial trends present, without suggesting the detailed boundaries implied by the two dimensional maps (by either kriging or DWLS).

An example of the use of the three-dimensional DWLS mapping technique is given for the Lilongwe area in Figure 24. Here, the spatial distributions of three plant variables indicative of P status are shown. There was a close correspondence between the distribution of tissue P at the first (vegetative, Figure 24a) maize sampling and that at the second (reproductive, Figure 24b) maize sampling stage, there being a "ridge" of high tissue P running north-south down the center of the area in both cases. The extremely high tissue P values at the northern end of the area are not reflected in the DRIS indices because the concentrations of other nutrients were also quite high in that zone of generally fertile soils. The increase in P status at the southern end, on the other hand, is even more pronounced in the DRIS data than in the tissue concentration data, because that zone contained relatively sandy soils with lower P fixation potential and generally lower levels of N, S and other nutrients.

A final example is given in Figure 25, which shows the distribution of DRIS Indices for three micronutrients in the Lilongwe area. The DRIS indices for the two metals, Cu and Zn, dropped off with the decreasing clay content of the soils in the southern end of the Lilongwe area. The boron DRIS index also declined slightly towards the southern end of the sampling area.

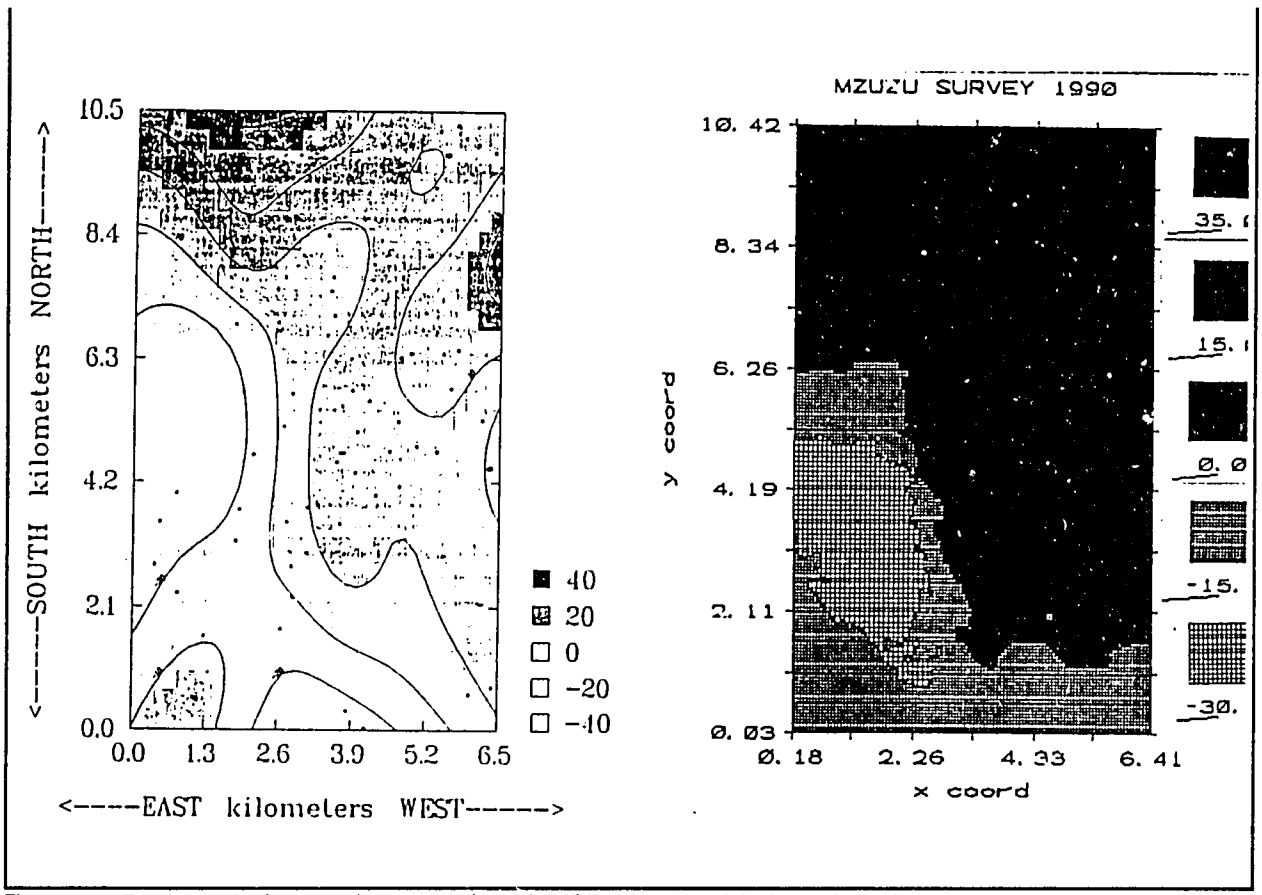

Figure 23. Two methods for mapping spatial variability in DRIS P Index values from the 1990 Mzuzu area survey: distance-weighted least squares regression (left) and point kriging following semi-variogram analysis (right).

The dramatic drop in B DRIS index in the northwest quadrant reflects several samples with tissue B concentrations of less than 1 mg B/kg, which, as has already been discussed, led to extremely low B DRIS index values. We do not know what circumstances peculiar to that part of the Lilongwe sample area lead to such low B values.

In summary, the localized fertility maps produced from our survey data would be useful in pointing out zones in which particular fertilizer trials might be best situated, or in correlating fertilizer response with soils information. However, unless clearly defined, contrasting, and relatively homogeneous soil zones are present, these maps should not be used to modify recommendations for individual small holder farms.

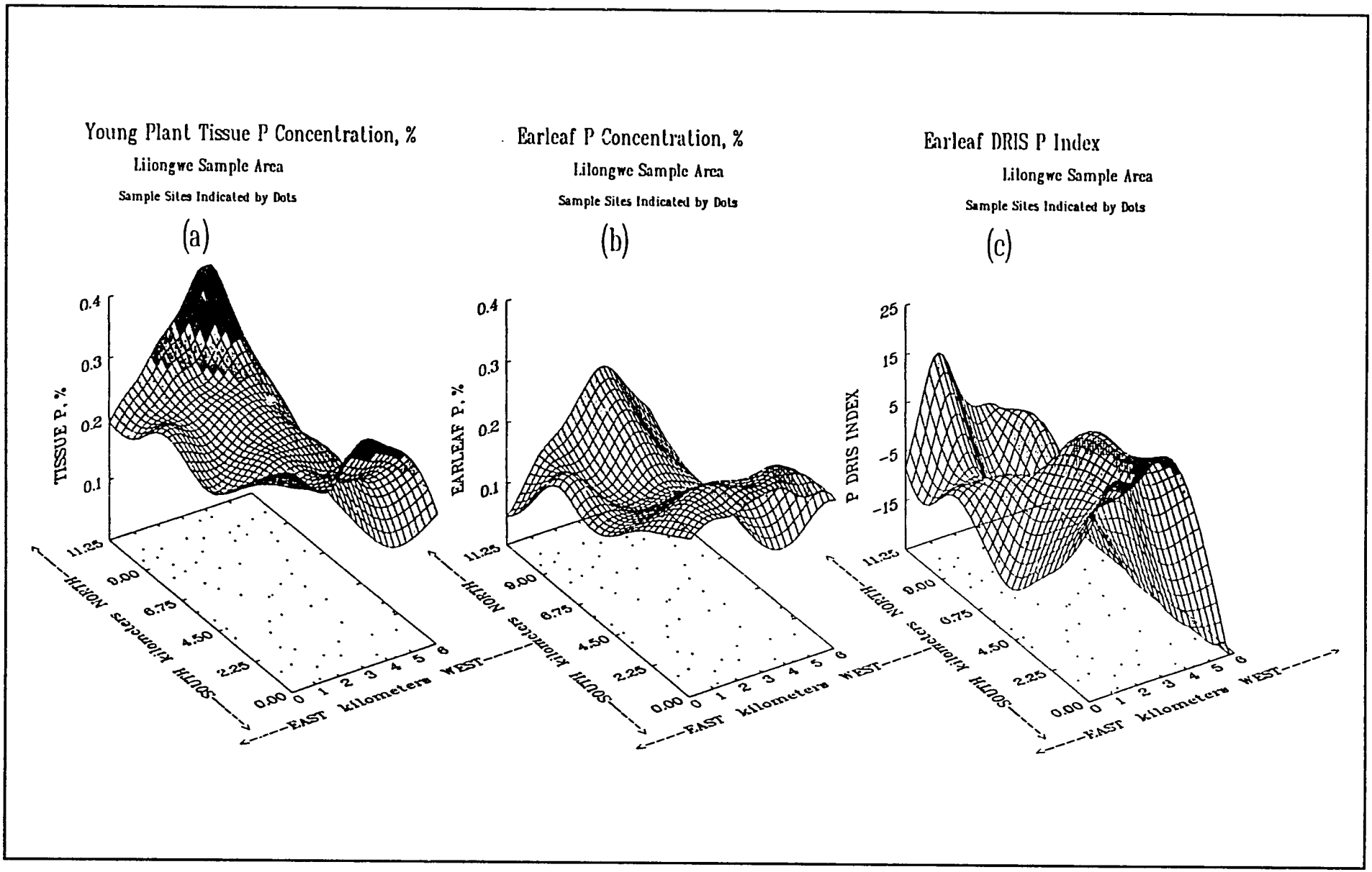

Figure 24. Spatial distribution (DWLS) of young plant tissue P, earleaf P, and earleaf DRIS P Index in the 1990 survey of the Lilongwe area.

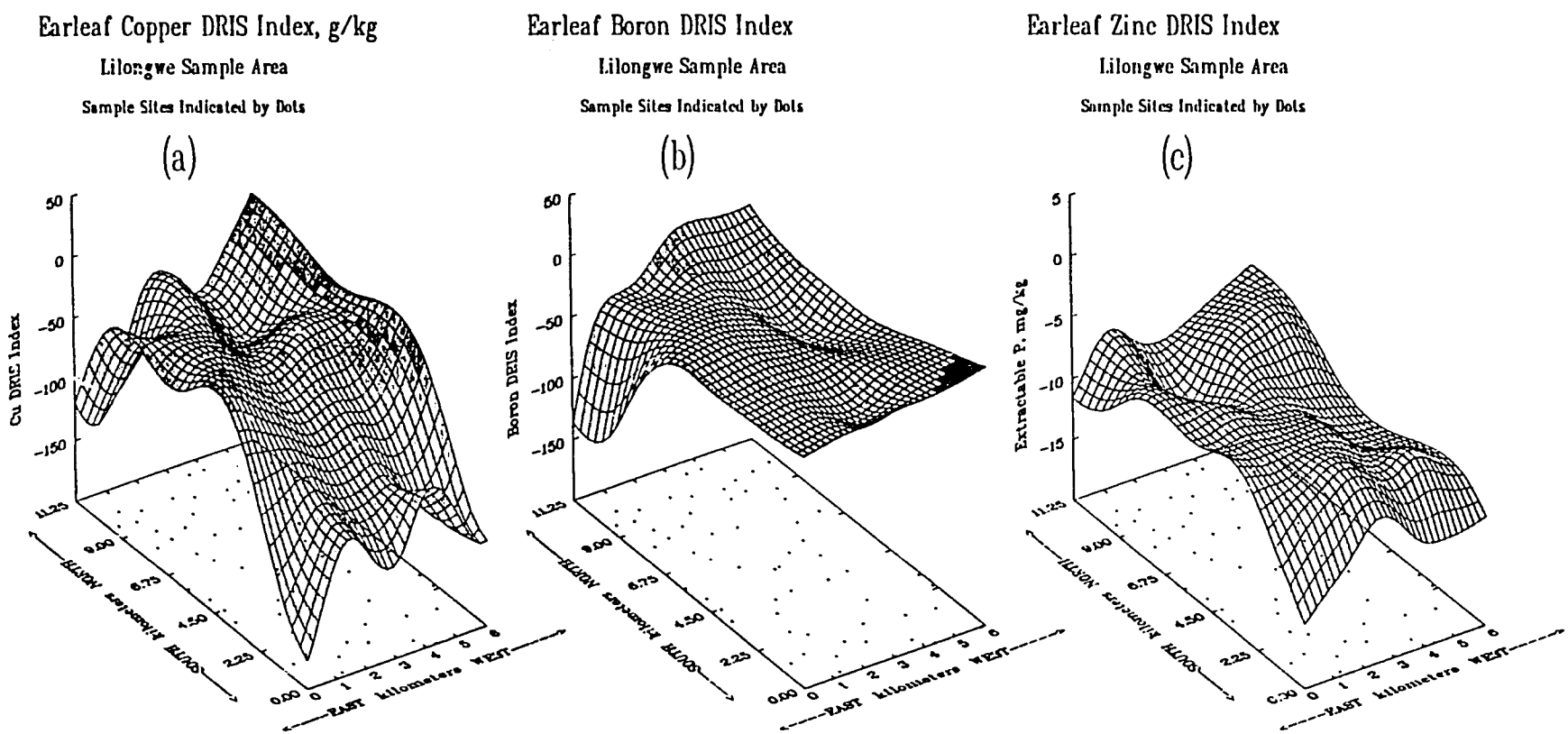

Figure 25. Spatial distribution (DWLS) of earleaf DRIS Indices for Copper, Boron, and Zinc in the 1990 survey of the Lilongwe area.

On-Farm Experiments

The objective of the final phase of the project was to validate the results of the surveys by conducting fertilizer trials on a sub-set of the sampled farms in each of the four sampling areas. This objective was addressed in 1990 by initiating experiments on 20 farms (five in each area) with two replicate blocks per farm. The treatments used in the experiments tested maize response to those nutrients that field observations or lab results from preliminary 1989 survey suggested were in limiting supply in one or more of the sampling areas. It was later discovered that there had been problems with the accuracy of the lab analyses of the 1989 plant and soil samples. Therefore, not all of the appropriate nutrients may have been tested. The 1990

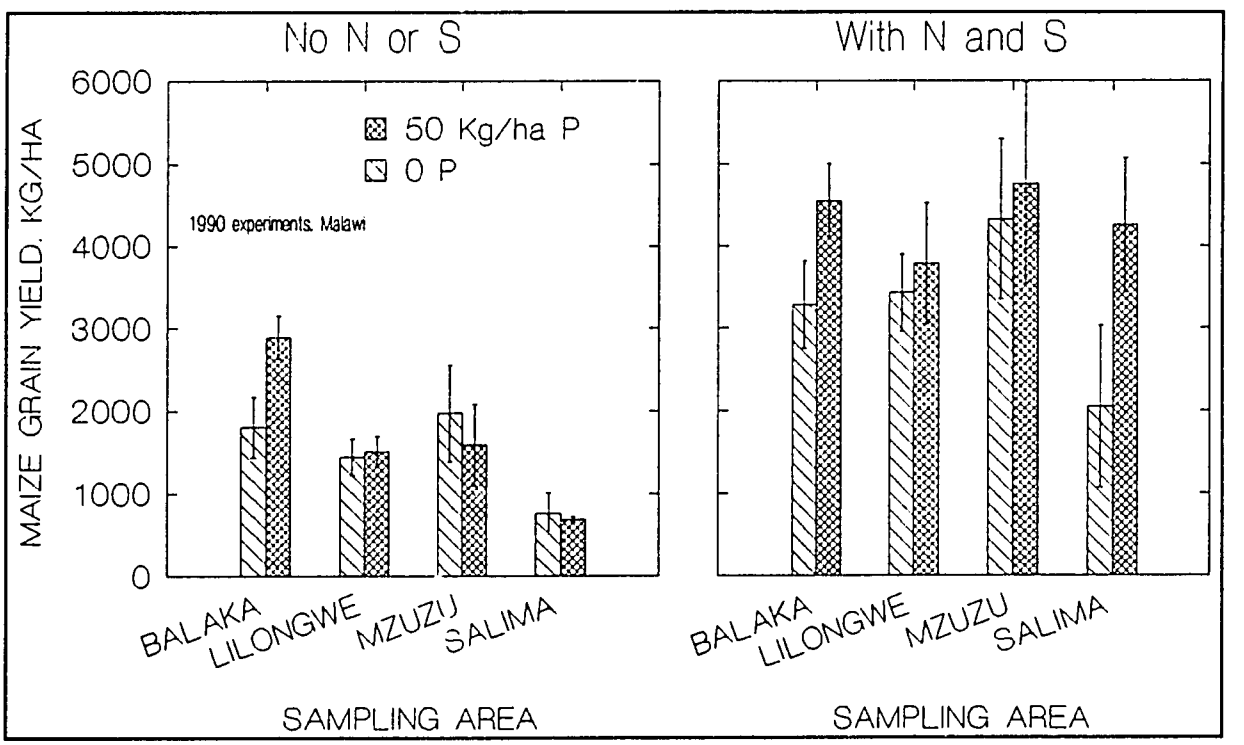

Figure 26. Maize yield responses to applied P with or without applied N. Data are from 14.5 on-farm experiments completed in 1990 in four areas of Malawi. Error bars are two SE.

experiments tested maize response to N, P, and S at all sites, and two additional nutrients (Mg, Zn, Cu or Mn) according to which appeared, from the 1989 survey, to be most limiting. All the nutrients (except N) were tested both with and without application of 80 kg/ha of N. Except for application of the fertilizer materials and harvest of samples, crop management was left to cooperating farmer. Of the 20 experiments, five and a half were lost prior to grain harvest, as a result of drought, termites, cattle, thieves, or premature harvest by the farmer. The results of the remaining 14.5 experiments will be discussed briefly.

We neither visually observed nor measured any significant positive response to Mg, Cu, Mn or Zn (applied as oxides) in any of the 1990 experiments. At one site in the Mzuzu area, Zn gave a significant negative response, which we speculate may have been the result of a Zn-P interaction that reduced P availability.

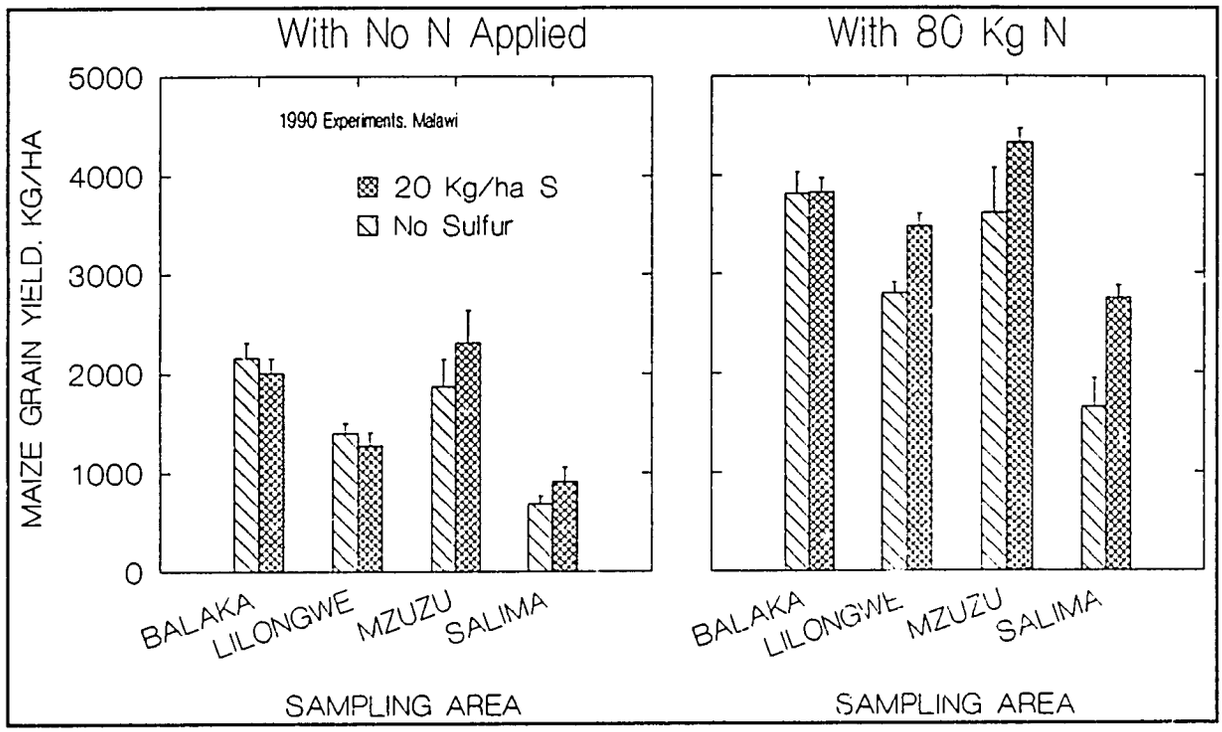

Figure 27. Maize yield response to application of 20 kg/ha sulfur, with or without application of N. Data are from 14.5 on-farm experiments completed in 1990 in four areas in Malawi. Error bars are two SE.

Nitrogen, P and S all produced significant responses at some of the sites. By far the greatest responses were to N fertilization, which produced a significant response at all but one site. The mean response to the 80 kg/ha of N ranged from 1400 in Salima to 1,900 kg/ha of maize grain in Mzuzu. These results indicate that the N responses were in the range of 18 to 24 kg grain /kg N applied, very similar to the 11 to 23 kg grain / kg N reported for the first 60 kg N in experiments by others in Malawi (Saka, et al, 1992). The general N response can be seen by comparing the left side (no N applied) to the right side (80 kg N/ha applied) of Figures 26 and 27. It can also be seen from these figures that the yields of unfertilized maize were in the range of approximately 1,000 to 2,000 kg/ha of grain. Most of these yields were from open-pollinated local land races of maize. These yields are similar to unfertilized open-pollinated maize yields reported from many trials in Malawi over the past several decades (Malawi Government, 1977, Weil, 1985). The occurrence of typical yields and N responses in our on-farm experiments lends credibility to our study and suggests that we succeeded in sampling "typical" Malawi

small-holder fields.

In the 1990 experiments, the response of maize to applied P was so highly variable as to be statistically significant only in the Balaka area, and there only at two sites. It is possible that in the Lilongwe and Mzuzu areas, where soil P sorption capacity is quite high, the 50 kg P/ha applied may not have been enough to overcome the "fixation" reactions. That is, larger P applications may have resulted in more positive responses. However, we do not believe this to be the case since the 1991 experiments produced several significant responses to the same level of P application. Figure 26 shows that the responses to P in 1990 were generally more consistently positive, if not statistically significant, when N was also applied. Part of the variability in the yield shown in Figure 26 is the result of the considerable effect of S on maize yields, since the results shown are averaged over treatments with and without applied S.

The effect of S on maize yield was less variable than that of P, and therefore more often statistically significant, in the 1990 experiments (Figure 27). The analysis of variance showed a significant N x S interaction, a trend also evident from Figure 27. This interaction means that the effect of S was generally significant only when N was also applied. Although the addition of N without S never decreased grain yields, the practice did exacerbate S deficiency symptoms in several experiments. The variability in Figure 27 is much lower than that in Figure 26 because the data in the former were averaged over the two P levels, and P had relatively little effect on yields. When 80 kg N/ha was applied, the application of 20 kg S/ha gave a significant increase in maize yield at all sites, except at those in the Balaka area in which the response to S was significant at only one site. In Salima, where the responses to S were greatest, a kg of S produced approximately 55 kg of extra maize grain. In fact, the returns per kg of added S could have been considerably greater than this, since the following year's experiments indicated that the same response could have been obtained with much less S (see below).

Since yield responses to soil nutrients tend to vary from year to year with weather conditions, and since some of the results of the 190 experiments were inconclusive due to the loss of nearly one third of the on-farm experiments that year, 20 new on-farm field experiments were conducted in 1991. Because S appeared to give widespread response in the 1990 experiments, and micronutrients did not, the 1991 experiments were modified to include several levels of S, and no micronutrients, except Zn, in the Mzuzu area. Obviously, had we been able to get accurate tissue analyses from the 1990 survey in time to re-design the 1991 experiments, we would have included treatments to test the validity of the extreme values for B and Cu that were eventually found to occur in the 1990 survey samples (see section on tissue analyses, above).

The main results obtained from the 1991 experiments are summarized in **Figures 28-30** and in **Table 9.** Of the nutrients tested, N most commonly produced a positive response in maize grain yields. At all but one site, maize responded significantly to the application of 80 kg N / ha, whether or not other nutrients were also applied. However, the effectiveness of N fertilizer was enhanced in all areas when accompanied by application of P and S

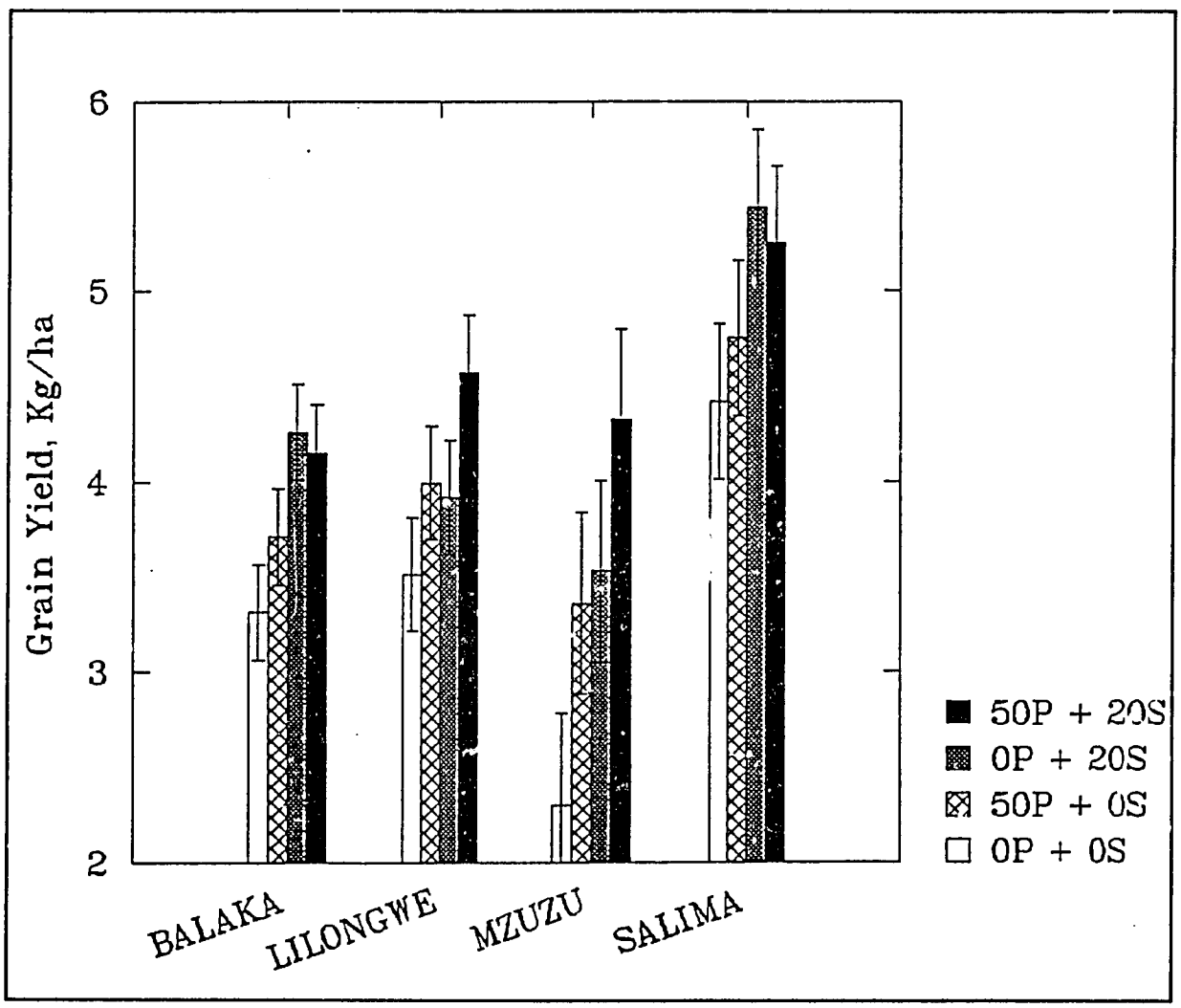

Figure 28. Effect of 50 kg P/ha or 20 kg S /ha on maize yields in Malawi. Means of 3 replications at either 4 or 5 sites in each area in 1991. Bars are two SE. All plots received 80 Kg/Ha of nitrogen as urea.

fertilizer. Yields with no N applied averaged 1121 kg grain/ha (similar to previous reports and to the 1990 experiments). With 80 kg N/ ha, yields increased to an average of 2940 kg grain/ha in the absence of other fertilizer. When both P and S were also applied, the 80 kg N/ha increased yields to an average of 4.016 kg grain /ha. Responses to N ranged from 120 to 230 per cent. These trends represent an average return to N of 23 kg grain/kg N if used alone,

and 36 kg grain/kg N when used in conjunction with P and S fertilizer. The interaction between N and P-S application was greatest in the Mzuzu area where both P and S appear to be quite limiting. In Mzuzu, N fertilizer increased yields by an average of 2840 kg grain /ha when P and S were supplied, but only 976 kg grain /ha when P and S were not supplied.

After N, the next most prevalent responses were those to S. In the Lake Shore areas significant responses to S occurred in 67 per cent of the experiments, either in terms of grain yield increase per ha or per plant. (With stands losses from thieves and cattle, yield data calculated per plant may be more reliable than those calculated per ha.) The comparable figure for the more weathered, residual soil areas (Mzuzu and Lilongwe) was 37 per cent. The interaction between fertilizers was even greater for S than for N. As an example of this interaction, the yields of maize with N and S fertilization in the Mzuzu experiments are shown in Figure 29. When S was applied alone, no significant yield responses occurred; in some experiments the mean yield with S was slightly less than without S. When N and P were also applied, S application of 5 kg S/ha significantly increased average yields from 3458 to 3941 kg grain/ha, or approximately 96 kg grain/kg S applied. Responses to S in conjunction with N were somewhat lower, on the average, in Lilongwe than in the other areas.

Figure 30 shows the average response in each area to S application from 0 to 20 kg S/ha (with 50 kg P/ha and 80 kg N/ha in all cases). The responses indicate that the first increment of 5 kg S/ha (plus the 6 to 7 kg S supplied by the P fertilizer-see discussion below) was generally sufficient for optimal yields. Generally, linear-plateau models (shown in Figure 30) gave a better fit to the data than did quadratic models. The data suggests that an application rate of 5 to 6 kg S/ha is sufficient for maximum response when P is also applied. If these trends hold up, they certainly imply an attractive economic return to amending N fertilizer with S. The regular use of ammonium sulfate fertilizer would supply much more S than needed, as well as potentially cause problems with soil acidity. Occasional

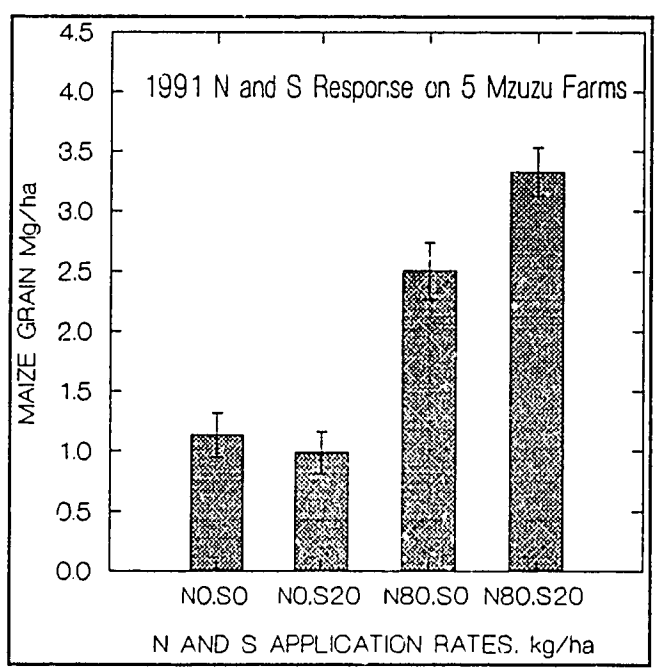

Figure 29. Effect of N and S on maize yields for 1991 experiments in Mzuzu. Means for 0 and 50 kg/ha P fertilization rates at 5 sites. N, S and NxS effects were significant. Error bars are two SE.

use of ammonium sulfate, in rotation or combination with other N fertilizers, would most likely be quite beneficial. The oportunities to use indigenous S mineral deposits, such as gypsum orpyrite, should be investigated.

There were fewer responses to P than to S or N. The interaction with N fertilization was similar to that in the case of S, just discussed. When no N was applied, P produced no positive yield responses, or even slight yield declines. With both N and S applied as well, the application of 50 kg P/ha increased average yields from 3756 to 4016 kg grain/ha. This yield response represents an increase of 5.2 kg grain/kg P. In the absence of S application, the measured response to P was somewhat greater, 10.4 kg grain/kg P. Significant negative P x S interactions occurred in several experiments. This result, along with field observations that foliar symptoms of S deficiency were reduced by P application, suggests that the S in the triple super phosphate (TSP), used to supply P in these experiments, provided significant quantities of S as well P. The TSP available in Malawi contained close to 2.9 per cent S. Material available in Maryland had a similar S content. An application of 50 kg P/ha required the use of 263 kg/ha of TSP, bringing with it approximately 7 kg S/ha (0-44-0 is 44 per cent P_2O_5 or 19 per cent P, thus 50/0.19 = 263 kg TSP/ha, and 0.029 x 263= 7.7 kg S). Thus the P fertilizer used in our experiments supplied a significant level of S, as well. It consequently must be considered that some of the responses accorded to P may have, in fact, been due partially to S. We attempted to sort out this potential confounding of P with S treatments by using diammonium phosphate (DAP) in a series of follow-up experiments, but these efforts were foiled by the severe drought that occurred throughout Malawi in 1992, destroying all the field experiments we initiated that year.

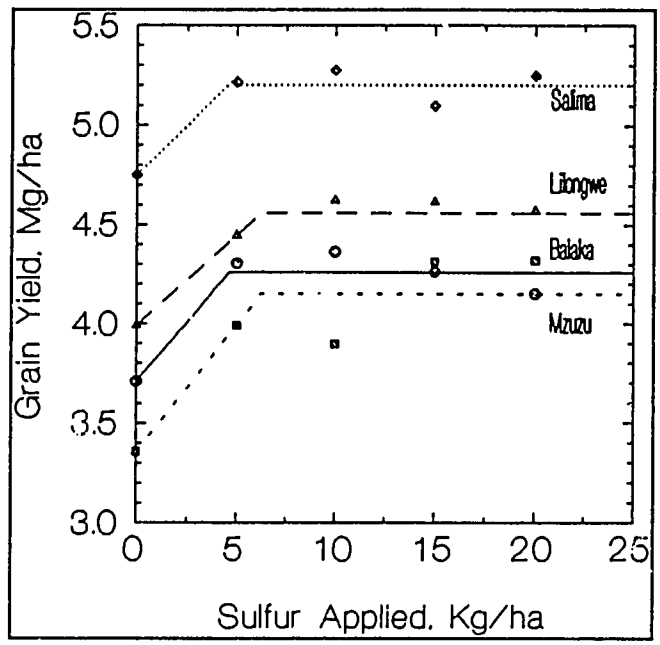

Figure 30. Maize yield response to sulfur applied as gypsum in 18 on-farm experiments in four areas in Malawi. Data from 1991 are fit to linear-plateau models.

A final point to consider with regard to the on-farm experiments is the value of the DRIS Indices in predicting the growth responses measured. Because of the laboratory problems discussed earlier, the data set available to us for investigating this question is somewhat limited. We have two sets of yield data

for on-farm experiments, namely from 1990 and 1991. However, from these plots we have the corresponding tissue samples only for young plants from 1991, and only for earleaves from 1990.

Figure 31 shows the relationship between the DRIS Index data and the maize response data for a total of 32.5 on-farm experiments completed during the two years. If the DRIS indices effectively reflected the nutrient requirements of the crops, then we would expect the maize to give the greatest response to a nutrient at a site for which the DRIS Index was lowest or most negative. Where the DRIS index was positive, we would not expect maize to respond positively to the application of the nutrient in question. Therefore, as the DRIS Index increases along the horizontal axis in

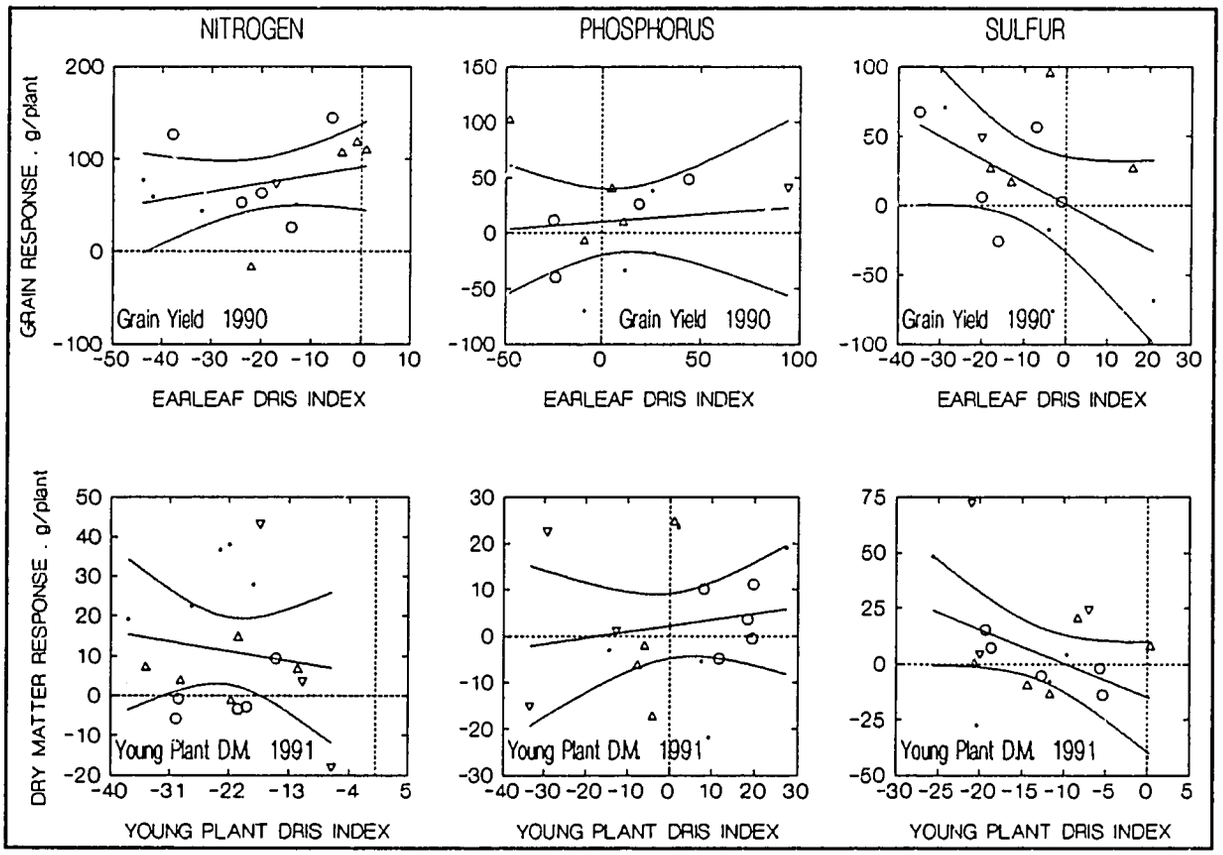

Figure 31. Relationship between earleaf or young plant DRIS Indices (for no-fertilizer control plots) and grain or dry matter responses to N, P, and S in 1991 experiments. Linear regression with 95% confidence interval.

Figure 31, we expect the maize response to decrease. We would expect no data in the upper right quadrant, in which both maize response, and the DRIS index are positive. This last expectation was nearly satisfied for N and S, but not for P. The relationship between DRIS Index and maize response was very weak for both N and P. Only for S does the relationship resemble what is theoretically expected. Similar analyses were performed using tissue concentrations instead of DRIS Indices, but the results were nearly

identical (data not shown). We conclude that either method of interpreting the tissue analysis data was of very limited value in predicting responses in a given experiment.

Research Conclusions

The tissue data, and to a lesser degree the soils data, were useful in delineating differences in fertilizer requirements among the four areas studied. Our hypothesis was that the results of the survey would be useful in predicting to which nutrients, and to what degree, maize would be likely to respond in each of the four areas studied. The nutrients for which the project produced the most maize response information are N, P, and S. Table X summarizes the project findings with regard to how these three nutrients varied among sample areas. The first section of Table X shows the frequency of maize responses in each area. Nitrogen produced responses in both young plant dry matter and in grain yields in nearly every experiment in all four areas. Responses to S were second most frequent, responses to P were least frequent. Lilongwe had the most responses to P. Salima had the most responses to S. From the second section of Table X it can be seen that the magnitude of maize response to N was greater in Salima than in the other areas. The magnitude of responses to P was clearly greatest in Mzuzu. The responses to S were clearly smallest in Lilongwe. By multiplying the frequency of responses by the mean magnitude of yield response, we produced an index of fertilizer response shown in

Table IX. Maize responses to fertilization with N, P, and S in 1991 experiments, and Median DRIS Index values for 1990 Survey in four areas in Malawi.

Sample Area	Nutrient Element		
	N	P	S
Significant responses / experiment[2]			
Balaka	3.4	1.00	1.80
Lilongwe	3.5	2.00	0.75
Mzuzu	3.0	1.25	1.00
Salima	3.0	0.2	2.00
Mean Grain Yield Response, Mg/ha			
Balaka	2.51	0.35	0.84
Lilongwe	2.84	0.43	0.36
Mzuzu	2.84	0.93	1.09
Salima	3.51	0.30	0.91
Yield Response x Number of Responses			
Balaka	8.5	0.35	1.51
Lilongwe	9.9	0.86	0.27
Mzuzu	8.5	1.40	1.09
Salima	10.5	0.06	1.82
Median Young Plant DRIS Index			
Balaka	- 1	0	+1
Lilongwe	- 5	0	+6
Mzuzu	- 2	-12	+4
Salima	-14	+ 7	-5

1/ Includes significant (P=0.95) responses for young plant dry matter, grain yield/ha, grain yield/plant, and moisture content of cobs.

the third section of Table X. Using this index we can rank the four sample areas with regard to their requirements for N, P and S as shown in Table XI.

Such rankings could form the basis of a more rational approach to fertilizer development and distribution. Given the limitations of the present study, we would recommend that a significant effort be made to enhance the use of N fertilizers in all areas, but especially in Salima and Lilongwe. Efforts to increase P fertilizer use should be concentrated in Mzuzu and Lilongwe. Phosphorus should not be wasted by general distribution in Salima. Finally, new efforts to increase the use of S should be focused on Salima and Balaka, with some use also encouraged in Mzuzu.

It is encouraging to note that at least one set of data from the sample survey is in accord with the above conclusions based on field experiments. In fact the above rankings can be predicted almost exactly from the data on young plant DRIS Indices for the survey samples. These data were given in Figure 16, and are summarized in the final section of Table 10. Note that the rankings (Table 11), and therefore the recommendations, suggested by these indices are identical to those derived from the experiments. DRIS Indices based on earleaves of post tasseling plants (Figure 17) were much more erratic, and failed to correspond with the results of the field experiments, other than to indicate the low P requirement in Salima. The availability indices presented in Table 8 were also based on post-tasseling earleaf samples, and did little to predict which areas were more in need of N, P or S, except again, with regard to the low requirement for P in Salima.

Table X. Comparison of two methods used in ranking four areas in Malawi according to their requirements for N, P, and S fertilizer.

Nutrient Required	Basis of Ranking Nutrient Requirement[1]	
	Yield Response Index from On-Farm Experiments	DRIS Indices From Survey of Young Maize Plants
N	Salima>Lilongwe>Mzuzu=Balaka	Salima>Lilongwe>Mzuzu=Balaka
P	Mzuzu>Lilongwe>Balaka>Salima	Mzuzu>Lilongwe>Balaka>Salima
S	Salima>Balaka>Mzuzu>Lilongwe	Salima>Balaka>Mzuzu>Lilongwe

1/ Using data from Table 10.

The soils data on plant-available P corresponded quite well to the experimental results. Unfortunately no soil tests exist that can reliably predict the need for N or S. The data available in this study on total soil C and N were of little predictive value. Data available on soil S was very limited, partly because of difficulty getting repeatable laboratory rsults for soil sulfate-S,

and partly because soil sampling to a greater depth than is practical in a rapid survey would be required to account for sulfate-S potentially available to maize.

Overall, the project pioneered the use of crop tissue surveys for predicting spatial variation in fertilizer requirements, both among widely different regions, and within a localized areas at a scale of a few kilometers. Clear differences were delineated between the four sample areas. Within each sample area certain spatial trends were revealed, as well. However, since none of the areas studied included broad zones of markedly contrasting soils, the localized patterns were not as clearly defined as the inter-regional ones.

6. Project Impact, Relevance and Technology Transfer.

a. Usefulness of Findings.

The results of this project should find immediate practical use in Malawi. The problem of efficient fertilizer utilization is of continuing agronomic and economic significance in Malawi. The project results should be of use in two ways. Firstly, the information gathered during the project can be used to guide fertilizer distribution in the general vicinity of the four study areas, all of which are in important Agricultural Development Divisions for maize production in Malawi. Secondly, the methods of fertility survey and analysis developed by the project can be used on a wider scale, to provide on-going guidance for national fertilizer importation, manufacture and distribution.

Although the results of this project have yet to be finalized, it was gratifying to see that the Government of Malawi has reacted positively to the attention we have called to the need for sulfur in many areas. A significant portion of the fertilizer imported in the past three years for small holder use is fortified with about 4 per cent S. The project has attracted positive attention in Malawi from officials in the Ministry of Agriculture, the University of Malawi, the Rockefeller Foundation, and the F.A.O. Efforts have been made to bring these institutions together to coordinate fertilizer-related activities. The project has shown the need for S fertilizers to be much more critical and widespread than was previously recognized. Partly as a result of these findings, the Department of Mines has begun to explore the possibility of making S fertilizer from indigenous gypsum deposits, and has begun a pilot mining and grinding operation. We anticipate that the results of this project will be used by the Ministry of Agriculture to revise its fertilizer distribution program to better allocate N, P, S, and possibly Zn fertilizers throughout the nation.

b. Impact of Project on Capacities and Capabilities of Collaborating Institutions and Individuals.

Dr. Weil, the principal investigator, and Dr. Mughogho, the principle collaborator, have worked closely together and have enjoyed an excellent working and personal relationship. Dr. Weil made six visits to Malawi, each for approximately one month's duration. During these visits, and between each, using telephone and FAX, Drs. Weil and Mughogho collaborated in designing experiments, trouble-shooting laboratory analyses, analyzing data, collecting samples, and conducting field experiments. Dr. Mughogho energetically maintained the project's momentum throughout the period. Unfortunately, there was much less effort on behalf of the

project from the collaborating scientists from the soil analysis laboratory the Ministry of Agriculture. They made relatively little effort to respond to our invitations to join the planning and the field work, and did very little to see that the analytical work in the lab was done in a timely and accurate manner. The efforts of Drs. Mughogho and Weil, and others, to assist in improving the procedures in the Ministry lab, were met more with hostility than with cooperation by the mid-level scientists. The junior technical staff of the laboratory, including those hired on project funds, generally responded more positively and showed improvement in their motivation and skills.

The project has had an obvious effect in strengthening scientific capacity at Bunda College of Agriculture and the Chitedze Agricultural Research Station, by the purchase and installation of some $20,000 worth of basic laboratory (semi-analytical electronic balance, automatic distilled water apparatus, muffle furnace, large capacity Wiley mill, etc.) and computer equipment, along with training, when needed, in the use of this equipment. A very useful 4-wheel drive vehicle has also been provided to Bunda College, which has helped in solving a critical transportation shortage at that institution. Three lab technicians were hired at the research station to work on project analyses, as well as to help in better staffing that facility. Unfortunately, the most experienced of the technicians at Chitedze resigned, during the first year of the project, to work in private industry. The leaders of this project joined officials of the Rockefeller Foundation and the F.A.O. to assist the Ministry of Agriculture in improving the performance and management of its analytical laboratories at Chitedze. Outdated procedures, insufficient supervision and management, and lack of proper training at this research station had resulted in critical problems in obtaining the reliable, accurate analyses needed to advance agriculture in the country.

The computer skills of Dr. Mughogho, several other Bunda scientists, and a number of students have been enhanced as a result of project activities, which included providing a portable computer work station to Bunda College. Six college students were hired on a part-time basis and have, as a result, received training in computer use, field research, cropping practices, soil science, and laboratory techniques. Of these students, Mr. R.R. Sibale is currently working for the Ministry of Agriculture as a Professional Officer; Mr. C.R. Mphaluwa is now working for the Forestry Department as a Technical Officer; Mr. G.Y.A. Mphepo is now a Secondary School Teacher; Mr. K.B. Lweya is completing a five year degree program at Bunda College; Mr. J.K. Munyenyembe is also completing a degree at Bunda; and Mr. Joseph B.J. Jonazi is a Staff Associate at Bunda, teaching Statistics and Biochemistry.

7. Project Activities and Outputs.

a. Meetings Attended.

American Society of Agronomy Annual Meetings, Division for International Agronomy. Las Vegas, NV. 11/89. Weil.

American Society of Agronomy Annual Meetings, Division for International Agronomy. San Antonio, TX. 11/90. Weil.

African Soil Science Society. Cairo, Egypt. 8/91. Mughogho.

Spatial Variability Workshop. Soil Science Society of America. Denver CO. 11/91. Weil.

World Bank Workshop on Using and Sustaining Africa's Soils. 1/92. Weil.

Agroecology Network meetings. Nairobi, Kenya. 3/92 Mughogho.

Int'l. Workshop on Agroforestry Research in the Miombo Ecological Zone of Southern Africa. Lilongwe, Malawi. 6/92. Mughogho, Weil.

African Soil Science Society. Nairobi, Kenya. 8/92 Mughogho.

American Society of Agronomy Annual Meetings, Division for International Agronomy. Minneapolis, MN. 11/92. Weil.

b. Training.

Practical research and computer training for six student assistants at Bunda College (listed in section 6b, above).

Training in Geostatistics, two-day workshop in Denver. 11/91. (Weil).

Training in basic computer skill and statistical analyses at Bunda College. (Mughogho).

Practical research and analytical skills training for three American student assistants in Maryland. 91-92.

Publications.

In print:

A volunteered paper was presented at the national meeting of the American Society of Agronomy in October, 1990 in Nevada.

This paper was written on the preliminary work done in Zimbabwe prior to USAID funding, but the present project was discussed as well. Reference: Weil, R. R., L. Mukurumbira, and P. Butai. 1989. Survey approach to enhancing site-specificity of fertilizer recommendations in peasant agriculture. Agronomy Abstracts. p.59.

Weil, R., L. Mukurumbira, and P. Butai. 1991. An approach to improving site-specific fertilizer recommendations in peasant agriculture. Tropical Agric. 68: 186-190. [Work completed prior to AID funding, but preliminary in nature to the current project.]

In press:

Weil, R.R. and S.K. Mughogho. 1993. Nutrient Cycling By Acacia albida in Agroforestry Systems. Chp. 8 in Ragland, etal (ed) Technologies for Sustainable Agriculture in the Tropics. Amer. Soc. of Agronomy Spec. Pub. (in press). [Review and work done as off-shoot of current project]

In preparation:

"Sulfur Status of Maize in Malawi" for Sulfur in Agriculture.

"Use of Rapid Crop Survey to Assess Regional Fertilizer Needs" for Tropical Agriculture.

"Spatial Variability and Covariance of Plant and Soil Fertility Parameters in Malawi" for Soil Science Society of America Journal.

"New Tools to Improve Efficiency of Fertilizer Use in Malawi" for Bunda Journal of Agricultural Research.

8. Project Productivity.

The project was generally successful in meeting its research goals. It has demonstrated that a rapid survey of farmer maize fields, especially in early growth stages, is a practical and effective approach for assessing the fertility requirements and problems in a geographic area. Details of methodology have been worked out to guide the planning, execution and analysis of such surveys on a large scale in Malawi. Differences in P and S requirements among regions were clearly identified by the project. Two sets of on-farm experiments were carried out (the project proposal called for only one set) to successfully validate the results of the survey for several important nutrients. Geostatistical and distance weighted regression techniques were successfully applied to describe the variability in nutrient status

at a scale of 0.1 to 10 km.

The project's success was somewhat limited by problems in the analyses at the soils lab at Chitedze. First, the results provided by that lab in 1989 were inaccurate enough with regard to several nutrients (primarily B and micronutrients) to misdirect the treatment choices for some of the on-farm experiments. Second, after a change in personnel at the Chitedze lab in 1990 and 1991, results became very unreliable and tardy, so that eventually all analytical work had to be done in the US. Third, the sample handling procedures at Chitedze resulted in the complete loss of about 20 per cent of the project soil samples (mainly samples from representative profiles) and about 10 per cent of the plant tissue samples. The volume of the remaining samples was so severely reduced that only limited analyses could be performed, especially in the case of the soil samples. This reduction limited the capacity of the project to correlate plant and soil data. The lack of a good set of soil S data was especially unfortunate.

Even the problems with the Chitedze lab led to positive developments in the project. The project personnel cooperated with others to help improve the management and productivity of the Chitedze lab. Although too late to directly impact on this project, new methods have now been established and new technical staff are now in place. Also, partially as a result of the difficulties experienced at the Chitedze lab, the Rockefeller Foundation is exploring the possibility of funding the development of an analytical lab at Bunda College of the University of Malawi in cooperation with the project collaborator there.

9. Future Work.

Several areas of work are developing as a result of this project's activities. First, one offshoot of the project has been interesting work on the influence of the tree, Acacia albida, on soil fertility, especially sulfur. Preliminary work was carried out in response to observations made by the project scientists in 1989 and 1990, while engaged in on-farm sampling for the project surveys. The preliminary study of the Acacia tree effects is encouraging enough to warrant a somewhat wider sampling, that might provide the basis for a future project on the utilization of this tree's unique role in nutrient cycling.

Second, larger scale surveys of the type developed by the project are warranted. The project personnel are working with the Ministry of Agriculture, especially the Maize Commodity Team, to coordinate the project results with their current soil fertility work.

Third, the project highlighted the importance of sulfur in several areas of Malawi and of phosphorus in others. Efforts to

increase the use of S are already underway. The principal investigator and principal collaborator have developed a proposal for future work aimed at utilizing indigenous resources to supply the S and P needs of Malawi farmers. This proposal also will develop integrated livestock and legume-based cropping systems to multiply the effects of indigenous P and S sources, by also enhancing nitrogen supplies and cycling. Both the World Bank and the Rockefeller Foundation have expressed an interest in the on-farm applied aspects of this work.

Dr. Mughogho is planning a nine-month sabbatical in 1993/94 to work in Dr. Weil's lab on methods of improving indigenous P and S sources.

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